Impregnation of railway sleepers - Process optimisation by using an oily wood preservative and a mechanical pre-treatment

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„Wissenschaftlich gesehen, ist jede Schwelle ein Individuum […]“

- Dr. Georg Schulz 1964

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Abstract

The use of creosote as a wood preservative has a long history. For more than 170 years wooden railway sleepers are impregnated with creosote. After initially using vacuum pressure processes for impregnation, empty cell processes have been developed quickly and are used until today. Because of political developments and its alarming properties against human health and environment, creosote will probably be banned from the European market in the near future. Today, most of the sleepers in track are concrete sleepers, but wooden sleepers are still essential for particular applications such as tracks with narrow curve radii, mountain tracks with uneven underground conditions and low ballast bed thicknesses, for switches, for railway bridges and for shunting stations. Without a successor product, wooden sleepers have to be installed either again without adequate protection against wood destroying organisms or will possibly be replaced by sleepers made from alternative materials like concrete, steel or polymers. To ensure the use of wooden sleepers as part of the track superstructure after a possible ban of creosote, two different types of process optimisation for sleepers made from European beech (*Fagus sylvatica* L.) have been evaluated regarding their potential.

The first type of process optimisation was carried out by a mechanical pre-treatment namely incising. It was evaluated regarding its influence on seasoning speed, check formation and dimensional stability. Incising reduced the formation of checks in length, width and depths for sleepers made from European beech until they were sufficiently seasoned. No decrease in seasoning duration as well as no influence on the moisture distribution inside the sleeper was shown due to incising. An increased dimensional stability during seasoning was also not achieved.

The second type of process optimisation focused on reaching a complete penetration of the sleeper cross section using an alternative oily wood preservative as possible replacement for creosote. The penetration behaviour of different alternative oily products after pressure impregnation is hardly investigated so far. Therefore, research has been carried out in regard of hydrophobic carrier substances and their viscosity and penetration behaviour for Beech sleepers. By increasing the temperature, the investigated hydrophobic carrier substances showed decreasing viscosities, also with the addition of copper hydroxide and a co-biocide as biocidal components. A macroscopically investigation of the penetration behaviour of three hydrophobic carrier substances in Beech and Scots pine sapwood (*Pinus sylvestris L.*) showed incomplete penetration of the cross section for Beech and complete penetration of the cross section for Scots pine sapwood, when end grains were sealed.

A microscopic analysis of two hydrophobic carrier substances showed similar penetration pathways compared to creosote. For Beech, most of the penetration of the hydrophobic carrier substances took place in longitudinal direction via vessels and fibers, whereas less penetration seemed to occur within the wood rays. For Scots pine sapwood, penetration in longitudinal direction took place through the lumen of the late- and earlywood, but also through resin canals.

The impregnation of European beech using an alternative oily wood preservative did not result in complete penetration of the specimen cross section, using empty cell and full cell processes. In case of empty cell processes, retentions were de- and increased by variations of air pressure intensity and fluid pressure duration. However increased retentions did not improve the penetration depth. Modified versions of the empty cell process including pre-heating of the specimens did also not improve preservative penetration at comparable retentions.

Measurements regarding pressure gradients during the impregnation of Beech sleepers were carried out, excluding a possible negative influence of compressed air as cause for the insufficient penetration of the alternative oily wood preservative. However, a substantial influence of the longitudinal direction on the air pressure distribution (up to 700 mm) became apparent. Furthermore, a delay in pressure distribution in transversal direction was also observed. Additional evaluations regarding the influence of the three anatomical directions on the preservative penetration, showed that preservative penetration is considerably more effective in axial direction during an applied fluid pressure. To take advantage of the axial preservative penetration, the existing drilling pattern, which improves the penetration of creosote in Beech sleepers, was adapted to the penetration behaviour of the alternative oily wood preservative. Although, results showed a considerable improvement in preservative penetration, a complete penetration of the cross section was not reached.

Further process optimisations using water-based, chromium-free and copper-based preservatives resulted in complete penetration of the sleeper cross section even without attached drilling pattern and incising. Hereby, the insufficient penetration of the sleeper cross section by the alternative oily wood preservative was compensated. Therefore, the potential of being the first step of a double impregnation in combination with the alternative oily wood preservative became apparent.

During the double impregnation a positive effect of incising on retention and -penetration of the alternative oily wood preservative was occurring in the area of the incision. Furthermore, it became evident, that a gross weight of at least 950 kg/m³ was needed for penetrating the peripheral area of the sleepers, to achieve an additional homogenous envelope treatment by the alternative oily wood preservative.

Both types of process optimisation showed great potential for improving the properties of Beech sleepers and ensuring the use of wooden sleepers even beyond a possible ban of creosote.

Zusammenfassung

Kreosot als Holzschutzmittel hat bereits eine lange Geschichte. Seit mehr als 170 Jahren werden hölzerne Eisenbahnschwellen mit Kreosot imprägniert. Während zunächst Vakuumdruckverfahren zur Imprägnierung verwendet wurden, wurden kurz darauf Sparverfahren entwickelt, welche bis heute eingesetzt werden. Aufgrund politischer Entwicklungen sowie seiner bedenklichen Eigenschaften für die menschliche Gesundheit und Umwelt, wird Kreosot in naher Zukunft mit hoher Wahrscheinlichkeit für den europäischen Markt verboten. Zwar werden heute vorwiegend Betonschwellen verbaut, gleichwohl sind Holzschwellen nach wie vor in einigen Bereichen unverzichtbar. Dies gilt insbesondere für Streckenabschnitte mit engen Kurvenradien, für Bergstrecken mit unebenen Untergrundverhältnissen und geringen Schotterbettstärken, für Weichen, für Eisenbahnbrücken und für Rangierbahnhöfe. Ohne ein Ersatzprodukt für Kreosot müssten Holzschwellen entweder wieder ohne ausreichenden Schutz gegen holzzerstörende Organismen eingebaut werden oder möglicherweise durch Schwellen aus alternativen Materialien wie Beton, Stahl oder Polymeren ersetzt werden. Um die zukünftige Verwendung von Holzschwellen im Gleisoberbau nach einem möglichen Verbot von Kreosot sicherzustellen, wurden folglich zwei verschiedene Arten der Prozessoptimierung für Schwellen aus europäischer Buche (*Fagus sylvatica* L.) auf ihr Potential untersucht.

Bei der ersten Art der Prozessoptimierung handelte es sich um eine mechanische Vorbehandlung mittels Schlitzperforation. Hierbei wurde der Einfluss der Schlitzperforation auf die Trocknungsdauer, die Rissbildung und die Dimensionsstabilität untersucht. Die Schlitzperforation zeigte einen positiven Einfluss auf die Rissbildung bei Schwellen aus europäischer Buche. Die Länge, Breite und Tiefe der auftretenden Risse konnte bis zum Erreichen der Tränkreife reduziert werden. Eine Verkürzung der Trocknungsdauer sowie ein Einfluss auf die Feuchteverteilung innerhalb der Schwelle konnte durch die Schlitzperforation wiederum nicht nachgewiesen werden. Auch eine erhöhte Dimensionsstabilität während der Trocknung wurde nicht erreicht.

Bei der zweiten Art der Prozessoptimierung wurde der Fokus auf eine vollständige Penetration des Schwellenquerschnitts unter Verwendung eines alternativen öligen Holzschutzmittels gelegt. Dieses soll als möglicher Ersatz für Kreosot dienen. Da das Penetrationsverhalten verschiedener alternativer öliger Produkte bei Buchenschwellen bisher nur wenig untersucht ist, wurden zunächst hydrophobe Trägersubstanzen hinsichtlich ihrer Viskosität sowie Eindringung in Buchenholz untersucht. Die untersuchten hydrophoben Trägersubstanzen

zeigten bei Temperaturerhöhung eine Abnahme in der Viskosität. Bei Zugabe von Kupferhydroxid und einem Co-Biozid nahm die Viskosität bei steigender Temperatur ebenfalls ab. Eine makroskopische Evaluierung des Penetrationsverhaltens der hydrophoben Trägersubstanzen in Buche und Kiefernsplintholz (*Pinus sylvestris* L.), zeigte eine unvollständige Penetration bei Buche und eine vollständige Penetration bei Kiefernsplintholz. Hierbei waren die Hirnseiten versiegelt.

Eine mikroskopische Analyse der Penetrationswege von zwei hydrophoben Trägersubstanzen zeigte Ähnlichkeiten im Vergleich zu Kreosot. Bei Buche erfolgte der größte Teil der Penetration in Längsrichtung über Gefäße und Fasern, während eine geringere Penetration innerhalb der Holzstrahlen stattzufinden schien. Bei Kiefernsplintholz erfolgte die Penetration in Längsrichtung durch das Lumen des Spät- und Frühholzes, aber auch durch die Harzkanäle.

Die Imprägnierung von Buche mit einem alternativen öligen Holzschutzmittel führte bei Spar- und Vollzellprozessen nicht zu einer vollständigen Durchdringung der Prüfkörperquerschnitte. Bei den Sparverfahren konnten die Einbringmenge durch eine Variation der Luftdruckintensität und der Flüssigkeitsdruckdauer verringert bzw. erhöht werden. Erhöhte Einbringmengen führten jedoch nicht zu einer Verbesserung der Schutzmittelpenetration. Ein Vorwärmen des Buchenholzes durch zwei modifizierte Varianten der angewendeten Sparverfahren führte ebenfalls zu vergleichbaren Einbringmengen. Erneut konnte eine Optimierung der Schutzmittelpenetration nicht erreicht werden.

Durchgeführte Messungen zum Druckverlauf während der Imprägnierung von Buchenschwellen, schlossen einen möglichen negativen Einfluss von komprimierter Luft als Ursache für die unzureichende Penetration des alternativen öligen Holzschutzmittels aus. Allerdings wurde ein erheblicher Einfluss der longitudinalen Richtung auf die Luftdruckverteilung (bis zu 700 mm) im Holzinneren festgestellt. Des Weiteren wurde eine Verzögerung der Druckverteilung in transversaler Richtung beobachtet. Weiterführende Untersuchungen bezüglich des Einflusses der drei holzanatomischen Richtungen auf die Schutzmittelpenetration zeigten, dass die Schutzmittelpenetration in axialer Richtung deutlich effektiver ist. Um die Vorteile der axialen Schutzmittelpenetration zu nutzen, wurde das bereits vorhandene Bohrbild zur Verbesserung der Kreosotpenetration an das Penetrationsverhalten des alternativen öligen Schutzmittels angepasst. Die Ergebnisse zeigten zwar eine deutliche Verbesserung der Schutzmittelpenetration, eine vollständige Durchdringung des Querschnittes wurde jedoch nicht erreicht.

Aufgrund dessen wurden weitere Prozessoptimierungen durchgeführt. Beim Einsatz von wasserbasierten, chromfreien und kupferbasierten Schutzmitteln konnte im Gegensatz zum alternativen öligen Schutzmittel, eine vollständige Durchdringung des Schwellenquerschnittes erreicht werden. Dies war auch ohne Bohrbild und Schlitzperforation möglich. Hierdurch konnte die unzureichende Penetration des öligen Schutzmittels im Schwelleninneren ausgeglichen werden. Somit kommt die Imprägnierung mit wasserbasierten Holzschutzmitteln, als erster Schritt einer Doppelimprägnierung in Kombination mit dem alternativen öligen Holzschutzmittel in Frage.

Bei der Doppelimprägnierung zeigte die Schlitzperforation einen positiven Effekt auf die Einbringmenge sowie Penetration des alternativen öligen Holzschutzmittels im Bereich der einzelnen Schlitze. Des Weiteren zeigte sich, dass für eine homogene Penetration des Randbereiches der Schwellen ein Rohgewicht von mindestens 950 kg/m³ erforderlich war, um eine zusätzliche homogene Penetration durch das alternative ölige Holzschutzmittel zu gewährleisten.

Beide Arten der Prozessoptimierung zeigten großes Potenzial, die Eigenschaften von Buchenschwellen zu verbessern und den Einsatz von Holzschwellen auch über ein mögliches Verbot von Kreosot hinaus zu gewährleisten.

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1 General introduction

1.1 The history of wooden railway sleepers

The history of wooden railway sleepers as part of the track superstructure is as old as the railroad itself. During the beginning of the railroad industry different sleeper types (single supports, long sleepers and cross ties), made from various raw materials (natural stone, wood or iron), have been in direct competition. At the end of the 18^{th} century, the cross tie made from wood and also steel won the competition against the other sleeper-types and ousted those nearly completely (Schramm 1952). The first installed sleepers were primarily made from oak (*Quercus spp.)* with a high percentage of heartwood. Due to the increasing need of wooden sleepers and the low availability of sleepers made from European oak (*Quercus robur* L.*, Quercus petraea* (Matt) Liebl.*, Quercus pubescens* Willd.), the industry had to fall back on sleepers made from Scots pine *(Pinus sylvestris* L.*)* and European beech (*Fagus sylvatica* L.). Based on the low natural durability of both wood species, the service life of the sleepers amounted 6 to 8 years (Scots pine) and 2.5 to 5 years (Beech) (Mörath1956) and therefore were not satisfactory. To increase the life span of the used wood species a method for preservation was needed. Even today, the wooden sleeper is still used in the form of track, turnout or bridge sleepers. According to EN 13145 (2011), the actual required dimensions must be specified by the customer during submission of the order. In most cases, the standard track sleeper has a length of 2600 mm and a cross section of 160 x 260 mm² and is made from Beech. Turnout sleepers show in most cases the same cross section, however can reach a length of up to 7000 mm. To ensure the track gauge, turnout sleepers are made from Oak, based on their high dimensional stability. Bridge sleepers on the other hand are also made from Oak, but have a far bigger cross section. Common dimensions from 230 x 230 mm² or 240 x 260 mm² up to 24 x 300 mm² are possible.

1.1.1 Creosote

The fast growing rail industry gave not only impulses towards the forming impregnation industry, but also towards production of creosote in industrial scale (Bach 1983). Creosote is a complex mixture of chemical compounds (Wälchli 1983). The main components of creosote are a large variety of mainly polycyclic aromatic hydrocarbons (PAH) (Novak 1956), which are extracted by distillation of coal tar at temperatures between 200 to 400°C.

In the beginning of its application, creosote was not subjected to any specific manufacturing conditions (Schulz 1978). Especially during the 19th century, the composition of creosote changed significantly over the years. Reasons were changes in sources and increasing interest in coal-tar distillation as source of valuable chemicals (Richardson 1994). First incomplete approaches regulating the creosote quality, are known from the 1860s. By the beginning of the 20th century, a confusing variety of quality regulations existed and led to the efforts of international harmonization (Schulz 1978). First actual standardisations regarding quality regulations of creosote as a wood preservative, were done by the “Scandinavian and Budapest Specifications” in 1937 and 1938. During the following years, the technical specifications of individual European countries became again widely varied and technically outdated. Therefore, a second approach of standardisation was done by the European Institute of Wood Preservation (W.E.I) in 1982, ensuring a high-class wood preservative with consistent quality. For this purpose, two types of impregnating oils (A and B) were used, which differed only slightly in their density and distillation range (Schulz 1983, Willeitner and Dieter 1984). Today, the European Institute for Wood Preservation (W.E.I.) is still in charge of the quality control as well as the specification of creosote in Europe (Militz and Mai 2008). Furthermore, the EN 13991 (2003) determines the specifications and the test methods for creosote used for industrial wood preservation and divides creosotes in three different types of oils mostly by the benzo[a]pyrene content, which is hinged on the distillation curve (Table 1).

Table 1: Benzo[a]pyrene content according to DIN EN 13991 (2003)

Parameter	Type A	Type B	Type C
Benzo[a]pyrene content	≤ 500 mg/kg	≤ 50 mg/kg	≤ 50 mg/kg

Since 2003, creosotes with a benz[a]pyrene content higher than 50 mg/kg are forbidden (Type A) and have been mostly replaced by creosote Type C. Creosote Type C has a reduced odour intensity and the low- and high boiling distillate fractions have been separated (Militz and Mai 2008).

Creosote has a reddish brown or dark color, a low viscose liquid content and a characteristic inherent odour. At 30°C, the viscosity is around 15 mPa*s, but can be decreased significantly by heating (Willeitner and Dieter 1984). At temperatures above 100°C the viscosity of creosote gets closer to the viscosity of water at 20°C (1,005 mPa*s). During impregnation of railway sleepers, the viscosity of creosote is therefore between 1.2 and 2.0 mPa*s (Broese van Groenou 1983, Bavendamm and Bellmann 1955). According to DIN 68811 (2007) the temperature of creosote for the impregnation of railway sleepers is depending on the applied impregnation process, but must not fall below 110°C.

Despite its big variety in composition and properties, creosote shows a generally good efficacy against wood destroying organisms (Mayfield 1951). Studies of Schulze and Becker (1948) showed differences in threshold values for single components and fractions, but also pointed out, that the efficacy against wood destroying organisms is not only based on single substances, but rather on their proportional quantity inside the creosote. Furthermore, Willeitner (1975) observed, that changing the composition of creosote by washing with acids and bases did not lead to significant changes in efficacy thresholds.

Next to the toxic effect on wood destroying fungi (especially soft rot), insects and marine borers, mostly due to polycyclic aromatic hydrocarbons (PAC), creosote has nearly no significant influence on the different mechanical strengths (Burmester and Becker 1963). Merely a reduction in tensile strength of Beech and Scots pine was recognised. In case of railway sleepers, the pressure resistance perpendicular to the grain is mainly important and was not influenced by the treatment with creosote. Generally speaking, the application of oily preservatives usually does not result in appreciable strength loss, because they apparently do not react with the wood cell wall components. However, if certain seasoning parameters are exceeded or excessive temperatures or pressures are employed during the actual treating process, strength loss could appear (Winandy 1996).

Additionally, creosote treated wood is also hard inflammable (Broese van Groenou 1955, Willeitner and Dieter 1984) and shows no positive influence on the electrical conductivity (Anonymous 1955, König 1962) as well as significant influence on the corrosion of fasteners like baseplates or sleeper screws (Halank 1959, Pfabigan and Reitbauer 2020). The oily component also induces an additional hydrophobicity, which reduces the moisture absorption of treated wood. Therefore, treated wood tends to less swelling and shrinking as well as checking (Bavendamm et al. 1963, Willeitner and Dieter 1984, Schulz 1987a). Another advantage of creosote is its migration behaviour within the wood after impregnation. Non-impregnated wooden structure, which can be exposed by checks during service life, can be recoated by creosote leaking out from the wood cells (Willeitner and Langner 1967, Willeitner and Dieter 1984).

1.1.2 The impregnation of wooden railway sleepers with creosote

To enhance the service life of wooden sleepers, the conservation by impregnation started in the end of the 18th century. In the beginning, sleepers were impregnated using full cell processes. In 1838, John Bethell combined the findings of Bréant, who invented the vacuum pressure impregnation and Franz Moll, who patented creosote as a wood preservative (Streckert 1989). While the United Kingdom used creosote from an early stage on, the United States of America and Germany initially used zinc-chloride solutions, which were cheaper, but had less biocidal effects and led to corrosion of metal fastening systems as well as on the wooden fiber (Mörath 1956). Finally, in 1849 Julius Rüttgers established the impregnation of sleepers with creosote in Germany (Streckert 1989), which, after standardising its process sequences, results in service life ten times longer compared to unimpregnated sleepers (Zycha 1965).

1.1.2.1 Impregnation using full cell processes

The original full cell process was firstly recommended by Bréant in 1832 for the impregnation of wood preserving salts (Lohwag 1967). The basic principle of the full cell process is to soak up as much preservative as possible into the wooden structure to completely fill all reached cells (Broese van Groenou 1963) and penetrate the cell walls (Langendorf 1988). In case of water-based preservatives, the excessive water will evaporate during drying of the wood, leaving the active ingredients in and attached to the cell wall (Langendorf 1988). Creosote on the other side is not able to dry out and will remain in the filled cells as viscid fluid (Leiße 1992).

For the implementation of a full cell process, the wood is firstly exposed to a vacuum phase (A), which removes most of the air within the wooden structure. Under maintenance of the vacuum, the preservative is flooded into the autoclave until the maximum level is reached (B). Afterwards the vacuum is released and the preservative starts penetrating the wooden structure (C). This is encouraged due to an applied fluid pressure (D). The pressure phase will be maintained until no further absorption of impregnation fluid is indicated. After releasing the pressure and removing the impregnation solution (E) a final vacuum can be drawn (F), in attempt to remove excessing preservative and avoiding subsequent leakage of preservative during service life (bleeding of the wood) (Richardson 1993, Leiße 1992) (Figure 1).

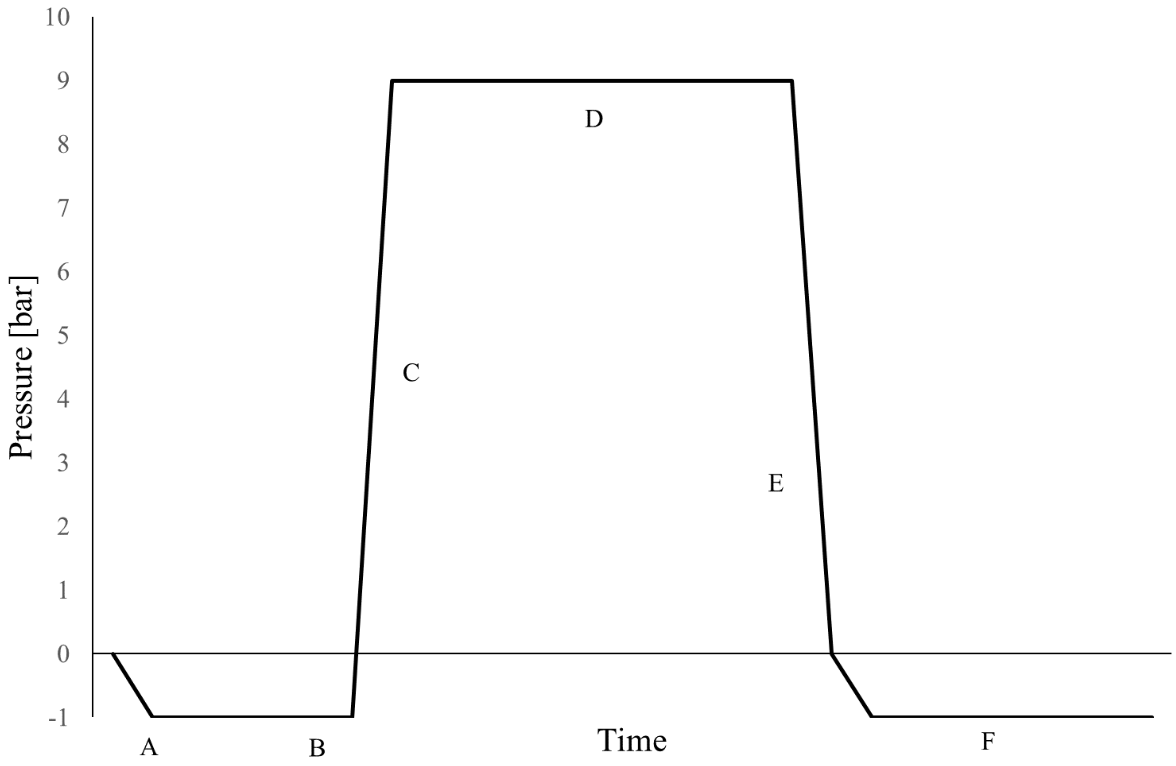


Figure 1: Diagram of a full cell process with an optional post-vacuum with (A) pre-vacuum, (B) flooding the autoclave under maintenance of the vacuum (C) released vacuum and increased fluid pressure, (D) maintenance of fluid pressure, (E) released fluid pressure and removing of the preservative, (F) optional post-vacuum

The impregnation using full cell processes though, led to enormous consumptions of creosote. The retention in sleepers made of Beech and Scots pine amounted around 277 kg/m³, while the retention of Oak sleepers was around 78 kg/m³ (Schramm 1952). Both retentions significantly exceeded the amount needed for impeccable protective effects (Broese van Groenou 1983). Today, the full cell process is normally used for the impregnation of water-based preservatives. The impregnation of creosote using full cell processes is only used in environments or fields of application, where very high retentions are necessary to protect the wood from extreme hazard situations such as marine piles (Richardson 1993).

1.1.2.2 Impregnation using empty cell processes

The strong expansion of railroad and telegraph lines resulted in increased demand for creosote-impregnated timbers. Since the creosote production did not increase to the same extent, prices rose, which made full cell impregnations no longer economically viable. Therefore, efforts optimizing process parameters to reduce the retention of creosote were made. In 1902, the first empty cell process was patented by Carl Wassermann (Rüping 1902) and refined by Max

Rüping (Peters 1950). The Rüping-process gave the opportunity to regulate the retention of creosote up to a certain extent by variation of air and fluid pressure intensity (Broese van Groenou 1983). The first step of a typical process sequence is an air pressure (A), which compresses the existing air inside the wood. Duration and intensity of the air pressure are based on size and permeability of the wood (Richardson 1993). Afterwards, the autoclave is flooded with the preservative under consistent air pressure (B). The following fluid pressure increase (C) is maintained for a selected period (D) and forces the preservative inside the wood. After pressure release and preservative removal (E), the compressed air inside the wood is able to expand ("kickback"). Excess amounts of preservative will be removed from the porous spaces of the wood and is supported by an applied post-vacuum (F) (Figure 2).

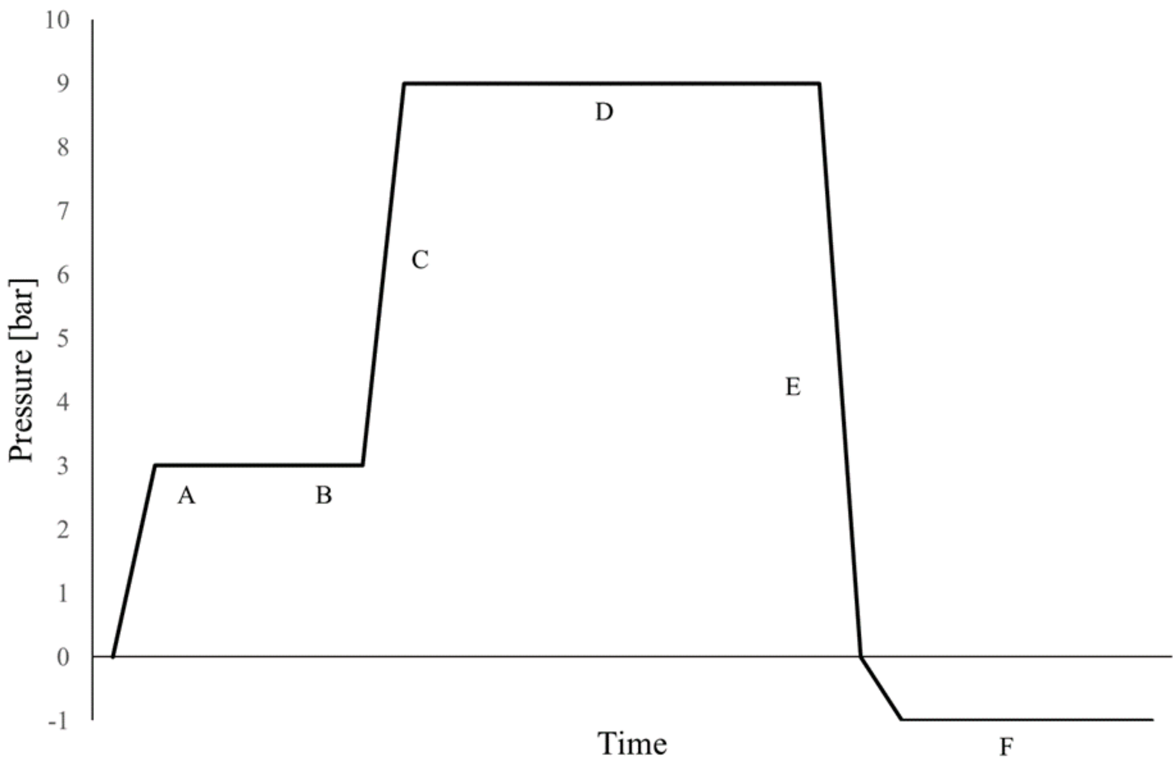


Figure 2: Diagram of a Rüping-process with (A) air pressure, (B) flooding the autoclave under maintenance of the air pressure, (C) increase of the fluid pressure, (D) maintenance of the fluid pressure, (E) released fluid pressure and removing of the preservative, (F) required post-vacuum

By using the Rüping-process, the average creosote retentions in sleepers made from Beech, Scots pine as well as from Oak were reduced without losses in penetration depth. While Beech sleepers showed a retention of 145 kg/m³, sleepers made from Scots pine and Oak showed both retentions below 100 kg/m³ (Schramm 1952). Shortly after the invention of the Rüping-process a second empty cell process was invented and patented by Lowry in 1906 (Lowry 1906). Unlike the Rüping-process, the Lowry-process renounces an increased initial air pressure. It solely uses the atmospheric pressure of the present air inside the wood as air pressure. Initially, the preservative is filled into the autoclave (A) and a pressure increase is carried out(B). After maintaining the fluid pressure for a certain period (C) the autoclave is emptied (D) and the impregnation is completed with a post-vacuum (E) (Figure 3).

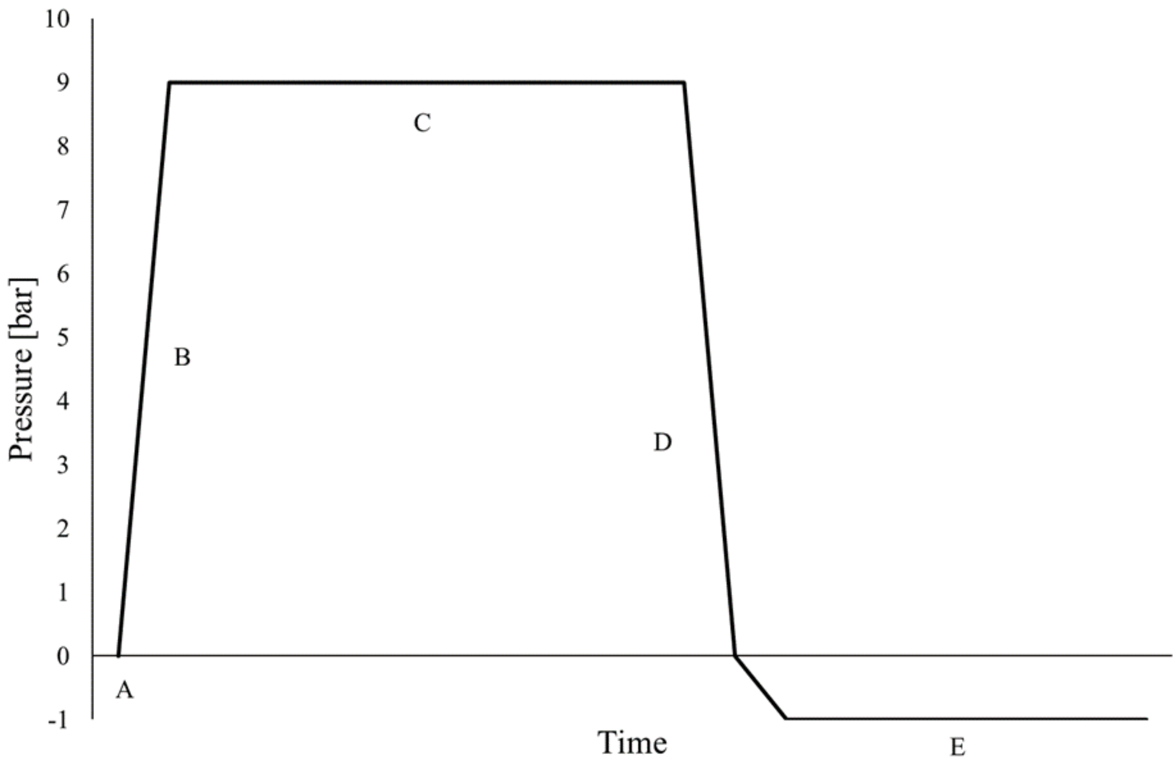


Figure 3: Diagram of a Lowry-process with (A) flooding the autoclave with preservative, (B) increase of the fluid pressure, (C) maintenance of the fluid pressure, (D) released fluid pressure and removing of the preservative, (E) required post-vacuum

Based on its simple handling, the empty cell process, in accordance to Rüping, is used for the impregnation of railway sleepers to this day (DIN 68811, 2007). According to DIN 68811 (2007) sleepers made of Oak and Scots pine are impregnated using the improved single Rüping-process. For Beech or other wood species, where a complete penetration of the cross section is possible as well as requested (Broese van Groenou 1963), in general the double Rüping-process is used since 1908 (Peters 1950). Generally speaking, the improved double Rüping-process combines two single Rüping-processes, but includes a pre-heating phase directly after filling the autoclave with the preservative. Like for the single Rüping-process, in the beginning an air pressure is applied and maintained for a defined period of time (A). Afterwards, the autoclave is filled with the preservative and the pre-heating begins. According to DIN 68811 (2007) this takes at least 150 minutes (B). Applying (C) and maintaining the fluid pressure (D), as well as depressurizing and emptying of the autoclave (E), are similar to the single Rüping-process. After holding atmospheric pressure (F) for at least 30 minutes, a second air pressure is applied and maintained (G). Here, no pre-heating phase is implemented. The autoclave is directly filled with the preservative and the fluid pressure is applied (H). After maintaining the fluid pressure for at least twice as long compared to the previous pressure phase (I), the autoclave is depressurized and emptied (J) and the final vacuum is applied (K) (Figure 4).

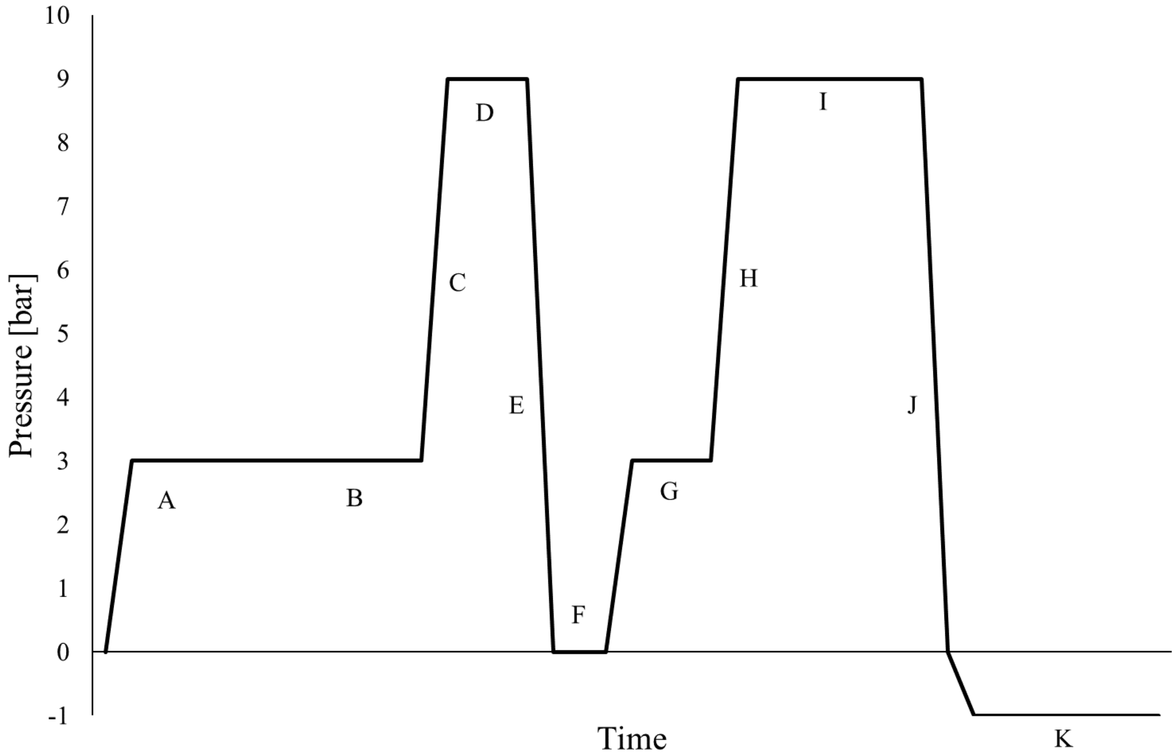


Figure 4: Diagram of an improved double Rüping-process with (A) air pressure, (B) flooding the autoclave under maintenance of the air pressure and pre-heating of at least 150 minutes, (C) increase of the fluid pressure, (D) maintenance of the fluid pressure, (E) released fluid pressure and removing of the preservative, (F) atmospheric pressure of at least 30 minutes, (G) second air pressure, (H) applied fluid pressure, (I) second fluid pressure (twice as long as first fluid pressure), (J) released fluid pressure and removing of the preservative, (K) required post-vacuum

1.1.3 History of process optimisation regarding Beech sleepers

Despite successful applications and good experiences, ongoing optimisations of Beech sleepers have been carried out over the years. In addition to reducing the gross weight from 800 kg/m³ to 750 kg/m³ before impregnation or increasing the average creosote retention from 145 kg/m³ to 175 kg/m³ in 1964 (Schulz 1964a, Schulz and Broese van Groenou 1967), Beech sleepers were optimised early, by drilling holes in the bottom. Since 1940, four diagonally arranged holes with a diameter of 16 mm were initially drilled in the middle of the bottom of the sleeper, in order to improve the creosote absorption and penetration (Halank 1959). In 1964, the drilling pattern was expanded to 8 holes (Schulz 1964a) and is still required today by the DIN 68811 (2007). Not only mechanical optimisations took place over the years. Additionally, various investigations including process optimisation have been implemented. Ongoing surveys regarding the optimisation of the impregnation quality led to the introduction of the improved Rüping-process in 1966 by the Deutsche Bahn (DB). Here the sleepers are pre-conditioned in hot creosote for 1-2 hours, directly after finishing the air pressure /filling phase of the Rüping-process. Without releasing the actual pressure, the sleepers and creosote are heated up together to temperatures above 100°C. Furthermore, the duration of the second pressure phase was reduced from three to two hours (Broese van Groenou 1983, Schulz and Broese van Groenou 1967). In the same year, pursuing tests regarding further optimisation potential took place by Schulz and Broese van Groenou (1967), who tested two variations. Both variations replaced the intermediate vacuum either by a 15-minute fluid pressure phase of 3.5 bar, or an aeration phase of 15 minutes after emptying the autoclave. Evaluating the creosote penetration showed an additional improvement, aerating the autoclave between both pressure phases (variation 2). Assumptions made by Schulz and Broese van Groenou (1967) regarding the influence of the intermediate vacuum cooling down the sleepers, were confirmed by investigations by Schulz (1987a). After continuously recording the temperature profile of Beech sleepers during the improved double Rüping-process, the avoidance of the intermediate vacuum between first and second fluid pressure phases actually showed a steady temperature rise and a better impregnation performance (Schulz 1987a). Further investigations regarding the improvement of the temperature profile in Beech sleepers were performed by Hösli (1980), using three different types of pulsation processes. While a significant raise in temperature within the sleepers was not achieved, markedly better results regarding the creosote penetration were obtained. Despite all these optimisations, various authors (Zycha 1965, Hösli and Bariska 1980, Hösli 1980) and also earlier studies from the project CreoSub showed that a complete penetration of the sleeper cross section is still not always guaranteed (Starck et al. 2017).

1.2 Background and Motivation

1.2.1 Actual use of wooden sleepers in Germany

The use of wooden sleepers decreases more and more due to the application of sleepers made from concrete. In 1954, only 3 % of the installed sleepers in the track network of the German railway (Deutsche Bahn, DB) were made from concrete. The amount increased in the following years up to 33 % in 1981. At the same time, the number of wooden sleepers decreased from 54 % (1951) to 45 % (1981). Equally, the purchase of wooden sleepers during the years from 1950 to 1985 reflected this trend. At the end of 1950, the purchase of wooden sleepers decreased from 80 % to nearly 50 %. In 1982 merely 18 % of the purchased sleepers were made from wood (Lewark 1991). Today, the annual needed quantity of wooden sleepers by the Deutsche Bahn AG amounts approximately 100.000 pieces of track sleepers made from Beech and 90.000 running meters turnout sleepers made from European oak. For the impregnation of these railway sleepers, creosote is still the classical and exclusively applied wood preservative.

Possible reasons for the increasing use of concrete sleepers are the mechanisation of the track construction and track maintenance. Hereby, costs for purchase, installation, maintenance, amortization, removal and disposal/ recycling are the main criterium (Belser 2014).

Nevertheless, wooden sleepers have several properties, which are still favourable today and thus ensure their use as part of the track superstructure. Especially for narrow curve radii, on mountain tracks with uneven underground conditions and low ballast bed thicknesses, for switches, for railway bridges and for shunting stations (Pfabigan and Reitbauer 2020). For the latter, the high resilience of the sleepers is important, especially in cases of derailments. Derailments appear mainly during shunting operations. Furthermore, the low weight of wooden sleepers simplifies any manipulation (individual replacements), especially in tunnels or train stations and is also important for exporting sleepers. Additional positive properties are the good electrical insulation as well as the structure- and airborne sound insulation (Li 2012, Lewark 1991).

1.2.2 Actual situation of creosote as wood preservative for railway sleepers

Initially, it is important to point out, that today's use of creosote as a wood preservative is restricted to certain industrial and commercially used products based on its alarming properties against human health and environment (REACH; regulation (EU) 1907/2006). This includes wooden railway sleepers. The use of creosote as a wood preservative on European level is further regulated by the biocidal products regulation (regulation (EU) 528/2012). As from 01.05.2013 (after inclusion into the Annex I of the directive 98/8/EG by the Commission Directive 2011/71/EU) creosote is subjected to authorization. An authorization can only be granted if no alternative products for the intended application, in this case the impregnation of wooden railway sleepers, are available (Schuhmacher-Wolz and Hassauer 2015).

In Europe, different research projects have been evaluating and examining different wood preservatives as possible alternatives for creosote as a wood preservative for railway sleepers. The project "Bahnschwelle 2020", which transferred the results gained in laboratory scale from the project "Rail-Sleeper" regarding the suitability of water-based wood preservatives for the impregnation of railway sleepers, can be named for instance. A second project was "CreoSub", which investigated different oily wood preservatives according their potential of being an alternative wood preservative for primarily railway sleepers, but also transmission poles. Other available alternatives regarding creosote as wood preservative are for example pentachlorophenol or copper naphthenate, which are both used in the United States of America for the preservation of wood in heavy duty applications. Pentachlorophenol hasn't been used for decades and copper naphthenate is not permitted by now in the European Union, but is under review for registration (Brient et al. 2020).

At the moment, creosote is still in use for the impregnation of railway sleepers in Germany. A possible ban of creosote would have major consequences for the railway industries, based on the fact, that without a successor product, wooden sleepers have to be installed either again without adequate protection against wood destroying organisms or will possibly be replaced by sleepers made from alternative materials like concrete, steel or polymers.

To ensure the future use of wooden railway sleepers as part of the track superstructure after the possible ban of creosote, ways of process optimisation have to be found. Possibilities for process optimisation include the use of alternative oily wood preservatives as well as the use of mechanical pre-treatment of wooden railway sleepers by incising.

1.3 Process optimisation of Beech sleepers

1.3.1 Process optimisation by impregnation of an alternative oily wood preservative

A homogeneous preservative penetration reaching the complete cross section of a wooden product in adequate amounts is important to ensure the protection against the deterioration of wood by fungi and insects. This is especially important for products, which are constantly exposed to conditions with high moisture contents like railway sleepers, transmission poles or marine applications. In case of Beech sleepers, the cross section is mostly consisting of a wooden tissue showing sapwood like properties. A high permeability towards fluids is given, but can also show a high variance (EN 350 2016). In most cases, the sleeper cross sections are also showing red heartwood. In accordance with EN 350 (2016), red heartwood is classified as hard to penetrate by fluids. The penetration of fluids is hindered due to formed tyloses. Therefore, the amount of red heartwood existing in a sleeper cross section is regulated by the EN 13145 (2011). Poorly or not penetrated areas of the sapwood like tissue (mostly in the core) can be exposed due to occurring checks during the service life (Findlay 1985). Wood destroying organisms are able to use this checks as entry-points and can cause decay from the inside (Halank 1959; Schulz 1965).

A variety of different oils have been used for impregnation of wood during the past years. Rapeseed-, linseed-, tall oil and its derivates as well as palm oil and coconut oil are of particular importance (Panov et al. 2010). Furthermore, some natural oils appear to be capable of preventing water uptake of wood (Hyvönen et al. 2006) and are able to show similar efficacy against wood destroying organisms as creosote or CCA without containing any fungicidal substances. However, this can only be achieved with extremely high retentions (Jermer et al. 1993, Paajanen and Ritschkoff 2002). In case of tall oil, Alfredsen and Flaete (2015) found retentions of 449 kg/m³ are needed in order to provide acceptable field performance and proposed a combination of tall oils and biocides for protection systems.

Actually, three different alternative oily wood preservatives are used to certain extents in the European Union. These alternative oily wood preservatives are based on environmentally acceptable biocides in combination with hydrophobic carrier substances. The hydrophobic carrier substances can be natural oils like crude tall oil or petroleum-based oils. For all three formulations, copper hydroxide ($Cu(OH)_2$) acts as the primary active ingredient with organic acid-co solvents (Brient et al. 2020).

In regard of optimizing an impregnation process, the material properties of the wood, as well as the wood preservative have to be examined (Hösli and Bosshard 1979). In case of creosote, this has been carried out by various process optimisations during the last 70 years, where improving the creosote penetration was always the main focus. A homogenous penetration of the wooden structure is not only determined by the used impregnation process, but also depending on other aspects such as the physical properties of the alternative oily wood preservative. Therefore, today’s impregnation processes for creosote cannot be transferred directly to new oily wood preservatives, which makes process optimisation become important again.

1.3.2 Process optimisation by a mechanical pre-treatment (incising)

Incising is a mechanical pre-treatment of wood, where axially oriented incisions are pressed into the surfaces either by knives running on toothed rollers, needles, laser or water jet (Pang et al. 2017). The history of incising is reviewed by Evans (2016), summarizing its way from being firstly carried out by a spiked hammer in Germany to industrial incision of wooden poles and railway sleepers in Great Britain and North America.

The arrangement of the incisions regarding their spacings and amount per square meter (incising pattern), as well as their depth and width is adjusted to the treated wood species and the dimension of the processed product. Where appearance is not of major concern, large knifes (oyster-knife teeth) are usually used at wide spacings. The knife size as well as the distance between the individual incisions decreases with smaller product dimension (Morrell and Winandy 1987, Keith and Chauret 1988). Incising is used to improve the penetration of wood preservatives especially of refractory wood species (Kartal and Lebow 2002). For many years, incising is already used to increase the amount of transverse area exposed to potential preservative flow. The longitudinal pathways exposed on these transverse faces are more receptive to penetration of fluids than the radial and tangential surfaces. Thus, there is an improvement in penetration in the area of the incising slit (Morris et al. 1994, Morrell et al. 1998). Furthermore, incising accelerates the drying by opening the wooden structure (Simpson 1985) and reduces the checking of wood (Morris et al. 1994, Franciosi 1956). However, the exact mechanism which is responsible for a reduction in check formation has not been identified today. Various authors addressed the mechanism being a reduction or redistribution of stresses, which has been summarized in more detail by Evans (2016).

1.4 Objectives

Due to their positive properties, wooden sleepers made from Beech are still a substantial component for the track superstructure in Germany.

An essential quality attribute of Beech sleepers is their durability in the track bed. Based on its high efficacy in use class four (ground contact), creosote treated sleepers show a service life up to 30 years or longer, if the sleepers are sufficiently treated. Nevertheless, creosoted sleepers sometimes show early failures based on insufficient penetration of the cross section. This insufficient penetration occurs especially in the sleeper middle. Due to the expected ban of creosote, the competition against sleepers made from alternative raw materials like concrete or polymers, will be further intensified. In order to ensure the continuous use of Beech sleepers, the use of an alternative preservative treatment, which guarantees equivalent quality requirements to creosote, is sought. This will be primarily influenced by a complete penetration of the sleeper cross section as well as a homogeneous distribution of the used wood preservative. Therefore, the focus of process optimisation using alternative wood preservatives is on ensuring an optimal penetration of the entire sleeper volume.

Another possibility to optimise Beech sleepers is the introduction of a mechanical pre-treatment by incising. The incising of railway sleepers is performed in the United States for many years and a reduction of checks, an acceleration of drying as well as an improvement of the preservative penetration are known positive effects for sleepers made from various wood species. Nevertheless, despite its positive effects, the incising of sleepers has never been used in Germany. Therefore, incising offers the possibility to significantly improve the competitiveness of Beech sleepers, compared to sleepers made of alternative materials.

Thus, the main objective of this thesis was the process optimisation of the Beech sleepers by using an alternative oily wood preservative for impregnation of the entire sleeper cross section as well as the use of incising as mechanical pre-treatment. Therefore, the following specific objectives were set:

- Determining the influence of incising on drying behaviour, check formation and dimensional stability of Beech sleepers during seasoning
- Quantifying the influence of viscosity of different oily carrier substances on the penetration in Beech and Scots pine sapwood and microscopical analysis of the anatomical penetration pathways

- Impregnating Beech sleepers using an alternative oily wood preservative with the main focus on reaching a complete penetration of the cross section respectively the sapwood like wooden structure to ensure a sufficient protection against the attack of wood destroying organisms

2 Process optimisation by mechanical pre-treatment

2.1 The influence of incising on drying behaviour, check formation and dimensional stability of Beech sleepers during seasoning

2.1.1 Introduction

The most common and simplest way of seasoning freshly sawn sleepers is air drying. Seasoning of freshly sawn sleepers to a moisture content between 20-40 % is necessary to implement an efficient preservative treatment (Koch 1985). Since moisture determination by dry weight is too complicated, the average raw density (gross weight) of the considered wood species is declared as significant value. According to DIN 68811 (2007) the gross weight of sleepers made from Beech (*Fagus sylvatica* L.) is not allowed to succeed 750 kg/m³, which equals a calculated moisture content of approximately 34 % (Schulz 1969). Under Central European climate conditions, Beech sleepers need approximately up to eight months of air seasoning to reach the required moisture content for impregnation. If freshly cut Beech sleepers are delivered by the end of March, they usually reach the required gross weight in the same year, probably around August. Deliveries of “April-sleepers” can still reach a gross weight less than 750 kg/m³ under favourable weather conditions, while “May-sleepers” do not reach the required moisture content until spring or early summer of the following year (Schulz 1969). During seasoning and until reaching the adequate moisture content for impregnation, sleepers in general are susceptible to checking. In order to prevent checking and or splitting, starting from the end grain, sleepers have been secured with various devices over the last decade. This included S-irons, C-irons, beagle irons, steel dowels or bands (Shunk 1976). Today, nail plates are one of the most common devices to decrease checking during seasoning (Webb and Webb 2016). However, this does not prevent checking completely, especially on the surface of all sleeper sides. If occurring checks become too large, reaching or running through the area of the later attached base plates, a sufficient holding power of the metal fasteners cannot be guaranteed during the period of service life. If continuous checks exceed a length of 250 mm, measured from the end grain, the sleepers have to be sorted out (culled) according to EN 13145 (2011). In addition to check formation, the dimensional stability of sleepers during or after seasoning, respectively, is also very important. The main factor influenced by the dimensional stability is the track accuracy. Increasing speeds and loads resulted in lower tolerances and in higher requirements regarding the track accuracy and dimensional stability (Schulz 1971a).

If too much deformed by longitudinal curvature of the narrow- and broad sides (EN 13145 2011, ÖBB Infra 2017), the sleepers have to be sorted out and are no longer applicable for subsequent production steps like planning the bedding area as well as drilling the holes for mounting the base plates.

Incising as mechanical pre-treatment is known to improve the uptake and penetration of wood preservatives, especially for refractory wood species (Kartal and Lebow 2002). Additionally, incising has also the ability to reduce checks in various wooden applications like sleepers, poles and posts. However, the positive effect of incising differs in its extent from product to product, whereby for sleepers it is clearly visible (Evans 2016). Today, incising of wooden sleepers, despite which wood species, is carried out in the United States to facilitate preservative penetration as well as to mitigate seasoning defects. Properly incised sleepers can often reduce seasoning checks that would occur during drying. Furthermore, incising green sleepers will give the possibility to achieve a more uniform drying/conditioning of the sleepers (Webb and Webb 2016).

In Europe, sleepers are not incised upon today, despite its favourable effects during seasoning. Especially Beech sleepers, which are highly susceptible to check formation (Hulzer 1979) and changes in dimensional stability during seasoning (Schulz 1971a) may possibly benefit from a stress reduction by incising. Additionally, a more uniform seasoning will eventually lead to a decrease in drying time. Seasoning durations of more than one year increase the risk of fungal infestation of the untreated sleepers until the time of impregnation. Supplementary, at the end of seasoning, not only the moisture content of the whole sleeper is important. In fact, also single moisture accumulations are able to have a negative impact on the impregnation quality (Schulz 1969) and may be reduced by incising.

All these aspects would contribute significantly to the economic efficiency of the production process, but most important would additionally improve the sleeper quality. Therefore, a possible influence of incising on following aspects has been evaluated:

- Duration of seasoning and moisture distribution within incised and not incised Beech sleepers until reaching the requested moisture content for impregnation
- Formation of drying checks during seasoning
- Dimensional stability of incised Beech sleepers

2.1.2 Materials and methods

2.1.2.1 Determination of drying behaviour and check formation during seasoning

Ten freshly cut Beech sleepers (2600 x 260 x 160 mm³) with an average gross weight of 932 kg/m³ were divided into two specimen collectives to investigate the influence of incising on drying and check formation. Collective 1 was mechanically pre-treated on all surfaces using the pilot incising machine from Fürstenberg-THP GmbH, Hüfingen, Germany receiving incisions (knife incisions) with a length and depth of 20 mm and a width of 3 mm, while collective 2 remained untreated. Monthly, the gross density in kg/m³ of the sleepers was gravimetrically determined. Therefore, the sleepers were weighed to the nearest 0.1 kg. From the current weight, the raw density (analogous to the so-called 'gross weight' according to DIN 68811, 1997) of the sleepers was calculated. Based on an average normal raw density of Beech of 710 kg/m³ (corresponding to an average dry density of 634 kg/m³) according to EN 350 (2016), the current global wood moisture content (MC) of the sleepers was calculated according to Eq. (1).

$$MC_{Sleeper} = \frac{(\rho_f \cdot V_{Sleeper}) \cdot (\rho_0 \cdot V_{Sleeper})}{\rho_0 \cdot V_{Sleeper}} \cdot 100 \quad (1)$$

$MC_{Sleeper}$ = Global moisture content of the sleeper [%]

ρ_f = Raw density wet [kg/m³]

ρ_0 = Dry density of beech = 634 kg/m³

$V_{Sleeper}$ = Sleeper volume = 0.10816 m³

Additionally, the local moisture content (MC) of the sleepers was continuously determined and recorded at nine previously defined positions using data loggers (Materialfox, Scanntronik, Zorneding, Germany) according to the electrical resistance principle. In order to determine the local moisture content, three pairs of holes were drilled at previously defined distances from the end of the sleeper using a Forstner drill (Table 2).

Table 2: Measuring points for continuous determination of local moisture content

Measuring point	Measuring depth [mm]	Distance towards sleeper end [mm]
S 1	25	325
S 2	50	325
S 3	80	325
S 4	25	650
S 5	50	650
S 6	80	650
S 7	25	1300
S 8	50	1300
S 9	80	1300

To avoid measuring the moisture content in the possibly existing red heartwood, usually located in the centre of the sleeper cross section or on the bottom of the sleeper, the depth of the holes and the distance to the sleeper side were varied, ensuring the measurement of only sapwood like wooden tissue (Figure 5). Stainless steel screws acted as electrodes for measuring the local moisture content. Previously drilled holes in the head of the screw served as a plug input for connecting the data logger. In the following step, the screws were screwed into the holes for a few millimetres and then sealed with silicone. The data logger cables were connected to the screws using banana plugs and were additionally sealed watertight with heat-shrink tubing (Figure 6).

The moisture content was calculated using resistance characteristics for Beech according to Brischke and Lampen (2014).

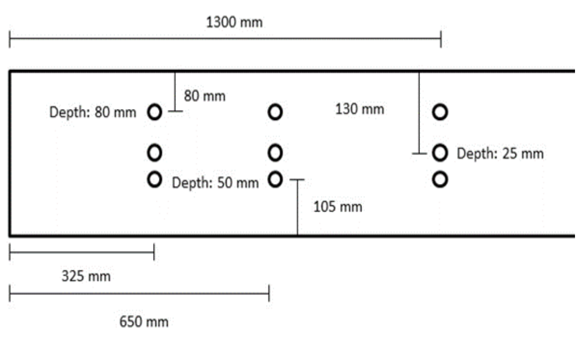


Figure 5: Schematic overview of the measuring points for continuous moisture content measurements

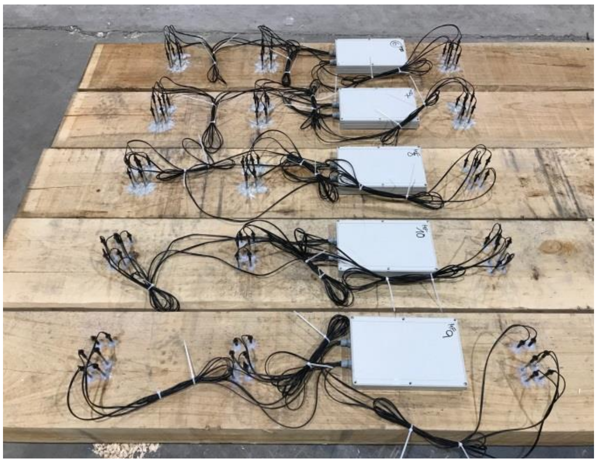


Figure 6: Sleepers equipped with dataloggers

The development of checks was evaluated on the remaining "free" sleeper section. Since all sleepers showed already existing checks at the beginning of the drying process, the ten largest checks, were initially defined on the upper surface (broadside) as well as on both side areas (narrow sides) of each sleeper for further evaluation. Until reaching the required raw density of ≤ 800 kg/m³ (ÖBB Infra 2017), the checks have been monthly evaluated measuring their length, width and depth in millimetres using a folding ruler and a feeler gauge. For later comparison of check development during seasoning, a classification system was defined, dividing check length, width and depth into five categories (Table 3).

Table 3: Categories, dividing check length, width and depth into five categories

	Categories [mm]				
	I	II	III	IV	V
Length	0-50	51-100	101-300	301-500	>500
Width	0-0.5	0.5-1.0	1.1-2.0	2.1-3.0	>3.0
Depth	0-10	11-20	21-30	31-40	>40

2.1.2.2 Influence of incision dimension on the drying behaviour

In parallel, the effect of the dimension of the applied incision on the drying behaviour was also evaluated on additional specimens in smaller dimension. For this purpose, two additional Beech sleepers, already equipped with a previously mechanically applied incising pattern, were each divided into 5 test specimens (400 x 260 x 160 mm³). The grain sides were sealed three times with a solvent-based clear coating to exclude longitudinal drying over the grain sides. Subsequently, the single incisions (20 x 20 x 2 mm³) of five test specimens were enlarged manually by hammering in a steel cutting edge (30 x 30 x 4 mm³) (Figure 7 and Figure 8).

Figure 7: Steel cutting edge for manual enlargement of the previously mechanically applied incising pattern

Figure 8: Test specimen with manually enlarged incising pattern (30 x 30 x 4 mm³)

Afterwards, the specimens were weighed and stored in a heated hall until all specimens had reached the required gross weight for impregnation according to the Austrian State Railway (gross weight ≤ 800 kg/m³) (ÖBB Infra 2017). Therefore, the specimens were weighed continuously at intervals of seven days and the gross weight was determined.

2.1.2.3 Evaluation of dimensional stability during seasoning

Whether freshly cut Beech sleepers show distortions during seasoning is not directly evident in the beginning of the examination. A direct comparison of incised and standard sleepers can therefore lead to misleading interpretations due to non-appearance of deformations. Therefore, only incised sleepers were included in this examination. For evaluating the possible effect of incising on the dimensional stability during seasoning, 700 freshly sawn Beech sleepers (2600 x 260 x 160 mm³) were mechanically pre-treated by incising the narrow- as well as the broad sides of each sleeper. Afterwards, the sleepers were stacked and stored outside according to DIN 68811 (2007). After reaching the requested gross weight of 800 kg/m³, the sleepers were examined visually for occurring deformation. Sleepers with deformation were sorted out for further evaluation using the parameter given by the technical delivery conditions for track- and cross ties from the Austrian Federal Railways (ÖBB) (ÖBB Infra 2017) (Table 4).

Table 4: Accepted tolerances given by the Austrian Federal Railways regarding the deformation of Beech sleepers

Type of deformation	Technical expression	Accepted tolerances
Longitudinal curvature of the narrow side	Spring	≤ 1.2% of the sleeper length (max. 30 mm)
Longitudinal curvature of the broad side	Bow	≤ 0.4 % of the sleeper length (max. 10 mm)
Torsion	Twist	≤ 0.3 % of the sleeper length (max. 8 mm)

The dimension of the occurring spring, bow and twist were measured using a straightedge and a folding ruler. To measure bow and spring, the straightedge was placed in centred position on the upper and narrow sides of the sleeper and the rise was measured using the folding ruler (Figure 9 and Figure 10). The twist was measured by placing the straightedge diagonally on the upper side of sleepers and calculating the difference of both rises from the diagonals.

Figure 9: Applied aiming stake for measuring the longitudinal curvature of the broad side

Figure 10: Measuring the longitudinal curvature of the broad side with the help of a folding ruler

2.1.3 Results and discussion

2.1.3.1 Determination of moisture content during seasoning

The moisture monitoring of Beech sleepers in standard dimensions with and without incising showed that the incising pattern used in this test setup had no significant influence on the drying rate. The required degree of seasoning for impregnation was not reached faster for sleepers with incising. The average global MC showed hardly any differences between mechanically pre-treated and untreated sleepers. Coincidently, the electrically measured local wood MC did not differ significantly between the collectives. In the first half of the drying period, the electrically determined mean wood MC of both sleeper collectives was clearly below the gravimetrically determined mean global MC of the sleepers. In the second half of the drying period, the electrically determined wood MC exceeded the mean global MC by several percent points. A clear wood MC gradient between the individual measurement points, even though placed at different measuring depths and distances from the end grain, did not occur for either of the two sleeper collectives (Figure 11 and Figure 12).

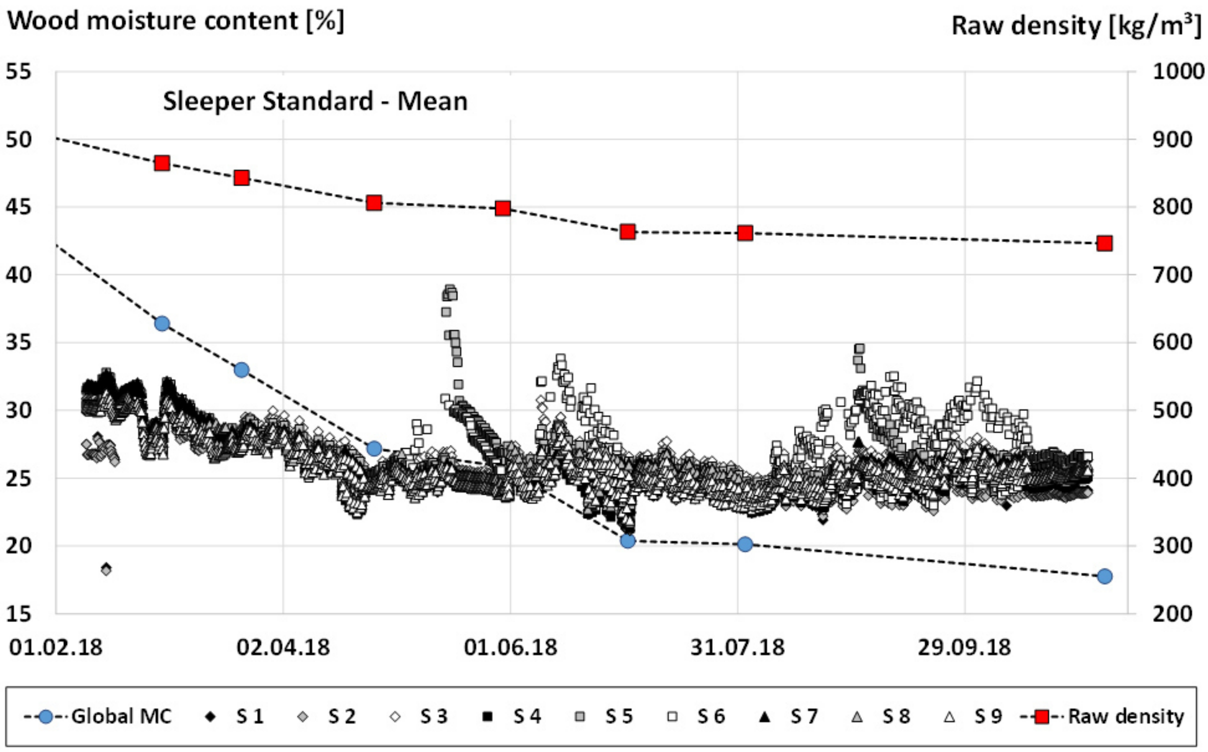


Figure 11: Electrically determined mean local moisture content (MC) at measuring points S1 to S9 of Beech sleepers in standard dimension without incising

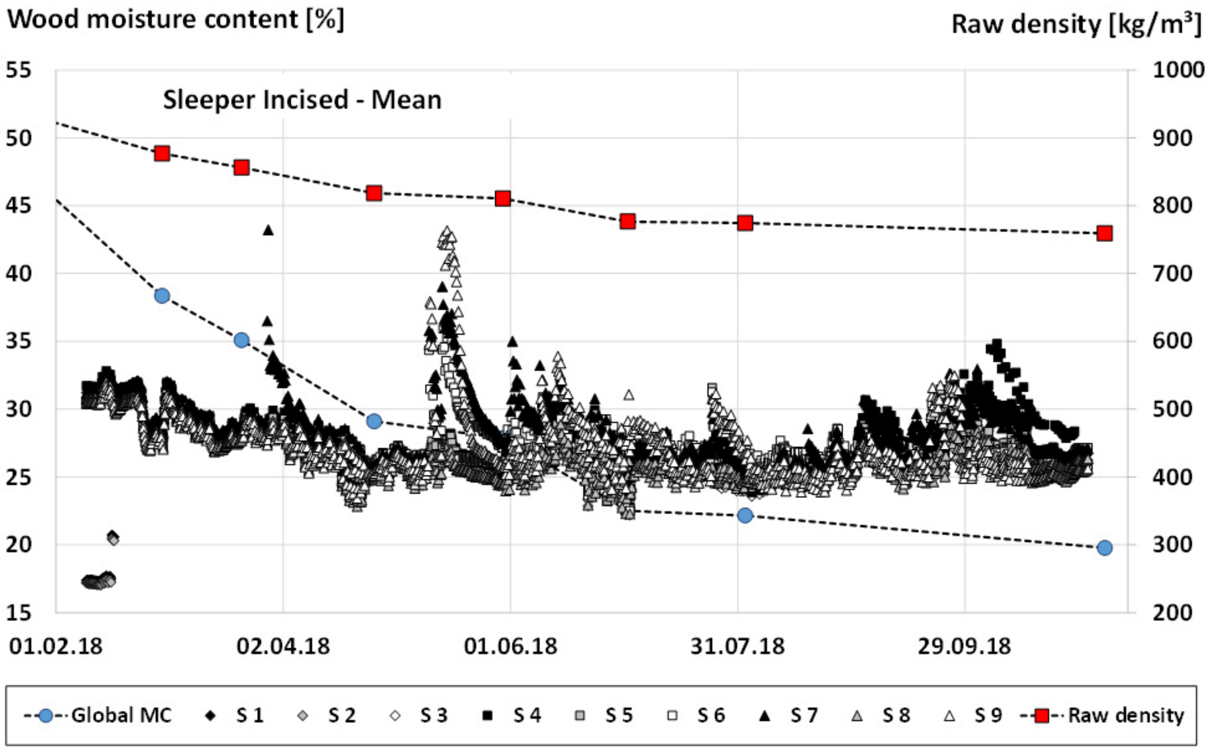


Figure 12: Electrically determined mean local moisture content (MC) at measuring points S1 to S9 of Beech sleepers in standard dimension with incising

During air drying of freshly sawn timber, water is removed by evaporation. Moving air conducts heat to the wood and carries away the evaporating moisture. While taking up the moisture, the air temperature drops. Cool and damp air is leaving the pile and fresh warm air continues the drying by entering the pile (Rietz and Page 1971).

The gravimetrically determined raw densities of the evaluated Beech sleepers were similar to results reported by Schulz (1969). Even though the sleepers examined by Schulz (1969) started with a higher raw density of around 1000 kg/m³ and were covered, an average raw density of 800 kg/m³ was also reached in June.

The measuring principle of resistance type moisture meters is based on decreasing electrical conductivity with increasing MC between oven dry state and fiber saturation. Resistance-based measurements of moisture contents above 25 % become increasingly inaccurate (Trübswetter 2009). Inaccuracies of more than 5 %-points are possible (Du et al. 1991). Since isolated electrodes had been used, the MC was only measured at the tip, so differences in moisture of the surrounding wooden structure may occur. This may explain to some extent the differences between the electrically determined local moisture content and the gravimetrically determined global moisture content. But this explanation is rather unlikely, since no considerable differences in MC were determined between the single measuring points. Therefore, a substantiated explanation cannot be given with the collected data.

Influence of incision dimension on the drying behaviour

At the beginning of the investigation, the specimens equipped with incisions in the dimensions of 20 x 20 x 2 mm³ (standard) had an average gross weight of approx. 1000 kg/m³. The average gross weight of the specimens with enlarged incisions in the dimensions 30 x 30 x 4 mm³ (enlarged) was about 900 kg/m³. In the first weeks, the specimens equipped with incisions in standard dimensions showed a faster reduction in the average gross weight. After a drying period of five weeks, the gross weight of the two specimen collectives had equalised (approx. 830 kg/m³). In the following weeks, both collectives reached the required moisture content for impregnation (800 kg/m³), whereby the specimens equipped with the standard incising pattern even showed a slightly lower average gross weight (Figure 13).

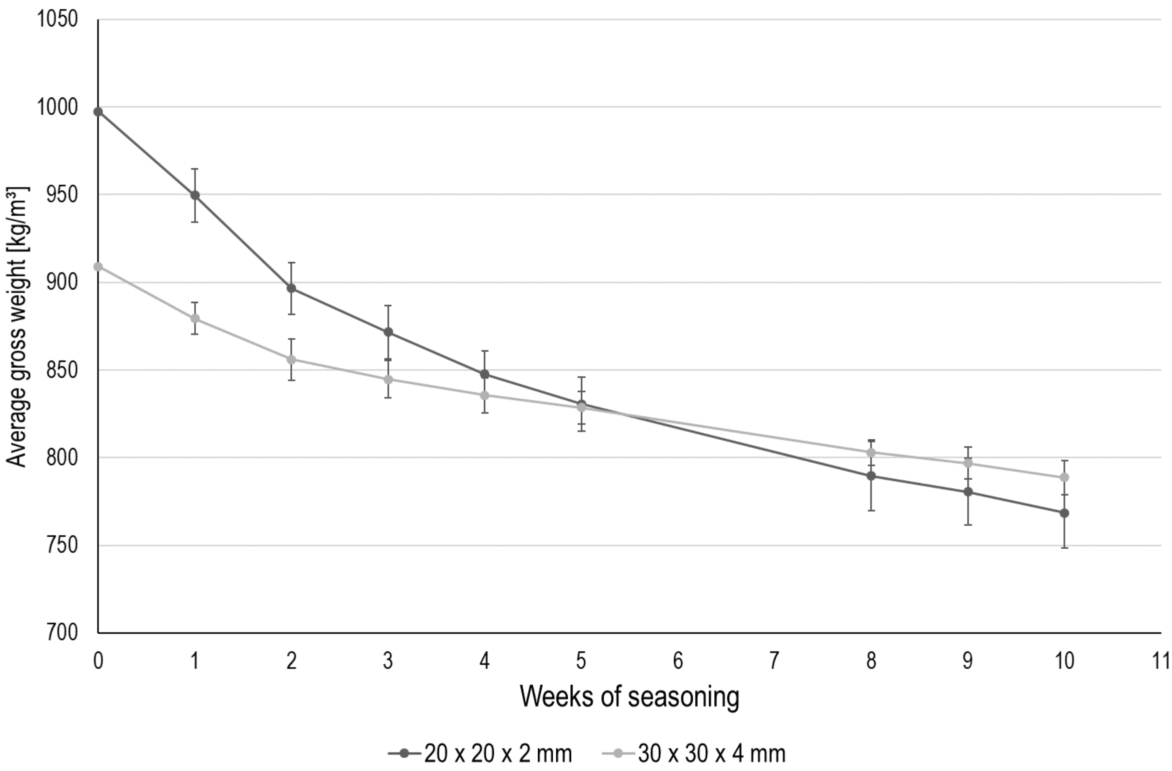


Figure 13: Development of the gross weight [kg/m³] of Beech specimens equipped with standard incisions (20 x 20 x 2 mm³) and enlarged incisions (30 x 30 x 4 mm³).

The discrepancy of the average gross weights between the two specimen collectives at the beginning of the examination can be attributed to the time required, to manually enlarge the incisions during specimen preparation. Franciosi (1956) also mentioned the possibility of a decreased moisture content during the time for handling and incising.

Hullberg (2010) conceded that incising has a positive influence on the drying time. However, there are also statements that incising has no influence on the drying speed (Suttie 2002). Studies by Franciosi (1956) also showed no influence of incising on the drying speed of railway sleepers made of Beech. One possible explanation is the high permeability of Beech. During drying, evaporation on the wood surface as well as the internal moisture movement play a role. By evaporation of water from the surface, free water located in the cell cavities and tubular elements is pulled by capillary action towards the surface, since water moves from zones of high moisture content to zones of low moisture content in the effort of reaching an equilibrium (Rietz and Page 1971). The drying of permeable wood species is primarily dominated by mass flow. In this phase, the permeability of the wood structure is primarily decisive. Diffusion as a transport mechanism only becomes relevant below fiber saturation (Keey et al. 2000). Due to the high permeability of Beech, a possible positive effect of incising would thus be masked during the drying of the Beech sleepers. The statement can be reinforced since enlarging the incisions did also not result in accelerated drying.

2.1.3.2 Formation of checks during seasoning

Incising reduced the formation of checks in Beech sleepers. Already during the first evaluation period at the beginning of the test, sleepers without incising showed comparatively longer checks. Table 5 to Table 7 compare the sum of check lengths, widths and depths at the beginning and after seasoning of the Beech sleepers on the surface and on the side surfaces. While there was an increase in the check length in sleepers without incising during seasoning, sleepers with incising showed hardly any changes in check length. The same applied to check widths and check depths. Sleepers without incising showed more, wider, and deeper checks during the whole evaluation period. Sleepers with incising also showed an increase in check width and check depth. However, this was considerably smaller.

Table 5: Comparison of the sum of check length of Beech sleepers with and without incising by categories. (I= 0-50 mm; II=51-100 mm; III=101-300 mm; IV=301-500 mm; >500 mm)

	Classification [%] sum of check length - Start										Classification [%] sum of check length - 32 weeks									
	Without incising					With incising					Without incising					With incising				
	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V
Broad side	18	**36**	**40**	6	0	**60**	34	6	0	0	2	17	**73**	**4**	**4**	**32**	**42**	24	2	0
Narrow sides	51	28	**19**	1	1	51	**34**	13	1	1	19	37	**37**	**5**	**2**	**49**	**42**	9	0	0

Table 6: Comparison of the sum of check width of Beech sleepers with and without incising by categories. (I= 0-0.5 mm; II=0.5-1.0 mm; III=1.1-2.0 mm; IV=2.1-3.0 mm; >3.0 mm)

	Classification [%] sum check width - Start										Classification [%] sum check width - 32 weeks									
	Without incising					With incising					Without incising					With incising				
	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V
Broad side	34	28	**26**	**8**	**4**	**40**	**50**	6	2	2	4	4	10	**29**	**52**	**14**	**22**	**24**	20	20
Narrow sides	49	21	**20**	**10**	0	**70**	**24**	5	1	0	29	22	**20**	**15**	**14**	**48**	**30**	10	10	2

Table 7: Comparison of the sum of check depth of Beech sleepers with and without incising by categories. (I= 0-10 mm; II=11-20 mm; III=21-30 mm; IV=31-40 mm; >40 mm)

	Classification [%] sum check depth - Start										Classification [%] sum check depth - 32 weeks									
	Without incising					With incising					Without incising					With incising				
	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V
Broad side	26	32	**24**	**10**	**8**	**26**	**60**	8	2	4	0	10	6	**17**	**67**	**8**	**24**	**20**	12	36
Narrow sides	34	42	**17**	**5**	**2**	**46**	**49**	4	0	1	5	29	17	**20**	**29**	**10**	**50**	**21**	10	9

The positive effect of incising on the check formation of Beech sleepers is exemplarily shown in Figure 14. While the sleeper without incising (S 10.10) showed already clearly recognizable checks on the surface at the beginning of seasoning, larger checks on the sleeper with incising (I 10.2) were only visible at the end grain. During 32 weeks of seasoning, the sleepers reached a proper degree of seasoning and the checks in the non-perforated sleeper top side had increased considerably in length, width and depth. The sleeper with incising pattern showed an enlargement of the checks only at the end grain.

Figure 14: Examples of positively influenced checks performance due to incising of Beech sleepers (n=5) for both incised and not incised sleepers) between 13.02.2018 (left) and 07.11.2018 (right)

A check is the separation of the fiber bond in the longitudinal direction of the wood. The formation of checks, especially for long and thick sawn timber is an extraordinarily complicated and complex process (Bavendamm et al. 1963). Different factors can be decisive such as, moisture gradients, anisotropic shrinkage and growth stresses (Fang et al. 2008, Niemz and Sonderegger 2017).

A reduction of check formation during seasoning of Beech sleepers by means of incising was also verified by Franciosi (1956), who compared 255 incised Beech sleepers with 255 not incised Beech sleepers. Furthermore, the same (but now impregnated) sleepers have been re-evaluated after 10 years of service life showing also a positive effect of incising on the check formation in the track. Only 32 % of the sleepers without incising were rated as “sound”, based on their check development. Sleepers with incising, on the other hand, showed less check development, so that 50 % of the sleepers received the rating “sound” (Franciosi 1967).

Present growth stresses can lead to checks in the standing trunk, during logging and in various working and processing operations. Particularly tangential tensile stresses in the outer parts as well as tangential and radial tensile stresses in the interior of the trunk, have to be mentioned regarding the development of tangential and radial checks beginning in the heartwood (Bavendamm et al. 1963). With regard to the exact mechanisms behind the reduction of check formation by means of incising, different approaches are discussed in the literature. While Hill (1923) and Edscorn and Davis (1989) suggested a stress relaxation for the reduction of check formation, Meierhofer (1986) proposed stress compensating effects, which lead to the development of many small checks instead of a few large checks. In contrast, Burnes (1923) considered a concentration of stresses through the incising slits as a possibility for reducing large checks.

Next to growth stresses, also moisture gradients can be seen as cause for the checking of wood. Large cross sections are particularly susceptible to checking. Due to accelerated drying, large differences in MC between inner and outer wood sections appear and lead to inner tensions. If the resulting stresses exceed the strength of the wood, checks will form and the emerging tensions are thereby relieved again (Neuhaus 2009). The examination of the moisture distribution showed no considerable difference between the MC of incised and not incised sleepers at all measuring positions. Decreased moisture gradients by the applied incising pattern can therefore be excluded as probable cause for the reduction in check formation.

2.1.3.3 Dimensional stability during seasoning of Beech sleepers

After the evaluation of the 700 incised Beech sleepers, 95 % of the sleepers were sound and showed visually no bow, spring or twisting, or the deformation did not exceed the specified tolerances. 5 % of the sleepers were deformed to an extent, that they were selected for more detailed investigations (n=40). A more detailed evaluation of the deformation showed that 2 % of the sleepers exceeded the limit value with regard to deformation by twisting and 2 % by bow. Only 1 % of the sleepers showed an excessive curvature of the narrow side (spring) (Figure 15).

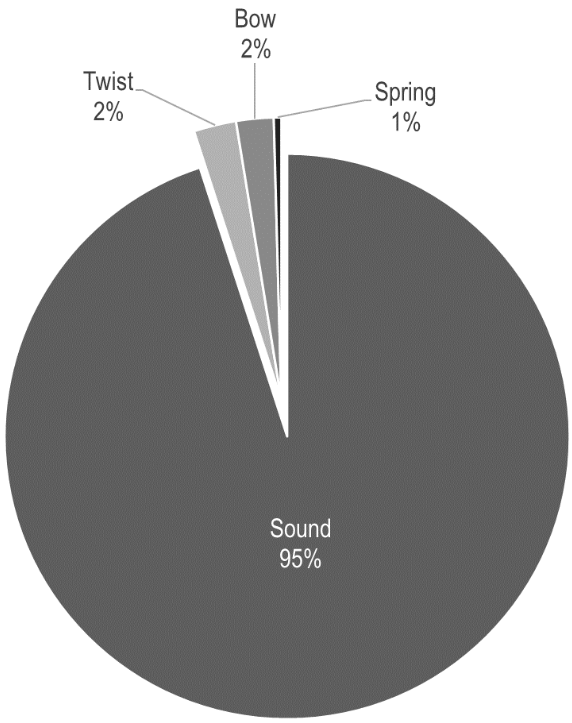


Figure 15: Distribution of the different deformation types of the evaluated Beech sleepers (n=700)

Warping of Beech sleepers during seasoning is very common. Every year, about 3 % of the sleepers purchased and stored for drying must be written off as waste due to excessive deformation (Werner 2008). According to Schulz (1971a) the deformation of Beech sleepers is caused either by the growth of the tree (spring) or by tension- and shrinkage (bow). Existing tensions will be released during logging or during cutting, especially if the cut is made directly through the middle of the trunk in radial direction. Longitudinal shrinkage is minimal compared to radial and tangential shrinking. For Beech, the longitudinal shrinkage is 0.3 %, while the radial and tangential shrinkage is 5.8 % respectively 11.8 % (Schulz 1971a).

Beimgraben (2002) suggested growth stresses being responsible for the warping of Beech. Growth stresses will be released after trees or logs are cut in sections and afterwards cause checks or warping of the timber products (Becker and Beimgraben 2001). Additionally, Bleile (2006) investigated the presence of reaction wood in Beech as probable cause for growth tensions in logs and distortions in sawn timber. It became evident, that the formation of tension wood leads to growth stresses in round woods as well as to distortions of sawn wood. Further examinations showed, that on average, only comparatively small changes in the location of the strongest reaction wood sections in radial direction of the trunk can be observed. Despite different types of wood modification, which are actually based on chemical or physical changes of the wooden structure itself (Scheiding et al. 2016), incising as mechanical pre-treatment is not actively changing the anatomical wooden structure and its properties. Therefore, influences of existing structural properties cannot be subsequently changed by incising, which indicates why warping of Beech sleepers is not positively influenced by incising.

2.1.4 Conclusions

Incising as mechanical pre-treatment for Beech sleepers has been evaluated regarding its influences on seasoning duration, moisture distribution, check formation and dimensional stability. Based on the results, following conclusions were drawn:

- During seasoning, incising showed no influence on the drying behaviour of Beech sleepers until reaching the required moisture content for impregnation. The time until the required moisture content for impregnation was reached, was not decreased.
- The moisture distribution within single sleepers was also not affected by the incising. There was no improved homogenisation of the moisture content visible.
- Incising seems to have no influence on the dimensional stability of Beech sleepers during seasoning. A comparable percentage of incised sleepers had to be excluded due to excessive deformation, as customary for not incised sleepers.
- Possible reasons why incising does not influence dimensional stability were discussed, but could not be deepened. In further investigations, the mechanism of the warping of Beech sleepers should be primarily investigated.
- A positive influence of incising on the check formation during seasoning became visible. Checks on the broad side and both narrow sides were reduced in length, width and depth, leading to a more uniform appearance.
- Different possibilities have been discussed regarding the exact mechanism behind the positive effect of incising on the check formation. For further verification of the exact mechanism behind the positive influence of incising, further investigations have to be implemented.

3 Process optimisation by impregnation of an alternative oily wood preservative

3.1 Penetration of different oily carrier substances in Beech and Scots pine sapwood and microscopic analysis of penetration pathways

3.1.1 Introduction

The penetration of the porous wooden structure by wood preservatives is influenced by various factors. Next to the impregnation process and its different sequences of vacuum and pressure, the penetration is also depending on the chemical composition and physical properties of the wood preservative. This includes viscosity, which is highly important for the impregnation of wood with oily products and has been investigated in numerous studies since the beginning of the 19th century (Teesdale and MacLean 1918, McLean 1926, 1927). The viscosity of liquids in general characterises their resistance to flow. Highly viscose fluids resist to flow, while fluids with a low viscosity flow easily (Owoyemi 2010).

Oily substances like crude tall oils, linseed and rapeseed oils are also used for the impregnation of wood and show an inhibitory effect against wood destroying organisms (Paajanen and Ritschkoff 2002). Paajanen and Ritschkoff (2002) indicated, that this inhibiting effect is not caused by broad-spectrum toxic mechanisms but moreover related to hydrophobicity. Alfredsen and Flaete (2015) also found an inhibitory effect of tall oils against wood destroying organisms, but at extremely high retentions of more than 400 kg/m³ in order to provide acceptable field performance. Since high retentions also face challenges like bleeding, the addition of biocidal components is proposed for wood protection systems including tall oils to increase their performance (Alfredsen and Flaete 2015). By adding biocidal components, important physical properties like viscosity may be increased, so the penetration behaviour of the applied product will be changed.

During impregnation, liquids enter the porous wooden structure. The anatomical structure influences the permeability of wood. Hardwoods have, based on a large variety of cell types, a more complex structure than softwoods (Kumar and Dobriya 1993). However, the main fluid flow is occurring in longitudinal direction through the tubular elements in both soft- and hardwoods (Cǒté 1963). Siau (1984) summarized, that the penetration of softwoods is occurring mainly in longitudinal direction from tracheid to tracheid via bordered pit pairs in combination with liquid flow from ray tracheids to longitudinal tracheids. Radial penetration will probably take place mostly from the rays to longitudinal tracheids. Pitted radial surfaces will promote tangential flow. In hardwoods, the main entrance for fluids are the vessels. Fluids are able to flow from vessels to fibers, vertical parenchyma and rays. Rays are generally less easy to be penetrated (Siau 1984). A greater understanding regarding the penetration behavior of creosote during impregnation was received by microscopically evaluating the penetration pathways (Liese 1951, Bosshard 1965, Behr et al. 1969). Since selected process parameters, viscosity and the wood species play a superior role regarding penetration, a microscopic analysis of the penetration pathways of alternative oily carrier substances will also be of great importance to gain further insights. To achieve this, the following aspects have been examined for later process optimisation:

- Influence of viscosity of different hydrophobic carrier substances on the penetration of Beech and Scots pine sapwood
- Influence of the addition of biocidal components on the viscosity and penetration of a selected hydrophobic carrier substance in Beech
- Microscopic analyses of the penetration pathways of hydrophobic carrier substances in Beech and Scots pine sapwood

3.1.2 Materials and methods

3.1.2.1 Hydrophobic carrier substances

Three different hydrophobic carrier substances have been used for the following investigation. Their origin of production is shortly explained in Table 8.

Table 8: Description of the different hydrophobic carrier substances

Hydrophobic carrier substances	Description of production origin
Product no. 1	Plant based by-product from paper manufacturing
Product no. 2	Chemically modified plant-oil
Product no. 3	Processed petroleum product

3.1.2.2 Specimen preparation

For examination of penetration depth and distribution of the three hydrophobic carrier substances, specimens from Beech and Scots pine sapwood in dimensions of 500 x 50 x 25 mm³ and free from defects were used. To examine the longitudinal influence on penetration, each specimen collective was divided into two groups. In each case six specimens with and without sealed end grain sides were impregnated. The sealing was carried out via Pyroplast Top W (Sika, Stuttgart, Germany).

After drying of the sealing, the specimens were weighed and measured for calculation of the retention in kg/m³ after impregnation. The retention was calculated according to Eq. (2).

$$Retention = \frac{M_1 - M_0}{V_{Specimen}} \qquad (2)$$

Retention = Preservative uptake in kilogram per cubic meter [kg/m³]

M_1 = Weight of specimen after impregnation [kg]

M_0 = Mass of specimen before impregnation [kg]

$V_{Specimen}$ = Volume of specimen [m³]

3.1.2.3 Addition of biocidal components

Biocidal components were added to product no. 1. For adding the single biocidal components, product no.1 was initially decanted in 2 metal buckets. Afterwards, both solutions were heated up to approximately 60°C using an electrical milk heater for cattle. A previously defined amount of copper hydroxide ($Cu(OH)_2$) was added to bucket 1. In bucket 2, the same amount of $Cu(OH)_2$ as well as a defined amount of an organic co-biocide were added. Due to confidentiality reasons, exact quantities of both biocidal components cannot be given. The $Cu(OH)_2$ powder was added in small amounts at a time to reduce the risk of agglomeration. To achieve a better solubility, the solution was continuously stirred using an Ultraturrax. The alternative oily wood preservative on copper basis was used as reference. Table 9 summarizes the used solutions and gives the later used abbreviations.

Table 9: Added biocidal components to product no. 1 and used abbreviations

Solutions	Abbreviation
Product no.1 and $Cu(OH)_2$	P1CH
Product no. 1 and $Cu(OH)_2$ and co-biocide	P1CHCB
Alternative oily wood preservative serving as reference product	REF

3.1.2.4 Impregnation of specimens

Since a complete penetration of the wooden structure by the hydrophobic carrier substances was the main focus of the investigation, the specimens were impregnated using a full cell process (vacuum: -0.85 to –0.80 bar for 60 min; fluid pressure: 8 bar for 120 min), instead of an empty cell process, which is typical for the impregnation of wood with oily wood preservatives. A full cell process was used to ensure a homogeneous penetration of the specimen cross section and to exclude penetration hindering effects by present air, especially by the applied air pressure from an empty cell process. The temperature of hydrophobic carrier substances no. 1 and no. 2 as well as the mixtures of hydrophobic carrier substance no. 1 with the biocidal components was approximately 60°C during impregnation. The impregnation of substance no. 3 took place at room temperature. After impregnation, the specimens were weighed again for calculation of the retention in kg/m^3 in accordance to Eq. (2).

After a drying period of 24 hours the specimens were cut in the middle for a visual determination of the penetration depth of all solutions.

3.1.2.5 Viscosity determination of the different hydrobhobic carrier substances at different temperatures

The viscosities of all evaluated solutions were measured at room temperature (approximately 23-25°C), 40°C, 60°C and 80°C using a rotational viscometer (HAAKE ViscoTester 7L, Thermo Electron, Karlsruhe, Germany). Approximately 800 ml of each solution was filled into a beaker and was heated up using a heating plate. Afterwards, the viscosity of each solution was measured using the enclosed spindle (size L1). Depending on the viscosity of the different solutions, an observation under different rotational speeds between 30-200 min^{-1} was necessary.

3.1.2.6 Microscopic analysis of the penetration of hydrophobic carrier substances

For microscopic analyses of the penetration pathways of the hydrophobic carrier substances the product with the highest viscosity (product no.1) and the lowest viscosity (product no.3) were selected. Therefore, product no.2 was excluded from the microscopic analysis. The specimen preparation was carried out as followed:

Initially, slices of the impregnated specimens of Beech and Scots pine sapwood were cut from the middle part of the sealed specimens. To decrease the mobility of the substances during further specimen preparation, the slices were stored in the freezer at approximately -19°C for at least 24 hours.

For Beech and Scots pine sapwood, specimens with a dimension of approximately 10 x 10 x 10 mm³ were cut from the fully penetrated area of the frozen slices. As reference, non-impregnated Beech and Scots pine sapwood specimens were prepared. Smooth axial specimen surfaces were obtained using a microtome knife.

The verification of the hydrophobic carrier substances inside the wooden structure was carried out by staining in combination with UV light, since wooden material that contains coloring agent is not covered with oil. Oil-covered wooden material will seal of the coloring agent and due to the UV-light will appear fluorescent. A 0.5 % aqueous solution of Fuchsin Standard (Fluka Chemie AG, Buchs, Switzerland) was used as coloring agent. The smooth surfaces of all specimens were immersed for 30 minutes. Afterwards, the coloring agent was leached out in demineralised water for 30 minutes. Before microscopic analyses the specimens were dried on a heating plate at 25°C to remove residual water. For determination of non-stained wooden material under UV-light, untreated specimens were analysed.

For microscopic analysis of the penetration pathways a light microscope (Nikon Eclipse E 600) with an additional UV-light adapter (Y-FL) was used. All pictures were acquired at a magnification of 10x.

3.1.3 Results and discussion

3.1.3.1 Viscosity and penetration of different oily carrier substances in Beech and Scots pine sapwood

Figure 16 shows that increasing temperature leads to a decrease in viscosity of all products. At all measured temperatures, product no. 1 had the highest viscosity followed by product no. 2 and product no. 3.

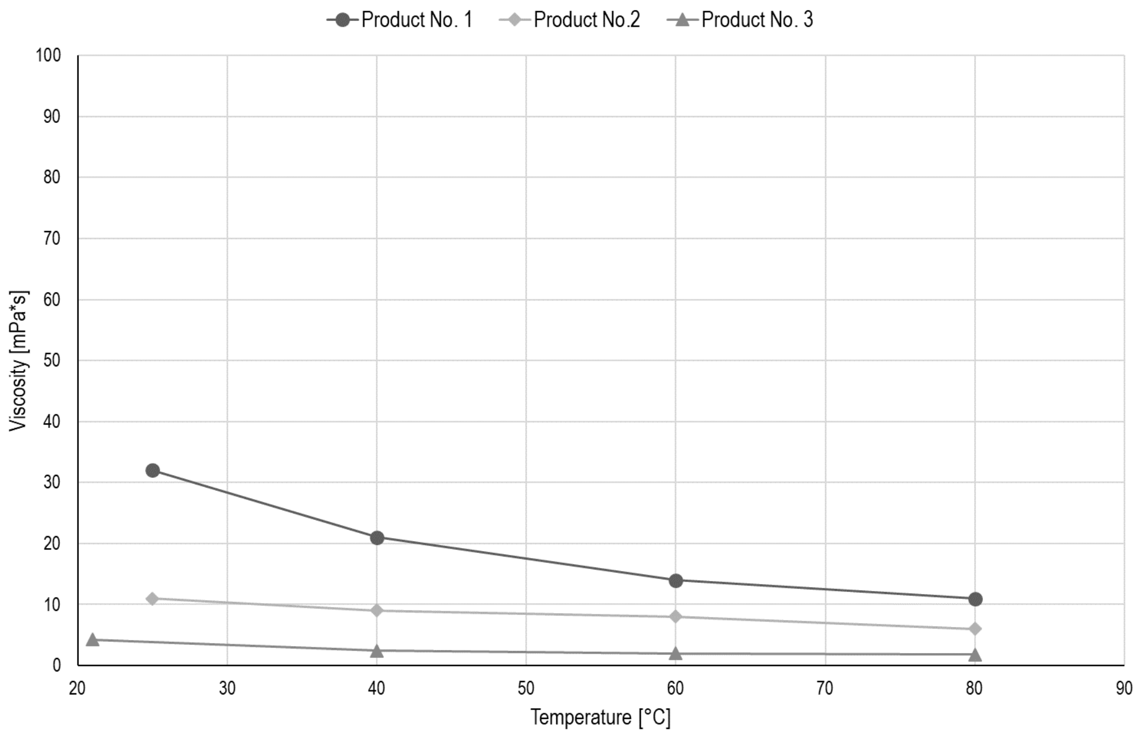


Figure 16: Influence of increasing temperature on the viscosity of different hydrophobic carrier substances

The penetration depth in combination with the average retention [kg/m^3] and the standard deviation (SD) in Beech and Scots pine sapwood of the differently viscous hydrophobic carrier substances is exemplary presented. Figure 17 shows that all products penetrated the complete cross section of the unsealed specimens of Beech at similar retentions. Also, the Scots pine sapwood samples were completely penetrated, while product 1 and 2 showed significantly higher average retentions compared to Beech (Figure 17).

Beech

Product no. 1	Product no. 2	Product no. 3
[394 kg/m³ (21)]	[400 kg/m³ (20)]	[395 kg/m³ (20)]

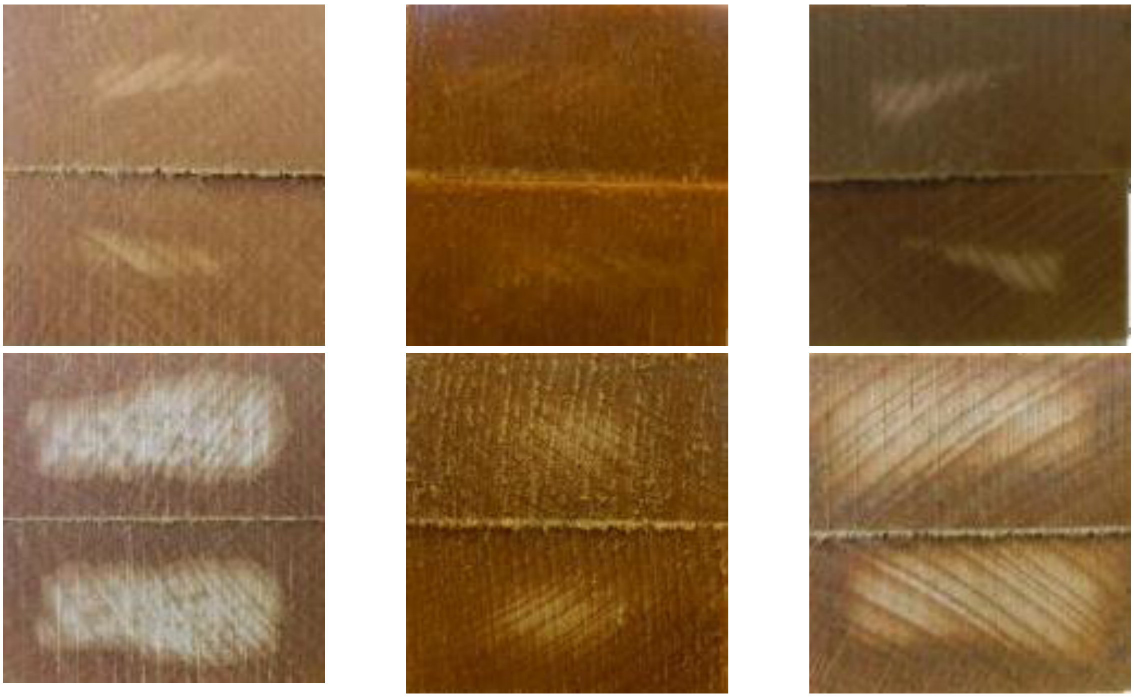
Scots pine sapwood

Product no. 1	Product no. 2	Product no.3
[507 kg/m³ (21)]	[504 kg/m³ (22)]	[398 kg/m³ (65)]

Figure 17: Penetration depth, average retention [kg/m³] and (SD) of the hydrophobic carrier substances at centric cut specimens out of Beech and Scots pine sapwood without sealed grain sides

For the sealed specimens, the average retention in kg/m^3 as well as the penetration depth of all three hydrophobic carrier substances in Beech differed from the unsealed specimens. Each specimen collective showed single specimens with nearly completely penetrated cross sections by all three substances, while others were penetrated poorly. The sealed specimens of Scots pine sapwood showed similar average retentions for all three products compared to the unsealed specimen. Unlike Beech, the cross sections of all specimen collectives were fully penetrated (Figure 18).

Beech



Product no. 1	Product no. 2	Product no. 3
[328 kg/m³ (41)]	[384 kg/m³ (32)]	[310 kg/m³ (45)]

Scots pine sapwood

Product no. 1	Product no. 2	Product no.3
[517 kg/m³ (19)]	[479 kg/m³ (40)]	[366 kg/m³ (50)]

Figure 18: Penetration depth, average retention [kg/m³] and (SD) of the hydrophobic carrier substances at centric cut specimens out of Beech and Scots pine sapwood with sealed grain sides

The low viscosity of the different hydrophobic carrier substances does not seem to influence penetration primarily. The complete penetration of the cross section of the unsealed Beech and Scots pine sapwood specimens can be attributed to the solution uptake in longitudinal direction. The movement of gases, but also fluids in the wooden tissue is primarily occurring through the perforated vessels in longitudinal direction (Côté 1963).

In case of Beech, the sealed specimens showed, that a low viscosity is not automatically improving the penetration of the hydrophobic carrier substances. Despite having the lowest viscosity (comparable to creosote at 80-100°C (Broese van Groenou 1983)), product no. 3 showed the worst transversal penetration.

Regarding the influence of viscosity on penetration, Hösli and Bavendamm (1979) found that even for creosote a temperature of 60°C (viscosity approximately 4.5 mPa*s) would be sufficient, since the penetration speed at a given pressure and higher temperatures could not be further increased. But they also found, that the influence of the surface tension, determining which pores will be penetrated, will increase only from temperatures way above 60 °C.

It has to be considered that in general the movement of liquids in the transversal direction of wood is more difficult (Murmanis and Chudnoff 1979) compared to the longitudinal direction. The movement of oily products can be hindered by the wood rays (Behr et al. 1969). Moreover, is not taking place within the rays (Liese 1951). Insufficient evacuation of the cross section could be another explanation for the incomplete penetration of the cross section. In this case, the penetrating substance is compressing residual air in the middle of the specimens (Liese 1951).

The complete penetration of the cross section of the sealed Scots pine sapwood specimens can be explained as follows:

Softwoods have a simpler wooden structure compared to hardwoods (Kumar and Dobriya 1993). Behr et al (1969) concluded, that rays in softwoods are more important for transport and storage of non-polar fluids than in hardwoods, which has also been confirmed by Bosshard (1965) after examination of creosote treated transmission poles out of Scots pine sapwood. Creosote can easily flow into the longitudinal elements at the contact points with the rays since the membranes of the window like pits are destroyed due to the high pressure. Furthermore, Bosshard (1965) found that next to wood rays also resin canals become important pathways, facilitating the transversal creosote penetration.

3.1.3.2 Influence of added biocidal components on the penetration of a hydrophobic carrier substance in Beech

Figure 19 shows that adding $Cu(OH)_2$ and a co-biocide (P1CH and P1CHCB) increases the viscosity of the hydrophobic carrier substance product no. 1. at room temperature. Increasing the temperature decreased the viscosity of both solutions and aligned the viscosity of the pure hydrophobic carrier substance at 60 °C. At temperatures above 70 °C, the viscosities of both mixtures decreased even below the viscosity of product no.1 (Figure 19).

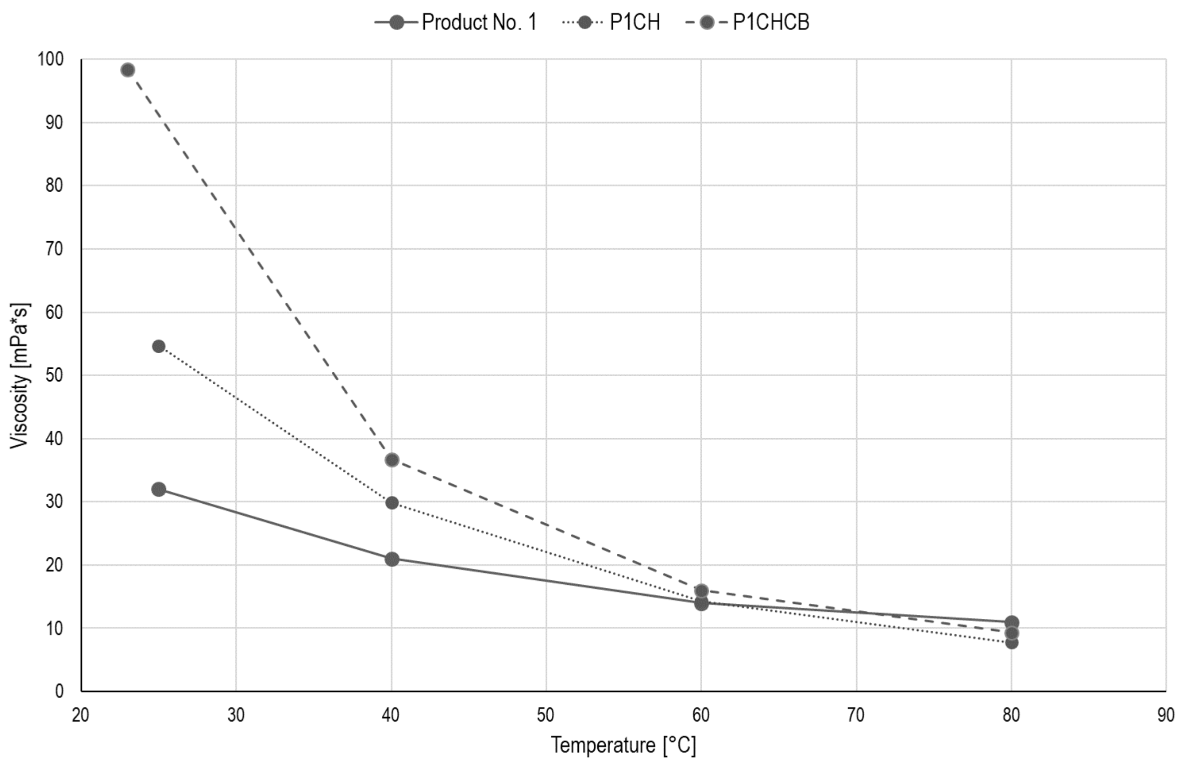
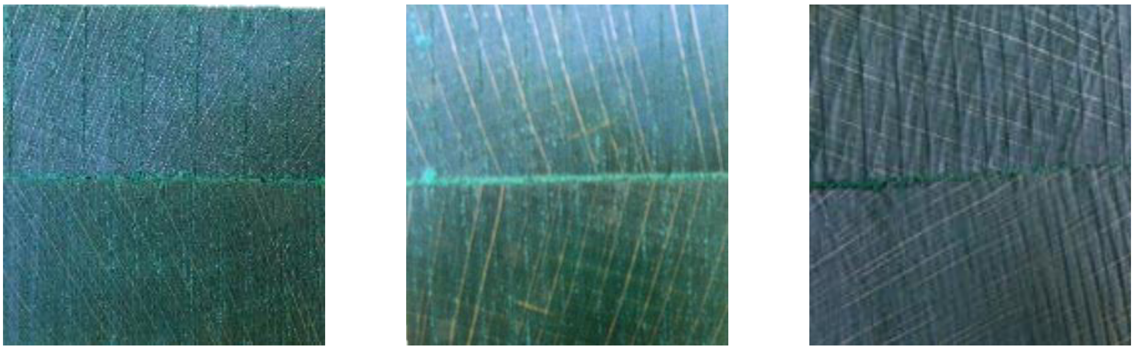


Figure 19: Influence of copper hydroxide $Cu(OH)_2$ and copper hydroxide $Cu(OH)_2$ in combination with a co-biocide on the viscosity of hydrophobic carrier substance no. 1 (Product No.1) at increasing temperatures

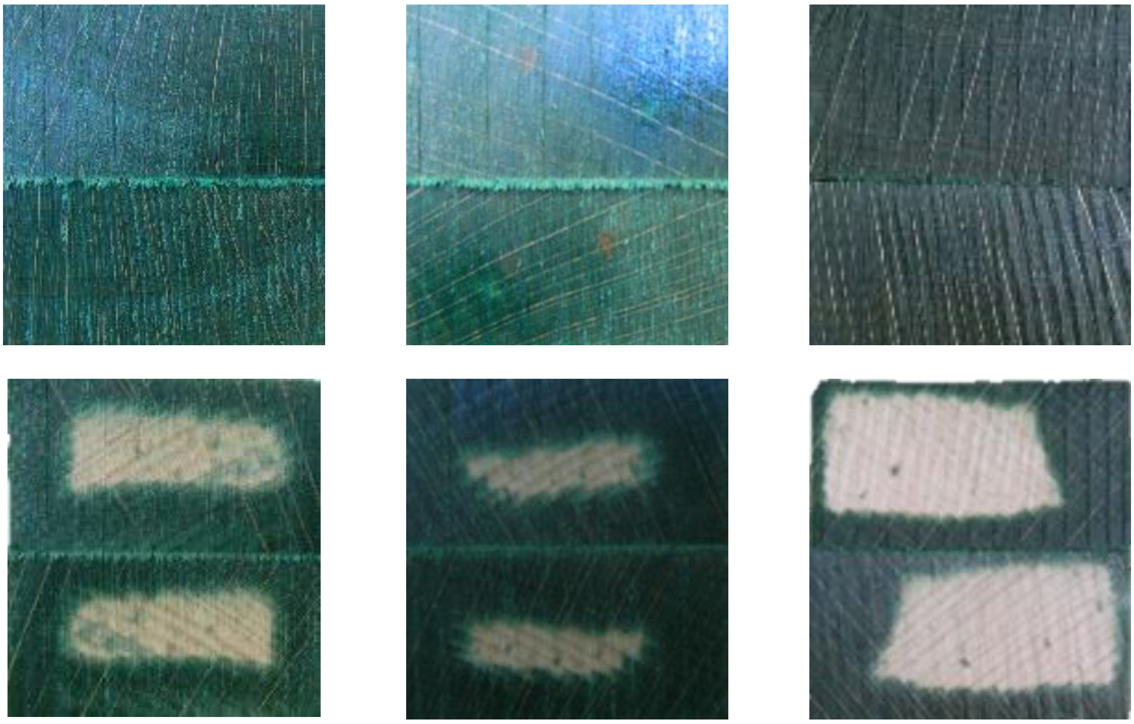
Figure 20 shows the average retention in kg/m³ and the penetration depth of P1CH and P1CHCB Both mixtures as well as the alternative oily wood preservative as reference (REF) showed similar average retentions and a complete penetration of the cross section without sealed grain sides. Additionally, the average retentions were similar to the average retention of the collective impregnated with pure product no.1.



Product no. 1 + copper hydroxide [440 kg/m³ (48)]	Product no. 1 +copper hydroxide + co-biocide [433 kg/m³ (29)]	Alternative oily wood preservative [413 kg/m³ (18)]

Figure 20: Penetration depth, average retention [kg/m³] and (SD) of hydrophobic carrier substance (product no.1) with copper hydroxide $Cu(OH)_2$ (P1CH), copper hydroxide $Cu(OH)_2$ in combination with a co biocide (P1CHCB) and the alternative oily wood preservative (REF) at centric cut specimens out of Beech without sealed end-grain.

For the sealed specimens, the average retention in kg/m^3 as well as the penetration depth of all solutions (P1CH, P1CHCB and REF) differed from the unsealed specimens. Each specimen collective showed single specimens with completely penetrated cross sections, while others were penetrated poorly (Figure 21). The average retentions of all three solutions did not differ significantly, but were in average noticeably lower compared to the not sealed specimen collectives.



Product no. 1 + copper hydroxide [369 kg/m³ (42)] | Product no. 1 + copper hydroxide + co-biocide [381 kg/m³ (38)] | Alternative oily wood preservative [385 kg/m³ (83)]

Figure 21: Penetration depth and average retention [kg/m³] and (SD) of hydrophobic carrier substance (product no.1) with copper hydroxide $Cu(OH)_2$ (P1CH), copper hydroxide $Cu(OH)_2$ in combination with a co biocide (P1CHCB) and the alternative oily wood preservative (REF) at centric cut specimens out of Beech with sealed end-grain.

Adding the biocidal components solely increased the viscosity of the hydrophobic carrier substance at temperatures up to 60°C. By mixing $Cu(OH)_2$ with the oily carrier substance a metal soap is created, which increases the viscosity. By adding the co-biocide, the viscosity was almost doubled. This can be attributed to the relatively high viscosity of the co-biocide at room temperature. The addition of both active ingredients to the hydrophobic carrier substance (product no. 1) did not result in considerable changes in the average retention as well as penetration pattern. Thus, an influence of copper hydroxide or the co-biocide on the penetration behaviour can be excluded. Moreover, copper is the primary active ingredient used in wood preservatives, to successfully protect wood above and in ground contact for more than a century (Richardson, 1997). Copper is used as water-based soluble copper formulations, but also as oil-based copper complexes and water-based micronized copper formulations (Freeman and McIntyre 2008). Water-soluble formulations include for example chromated copper arsenate (CCA) or ammoniacal copper quat (ACQ) or copper-HDO (bis-(N-cyclohexyl-diazeniumdioxy)-copper). Copper naphthenate on the other hand is an alternative oily wood preservative based on the reaction product of copper salts and naphthenic acid (Ibach 1999).

Today, copper naphthenate is also the leading alternative for the impregnation of railway sleepers in North America (Gauntt 2019).

3.1.3.3 Microscopic analysis of penetration pathways

Non-stained, untreated cellular structures were fluorescent under UV- light, while with Fuchsin stained untreated structures showed a clear red color (Figure 22 and Figure 23).

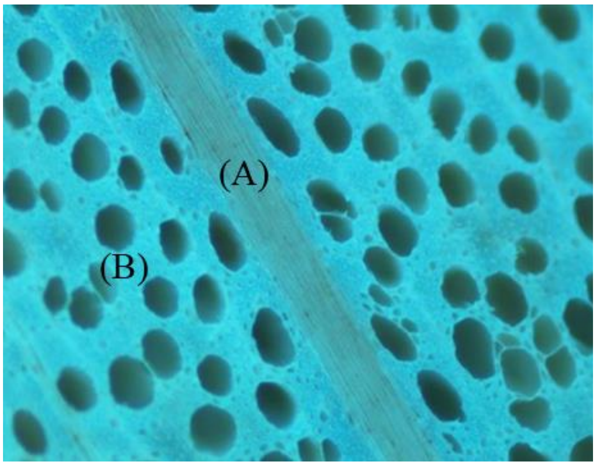


Figure 22: Cross section of non-stained untreated Beech under UV-light; Nikon Eclipse E 600; magnification 10x; (A) Wood ray, (B) Vessels

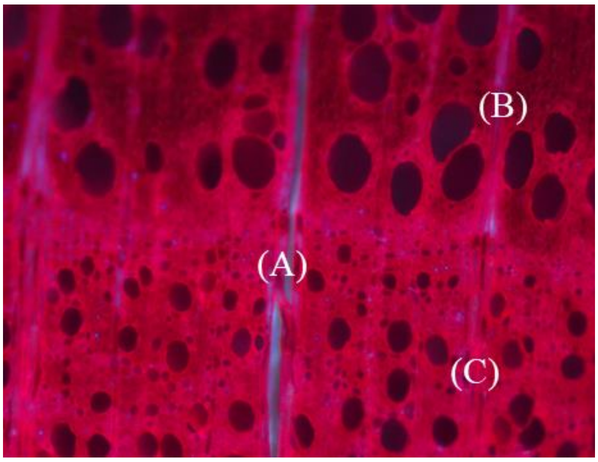


Figure 23: Cross section of stained untreated of Beech under UV-light; Nikon Eclipse E 600; magnification 10x; (A) Wood ray, (B) Early wood with vessels, (C) Late wood with vessels

<u>Beech</u>

Beech impregnated with hydrophobic carrier substances no.1 and no. 3 showed staining of the fibers and the wood rays (Figure 24 and Figure 25). For Beech impregnated with hydrophobic carrier substance no. 1, small fluorescent traces were seen in the fiber area. Additionally, residues of the substance were recognized in a number of big vessels in the earlywood, but more extensively in the smaller vessels of the latewood and lumen of the fibers. The wood rays showed also intense red staining (Figure 24), which indicated that none or only marginal amounts of carrier substance were in the ray cells. Beech impregnated with substance no.3 showed fluorescent fiber lumens, partially filled big vessels and filled small vessels. The cellular structure of the wood rays showed stained, but also fluorescing parts (Figure 25).

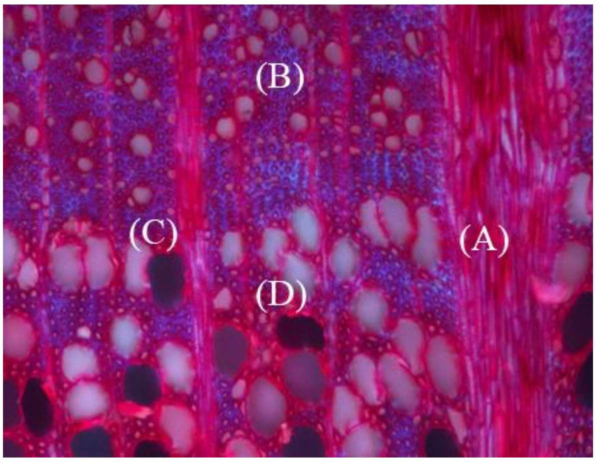


Figure 24: Cross section of stained Beech impregnated with hydrophobic carrier substance no.1 under UV-light; Nikon Eclipse E 600; magnification 10x; (A) Stained wood ray; (B) Stained but filled fibers in the late wood; (C) Empty vessel in the early wood; (D) Filled early wood vessels

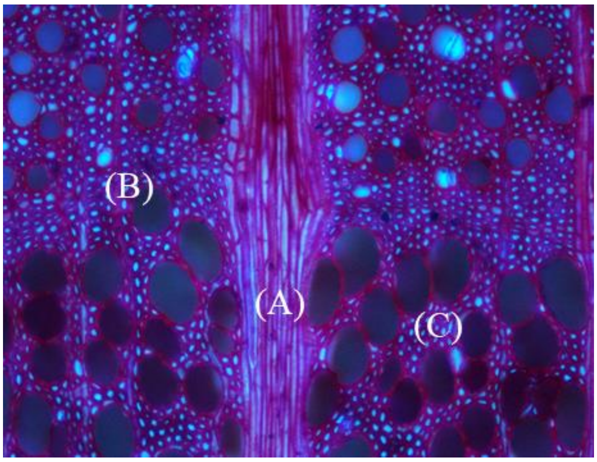


Figure 25: Cross section of stained Beech impregnated with hydrophobic carrier substance no.3 under UV-light; Nikon Eclipse E 600; magnification 10x; (A) Partially non-stained wood ray; (B) Filled fibers in the late wood; (C) empty vessel in the early wood

The stained cellular structure of Beech clearly indicated the absence of oil. Present oil would inhibit staining and the cellular structure would be fluorescing. Desmaris et al. (2016) suggested, that based on its non-polarity and molecule size, oil does not enter the cell walls and can only residue on its surfaces. The slight fluorescing parts on the surface of the cellular structure of the fibers of Beech may be artifacts of the oily carrier substance no.1, dragged during cutting of the samples.

The complete red staining of the multiseriate wood ray of Beech impregnated with hydrophobic carrier substance no. 1 indicates the absence of the product inside the wood ray. Also, Liese (1951) found no oil in the wood rays of Beech after impregnation with creosote. The fluorescing parts of the wood ray from Beech impregnated with substance no.3 may indicate its presence, but even enclosed air may be possible. Behr et al. (1969) found similar results during their investigations, where wide rays especially in Beech were filled with air after impregnation of creosote.

Scots pine sapwood

Scots pine sapwood impregnated with hydrophobic carrier substances no. 1 and no. 3 showed comparable staining patterns to Beech. In case of both impregnated substances, the cellular structure was stained with the coloring agent (Figure 26 and Figure 27). Scots pine sapwood impregnated with substance no. 1 showed fluorescing areas in the latewood tracheids. There were also residues of the hydrophobic carrier substance in the latewood lumens. Furthermore, less residues of the substance were remaining in the earlywood tracheid lumens. Partially filled tracheids appeared slightly fluorescent (Figure 26).

Scots pine sapwood impregnated with hydrophobic carrier substance no. 3 showed clearly fluorescing lumen of the latewood tracheids. Also, most of the bigger earlywood tracheids were partially filled and appeared slightly fluorescent. Furthermore, the resin canal also appeared clearly fluorescent (Figure 27).

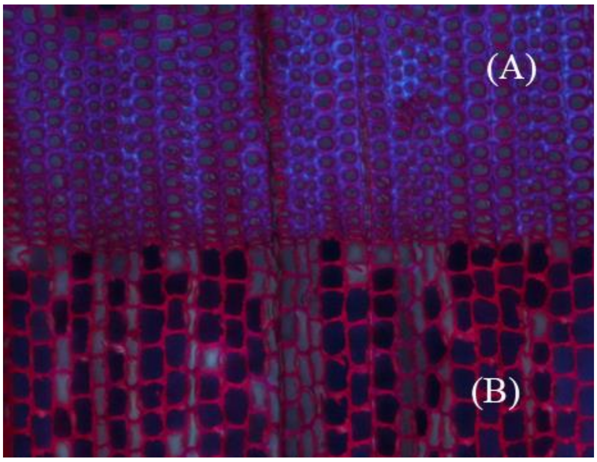


Figure 26: Cross section of stained Scots pine sapwood impregnated with hydrophobic carrier substance no.1 under UV-light; Nikon Eclipse E 600; magnification 10x; (A) Fluorescing late wood tracheids; (B) Stained cellular structure in the early wood

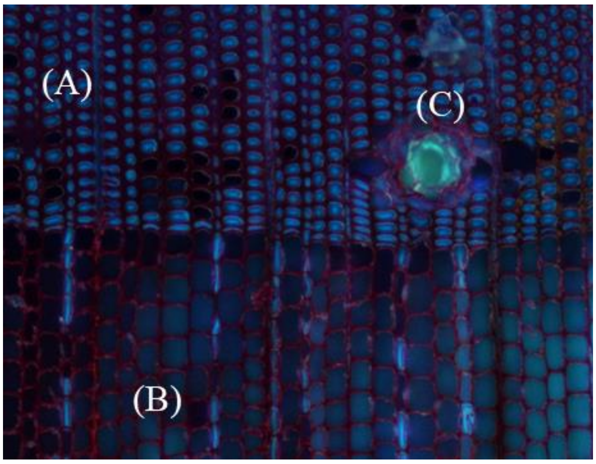


Figure 27: Cross section of stained Scots pine sapwood impregnated with hydrophobic carrier substance no.3 under UV-light; Nikon Eclipse E 600; magnification 10x; (A) Fluorescing lumen of the late wood tracheids; (B) Slightly fluorescing partially filled early wood tracheids; (C) Clearly fluorescent resin canal

As for Beech, the fluorescing surfaces of the cellular structure of Scots pine sapwood impregnated with hydrophobic carrier substance no. 1 can be explained by artifacts dragged during cutting of the samples. The increased appearance of substance residues in the small vessels and small lumen of the hardwood-fibers, as well as in the small lumen of the latewood tracheids of softwood can be explained as follows:

Generally, the main entrance for fluids in hard- as well as in softwoods is occurring through the tubular elements in longitudinal direction (Cŏté 1963). In case of hardwoods, fluids are able to flow from vessels to fibers, while in softwoods the fluid flow occurs from tracheid to tracheid in combination with liquid flow from ray tracheids to longitudinal tracheids (Siau 1984). Behr et al (1969) found comparable results during the examination of penetration pathways of creosote and pentachlorophenol in different hard- and softwood species including Beech and Southern yellow pine. According to Siau (1984) the capillary tension is increasing with decreasing diameter. Therefore, liquids in capillaries with small diameters need more force for exit. Thus, during preparation, the hydrophobic carrier substances were possibly removed more easily from vessels or tracheids with larger diameter.
Penetrated resin canals were also recognized by Bosshard (1965) during the examination of creosote impregnated Scots pine sapwood transmission poles. An alteration of the resin canals occurred based on the impregnation, which lead to an opening for fluid transport.

3.1.4 Conclusions

The viscosity of three different hydrophobic carrier substances and its influence on the penetration of Beech and Scots pine sapwood were investigated. Based on the results, following conclusions were drawn:

- The viscosity of the selected hydrophobic carrier substances has a minor influence on the penetration of Beech. Even at the lowest viscosity, a complete penetration of the specimen cross section is only possible by including penetration in longitudinal direction. By excluding the longitudinal penetration pathways, even at the lowest viscosity a complete penetration of the cross section was not possible.
- In Scots pine sapwood, the viscosity had also no influence on the penetration. In contrast to Beech, a complete penetration at the highest, as well as at the lowest viscosity was possible even under exclusion of longitudinal penetration pathways.
- The addition of $Cu(OH)_2$ and a co-biocide did not increase the viscosity at 60°C of the oily carrier substance no.1 and had also no influence on its penetration behaviour in Beech.
- Complete penetration of the specimen cross section was only possible under the longitudinal influence. The alternative oily wood preservative, which was used as reference showed also comparable penetration patterns like both mixtures.

After additional analysis of the penetration pathways of two different hydrophobic carrier substances on microscopic level, the following can be concluded:

- The penetration of hydrophobic carrier substances in Beech took place in longitudinal direction via vessels and fibers. Less penetration seems to be occurring within the wood rays.
- For Scots pine sapwood the penetration of hydrophobic carrier substances took place in longitudinal direction mostly through the lumen of the late- and earlywood, but also through resin canals. After impregnation, hydrophobic carrier substances remain more often in the smaller lumen of the latewood tracheids.
- The penetration pathways for the examined hydrophobic carrier substances in Beech and Scots pine sapwood were similar to those of creosote and pentachlorophenol as shown in previous studies by Bosshard (1965) and Behr et al. (1969).

3.2 Impregnation of an alternative oily wood preservative in technical scale

3.2.1 Introduction

Today, the use of creosote as wood preservative for the impregnation of Beech sleepers (*Fagus sylvatica* L.) is more than 170 years old (Pfabigan and Reitbauer 2020). Even though the service life of sleepers can be prolonged by the factor of ten due to impregnation, early failures appear and result in unnecessary sleeper exchanges. Since creosote treated wood shows a high efficacy against the deterioration by wood destroying organisms, non-treated spots in the middle of the sleeper are from most importance (Zycha 1965). Occurring checks are able to reach into these not impregnated spots and serve as entry points for water and fungi (Zycha 1957). A complete and homogenous penetration of the complete sleeper volume is therefore the most important criterion to ensure an efficient preservation against the deterioration by wood destroying organisms. This also applies for alternative oily wood preservatives, if used for the impregnation of railway sleepers made from Beech.

Nevertheless, also economic and ecological aspects have to be considered as fundamental for process optimisation. In economic terms, an optimal retention in combination with short process durations is vitally important to make the production affordable. Too high retentions can only be compensated by increasing end product prices. Also, unnecessarily long impregnation processes will raise the production costs by high energy consumption and will decrease the possible workload of the impregnation plant.

Ecologically, it is very important to minimize the pollution of the environment during the service life of the treated product. Pollution by leaching of the product itself (oily products) or the leaching of certain preservative components like copper (water-based products) is possible. The highest amount of leaching occurs within the first month of service and increases with high retention levels and high proportions of exposed surface, especially end-grains (Freeman and McIntyre 2008). Oily products, for example creosote, will not dry and remain inside the wooden structure as highly viscose fluid (Leiße 1992). Especially creosote tends to “bleed” after impregnation if exposed to sunshine (Findlay 1985).

Since creosote will possibly be banned in the near future, different oily preservatives are used in the EU at the moment. All contain copper hydroxide as the primary active ingredient and also organic acid co-solvents (Brient et al. 2020). Nevertheless, nearly all knowledge regarding the impregnation of railway sleepers made from Beech is mainly existing from past studies made with creosote.

Even though alternative hydrophobic carrier substances seem to have comparable penetration pathways like creosote (Chapter 3.1), a process optimisation for alternative oily wood preservatives is still necessary to ensure a complete and homogeneous penetration of the sleeper cross section. Therefore, the following objectives have been set:

- Reaching full penetration of the cross section by using empty- as well as full cell processes
- Optimising preservative retentions by adjusting single process parameters
- Improving preservative retention and penetration by modification of the commonly used impregnation processes

3.2.2 Materials and methods

3.2.2.1 Alternative oily wood preservative

An alternative oily wood preservative was used for impregnation of all specimens. The preservative is a combination of a hydrophobic carrier substance, which is a by-product from the paper production, and biocidal components. The main biocidal components are copper hydroxide ($Cu(OH)_2$) and an organic co-biocide. An impregnation can be carried out at temperatures up to 60 °C due to the temperature stability of the individual active substances. Higher temperatures will lead to loss in efficacy of single preservative components. For reasons of confidentiality, the name of the alternative oily wood preservative cannot be further disclosed. The same applies for the exact chemical composition of the product.

3.2.2.2 Sample preparation

All following investigations have been carried out using specimens, cut out of railway sleepers made from Beech, which the Fürstenberg-THP GmbH, Hüfingen, Germany, provided with dimensions of 2600 x 260 x 160 mm³. For specimen preparation, the sleepers were shortened from both grain sides up to 2000 mm length to exclude end grain checks. Afterwards, the 2000 mm sleepers were halved and quartered (Figure 28).

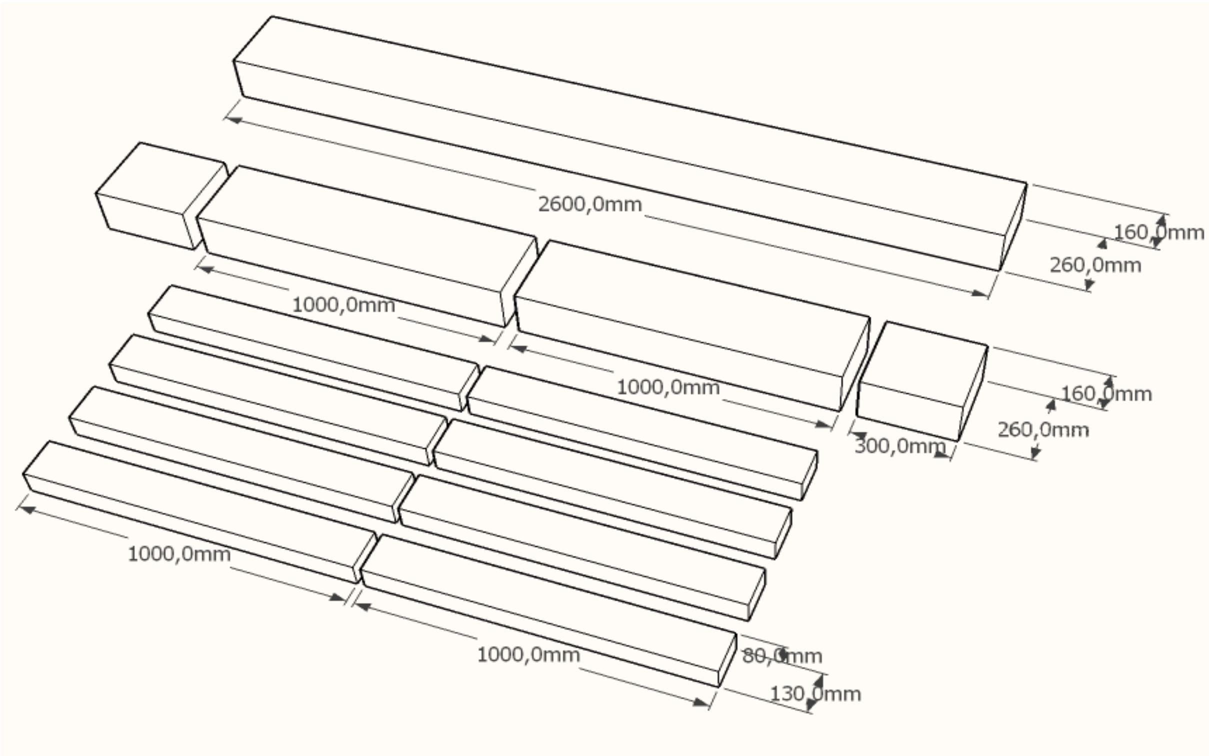


Figure 28: Preparation of specimens for process optimisation from Beech sleepers in standard dimension of 2600 x 260 x 160 mm³

Thus, it was possible to prepare eight specimens with the dimensions of 1000 x 130 x 80 mm^3 out of one railway sleeper. All end-grains were sealed three times using Pyroplast Top W (Sika, Stuttgart, Germany) to exclude longitudinal penetration of the alternative oily wood preservative. All specimens have been weighed before and after impregnation to determine the retention of the alternative oily wood preservative in kg/m³. The retention was calculated in accordance to Eq. (2).

3.2.2.3 Impregnation plant in technical scale

In order to be able to impregnate railway sleepers with oily wood preservatives, an impregnation plant must be able to perform empty cell processes like a Rüping-process. The impregnation plant in technical scale, reconstructed by the company Prokmet, Poznan, Poland, is able to perform empty cell processes. However, the possibility to perform full cell processes is also given. The plant consists of two tanks for storing the oily wood preservative and an autoclave for impregnating the railway sleepers. The autoclave has a length of 2000 mm and a diameter of approximately 300 mm. During impregnation using a Rüping-process, an air pressure up to five bar can be applied. The fluid pressure can be increased up to 15 bar for all used impregnation processes. Additionally, a vacuum of -0.9 bar is possible, either as first process step during a full cell process or as post-vacuum during empty cell processes. Figure 29 shows a schematic construction plan of the necessary parts for full- and empty cell processes.

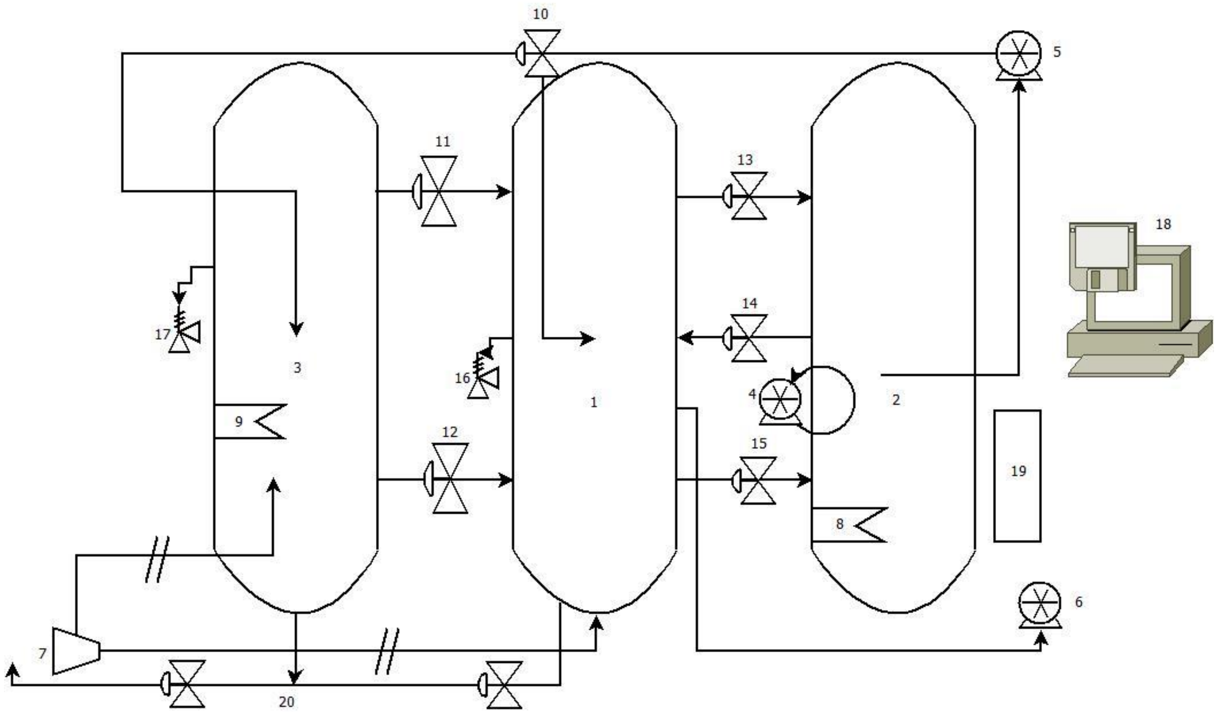


Figure 29: Schematic construction plan of the used impregnation plant in technical scale. (1) autoclave; (2) storage tank 1; (3) storage tank 2; (4) circulation pump 1; (5) circulation pump 2; (6) vacuum pump; (7) compressor; (8-9) heating rods; (10-15) compressed air valves; (16-17) safety relief valves; (18) computer control; (19-20) ventilation system

The first steps of the impregnation procedure were identical for full- as well as empty cell processes. First of all, the alternative oily wood preservative was heated up to the required temperature in storage tank 1 (2). During the heating, the circulation pump (4) was switched on for preservative circulation inside the storage tank 1 (2). Both steps were manually adjusted, using the control system (19). The constant fluid flow prevented the destruction of the preservative by overheating due to longer direct contact with the heating rods (8). In the meantime, the wood was placed into the autoclave (1). By using the computer control (18), the impregnation program was selected. If a full cell process was selected, following steps were automatically performed by the impregnation software:

The impregnation software started the pre- vacuum phase. The vacuum pump (6) removed the air out of the autoclave (1) until the required vacuum was reached. Afterwards the autoclave was flooded with the preservative by opening the compressed air valve (14). The preservative was sucked from the storage tank 1 (2) inside the autoclave (1) by the applied vacuum. In the subsequent pressure phase, the fluid pressure was built up by pumping preservative from storage tank 1 (2) into the autoclave via the circulation pump (5). Pressure decrease due to penetration of the preservative inside the wood was compensated by continuous but interrupted pump (5) operation. After finishing the fluid pressure phase, the pressure was released over the ventilation system (20) and the preservative flooded back into the storage tank 1. The program automatically switched into the post-vacuum stage and the vacuum pump (6) generated the post-vacuum. The ventilation of the autoclave after the process end took place by a ventilation system (20).

If an empty cell process was selected, the impregnation procedure differed from the full cell process. As additional step before starting the impregnation program, the preservative had to be pumped from storage tank 1 (2) to storage tank 2 (3) by manually switching on the circulation pump (5). The pump stopped automatically when storage tank 2 (3) was filled to a certain level. After starting the impregnation program, the air pressure phase was started and compressed air flowed into the autoclave until the requested air pressure was reached. Simultaneously the pressure in storage tank 2 (3) was adjusted to the same level as the autoclave by compressed air for later flooding of the autoclave. After finishing the air pressure phase, the preservative was flooded into the autoclave by gravity and the storage tank 2 (3) was ventilated via the ventilation system (20). The procedure of the fluid pressure- as well as the post-vacuum phase did not differ from the full cell process.

The impregnation plant used for the impregnation of the alternative oily wood preservative fulfilled most of the required features for the impregnation of oily wood preservatives with full- and empty cell processes. Nevertheless, the implementation of additional impregnation processes like a pulsation process were planned. This required a modification allowing alternating pressure during the fluid pressure phases.

3.2.2.4 Empty cell processes

Rüping-processes

Different Rüping-processes have been carried out to examine the retention in kg/m³ and penetration depth of the oily product in specimens made from Beech. The single Rüping-processes varied in pressure and duration of the applied air and fluid pressure and the duration of the post-vacuum section (Table 10).

Table 10: Detailed process parameter of the carried out Rüping-processes

Rüping-processes	Process section: Air pressure		Fluid Pressure		Post-vacuum	
	Pressure [bar]	Duration [min]	Pressure [bar]	Duration [min]	Pressure [bar]	Duration [min]
Process 1	4	60	8	180	-0.85 to -0.8	60
Process 2	3	60	8	180	-0.85 to -0.8	60
Process 3	2	60	8	360	-0.85 to -0.8	60
Process 4	3	60	8	60	-0.85 to -0.8	600

Double Rüping-process

The double Rüping-process consisted of two assembled 'single' Rüping-processes. The detailed process parameters are shown in Table 11.

Table 11: Detailed process parameters of the carried out double Rüping-process

Process section	Pressure [bar]	Duration [min]
Air pressure (1)	3	120
Fluid pressure (1)	4	150
Post-vacuum (1)	-0.85 to -0.8	60
Air pressure (2)	3	5
Fluid pressure (2)	8	120
Post-vacuum (2)	-0.85 to -0.8	60

Lowry-process

A Lowry-process was applied for comparison of the influence on the applied air pressure section from the Rüping-process on the retention of the oily wood preservative. The detailed process parameters are shown in Table 12.

Table 12: Detailed process parameter of the carried out Lowry-process

Process section	Pressure[bar]	Duration [min]
Fluid pressure	8	180
Post-vacuum	-0.85 to -0.8	360

3.2.2.5 Full cell processes

Vacuum pressure process

For further examination of the retention in kg/m³ and penetration depth of the alternative oily wood preservative, two different full cell processes were carried out. The first full cell process consisted of a pre-vacuum-, a fluid pressure and a post-vacuum phase. Table 13 shows the detailed process parameters of the used full cell process.

Table 13: Detailed process parameters of the carried out full cell process

Process phases	Pressure [bar]	Duration [min]
Pre-vacuum	-0.85 to -0.8	60
Fluid pressure	8	180
Post-vacuum	-0.85 to -0.8	60

Double vacuum process

The second carried out full cell process was a double vacuum process, where the initial vacuum was followed by an impregnation under atmospheric pressure. For reducing the bleeding and a certain recovery of the alternative oily wood preservative, an additional post-vacuum was applied. Table 14 shows the detailed process parameters.

Table 14: Detailed process parameters of the carried out double vacuum process

Process phases	Intensity [bar]	Duration [min]
Pre-vacuum	-0.85 to -0.8	240
Fluid pressure	0	240
Post-vacuum	-0.85 to -0.8	600

3.2.2.6 Modified empty cell processes

Pre-conditioning of specimens

A pre-conditioning of the specimens before impregnation was carried out using four different methods. Before impregnation, the specimens were placed for two hours in either a steam oven or a drying chamber at 60°C. Additionally, specimens were pre-heated in the alternative oily wood preservative for two hours at 60°C. Finally, a pre-conditioning by means of an extended fluid pressure phase was implemented. Table 15 shows the detailed process parameters used for the different impregnation processes.

Table 15: Detailed process parameter for the impregnation of different pre-conditioned specimens

Pre-conditioning	Process section			
	Pressure		Post-vacuum	
	Intensity [bar]	Duration [min]	Intensity [bar]	Duration [min]
Steam oven Drying chamber Hot oil	8	60	-0.85 to -0.8	60
Extended pressure phase	8	180	-0.85 to -0.8	60

Rüping- and Lowry processes with alternating pressure phases

Furthermore, a Rüping- as well as a Lowry-process were modified by alternating the intensity and duration of the fluid pressure phase. A kind of pulsation was created, where hot alternative oily wood preservative was pressed into the wooden structure during the high-pressure phases and was removed after cooling down by the high internal pressure during the decreasing pressure period. The alternating pressure was realised by inducing respectively releasing compressed air via the earlier described reconstruction. Table 16 shows the detailed process parameters for both empty cell processes, whereby the air pressure phase was skipped during the Lowry-process.

Table 16: Detailed process parameter of the pulsating empty cell processes

Process section	Pressure [bar]	Duration [min]	Comment
Air pressure	3	60	Only implanted during the Rüping-process
Pulsating pressure	4-9	225	Alternating pressure intensity between 4-9 bar and durations between 1-30 minutes
Post-vacuum	-0.85 to -0.8	150	-

3.2.3 Results and discussion

3.2.3.1 Adaption and modification of the impregnation plant in laboratory scale

Compressed air connection for alternating pressure impregnation processes

The impregnation plant is designed to carry out standardised full cell and empty cell processes. In order to include alternating pressure processes to the investigation of process optimisation, a manual control of the pressure phase within the autoclave was enabled by means of compressed air. Therefore, a branch with drain valves was installed from the compressed air line to the autoclave. By pausing the pressure phase, a manually increase of the pressure within the autoclave can be carried out by the addition of compressed air. Furthermore, a reduction to the pressure stored in the program is also possible, which allows to generate an alternating pressure. Thus, in addition to alternating pressure processes, impregnations can also be carried out in a tub with water-based solutions (Figure 30).

Furthermore, working with the impregnation plant revealed problems, which were not identifiable from the beginning. These problems were from technical and constructive nature. Different adaptions and modifications were necessary to improve the functionality of the impregnation plant.

Deaeration of the circulation pump

The circulation of the preservative during heating is of great importance. A continuous, direct contact with the heating rods can lead to temperatures far above the temperature stability of the preservative. Since the circulating pump 1 (4) was mounted above the liquid level of the preservative, the suction of the pump was not assured and no circulation of the preservative took place.

Since it was not possible to transfer the circulating pump 1 (4) below the preservative level, it was necessary to construct a venting system for the circulating pump 1 (4) using the preservative from storage tank 1 (2). Therefore, a piping (1) was installed behind the circulating pump 2, which allows to pump the preservative through the circulating pump 1 back into the storage tank 1 and thus removes all air from the system. This is done manually by switching on the circulating pump 2 and opening two valves upstream and downstream of the circulating pump 1. If all air has been removed from the system, the circulating pump 2 can be stopped and the valves can be closed again. The circulation of the protective agent is then possible without problems (Figure 30).

Returning system for remaining preservative

For impregnation with Rüping-processes the preservative has to be pumped from storage tank 1 to storage tank 2. The circulation pump stops when a determined level of preservative was reached. After flooding the autoclave, a certain amount of preservative remained in storage tank 2. Simultaneously the fluid pressure in the autoclave is maintained using the remaining preservative from storage tank 1. Because the filling level in storage tank 2 was too high, too much preservative remained inside after flooding the autoclave. This led to a lack of preservative in storage tank 1, so the circulation pump was not able to apply the required fluid pressure inside the autoclave.

To solve this problem, a return line was installed connecting storage tank 2 with storage tank 1. After flooding the autoclave, the remaining preservative can be guided into storage tank 1 to increase the preservative level (Figure 30).

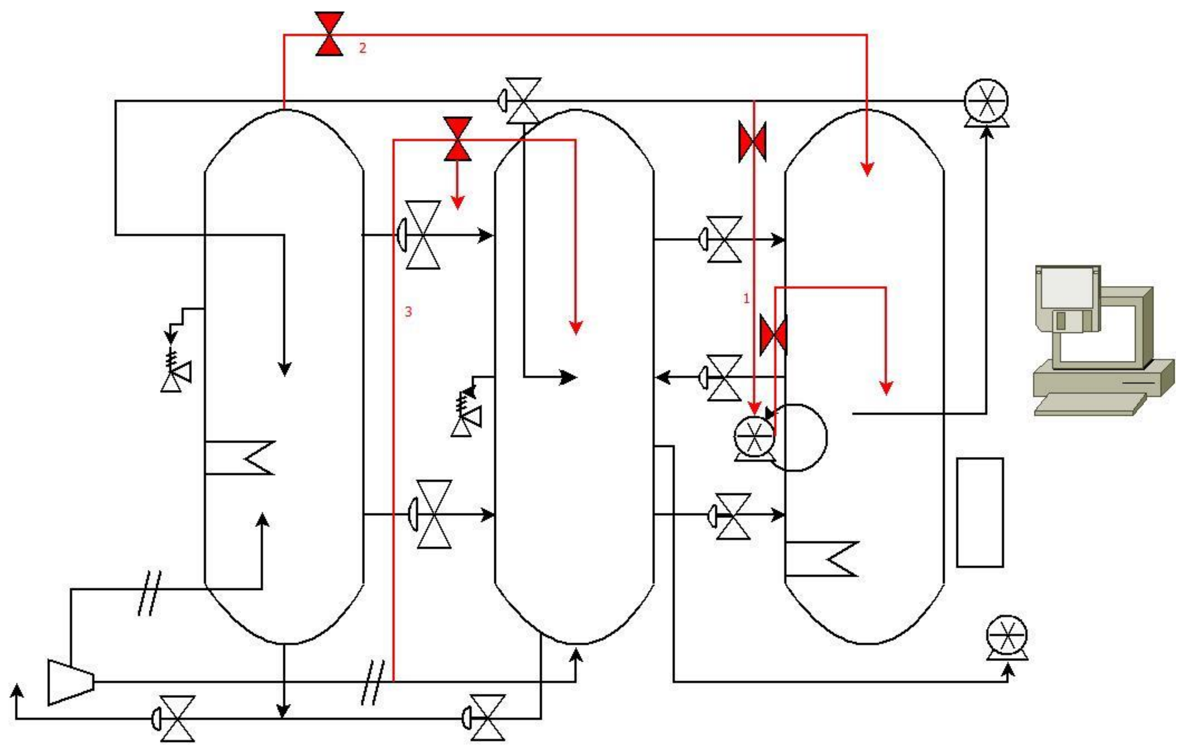


Figure 30: Modified and adapted schematic construction plan of the impregnation plant. (1) deaerating system for the circulation pump; (2) return line for remaining preservative; (3) compressed air connection for alternating pressure impregnation processes

3.2.3.2 Empty cell processes

Rüping-processes

The impregnation using a Rüping-process with an air pressure of 4 bar led to an average retention of 53.22 kg/m³. (Rüping-process 1). Decreasing the air pressure to 3 bar led to an increased preservative retention. An average retention of 65.76 kg/m³ was achieved (Rüping-process 2). The following impregnation by a Rüping-process using a decreased air pressure of only 2 bar in combination with an extended fluid pressure (Rüping-process 3) led to a considerable increase in preservative retention. In contrary to the previously carried out Rüping-processes an average retention of 148.22 kg/m³ was reached. The impregnation using a Rüping-process with a shortened fluid pressure phase of only 60 minutes and prolonged post-vacuum (600 minutes) led to an average retention of 60.83 kg/m³, comparable to the average retention of Rüping-process 1. Additionally, all specimens showed a dry surface after impregnation (Figure 31).

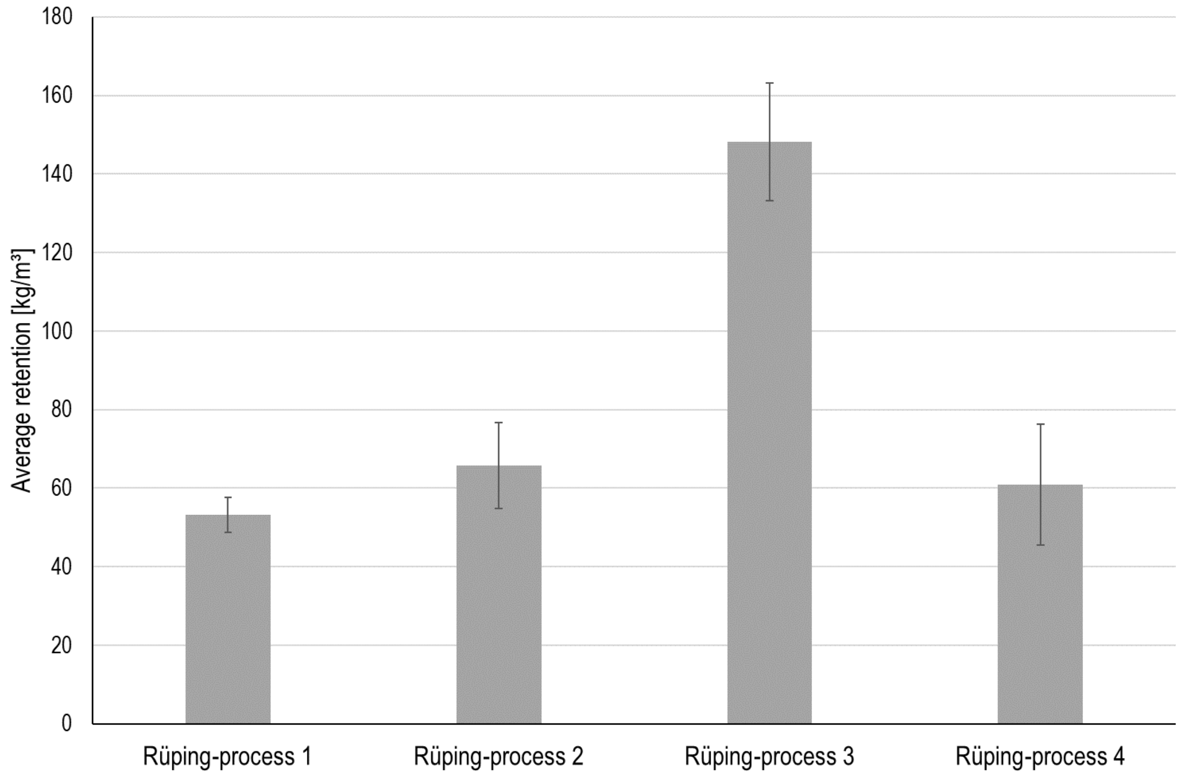


Figure 31: Average retention of the alternative oily wood preservative using Rüping-processes with varied pressure phases; **Rüping-process 1**: air pressure 4 bar for 60 min, fluid pressure 8 bar for 180 min; post-vacuum -0.85 bar for 60 min; **Rüping-process 2**: air pressure 3 bar for 60 min, fluid pressure 8 bar for 180 min, post-vacuum -0.85 bar for 60 min; **Rüping-process 3**: air pressure 2 bar for 60 min, fluid pressure 8 bar for 360 min, post-vacuum -0.85 bar for 60 min; **Rüping-process 4**: 3 bar air pressure for 60 min, fluid pressure for 60 min, post-vacuum for 600 min

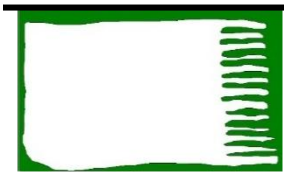
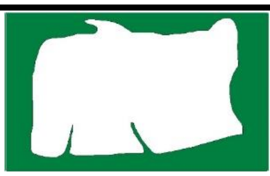
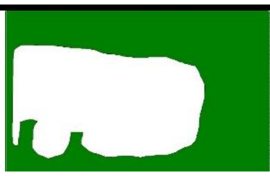
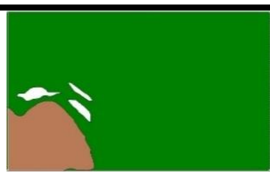
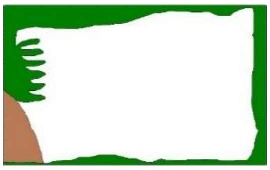
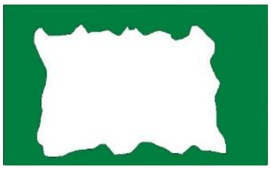
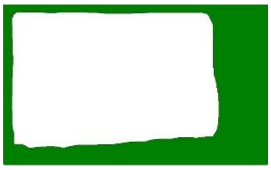
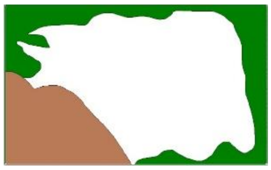
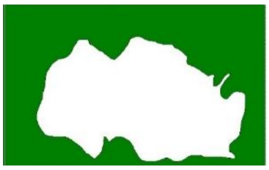
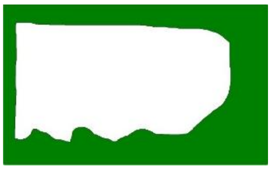
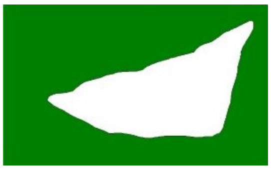
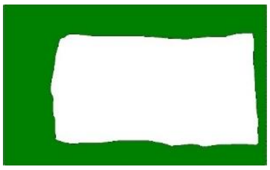
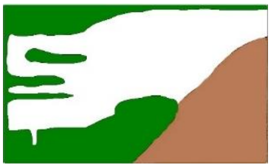
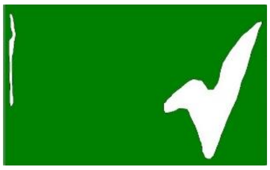
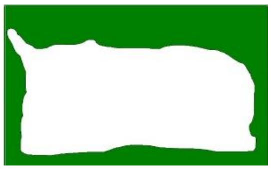
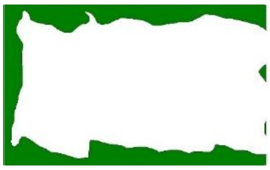
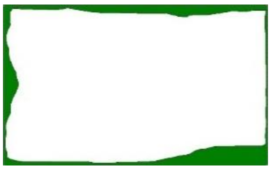
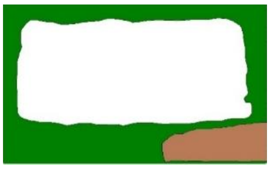
Increasing the intensity of an applied air pressure led to a decreasing retention of the alternative oily wood preservative. The results agree with Koljo (1954), who stated that for easy penetrateable wood species like Beech, the application of an air pressure and its relation towards the following fluid pressure, can influence the retention of oily wood preservatives in its quantity. Due to increasing air pressures, larger quantities of wood preservative are ejected from the wooden structure by the decompressed air, after releasing the fluid pressure. This resulted in lower preservative retentions.

The following fluid pressure phase is generally also able to influence the preservative penetration and distribution. Richardson (1993) granted a substantial influence on the retention for relatively porous wood species, which Broese van Groenou (1983) specifies for the impregnation of creosote by explaining that treatment duration is way more important than pressure increase. In case of the alternative oily wood preservative, shortening of the pressure phase had no considerable influence on the retention, while prolonging had.

The application of a post-vacuum supports the expanding air leaving the wooden structure and helps removing the excessive oily preservative (Leiße 1992). Broese van Groenou (1983) described the same effect for the impregnation with creosote. Today, a duration of at least 150 minutes is prescribed for the impregnation with creosote by the DIN 68811 (2007). In case of the alternative oily wood preservative, the duration of the post-vacuum may be even shortened to 60 minutes, since all specimens showed a dry surface and no difference in surface dryness was found at durations of 600 minutes. Nevertheless, this has to be further evaluated during industrial impregnation processes.

Table 17 summarizes the penetration depth of the alternative oily wood preservative, schematically. All specimens, showed no complete penetration of the cross section. The penetration pattern was rather inhomogeneous for all processes. On the one hand, a lower air pressure (Rüping-process 2) did increase the retention, but did not improve preservative penetration. Even after doubling the retention by decreasing the air pressure and extending the fluid pressure duration (Rüping-process 3), a complete penetration of the cross sections was still not achieved. On the other hand, shortening the pressure phase to 60 minutes did also not impair the preservative penetration. The specimens showed a similar penetration pattern as during the previous applied Rüping-processes with either only peripherical penetrated areas or nearly complete penetration of the cross section.

Table 17: Schematic penetration of the alternative oily wood preservative in specimens made from Beech (80 x 130 x 1000 mm^3) using Rüping-processes with varied pressure phases; Penetration depth of the alternative oily wood preservative in green; non-impregnable red heartwood in brown

Rüping-process 1	**Rüping-process 2**	**Rüping-process 3**	**Rüping-process 4**
 55.50 kg/m^3	 67.06 kg/m^3	 148.02 kg/m^3	 59.60 kg/m^3
 49.42 kg/m^3	 68.75 kg/m^3	 130.50 kg/m^3	 36.26 kg/m^3
 58.17 kg/m^3	 77.55 kg/m^3	 142.60 kg/m^3	 76.33 kg/m^3
 56.51 kg/m^3	 57.83 kg/m^3	 171.77 kg/m^3	 71.09 kg/m^3
 46.36 kg/m^3	 48.27 kg/m^3		
 53.36 kg/m^3	 75.10 kg/m^3		

All specimens, impregnated by the different Rüping-processes, showed an inhomogeneous penetration of the alternative oily wood preservative. A complete penetration of the specimen cross section was not reached in all cases. Additionally, a few specimens showed no penetration in the area of red heartwood. Based on the development of tylosis, red heartwood restricts the penetration and distribution of preservatives (Zycha 1948). This also applies for oily preservatives like creosote (Zycha 1965). Furthermore, the inhomogeneous penetration can be caused by different impact factors. A possible influence of the applied process phases will be discussed in the following:

MacLean (1952) stated, that increasing the preliminary air pressure increases the resistance towards penetration and may result in erratic penetration. Consequently, decreasing the air pressure should have resulted in an improvement in penetration depth. Even though the retention of the alternative oily wood preservative was increased, the penetration depth remained inhomogeneous and a complete penetration of the cross sections was not achieved.

Additionally, the effectiveness of the fluid pressure phase is decreasing by increasing penetration depth, based on the resistance of the wooden structure (MacLean 1952). Calculations regarding the theory of pressure decrease inside wood during pressure impregnation done by Riechert (1976) support this statement. A pressure increase inside the wood is occurring slowly due to the penetrating solution. Therefore, an extension of fluid pressure duration, which Broese van Groenou (1983) defined as more important than pressure increase, should have resulted in improved preservative penetration. In case of the alternative oily wood preservative, the combination of prolonged fluid pressure with a decreased air pressure did not positively affect the penetration depth. Even though the retentions increased above 120 kg/m³.

Another approach explaining the insufficient penetration of the alternative oily wood preservative is reaching a pressure compensation inside the wood during impregnation. On the one hand, wood preservatives are able to compress air inside the wooden structure, while entering (Liese 1951). On the other hand, the effectiveness of the fluid pressure decreases (MacLean 1952). The already induced air was eventually compressed by the entering preservative until a complete penetration was no longer possible based on pressure compensation in combination with decreasing pressure inside the wooden sleeper.

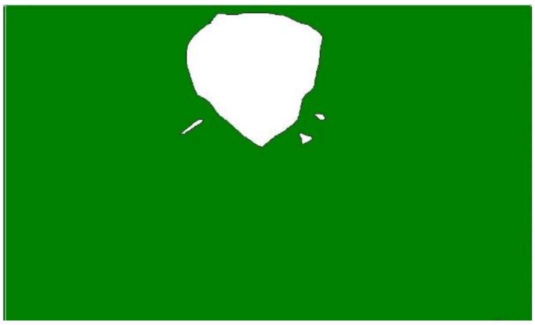
Double Rüping-processes

The impregnation using a double Rüping-process resulted in slightly lower retentions compared to the Rüping-process with decreased air pressure and prolonged fluid pressure. In comparison to the single Rüping-processes using 3 and 4 bar air pressure, the average retention (111.93 kg/m³) was considerably higher. The specimen showed a minimum retention of 89.14 kg/m³ (DRP 4) and a maximum retention of 127.69 kg/m³ (DRP 1). Table 18 shows the retention of the impregnated specimens.

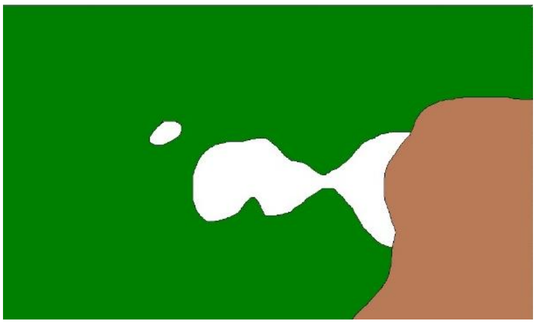
Table 18: Retention of the alternative oily wood preservative using a double Rüping-process

Specimen no.	Retention [kg/m³]
DRP 1	127.69
DRP 2	117.40
DRP 3	113.75
DRP 4	89.14
Mean value	**111.93**
Standard deviation	**14.13**

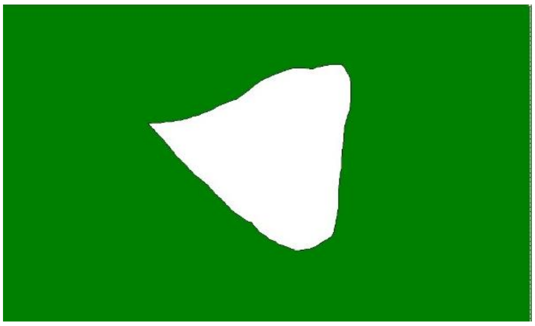
Even for the double Rüping-process, a complete penetration of all specimen cross sections was not possible. On the one hand, specimen DRP 1 (127.69 kg/m³) and DRP 2 (117.40 kg/m³) showed rather complete penetration of the cross sections, leaving both unimpregnated areas in the upper middle of the specimen. DRP 3 (113.75 kg/m³) showed also nearly complete penetration of the cross section. Only the not penetrateable red heartwood remained unimpregnated. On the other hand, DRP 4 (89.14 kg/m³) showed a rather incomplete penetration of the cross section. While the lower half of the specimen was completely penetrated, the upper part remained nearly unimpregnated (Figure 32).



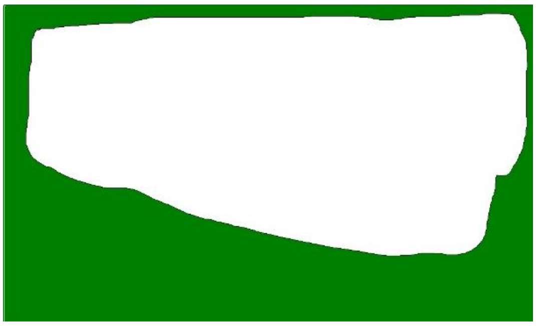
127.69 kg/m³



117.40 kg/m³



113.75 kg/m³



89.14 kg/m³

Figure 32: Schematic penetration behaviour of the alternative oily wood preservative impregnated by a double Rüping-process in specimens with a dimension of 80 x 130 x 1000 mm³

The basic principle of the double Rüping-process is to wet and pre-heat the wooden structure during the first pressure period to ensure a more homogeneous penetration of the preservative during the second fluid pressure (Hösli and Bariska 1980). Especially during the first fluid pressure, the required amount of oil is inserted into the wooden structure and is afterwards well distributed during the second fluid pressure (Peters 1950). Two fluid pressure phases had probably a positive effect on the preservative uptake and led to an increased retention, compared to the single Rüping-processes 1 and 2. The still higher retention of the Rüping-process 3 with decreased air pressure is caused by the weaker recovery effect, based on air pressure intensity.

Lowry-process

The impregnation using a Lowry-process resulted in retentions comparable to the single Rüping-process with decreased air pressure and prolonged fluid pressure as well as the double Rüping-process. An average retention of 118.43 kg/m³ was reached, while the minimum retention was 97.52 kg/m³ (LP 3) and the maximum retention 135.63 kg/m³ (LP 4).

Table 19: Retention of the alternative oily wood preservative using a Lowry-process

Specimen no.	Retention [kg/m³]
LP 1	134.30
LP 2	106.27
LP 3	97.52
LP 4	135.63
Average value	**118.43**
Standard deviation	**16.83**

The visual evaluation of the penetration depth showed again no complete penetration of the specimen cross section for all specimens. While LP 4 showed a nearly complete penetration of the cross section at 135.63 kg/m³, LP 1 showed only half of the cross section penetrated by the alternative oily wood preservative at a retention of 134.30 kg/m³. LP 2 and 3 showed poorly penetrated cross sections even at retentions around 100 kg/m³. As for other impregnation processes, the penetration of the alternative oily wood preservative seems to be deeper from the lower broad side of the specimens. All specimens showed rather poor penetration from the upper broad side as well as from the narrow sides (Figure 33).

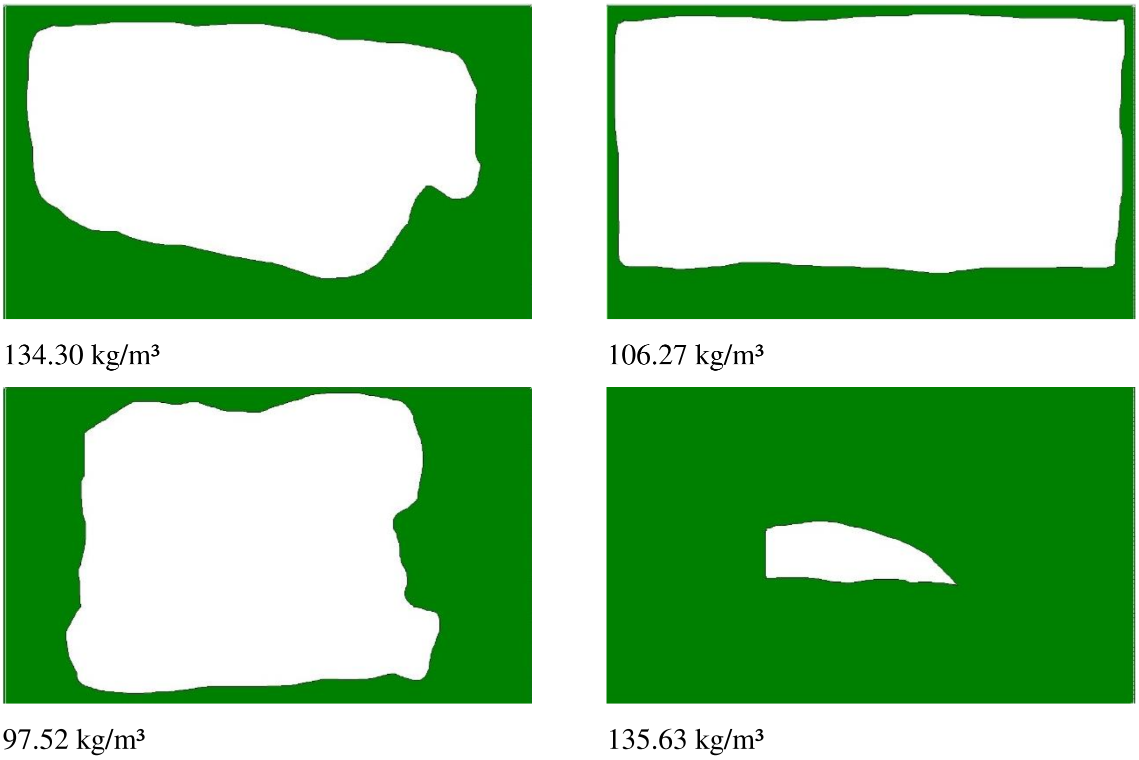


Figure 33: Schematic penetration behaviour of the alternative oily wood preservative impregnated by a Lowry-process in specimens with a dimension of 80 x 130 x 1000 mm³

Lowry-processes are intended to show slightly higher retentions compared to single Rüping-processes, because they only use atmospheric pressure as air pressure (Schneider 2000). When wood is impregnated by a Lowry-process, the recovery of the inserted wood preservative is therefore never as effective as for a Rüping-process (Richardson 1993). In case of the alternative oily wood preservative, this effect became visible. Higher retentions were achieved at comparable fluid pressure durations (Rüping-processes 1 and 2). Nevertheless, most of the specimen showed comparable penetration patterns.

3.2.3.3 Full cell processes

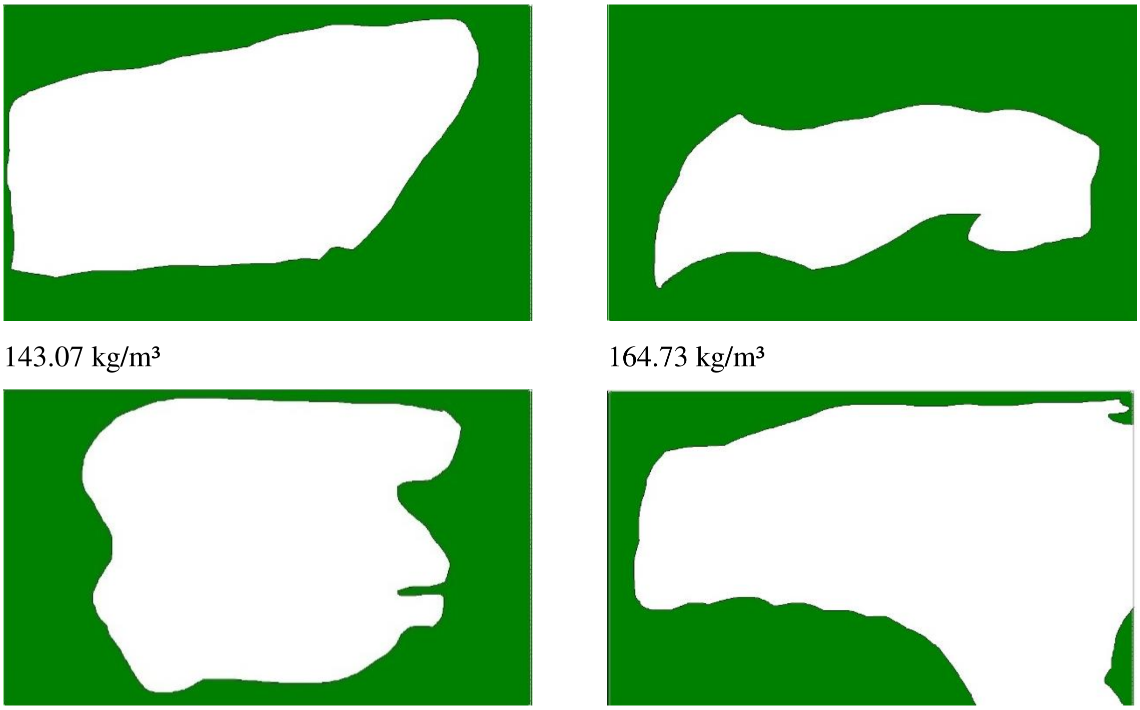
Vacuum pressure process

The impregnation using a vacuum pressure process resulted in an average retention of 137.78 kg/m³. While the minimum retention was 91.55 kg/m³ (VDRP 4), the maximum retention was 164.73 kg/m³ (VDRP 2). Table 20 shows the retentions of all specimens.

Table 20: Retention of the alternative oily wood preservative using a vacuum pressure process

Specimen no.	Retention [kg/m³]
VDRP 1	143.07
VDRP 2	164.73
VDRP 3	151.75
VDRP 4	91.55
Mean value	**137.78**
Standard deviation	**27.78**

Again, a complete penetration of the specimen cross section was not possible. Like for the empty cell processes, the penetration pattern of the alternative oily wood preservative was very inhomogeneous. While two specimens showed a slightly deeper penetration, either from the narrow side (VDRP 3) or from the top (VDRP 2), the others showed solely a minimal penetration depth from all sides (VDRP 1 and VDRP 4). As seen before during the other carried out processes, all specimens showed a dry surface (Figure 34).



143.07 kg/m³ 164.73 kg/m³

151.75 kg/m³ 91.55 kg/m³

Figure 34: Schematic penetration behaviour of the alternative oily wood preservative impregnated by a vacuum pressure process in specimens with a dimension of 80 x 130 x 1000 mm³

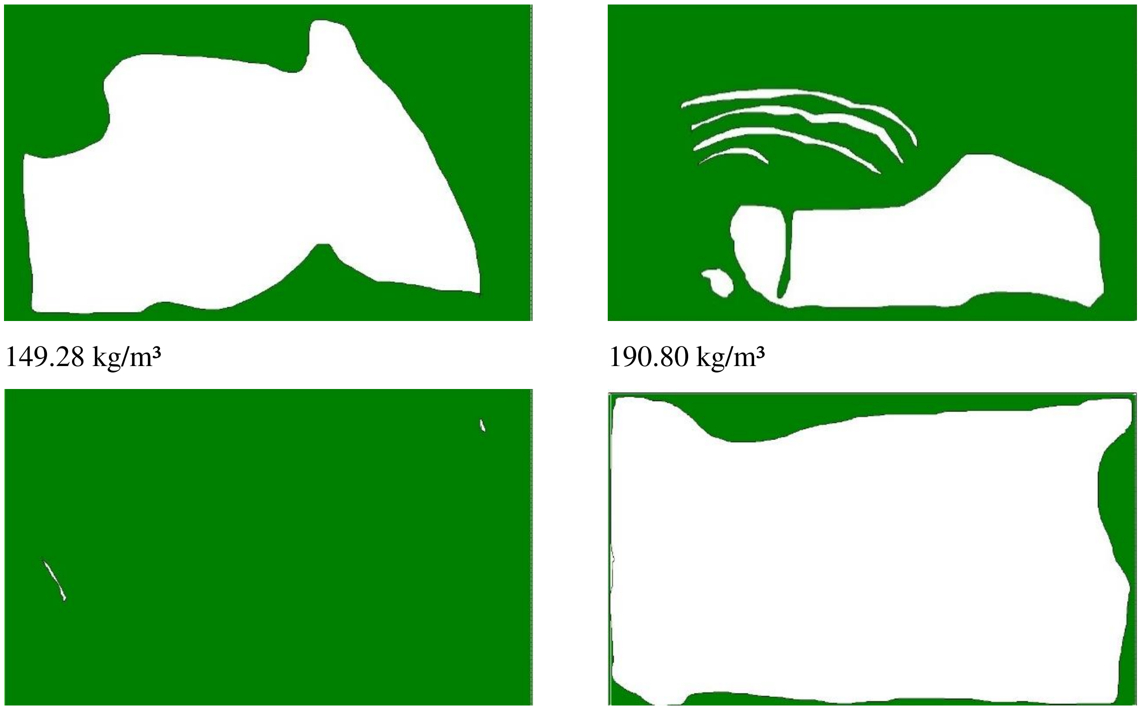
Double vacuum process

The impregnation using a double vacuum process led to an average retention of 185.55 kg/m³. While the minimum retention was 48.19 kg/m³ (VTV 4), the maximum retention was 245.94 kg/m³ (VTV 3). Table 21 shows the varying retentions from all specimens.

Table 21: Retention of the alternative oily wood preservative using a double vacuum process

Specimen no.	Retention [kg/m³]
VTV 1	149.28
VTV 2	190.80
VTV 3	245.94
VTV 4	48.19
Mean value	**185.55**
Standard deviation	**72.36**

Three of four specimens (VTV 1, VTV 2 and VTV 4) showed again an inhomogeneous penetration of the specimen cross section. While VTV 1 showed a deeper penetration from both narrow sides and from the top, VTV 2 showed a rather deep penetration solely from the top of the specimen. In contrast, VTV 4 showed nearly no penetration from all 4 sides of the specimen, and VTV 3 showed a complete penetration of the cross section. Both penetration depths were in relation with the reached retentions of 48.19 kg/m³ (VTV 4) and 245.94 kg/m³ (VTV 3) (Figure 35).



149.28 kg/m³ 190.80 kg/m³

245.94 kg/m³ 48.19 kg/m³

Figure 35: Schematic penetration behaviour of the alternative oily wood preservative impregnated by a double vacuum process in specimens with a dimension of 80 x 130 x 1000 mm³

The aim of a full cell process is to fill all porous spaces of the wood with the wood preservative. In the beginning, the vacuum removes most of the air within the porous structure of the wood. The following fluid pressure phase supports the preservative entering and filling all pores. The impregnation of Beech sleepers with creosote using vacuum pressure processes led to retentions up to 277 kg/m³ (Schramm 1952). The average retentions of both full cell processes (vacuum pressure and double vacuum) were considerably lower and showed comparable retentions to the earlier carried out Rüping-process 2.

Unexpectedly, the average retention of the alternative oily wood preservative using a double vacuum process was even higher compared to the vacuum pressure process. By applying a fluid pressure during the vacuum pressure process, the penetration is encouraged (Richardson 1993). This should have resulted in higher retentions compared to the double vacuum process. Normally, double vacuum processes are only applied for products with a limited need for penetration (Richardson 1993).

The great difference between completely and poorly penetrated cross sections, cannot be clearly explained. All specimens in each collective have been cut from the same sleeper and have been stored under the same conditions. Therefore, variations regarding the specimen quality should have been minimized. The results rather illustrate how inhomogeneous the penetration of the alternative oily wood preservative can occur.

Since an applied vacuum during the first process stage of the empty cell process is removing most of the air from the porous wooden structure, a hindering effect of compressed air should theoretically be excluded for these specimens. Since a complete penetration was still not possible by the alternative oily wood preservative, the following aspect has to be taken in account for discussion.

According to Richardson (1993) the duration of a vacuum phase is depending on the permeability of the wood species and also on the cross section and can last between 15 minutes and several hours. Thus, the question arises whether the applied vacuum of 60-240 minutes was sufficient to evacuate the specimen cross section especially while excluding the influence of permeability in axial direction.

3.2.3.4 Modified empty cell processes

Impregnation of pre-conditioned specimens

The impregnation of differently pre-conditioned specimens resulted in comparable average retentions. While the specimens pre-conditioned in a steam oven showed the lowest average retention (105.28 kg/m³ (13.26)), the specimens pre-conditioned in the drying chamber as well as in hot oil showed with 121.25 kg/m³ (17.49) and 125.70 kg/m³ (26.56) slightly higher average retentions. The pre-conditioning using an extended pressure phase showed with 149.83 kg/m³ (22.16) the highest average retention (Figure 36).

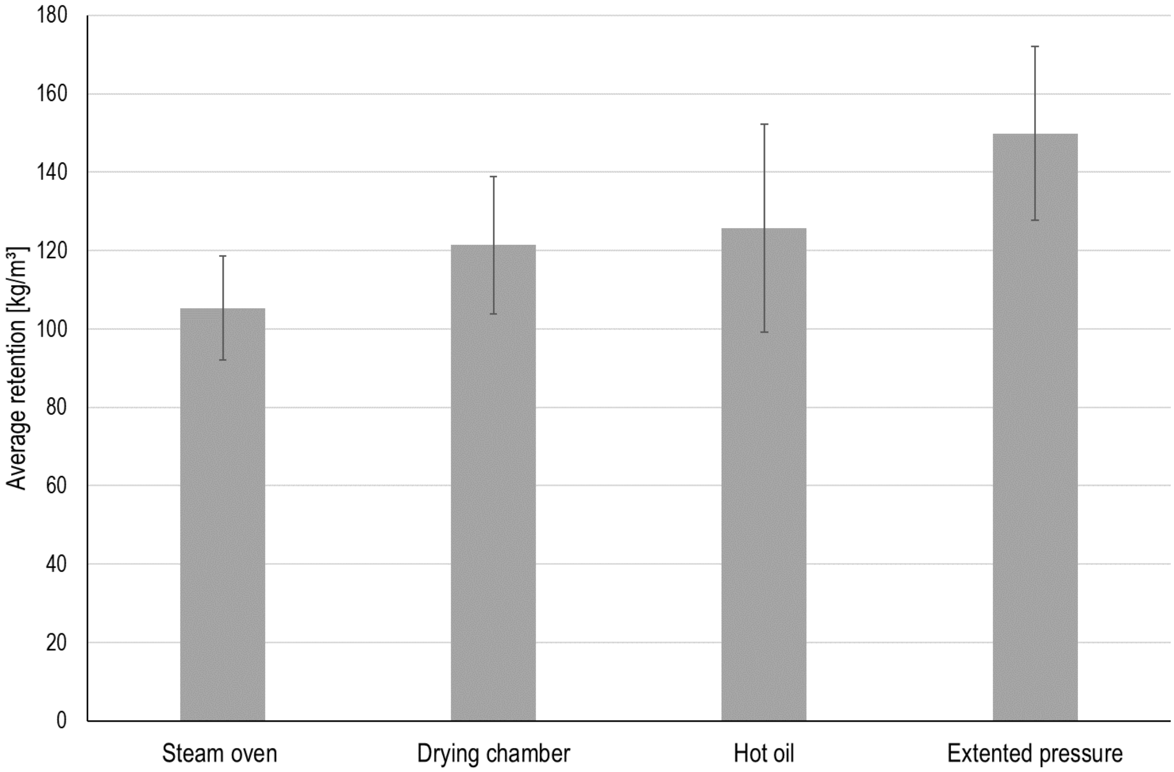
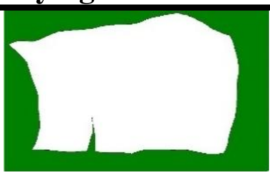
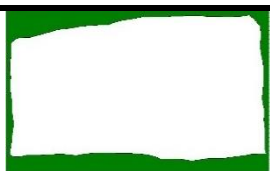
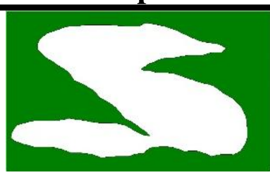
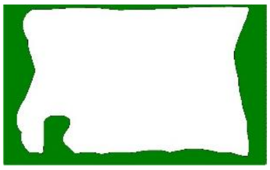
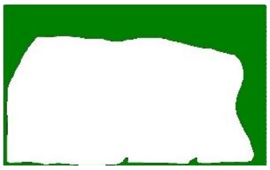
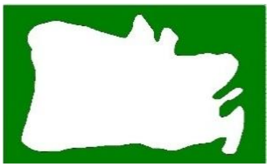
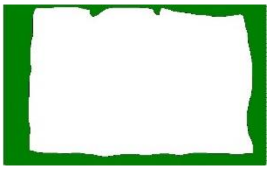
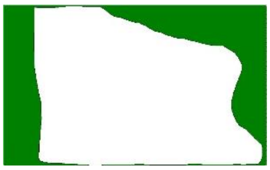
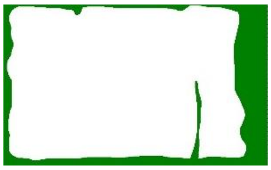
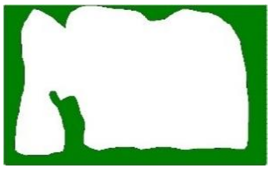
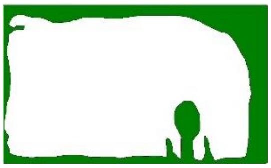
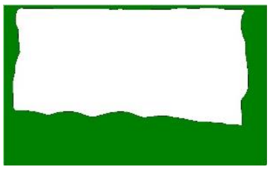
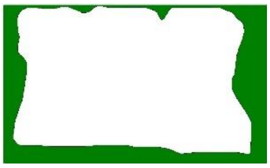
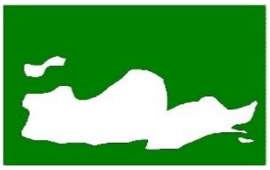
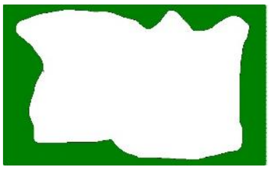


Figure 36: Retention of the alternative oily wood preservative using differently pre-conditioned specimens

Like for the single Rüping-processes, the double Rüping-process and the Lowry-process, no complete penetration of the specimen cross section was possible at retentions of more than 80 kg/m³. For every kind of pre-conditioning, all specimens showed again a very inhomogeneous penetration pattern, but again a dry surface. Table 22 summarises the penetration pattern of all specimens. Specimens pre-conditioned in the steam oven as well as pre-conditioned in the drying chamber showed a preservative penetration only in the peripheral areas of the specimens. In both cases, at least one of the four sides was slightly deeper penetrated, compared to the remaining sides, but no distinct pattern was recognisable. Specimens pre-conditioned in hot oil as well as pre-conditioned due to a prolonged pressure phase, also showed in most cases a comparable penetration pattern. Again, only the peripheral areas of the specimens were penetrated, while two sides showed a slightly deeper penetration. Additionally, other specimens in both processes showed a slightly deeper preservative penetration, but no complete penetration of the specimen cross section was reached.

Table 22: Schematic penetration of the alternative oily wood preservative in specimens made from Beech (80 x 130 x 1000 mm^3) pre-conditioned using a steam oven, a drying chamber, hot oil and extended pressure; Penetration depth of the alternative oily wood preservative in green

Pre-conditioned in steam oven	**Pre-conditioned in drying chamber**	**Pre-conditioned in hot oil**	**Pre-conditioned by extended pressure**
 111.18 kg/m^3	 151.34 kg/m^3	 92.28 kg/m^3	 183.29 kg/m^3
 106.29 kg/m^3	 115.68 kg/m^3	 128.26 kg/m^3	 127.20 kg/m^3
 83.89 kg/m^3	 108.90 kg/m^3	 116.40 kg/m^3	 156.14 kg/m^3
 119.76 kg/m^3	 109.64 kg/m^3	 165.86 kg/m^3	 132.69 kg/m^3

During the penetration of wood, previously heated wood preservative (for example creosote) cools down and thus experiences a strong increase in viscosity (Schulz 1987 b). Studies on the temperature development during the impregnation of Beech sleepers with creosote by Hösli and Bariska (1980) have shown rather small temperature increases inside Beech sleepers during the first phase of a double Rüping-process without pre-heating. During the first fluid pressure, the core temperature solely increased from 25°C to 35°C.

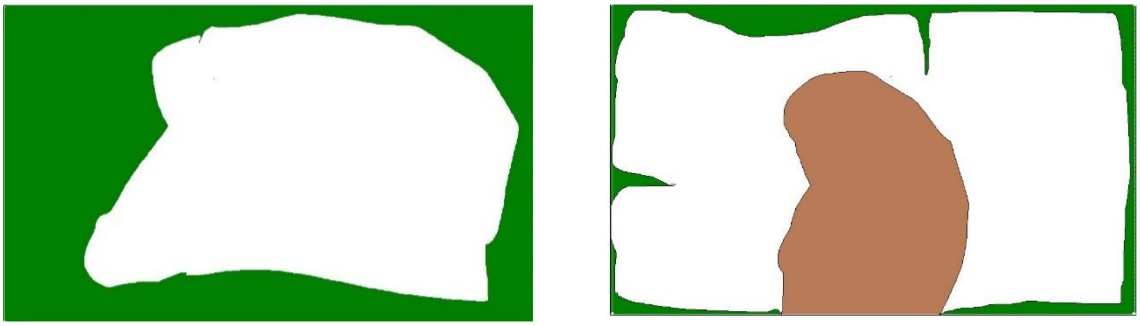
An increased temperature of wood can improve the impregnation and penetration since viscosity and surface tension are temperature-dependent variables (Hösli 1980). By pre-conditioning the specimens, a cooling of the alternative oily wood preservative in combination with increasing viscosity should be counteracted. Based on the reappearing poor and inhomogeneous penetration of the alternative oily wood preservative, different aspects have to be discussed as possible reasons.

Initially, the specimen cross sections have probably not been sufficiently warmed by the different types of pre-conditioning. Based on its high pore content, wood is classified to be a poor heat conductor (Niemz and Sonderegger 2017). The selected pre-conditioning duration of 2 hours was potentially too short to enable a complete heating of the specimen cross sections and solely heated the peripheral area of the specimens. This assumption can be reinforced by the work of Schulz (1987a), who found a core temperature in Beech sleepers, impregnated with creosote in a double Rüping-process, between 70-73°C after 6 hours of impregnation.

Additionally, the anatomical directions have a strong effect on the thermal conductivity as well. In axial direction, the thermal conductivity is approximately 1.5 to 2.75 times higher than perpendicular to the grain (Sonderegger et al. 2011). By sealing the grain sides of the specimens, the heating of the specimen core has also been restricted. However, the longitudinal effect is only important for very short specimens in laboratory scale and can be ignored in case of railway sleepers in standard dimensions. If the diameter is 5-6 times the length, end heating will have no influence or is a negligible factor for heating wood at its midportion. Apart from the anatomical direction, the density and the moisture content, McLean (1952) defined the heating medium as a principal factor affecting the rate of temperature change. Steam heats wood faster than liquids and liquids faster than heating plates or dry air. The heating rate at identical temperatures is additionally variating due to factors like surface contact, rate of circulation and limited surface penetration, if liquids are used (McLean 1952).

<u>Rüping- and Lowry-processes with alternating fluid pressure</u>

As for all previous impregnations, the use of pulsating empty cell processes with alternating fluid pressure intensities and durations resulted again in an inhomogeneous penetration of the cross section. In direct comparison, the carried out Rüping-process showed a deeper penetration at a retention of 73.60 kg/m³ on the left narrow side and on the bottom side of the sleeper. The impregnation of the alternative oily wood preservative using a pulsating Lowry-process resulted in a retention of 108.24 kg/m³. Even though the retention was considerably higher, the penetration was less deep compared to the Rüping-process (Figure 37).



73.60 kg/m³ 108.24 kg/m³

Figure 37: Schematic penetration behaviour of the alternative oily wood preservative impregnated by a Rüping- and a Lowry-process with alternating fluid pressure in Beech sleepers in standard dimension (2600 x 260 160 mm³)

Since the pre-conditioning using different heating devices did not improve the penetration of the specimen cross section, the main goal of the pulsation process was also to improve the penetration of the alternative oily wood preservative. The investigations were carried out in accordance with Hösli (1980), who attempted to increase the temperature inside of Beech sleepers by using the pulsation process for the impregnation of creosote. Despite an insignificant increase in temperature, the use of the pulsation process resulted in a significantly improved penetration of the sleepers with creosote.

Heated oily preservatives cool down during penetration of unheated wood and are subjected to a significant increase in viscosity and therefore deteriorated penetration (Schulz 1987a). The main mechanism of the pulsation process was to remove the cooled down alternative oily wood preservative and replace it with hot oil from the autoclave and thereby improve the heating and the penetration (Hösli 1980). Again, for the alternative oily wood preservative the use of the pulsation process did not result in an improvement of penetration, which either indicates a still insufficient heating of the sleeper cross section, an existing cushion of compressed air preventing preservative penetration or hampered penetration in transversal direction, which is furthermore underlined by the excluded penetration in longitudinal direction by the sealed end grains.

3.2.4 Conclusions

Parts of the results from the carried out impregnation processes using the alternative oily wood preservative, clearly showed parallels to creosote. Based on these results the following conclusions were drawn:

- By increasing- or decreasing the air pressure, the retention of the alternative oily wood preservative can be controlled, as it is also possible for creosote.
- Increasing the fluid pressure led to higher retentions and the post-vacuum prevents from bleeding and provides a dry surface after impregnation.
- Increased retentions of the alternative oily wood preservative did not necessarily result in deeper and more homogeneously penetration of the specimen cross sections.

Further results from the carried out impregnation processes differed from the impregnation using creosote. Based on these results, the following conclusions were drawn:

- For all impregnation processes a complete penetration of the specimen cross sections respectively the sapwood like tissue was not possible. A strongly inhomogeneous penetration pattern was visible for all specimens.
- Pre-conditioning of the specimens using different heating devices also did not improve penetration, possibly based on too short conditioning durations and high dimensions.

Since a complete penetration of the sapwood like tissue was not possible by the alternative oily wood preservative, possible causes were discussed and the following conclusions were drawn:

- The influence of remaining air inside the specimens is considered as possible cause for the insufficient preservative penetration. Either caused by compressed present air, the applied air pressure or by an insufficient removal of air from the specimens cross section.
- A closer examination of the pressure distribution inside sleepers during all steps of the carried out impregnation processes is therefore of great importance and recommended for further investigations.

3.3 Pressure gradients during impregnation with an alternative oily wood preservative

3.3.1 Introduction

The impregnation of specimens prepared from Beech sleepers (*Fagus sylvatica* L.) using various impregnation processes did not result in a complete penetration of the sapwood like tissue. One possible factor for the insufficient penetration may be remaining and compressed air inside the specimen, hindering the penetration due to pressure compensation.

It depends on the pressure gradient, in which way fluids enter the wooden structure (Hösli and Bariska 1980). Pressure gradients primarily depend on the permeability of the wood and the rate of pressure application (Schneider 2000). Both vacuum and pressure have an influence on fluid penetration. In case of full cell processes, the initial vacuum allows larger pressure differences between the surface and the interior of the wood (Perry 1978). It is also used to remove air from the porous wooden structure, so the air will not resist preservative penetration, when being compressed during the pressure stage (Richardson 1980). However, during empty cell processes the already existing (Lowry-process) or intentionally inserted air (Rüping-process) is deliberately trapped. By later expansion, excessive preservative will be removed from open pore spaces (Richardson 1980).

Pressure measurements during impregnation give the opportunity to optimise treating processes by eventually quantifying the effects of process and wood variables. Furthermore, it could help to explain difficulties encountered during the development of treatment schedules for untested wood species or treating media (Schneider 2000).

To investigate the possible influence of pressure compensation on the penetration of an alternative oily wood preservative in Beech sleepers, the following aspects were investigated:

- Distribution of pressure inside Beech sleepers during the different process phases without wood preservative under inclusion and exclusion of the end grain
- Pressure distribution during the impregnation of Beech sleepers with an alternative oily wood preservative using full- and empty cell processes

3.3.2 Materials and methods

3.3.2.1 Measurement of pressure gradients inside a Beech sleeper

The impregnation plant in technical scale is restricted in its length. Therefore, two shortened railway sleepers with the dimension of 1400 x 260 x 160 mm³ have been used for the measurement of the pressure gradient. To eliminate either preservative uptake or pressure distribution by the end grain, both grain sides were sealed using "End Grain Sealer" (Akzonobel, Stockholm, Sweden), before the measurement started. For each sleeper a 3.5 mm wide and 80 mm deep hole was drilled perpendicular to the sleeper's axes located in the center of the sleeper. Afterwards, the hole was enlarged up to 6 mm at a depth of 75 mm.
The measurement of vacuum and pressure was carried out with the help of a handmade probe consisting of a 3.5 mm wide capillary tube with a soldered thread. The probe was inserted into the 3.5 mm wide hole. To prevent clogging of the probe caused by the epoxy resin adhesive (Araldite 2011, Huntsman, Kortenberg, Belgium), fine sawdust was packed around the probe. Afterwards the hole was back-filled with epoxy resin adhesive, to ensure an airtight bonding. The probe was connected to the inner side of the autoclave by means of a capillary line. A pressure gauge was connected to the outer side of the autoclave for analog reading of the pressure, also by means of a second capillary line (Figure 38).

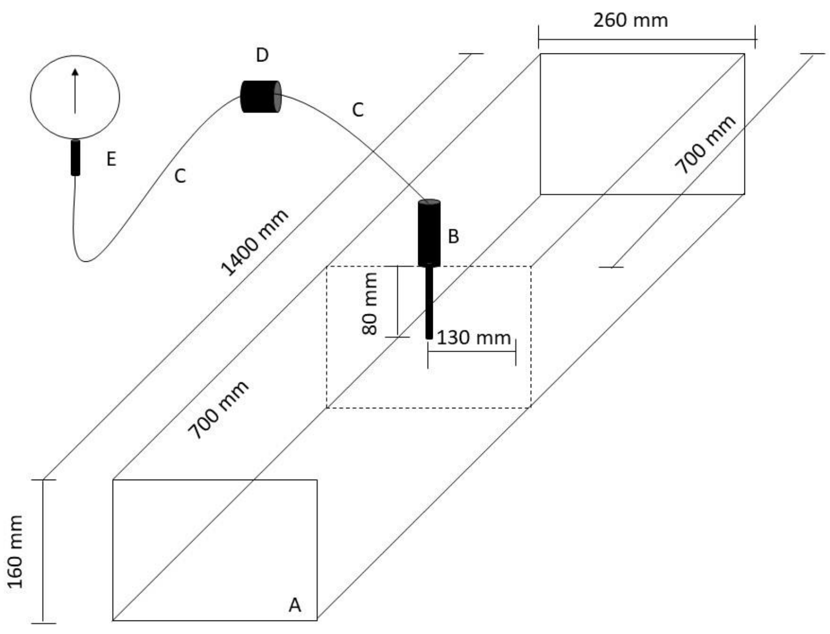


Figure 38: Sketch showing the experimental procedure for pressure measurements with (A) Beech sleeper, (B) Pressure probe, (C) Capillary lines, (D) Connection with the autoclave, (E) Pressure gauge

3.3.2.2 Reference measurement

First, a reference measurement was carried out to ensure that the constructed probe gave similar results compared to the integrated digital pressure probe from the plant control. Therefore, the pressure probe was placed into the autoclave and a vacuum (-0.9 bar) as well as an air pressure (9 bar) were applied subsequently. At a 2-minute interval, the pressure values were noted from the pressure gauge and compared with the integrated pressure probe from the plant control.

3.3.2.3 Distribution of vacuum and pressure inside a sleeper during sections of impregnation processes without preservative and the influence of the longitudinal direction

To visualize the distribution of pressure inside Beech sleepers during phases of impregnation processes without solution, a measurement of the pressure gradient of sealed sleepers was carried out. Therefore, a vacuum and pressure phase were run. Again, both values (inside the sleeper and inside the autoclave) were recorded in 2-minute intervals. The measurement was carried out as long as the pressure inside the sleeper was approximating the pressure level inside the autoclave. Afterwards, the autoclave was aerated.
To clarify the strong impact of the longitudinal direction on the distribution of vacuum and pressure inside the sleeper, the measurement was repeated. Therefore, the sealing was removed before starting the vacuum/pressure phase for the second time.

3.3.2.4 Pressure gradient during impregnation of Beech using an alternative oily wood preservative

Before impregnation, all sleepers were cut to a length of 1000 mm and were re-sealed three times to minimize the influence of the end grain on the distribution of vacuum, pressure and the oily wood preservative inside the sleeper. Additionally, a second pressure probe was glued into the sleeper at 20 mm depth next to the first pressure probe. Hereby, a better distinction of the pressure gradient in different depths was possible.
For impregnation a full cell process (vacuum pressure) as well as an empty cell process (Rüping-process) were used. The sleepers were placed into a big tub to avoid a complete flooding of the autoclave. For the full cell process a vacuum of -0.95 bar was applied for 1 hour. With the help of the vacuum, the pre-heated alternative oily wood preservative (60-85 °C) was aspirated into the tub. The pressure was kept at 9 bar for 180 minutes. The pressure was recorded every 2 minutes.

For the empty cell process, an air pressure of 3 bar was applied for 10 minutes. Afterwards, the pre-heated alternative oily wood preservative was pumped into the tub, using an external pressure pump. The pressure was kept at 9 bar for 130 minutes.

After finishing the impregnation processes, the oily wood preservative was removed from the tub into the storage tank, using the applied pressure. The following vacuum was again kept for 60 minutes for the full cell process and approximately 50 minutes for the empty cell process.

3.3.3 Results and Discussion

3.3.3.1 Reference measurement

As can be seen from Figure 39, the pressure gradient recorded with the handmade probe differed minimally from the integrated digital pressure probe of the autoclave. The difference between the values during the vacuum phase can be explained by the comparison of the built-in readouts. On the basis of the broad categories of the analog pressure gauge, exact values up to 2 decimals could not be as precisely read as the digital pressure display of the integrated pressure gauge of the autoclave.

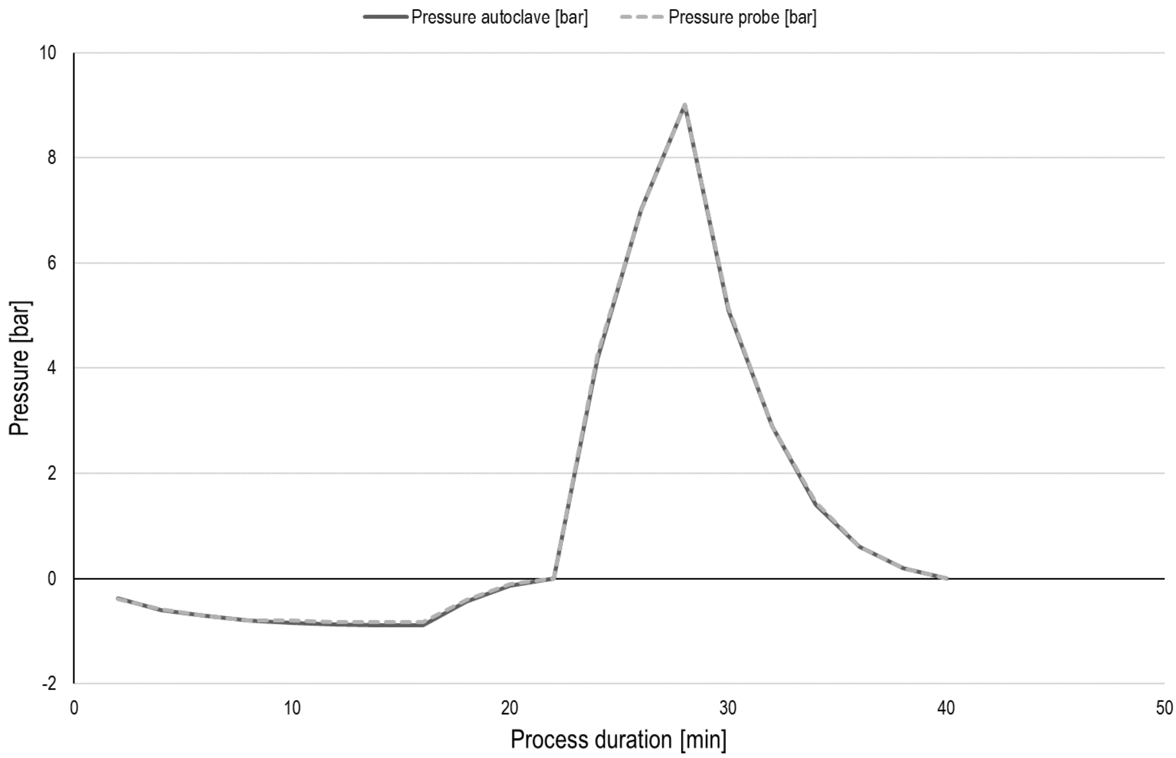


Figure 39: Comparison of the applied pressure recorded by the handmade probe and the integrated probe from the plant control system

3.3.3.2 Pressure distribution during vacuum and air pressure phases inside a sleeper

Figure 40 and Figure 41 show the distribution of pressure during applied vacuum and air pressure phases inside two sealed and later unsealed sleepers (1;2). The pressure inside unsealed sleeper 1 was decreasing and increasing nearly simultaneously to the vacuum/pressure of the autoclave (Figure 40). The pressure compensation in the unsealed sleeper 2 was shortly delayed during the pressure phase (Figure 41). For sealed sleepers a vacuum compensation was not reached using a vacuum of approximately -0.9 bar. Sleeper 1 and 2 reached only -0.80 to -0.81 bar after different periods of time. Equally the pressure compensation in both sleepers was reached delayed to the pressure inside the autoclave. While the pressure compensation in sleeper 1 was reached with a delay of around 20 minutes, the compensation in sleeper 2 was reached faster, but was not maintained from its beginning. During aeration of the autoclave, the vacuum inside the sealed sleepers was remaining for a short period. The same applied for the pressure inside the sealed sleepers during deflation of the autoclave (Figure 40 and Figure 41).

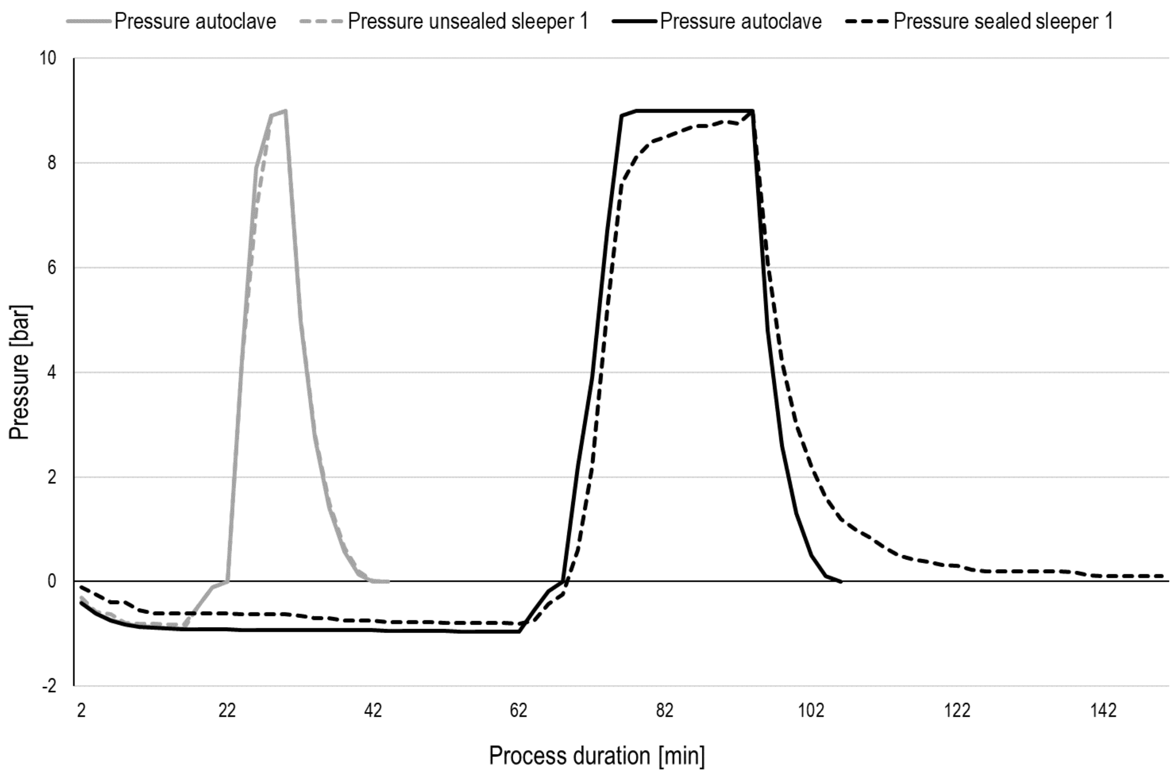


Figure 40: Pressure distribution inside Beech sleeper (1) with sealed and unsealed end grains during vacuum and air pressure phases

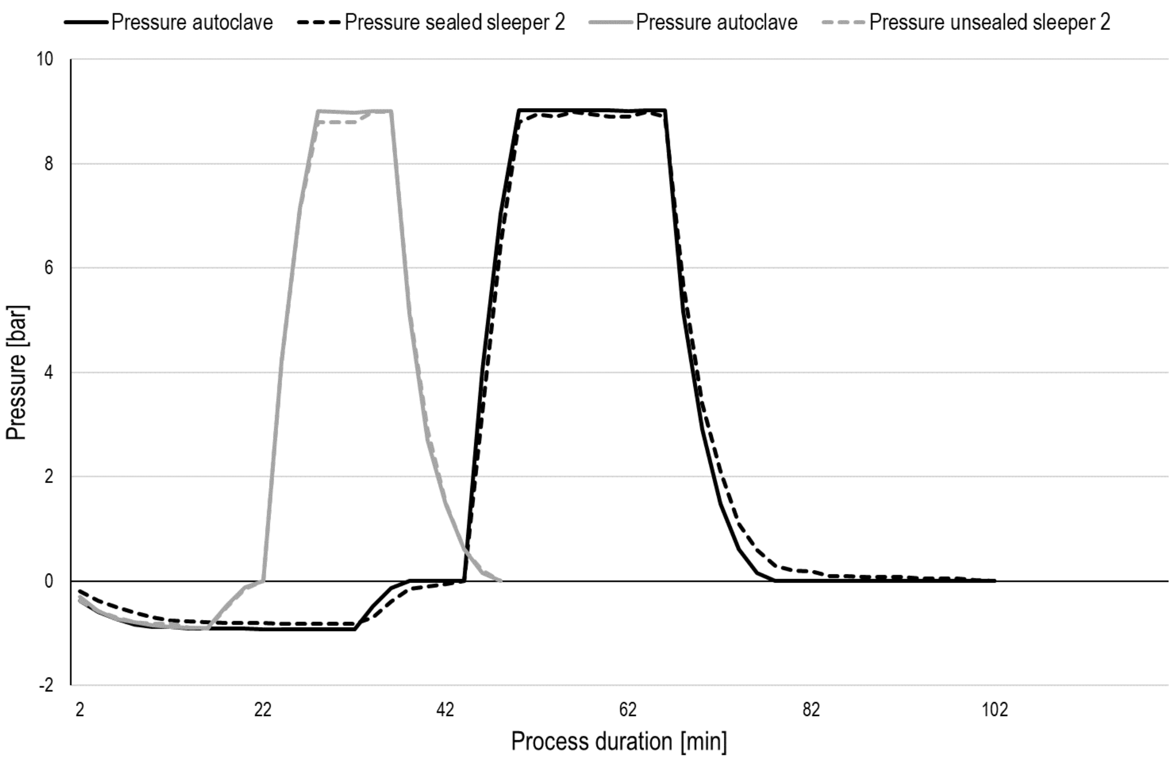


Figure 41: Pressure distribution inside Beech sleeper (2) with sealed and unsealed end grains during vacuum and air pressure phases

A direct measurement of the pressure distribution within the sleepers can only be without error, if the pressure probes have been glued in airtight. Improper sealing would result in a measurement of the pressure inside the autoclave instead of the wood. Since a delayed pressure de- and increase during the applied vacuum and pressure phases occurred, improper sealing of the pressure probes can be excluded. An existing leakage could be detected throughout sudden initial pressure changes (Arganbright and Resch 1970) or the absence of a characteristic initial pressure phase seen during a typical treatment (Schneider 2000). Both were not occurring during these tests.

The faster achievement of pressure compensation during applied vacuum and pressure of the unsealed sleepers is caused by the unsealed end grains. The longitudinal movement of fluids and gases in hardwoods is primarily through the perforated vessels (Côté 1963, Böhner 1977). Based on the low viscosity of air (Hösli and Bariska 1980), a faster pressure compensation could be reached. Because of sealing the end-grain sides, the axial influence on pressure distribution is diminished and leads to longer durations reaching pressure compensation. A penetration of air can only take place in transversal direction. In radial and tangential direction, the permeability is considerably lower. In tangential direction, late- and early wood are penetrated simultaneously, but the permeability is more influenced by the high permeability of the earlywood. Whereas in radial direction late- and early wood are penetrated consecutively and therefore the permeability more dominated by the low permeability of the late wood. Wood rays on the other hand show comparatively high permeability (Böhner 1970).

During earlier impregnations with fluids an influence based on the longitudinal direction (50-70 c), can be expected. On the basis of the present results, the same can be applied for air.

3.3.3.3 Pressure gradient during impregnation of Beech using an alternative oily wood preservative

Full cell process

Initial tests of measuring the pressure gradient during a full cell process have shown that a 60-minute-long pre-vacuum will lead to pressure compensation (-0.92 bar) in a depth of 20 mm. The vacuum in 80 mm depth was a little bit lower (-0.84 bar). A pressure compensation could not be reached. During the pressure phase (9 bar) of 3 hours, the vacuum started to decrease. At the end of the pressure phase, a pressure of approximately 0.78 bar was reached at 80 mm depth. During deflation of the autoclave the pressure was decreasing again and at the end of the applied post-vacuum, a pressure of -0.44 bar was provided. After repeated aeration of the autoclave the vacuum remained and even decreased up to -0.5 bar. Simultaneously, the vacuum in 20 mm depth decreased at the beginning of the pressure phase from -0.84 to -0.81 bar, but did not further increase during the pressure phase. Also, during the post-vacuum phase and after aeration the pressure was stable (Figure 42).

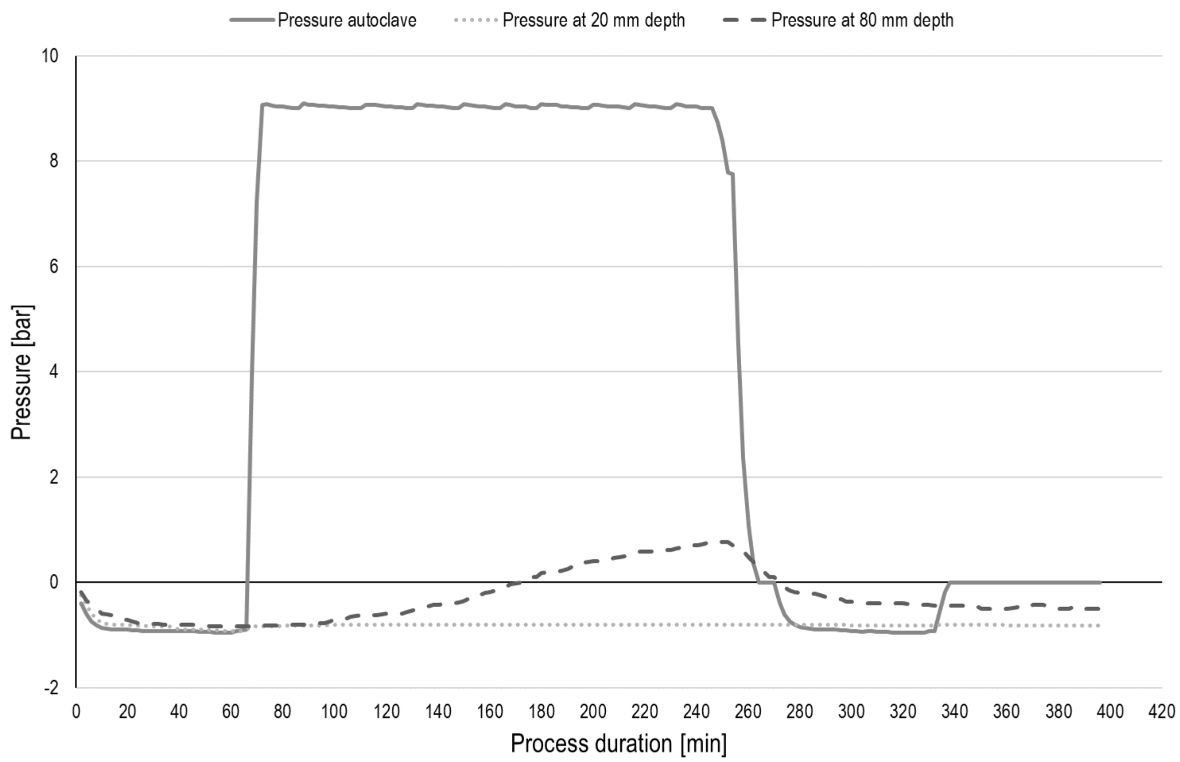


Figure 42: Pressure compensation during an impregnation of a sealed Beech sleeper using a full cell process

The slowly increasing pressure at a depth of 80 mm can be explained as followed:
Since a pressure compensation could not be reached during the vacuum phase, residual air is present inside the porous structure of the sleeper. The penetrating oil compresses the air towards the inner part of the wood (Liese 1951). In the post-vacuum phase, the applied vacuum supports the compressed air expanding. As viscosity is increasing with decreasing temperature during the penetration of the wood (Richardson 1980), it is not possible to reach pressure compensation during the post-vacuum. The highly viscose oil possibly provides a barrier, which inhibits air leaving the wood. This “barrier effect” is also present after aeration of the autoclave and leads to a remaining vacuum at 80 mm depth for a certain period. Furthermore, the “barrier effect” will also explain the remaining vacuum in 20 mm depth. Penetrating oil is filling the porous space around the pressure probe and builds up a closed system. The applied vacuum remains in this now closed system. After cutting the sleeper, the wooden structure surrounding the pressure probe was completely filled with oil, which visually supported the consideration made above.

Empty cell process:

The results showed, that the initial air pressure of 2 bar was compensated simultaneously in 20 mm as well as in 80 mm depth. The following fluid pressure of 9 bar led to a delay of pressure compensation in 20 mm depth of approximately 80 minutes. Simultaneously, a pressure compensation in 80 mm depth could not be reached during the entire fluid pressure phase. The pressure increased solely up to 6.75 bar. During deflation, the pressure at both measuring points was not decreasing equally with the pressure of the autoclave. While at a depth of 20 mm the applied pressure decreased with a delay of approximately 10 minutes, the pressure in 80 mm depth remained at approximately 3 bar for the rest of the measuring period, even during the post-vacuum phase (Figure 43).

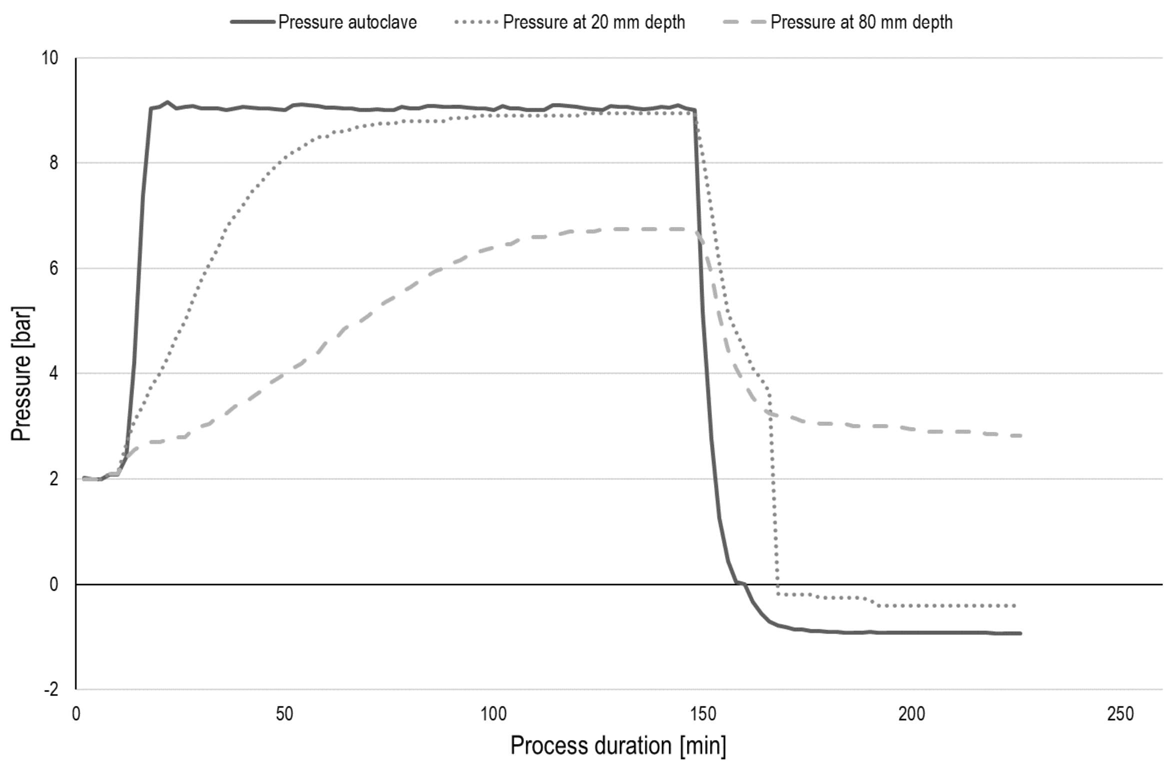


Figure 43: Pressure compensation during an impregnation of a sealed Beech sleeper using an empty cell process (Rüping-process)

The delayed pressure compensation in 20 mm depth, can be explained as follows. Due to the penetration impeding effect of trapped air (Hösli and Bosshard 1979), respectively the applied air pressure (McLean 1952), the penetration of the alternative oily wood preservative is slowed down. The applied fluid pressure builds up slowly inside the penetrated area as Riechert (1976) calculated for more resistant species compared to Beech. Like the pressure compensation at

80 mm during the vacuum pressure impregnation, the inserted air from the initially applied air pressure (2 bar) is again compressed by the penetrating solution and causes the pressure increase. The missing pressure compensation in 80 mm depth after approximately 120 minutes is probably based on incomplete penetration of the cross section by the alternative oily wood preservative. Hösli and Bariska (1980) found similar pressure ratios during the first fluid pressure using a double Rüping-process for the impregnation of Beech sleepers with creosote. A comparable pressure increase of approximately 6.5 bar was measured at 0.7 m and 1.25 m from the grain and an incomplete penetration of the sleeper cross section was also mentioned as probable cause. Possible reasons for the incomplete penetration are increasing viscosity as well as surface tension based on the decreasing temperature during penetration of the cold wooden structure. The delayed pressure compensation after releasing the fluid pressure and incomplete pressure compensation during the post-vacuum phase, were also found by Hösli and Bariska (1980) and were justified by viscous flow of the exiting oil and the occurring air bubbles from the compressed air. Additionally, the remaining pressure at 80 mm depth during the post-vacuum phase can be explained by the earlier clarified "barrier effect" of the highly viscose preservative filling up the porous structure of the wood.

3.3.4 Conclusions

Based on the pressure measurements carried out on Beech sleepers exposed to different air pressures and impregnation processes, the following general conclusions regarding the measurement method were drawn:

- The method used to determine the pressure development during the individual process sections of the full and empty cell process generally worked. Especially during process sections without fluid.
- During the empty cell process, the pressure development could be determined precisely at a depth of 20 mm and 80 mm throughout the complete impregnation process.
- Merely during the full cell process, the penetrating wood preservative caused problems due to the evacuated wooden structure. However, this only resulted in implausible values at a measuring depth of 20 mm. The pressure curve at a depth of 80 mm could still be determined due to the lack of penetration of the preservative.

Based on the results from the pressure measurements, the following conclusions were drawn:

- A substantial influence of the end grain up to 700 mm on the air pressure gradient was shown. Due to sealing the grain sides the longitudinal influence was diminished and a delayed pressure compensation was appearing based on the transversal wooden structure.
- A complete pressure compensation at 80 mm depth was not achieved during the fluid pressure phases of both types of impregnation processes.
- Penetrating wood preservative compressed remaining- as well as injected air inside the wooden sleeper during the fluid pressure phase to a certain extent.
- The pressure gradients inside the sleepers (at 80 mm depth) during both empty- and full cell processes indicated that compressed air was not the cause for the insufficient penetration of the sleeper cross section, especially since nearly all air was removed by the applied pre-vacuum in the full cell process.

Since compressed air can be excluded as possible cause for insufficient penetration of the sleeper cross section by the alternative oily wood preservative, the used impregnation processes are not the main cause of the insufficient preservative penetration. Additional factors influencing preservative penetration have to be evaluated in further investigations. This includes the influence of the anatomical directions on the preservative penetration.

3.4 Transversal and axial penetration of an oily wood preservative during impregnation

3.4.1 Introduction

The impregnation of wood by pressure processes results in a deeper and more uniform preservative penetration, compared to non-pressure processes. Nevertheless, aspects like the type of impregnation process, the wood moisture content, the preservative formulation and the porous structure of wood are able to influence preservative penetration and distribution (Tarmian et al. 2020, Rosenthal et al. 2010).

Previous results have shown, that compressed air, either from full- or empty cell processes, cannot be seen as cause for the incomplete penetration of the specimen cross section by the alternative oily wood preservative (Chapter 3.3). In fact, a considerable influence of the anatomical directions on the preservative penetration became evident during the previous impregnations. Especially penetration in axial direction seems to be essential for the penetration of Beech with hydrophobic carrier substances, respectively the alternative oily wood preservative (Chapter 3.1).

The capillary uptake of liquids by a porous material depends on the multiscale structure of the material, but also on the properties of the liquid. While polar liquids like water can be transported through the lumens and can additionally penetrate the cell walls, non-polar liquids like oil (for example creosote) may not enter the cell walls, but reside on the surface (Desmaris et al. 2016, Tarmian et al. 2020). The movement of liquids through wood is primarily along the grain and for most hardwood species in axial direction much better than in transverse direction (MacLean 1952, Leiße 1992). The transverse penetration of adjacent vessels is possible via bordered pits (Rosenthal 2010). Huber and Merz (1953) stated that for diffuse-porous hardwoods like Beech (*Fagus sylvatica* L.), the ratio of radial and tangential permeability to axial permeability is about 1:100.000.

However, the importance of transverse penetration increases with increasing product length and cross section, since axial penetration is not endlessly possible. In case of the impregnation of railway sleepers made from Beech, Zycha (1965) reported an axial penetration of creosote up to 500 mm, starting from the grain sides. At the same time, according to Peters (1950), a rather insufficient penetration of creosote in the transversal direction became evident. Especially in the middle of the sleeper, where the axial penetration from the grain sides is nearly diminished. The missing transverse penetration was compensated by an additional drilling pattern on the lower side of the sleeper, taking advantage of the good axial penetration (Peters 1950).

Since creosote shows differences in penetration depth regarding axial and transversal direction, the same effect may be responsible causing the insufficient penetration of the sapwood like tissue by the alternative oily wood preservative. Therefore, the following aspects have been evaluated:

- Determination and comparison of the retention in axial and transversal direction using the alternative oily wood preservative and water
- Evaluation of the retention and preservative penetration in axial direction for drilled specimens using the alternative oily wood preservative

3.4.2 Materials and methods

3.4.2.1 Transversal penetration

To investigate the influence of the transversal directions on the penetration behaviour of the alternative oily wood preservative, 12 cylindrical specimens (40 x 15 mm), depending on their anatomical direction (radial and tangential), were drilled with the help of a tenon cutter out of a railway sleeper out of Beech (Figure 44). To eliminate the influence of water on the penetration, the specimens were oven dried at 103 °C for 24 hours. Afterwards, the weight and dimension of the specimens were determined for later calculation of the retention in kg/m^3 according to Eq. (2). Thereon the specimens were pressed for two thirds of their length into a pressure resistant hose and were additionally fixated with a shrinking hose and a hose clamp (Figure 45). Afterwards, the prepared specimens were attached to an autoclave by using ball valves.

Figure 44: Specimens for radial (T2) and tangential (R1) penetration

Figure 45: Fixated specimen inside the hose additionally fixated with a shrink hose and a hose clamp

The autoclave was filled with the alternative oily wood preservative at room/surrounding temperature and a pressure of 8 bar was applied. Afterwards, each single ball valve was opened so the oily preservative could be pressed into the specimens for 20 minutes. Finally, the specimens were removed from the hoses and were weighed for calculation of the retention in kg/m^3 in accordance to Eq. (2). Afterwards, all steps were repeated using water as a reference. Preliminary tests showed, that the use of test specimens for determination of the longitudinal penetration had to be excluded from the test setup. Based on their significantly better permeability, it was not possible to apply a pressure of 8 bar for 20 minutes, because the complete penetration of the specimen cross section occurred within a few seconds.

3.4.2.2 Axial penetration

To determine the influence of the longitudinal direction on the penetration of the oily wood preservative, three specimen collectives made of Beech (500 x 50 x 25 mm^3) were prepared. After initially sealing all sides three times using “Pyrotect” (Sika, Stuttgart, Germany), collective one and two obtained centered single holes of either 5.5 mm or 8.0 mm diameter on the broadside, close to the grain of each specimen. Collective 3 obtained 3 shifted holes of 8 mm diameter in a distance of 8.0 mm from each other on both grain sides of the specimen. The location of the drilling holes was chosen in order to cover the complete cross section of the specimen (Figure 46).

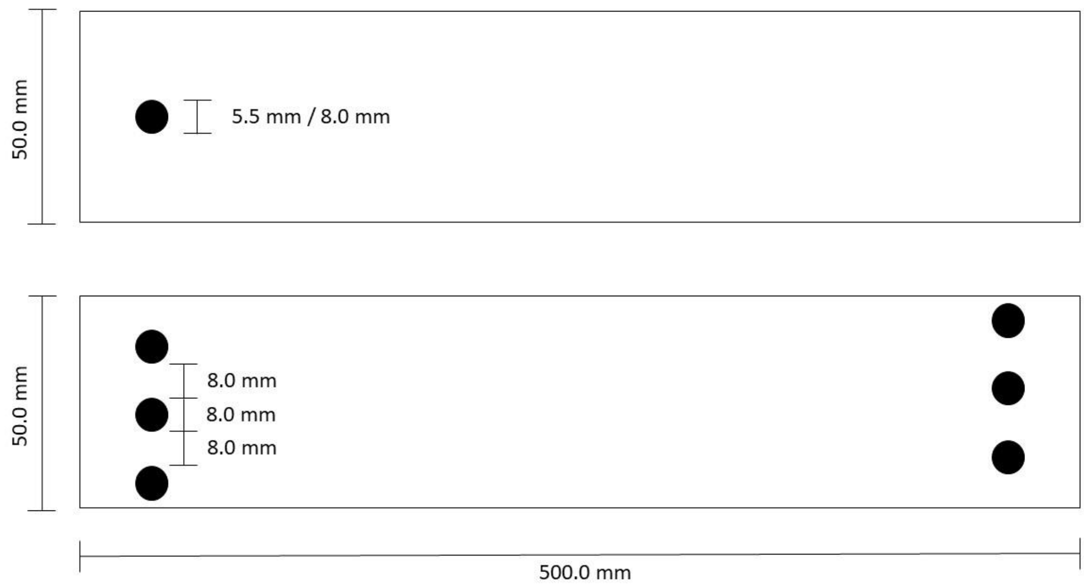


Figure 46: Sealed specimen with one centred hole (diameter 5.5 and 8.0 mm) and three shifted holes (diameter 8.0 mm) near the end grain

All specimens have been impregnated using a vacuum pressure process (- 0.85 bar, 60 min; 8 bar, 120 min). The temperature of the alternative oily wood preservative was approximately 65 °C. After impregnation, the retention in kg/m³ was determined in accordance to Eq. (2) and the penetration was visually analysed by dividing the specimens from the narrow side.

3.4.3 Results and discussion

3.4.3.1 Transversal penetration

Figure 47 shows the average retention in kg/m^3 of the alternative oily wood preservative and water in radial and tangential direction. In general, a higher uptake of water in radial (factor 2.1) than in tangential direction (factor 1.7) became apparent. The uptake of the alternative oily wood preservative in tangential direction was higher (105.9 kg/m^3), but was afflicted with a high standard deviation. Although the uptake in radial direction was lower (65.5 kg/m^3), it also showed a high standard deviation. The average retention of water showed comparable results. Likewise, the average retention in tangential direction was higher (177.0 kg/m³) compared to the uptake in radial direction (135. 6 kg/m³). Again, both average retentions were afflicted with high standard deviations.

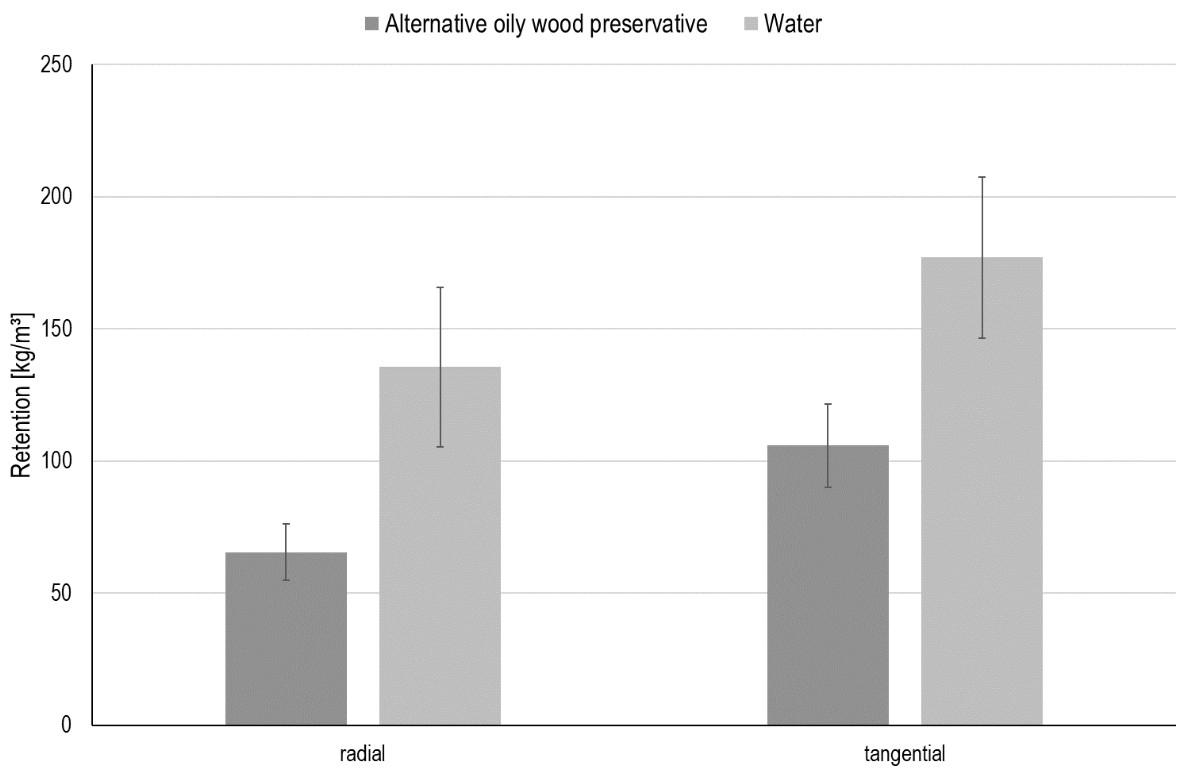


Figure 47: Retention in kg/m³ of the alternative oily wood preservative and water in radial [n=6] and tangential [n=6] direction

Based on the little number of replicate specimens (n=6), and in combination with the rather high standard deviation, it is not possible to make statistically verified statements about significant differences depending the uptake of both liquids in radial and tangential direction. However, a possible tendency seems to be appearing, which shows a lower uptake of the alternative oily wood preservative compared to the uptake of water in Beech.

Generally, the flow of aqueous solutions is restricted in transverse direction. Fluid flow can only take place in lateral direction via the rays or pits, which provide channels between the adjacent cells (Murmanis and Chudnoff 1979). The ratio of longitudinal to lateral flow is about 30 to 1 (Stamm 1973). In concern of oily products Behr et al. (1969) found that rays in hardwoods often hinder the penetration of oily preservatives. In Beech, he detected a lack of oil in wide rays. Liese (1951) also noticed no penetration of oily products in the wood rays. Scholz (2010) also found difficulties depending on the penetration of wood rays during impregnation of Beech with waxes.

In contrary to coniferous wood species like Scots pine sapwood (*Pinus sylvestris* L.) or Spruce (Picea abies L. Karst.), Larnøy et al. (2005) also found lower retentions in radial as in tangential direction using chitosan-based solutions for the impregnation of Beech. In Beech, vessels have a wide range of bordered pits in radial direction, which provide a connection between single vessels. Furthermore, a second connection between the vessels and the ray parenchyma is existing (Rosenthal and Bäucker 2013). In tangential direction vessels are connected through intervascular pits with only rudimental pit membranes (Ohtani and Ishida 1973). Since bordered pits in radial direction have an intact pit membrane, a penetration seems to be harder compared to the penetration through pits with rudimental pit membranes. Additionally, the possible lower retention of the alternative oily wood preservative in radial direction is intensified by the missing penetration through the wood rays.

3.4.3.2 Longitudinal penetration

Figure 48 shows the average retention of the alternative oily wood preservative in specimens with differently dimensioned and arranged drillings. Both single drillings (5.5 mm and 8.0 mm) showed similar average retentions of 26.5 kg/m³ and 24.1 kg/m³, while the shifted drillings showed a significantly higher average retention of 130.0 kg/m³.

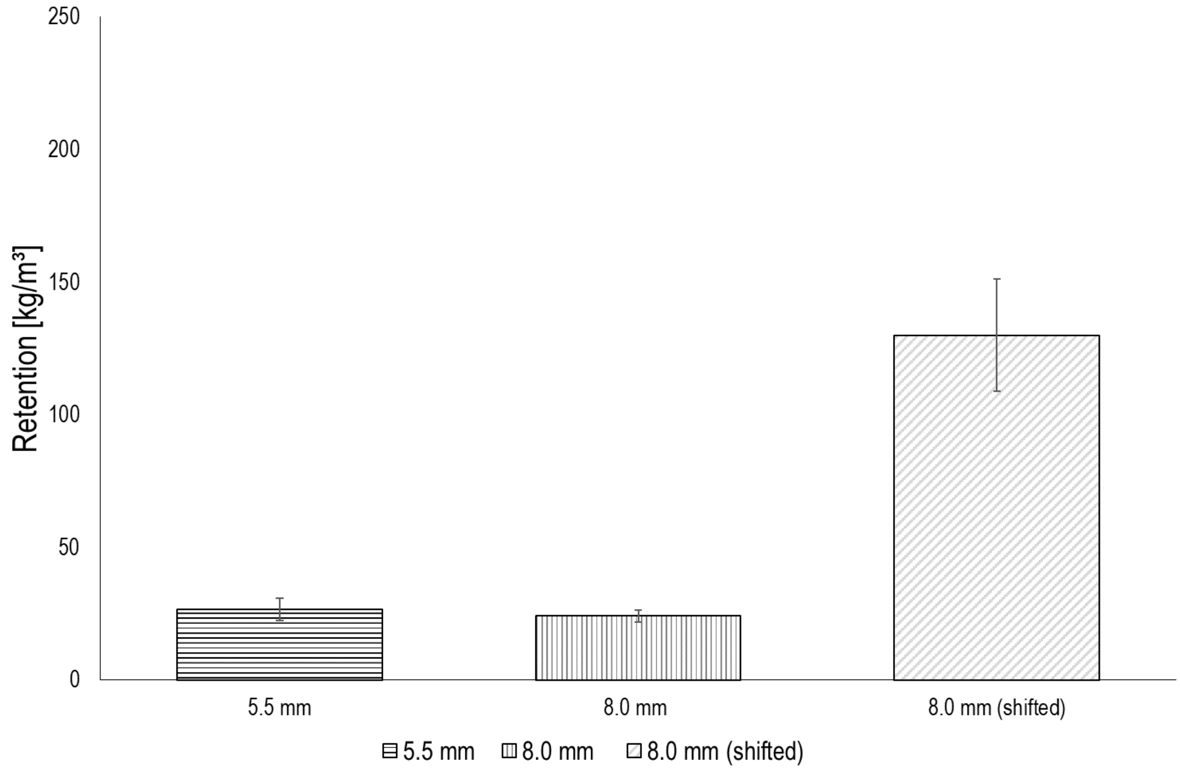


Figure 48: Average retention of the alternative oily wood preservative in specimens with differently dimensioned drillings [5.5 mm and 8.0 mm; number of drillings n=1] and shifted drillings [8.0 mm; number of drillings n=6]

The corresponding penetration pattern of the alternative oily wood preservative is exemplarily shown in Figure 49. For all specimens, a distinct penetration in longitudinal direction, along the fiber was visible. Penetration in transversal direction was not occurring. Based on a not completely parallel running fiber orientation, a homogeneous penetration of the complete specimen cross section was not achieved by the shifted (offset 8.0 mm) drillings.

Figure 49: Longitudinal penetration of the plant based oily wood preservative at drilled specimens [5.5 mm left; 8.0 mm middle; 8.0 mm shifted right]

The higher retention of specimens, equipped with three shifted holes on both grain sides, can be explained by the higher number of drillings. A higher number of drillings allows the alternative oily wood preservative to enter the wooden structure at more positions. The consistent penetration in longitudinal direction validates, that liquids in hardwoods are mainly transported through the longitudinally oriented vessels, consisting of numerous vessel elements (Liese 1957). For Beech, the end parts of these vessel elements can have differently shaped openings (simple or ladder-shaped), but generally do not restrict the flow (Rosenthal et al. 2010). This becomes evident also for the penetration of the alternative oily wood preservatives during impregnation, since a penetration of at least 0.5 m is possible without any difficulties.

3.4.4 Conclusions

Based on the evaluation of the transversal and axial penetration of the alternative oily wood preservative, the following general conclusion was drawn:

- A possible higher retention of the oily product in tangential direction under the influence of an applied pressure is shown. These results must be investigated in further tests in greater detail for statistical verification.

Parts of the results from the carried out evaluation of the axial and transversal penetration using the alternative oily wood preservative, clearly showed parallels to creosote. Based on these results the following conclusions were drawn:

- The already identified substantial influence of the longitudinal direction on the air pressure gradient remains just as important for the penetration of the alternative oily wood preservative.
- An impeded penetration in transversal direction is further clarified, since the penetration of the alternative oily wood preservative solely pursues the fibers opened by the bore holes.
- Based on the excellent penetration of the alternative oily wood preservative in longitudinal direction and the impeded transversal penetration it becomes evident, that a complete penetration of the cross section can only be reached under reinforced influence of the longitudinal direction.
- Therefore, the existing drilling pattern used for the impregnation of Beech sleepers with creosote, may be adapted towards the requirements of the alternative oily wood preservative and thus enables a complete penetration of the sleeper cross section.

3.5 Longitudinal penetration due to an alternative drilling pattern

3.5.1 Introduction

Previous results have shown, that a complete penetration of the sleeper cross section using the commonly known and applied impregnation processes is currently not possible (Chapter 3.2). Penetration in transversal direction can only be achieved with difficulty and is not sufficient enough to penetrate the complete sleeper cross section. In contrary, a great influence of the longitudinal direction on the penetration of the alternative oily wood preservative is emerging (Chapter 3.4).

The same effect is known for the penetration of creosote in Beech sleepers. Here, the longitudinal penetration is also way more efficient, compared to the radial or tangential penetration (Peters 1950). An improvement in creosote penetration had been achieved in 1940 by applying a drilling pattern. This consisted of four diagonally arranged drillings, located in the centre of the sleeper bottom. Still, only approximately 70-80% of the sleeper cross section was penetrated by creosote. For further improvement, the drilling pattern was extended to eight drillings in 1964 (Schulz 1964a) and is even until today required according to DIN 68111 (2007).

In order to improve the currently achieved penetration of the sleeper cross section by the alternative oily wood preservative, the existing drilling pattern was taken as general template to create an alternative drilling pattern. By adaption to the penetration behaviour of the alternative oily wood preservative, the alternative drilling pattern is considered to support the axial penetration and ensure a complete penetration of the sleeper cross section, especially in the middle of the sleeper. Therefore, the following objectives have been set:

- Development of an alternative drilling pattern for the impregnation of the alternative oily wood preservative
- Determination of the preservative retention and penetration after impregnation of Beech sleepers equipped with one and two drilling patterns

3.5.2 Materials and methods

3.5.2.1 Development of the drilling pattern and sleeper preparation

The objective of the alternative drilling pattern was to enhance the penetration of the alternative oily wood preservative regarding the cross section of railway sleepers made from Beech. Therefore, a pattern consisting of 28 single, shifted blind drillings, arranged in three rows with 100 mm spacing in between, was developed for later placement on the bottom side of the sleeper. Each drilling had a diameter of 8 mm and a depth of 140 mm. In order to keep the number of holes and the possible weakening of the wooden structure as low as possible, the drilling pattern was positioned 20 mm from the edge of the sleeper (Figure 50).

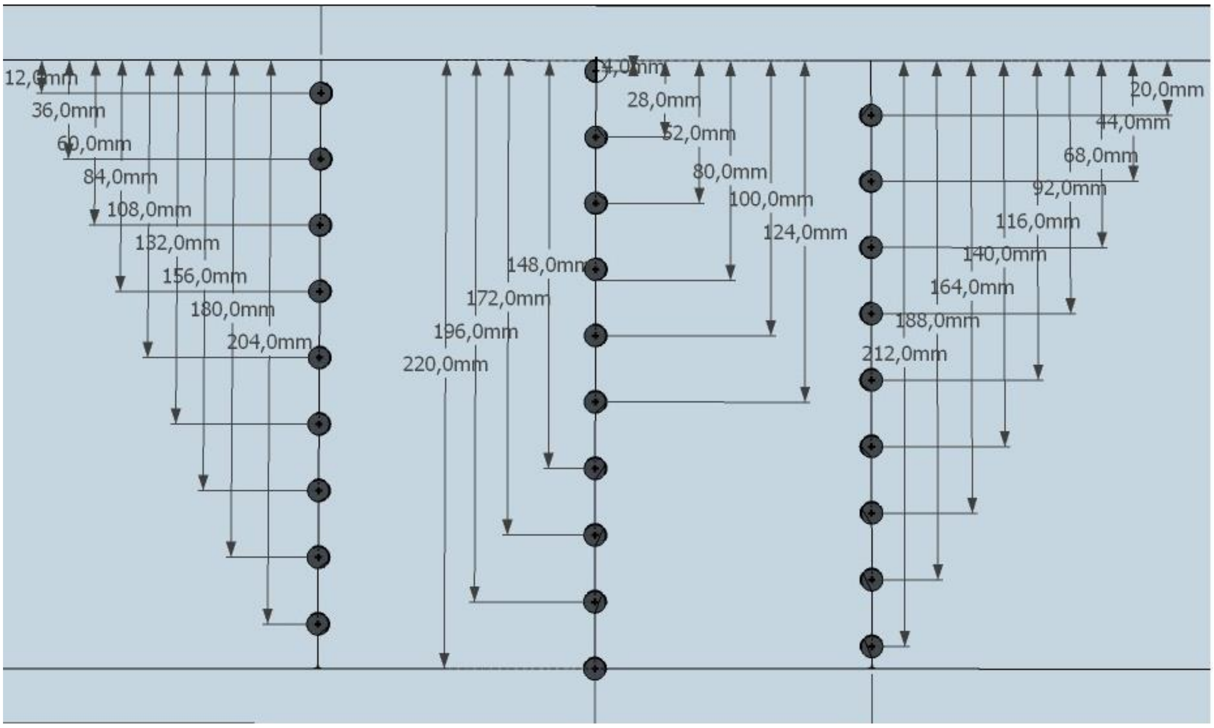


Figure 50: Detailed overview of the drilling pattern with drilling holes with a diameter of 8 mm and a depth of 140 mm

The standard track sleeper with its dimensions of 160 x 260 x 2600 mm³ was set as a basis for the positioning. Due to the longitudinal penetration, starting from the grain sides, an area of approximately 1200 mm remained, in which only a transverse penetration will take place. The alternative drilling pattern was placed in the centre of the bottom side (Figure 51).

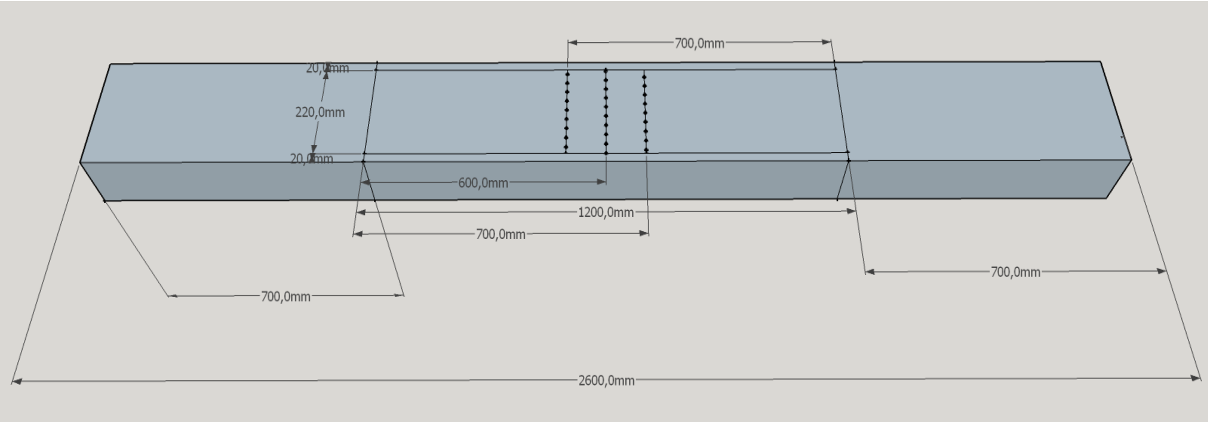


Figure 51: Standard track sleeper (2600 x 260 x 160 mm³) with attached drilling pattern

Additionally, a second drilling pattern was added in order to increase the effect of the longitudinal penetration and to maximize the penetration of the sleeper cross section. Therefore, the single drilling patterns were shifted from the middle, starting at 890 mm from each grain side (Figure 52).

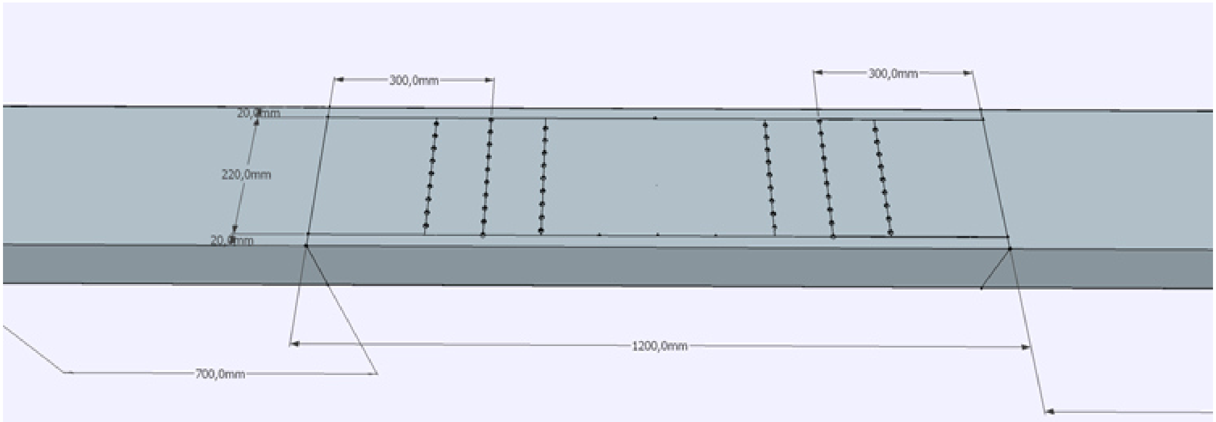


Figure 52: Standard track sleeper (2600 x 260 x 160 mm³) with two attached drilling patterns

Based on the dimension of the laboratory impregnation plant, only sleepers with a length of 2000 mm could be impregnated. Therefore, the sleepers were shortened unilaterally. On the shortened side, the grain was sealed three times using Pyroplast Top W (Sika, Stuttgart, Germany) in order to prevent the longitudinal penetration from covering the effect of the drilling pattern.

3.5.2.2 Impregnation

The track sleepers with the attached drilling patterns (single and double) were initially impregnated using a Rüping-process with a prolonged post-vacuum (Table 23).

Table 23: Detailed process parameter of the Rüping-process

Process section	Pressure [bar]	Duration [min]
Air pressure	3	60
Fluid pressure	8	180
Post-vacuum	-0.85 to -0.80	1020

Additionally, a second impregnation of a track sleeper with two drilling patterns was carried out using a vacuum pressure process (Table 24).

Table 24: Detailed process parameter of the vacuum pressure process

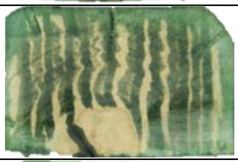
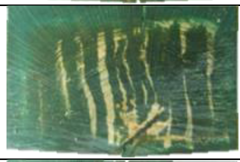
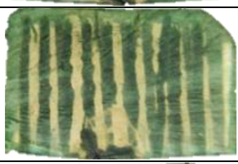
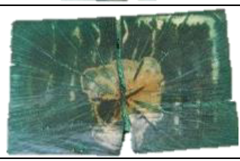
Process section	Pressure [bar]	Duration [min]
Pre-vacuum	-0.85 to -0.80	180
Fluid pressure	8	180
Post-vacuum	-0.85 to -0.80	1020

3.5.3 Results and discussion

The impregnation using a Rüping-process led to similar retentions. While the sleeper, equipped with the single drilling pattern, showed a retention of 84.7 kg/m³, the sleeper equipped with two drilling patterns showed a retention of 89.1 kg/m³. At the same time, impregnating a sleeper with two drilling patterns using a vacuum pressure process resulted in a retention of 256.1 kg/m³.

The results show, that the application of a single, centred drilling pattern did not result in a complete penetration of the central area, which is difficult to impregnate. While the sections of the drillings showed a good penetration of the alternative oily wood preservative, the areas between the drillings remained unimpregnated. Furthermore, a penetration depth in longitudinal direction of at least 500 mm was not achieved. Merely 200 mm in either direction from the drilling pattern was penetrated by the alternative oily wood preservative. The same applied for the penetration starting from the unsealed grain side of the sleeper. Again, a longitudinal penetration of only approximately 200 mm occurred, which left a nearly unimpregnated inner area of at least 600 mm, until the effect of the drilling pattern became slightly evident. The sleeper, equipped with two drilling patterns, showed a comparable longitudinal penetration depth from the unsealed grain side of the sleeper. Due to the additional drilling pattern in combination with the offset closer to the grain side, a slight penetration already occurred at 600 mm from the grain side. From there, the complete sleeper was penetrated by the alternative oily wood preservative in the sections of the drillings. Again, the areas between the drillings remained unimpregnated. The same appears for the sleeper impregnated with a vacuum pressure process, but the penetration of the alternative oily wood preservative was in general more extensive (Table 25).

Table 25: Comparison of the penetration depth of the alternative oily wood preservative in Beech sleepers with different drilling patterns

Distance unsealed grain side	Rüping-process single drilling pattern	Rüping-process double drilling pattern	Vacuum pressure process double drilling pattern
200 mm			
400 mm			
600 mm			
800 mm			
1000 mm			
1200 mm			
1400 mm			
1600 mm			
1800 mm			
2000 mm			

The influence of the air pressure (Rüping-process) or pre-vacuum (vacuum pressure process) on the retention is clarified again. The air pressure leads to a kick-back effect, which removes the alternative oily wood preservative from the filled porous spaces and reduces the retention. The evacuation of the porous spaces by the pre-vacuum leads to completely filled cells, which increases the retention significantly. The retention of the alternative oily wood preservative in Beech sleepers, equipped with the alternative drilling pattern, was now similar to the retention of creosote impregnated Beech sleepers using a vacuum pressure (277 kg/m³) or Rüping-process (< 100kg/m³) (Schramm 1952).

Axial penetration of creosote up to 500 mm is possible, either starting from the grain sides or by the attached drilling pattern (Zycha 1965). Therefore, a big influence on the longitudinal penetration of the alternative oily wood preservative by the unsealed grain side as well as by the applied drilling patterns, was expected. However, this could not be found using sleepers in standard dimensions. Reasons for a restricted longitudinal penetration during the impregnation with creosote were found by Gelinsky (1939) during his study of discolored Beech sleepers. In all examined sleepers, he found two types of discoloration, which differed in their location as well as in their formation.

The first discoloration found by Gelinsky (1939) was lightly brownish red and was located in the inner part of the sleeper, framed by a ring of approximately 20-40 mm of white wood and was not caused by fungal infestation. Tuzson (1905) described the origin of the brownish color by excreted components, which were microscopically visible as droplets, grains and wall coverings. These wall coverings were found in all structural elements even in the parenchymal cells. Furthermore, additional tyloses were found in the vessels, which were similar to the ones found in red heartwood of Beech. In case of creosote, this kind of discoloration had also a hindering effect on the penetration, but was not considered as significant as the discoloration caused by fungal infestation. By using drying technologies, for example kiln drying, for reaching the requested moisture content before impregnation, the discoloration could be reduced and the penetration of creosote was further improved (Gelinsky 1939). Since, the drilling pattern was attached immediately before impregnation, a discoloration of the inner cross section also occurred in the area of the drilling holes. Therefore, a possible effect on the penetration of the oily wood preservative is conceivable.

The second discoloration resulted from slowly drying due to unfavourable storage and is associated with a fungal infestation beginning from the grain side. Tuzson (1905) described the visual appearance of the fungal infestation as widening white stripes resulting in later occurring white rot, clearly visible without magnification. Therefore, a fungal infestation, as cause for the poor penetration in longitudinal direction, especially from the grain side, can be excluded. None of the mentioned aspects were visible. Additionally, the drilling patterns were drilled immediately before impregnation, so a fungal infestation was also not possible by using the drilling holes as entrance into the wooden structure.

Further reasons for restricted penetration were named by Zycha (1965) including overgrown knots and scarred injuries. But also, the possibility of clogging by dust had been discussed.

The drilling pattern for Beech sleepers, which was established in 1940 (Halank 1959) and expended in 1960 (Schulz 1964a) is used to improve the penetration of creosote. The use of the adapted drilling pattern also improved the penetration of the inner part of the cross section to a certain extent. However, a complete penetration of the sleeper cross section by the shifted drilling holes was not possible. This can be explained as follows:

For railway sleepers in standard dimension, the fiber orientation is normally not as parallel with the course of the narrow sides, as for the specimen in laboratory scale. Due to not parallel running fibers, the planned continuous penetration from drilling hole to drilling hole was not possible. A second approach, framing compressed air inside the wooden sleeper acting as a barrier can be excluded. Based on the carried out vacuum pressure process, even under consideration of nearly complete evacuation of the spaces between the drilling holes, a complete penetration should be possible. The insufficient penetration in transversal direction becomes again evident. Similar results were also found by Zycha (1965). Here, creosote was not able to penetrate the wooden structure. Either from the attached drilling pattern, consisting of four centred drilling holes at the bottom of the sleeper, or the end grain, a sufficient penetration did not occur. Ingrown knots, scarred tissue or even moisture contents above fiber saturation were identified as probable causes for the insufficient penetration. Furthermore, axially cut sleepers showed also no transversal penetration of creosote in the area of the drilling holes.

Since Beech is not durable, and assigned to durability class 5 (DC5, EN 350, 2016), a deep penetration of the entire sleeper volume is necessary to ensure sufficiently high protection against wood-destroying organisms. Otherwise, unimpregnated areas can be exposed by occurring checks (Findlay 1985) and allow wood destroying organisms to enter the wooden structure and cause decay from the inside (Halank 1959, Schulz 1965).

3.5.4 Conclusions

Parts of the results from the evaluation of the retention and preservative penetration by the developed drilling pattern, clearly showed parallels to creosote. Based on these results, the following conclusions were drawn:

- By applying the alternative drilling pattern, retentions of the alternative oily wood preservative comparable to creosote could be achieved during the impregnation using a Rüping- and a vacuum pressure process.

Further results from the carried out evaluation differed from the impregnation using creosote. Based on these results, the following conclusions were drawn:

- Due to reduced longitudinal penetration, the central application of a single drilling pattern led to an insufficient distribution of the alternative oily wood preservative over the entire sleeper length and cross section.
- The distribution of the preservative in the longitudinal direction was improved by relocation and additional application of a second drilling pattern. However, the penetration over the entire sleeper length and cross section remained insufficient also based on the impeded transversal penetration.

Probable causes for the insufficient penetration of the alternative oily wood preservative have been discussed and the following conclusion was drawn:

- The possible influence of appearing discolorations of Beech sleepers on the penetration of the alternative oily wood preservative has to be evaluated in further investigations as probable cause for the insufficient penetration of the cross section.

3.6 Impregnation of mechanically pre-treated Beech sleepers with water-based wood preservatives and the influence of different gross weights on retention and penetration

3.6.1 Introduction

Using different impregnation processes with varying process parameters (Chapter 3.2), as well as the application of an alternative drilling pattern (Chapter 3.5), did not lead to a complete and homogenous penetration of the alternative oily wood preservative in Beech sleepers. To provide a continuous preservation of the complete sleeper volume, a complete penetration of the sleeper cross section in standard dimension using water-based preservatives was considered.

Even though creosote, as a wood preservative for sleepers, has been used for decades and is the preservative of choice until today, there have also been repeated attempts over the years to successfully impregnate railway sleepers with water-based wood preservatives.

The two main types of liquid carriers used in wood preservation are organic solvent and water-based systems (O'Leary and Hodges 2001). Water-based wood preservatives are a combination of non-organic salts with insoluble organic active ingredients. By means of emulsifiers, latter will be made dilutable in water (Militz and Mai 2008). Polar solutions like water-based preservatives are able to penetrate the cell wall (Furuno et al. 2004) and cause swelling of the wood (O'Leary and Hodges 2001), which makes it more receptive for treatment (Rhatigan et al. 2004).

In 1956 and 1962 field trials had been started, where Beech (*Fagus sylvatica* L.) and Scots pine (*Pinus sylvestris* L.) sleepers were impregnated using either a CFA (chromium-, fluorine- and arsenic containing) based preservative or a CCB (chromium-, copper and boron-containing) preservative. For both preservatives, Beech sleepers showed fiber fractures and transversal checks after a short time, while pine sleepers showed significantly less fractures as well as checks. Since the creosote treated references for both trials showed only insignificant fiber fractures and no fungal attack (Schulz 1964b, Schulz 1987b), none of the water-based preservative types prevailed and were used as replacement for creosote.

Today, copper-amine based preservatives are on the market for 20 years. Based on their high efficacy in use class 4 applications like utility poles, a possibility for acting as creosote replacement is given, even though little knowledge is given regarding required moisture contents for impregnation (Pfabigan et al. 2017).

According to DIN 68811 (2007) the gross weight for Beech sleepers before impregnation with creosote should be below 750 kg/m³ to ensure an efficient penetration of the complete cross section. Storage until the required gross weight is reached, is time-consuming as well as expensive. Especially regarding costs for interest and insurance. Furthermore, quality deficiencies can quickly occur if the sleepers are stored too long (Broese van Groenou and Bellmann 1958, Schulz 1969).

In order to provide a complete penetration of the sleeper cross section and volume as well as to potentially shorten the storage times until impregnation, the following was examined:

- Impregnation of Beech sleepers using two commercially available copper-based wood preservatives
- Visual examination of the preservative penetration as first indication for the later use of water-based wood preservatives for Beech sleepers
- Investigation of the influence on preservative retention and penetration by mechanical pre-treatment in combination with the alternative drilling pattern
- Examination of the influence of different gross weights on the retention and visual distribution of water-based preservatives

3.6.2 Materials and methods

3.6.2.1 Impregnation of mechanically pre-treated Beech sleepers with water-based wood preservatives

24 Beech sleepers in standard dimensions (2600 x 260 x 160 mm³) have been used for the investigation. All sleepers reached the required gross weight of < 750 kg/m³ before impregnation according to DIN 68811 (2007) and were divided in four collectives. While collective one and two remained without pre-treatment, collective three and four received the shifted double drilling pattern and were additionally mechanically pre-treated by incising. Table 26 shows an overview on the average gross weights and the mechanical pre-treatment of the sleeper collectives.

Table 26: Overview of sleeper collectives (1-4) for impregnation using two water-based, chromium-free wood preservatives

Collective	Water-based preservative	Average gross weight [kg/m³] (SD)
Standard sleeper Drilling pattern and incising	Preservative 1	744.3 (31.3) 727.3 (24.2)
Standard sleeper Drilling pattern and incising	Preservative 2	733.6 (19.3) 742.6 (32.0)

Following the mechanical pre-treatment, the sleepers were measured and weighed in order to determine the retention in kg/m³ in accordance to Eq. (2), after impregnation using a full cell process (Table 27). For impregnation of the sleepers, two commercially available, chromium-free water-based preservatives have been used. Both preservatives were copper-based containing different co biocides.

Table 27: Detailed process parameters of the full cell process for the impregnation of Beech

Process step	Pressure [bar]	Duration [min]
Pre-vacuum	-0.965 to -0.970	180
Fluid pressure	8	480

3.6.2.2 Influence of different gross weights on the retention and penetration of water-based wood preservatives

In the beginning, five different target gross weights were specified for later examination of their effect on retention and penetration of a water-based wood preservative (Table 28). Ten packages of sleepers (2600 x 260 x 160 mm³) were weighed to determine their average gross weight. Package nine with an average gross weight of 916.9 kg/m³ was selected for sampling the specimens. Afterwards, each sleeper (n=24) was weighed and based on their single gross weight, assigned to the corresponding target gross weight collective. Following, all sleepers were mechanically pre-treated by incising. Afterwards all sleepers were impregnated with a water-based wood preservative using a vacuum pressure process. Table 27 gives a detailed overview about the single process parameters. Finally, all sleepers were weight after impregnation to determine the retention in accordance to Eq. (2). For visual examination of the preservative penetration, one sleeper from each collective was cut at 300 mm, 800 mm and 1300 mm from the end grain.

Table 28: Target gross weights for examination of preservative retention and penetration and number of sleepers impregnated in each target gross weight

Target gross weights [kg/m³]				
800-830	830-860	860-900	900-930	930-1100
Number of impregnated sleepers				
4	4	6	4	6

3.6.3 Results and discussion

3.6.3.1 Impregnation of mechanically pre-treated Beech sleepers with water-based wood preservatives

The retention was not considerably different between the two water-based preservatives. While collective 1 showed an average retention of 498.6 kg/m³ (preservative 1), collective 3 showed an average retention of 521.5 kg/m³ (preservative 2). Also, the mechanical pre-treatment showed no influence on the amount of applied wood preservative. Collective 2 showed an average retention of 497.7 kg/m³ (preservative 1) and collective 4 an average retention of 493.1 kg/m³ (preservative 2) (Figure 53).

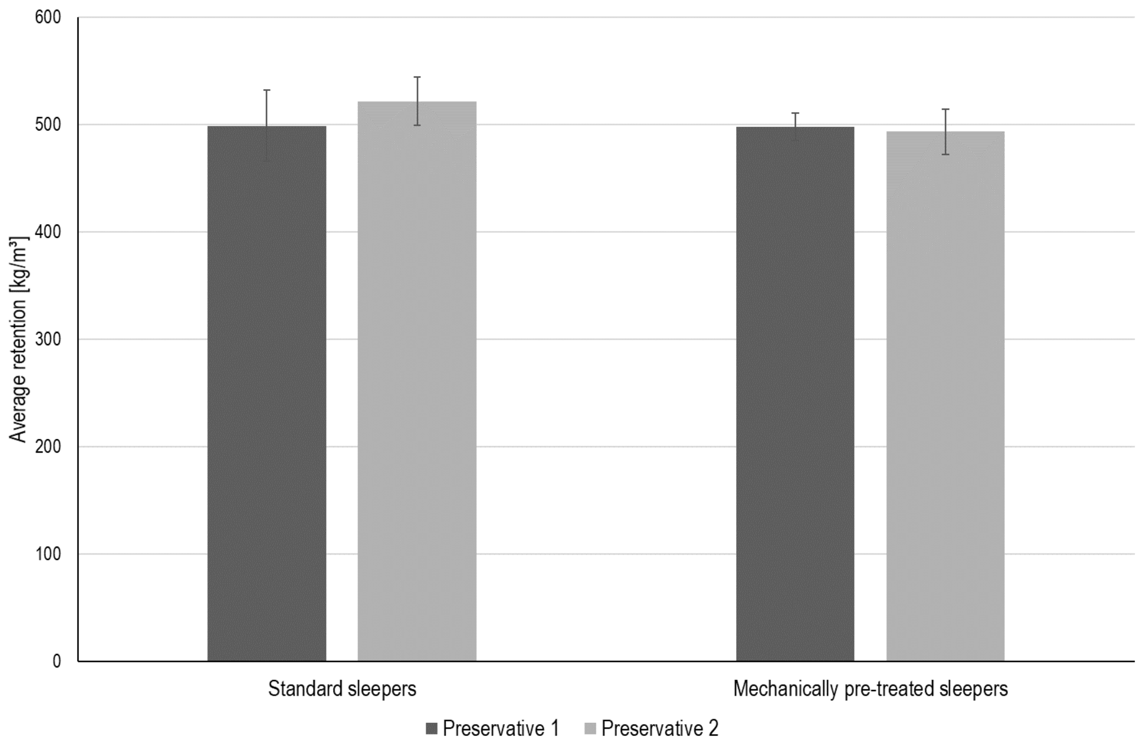


Figure 53: Average retention of two water-based wood preservatives in Beech sleepers with and without mechanical pre-treatment (standard sleepers) by an applied drilling pattern and incising

The visual evaluation of the preservative penetration also showed no influence of the mechanical pre-treatment (incising and drilling pattern). For all collectives, a complete penetration of the sleeper cross section was achieved. Solely the facultatively formed red heart of the Beech sleeper (standard sleepers) was not penetrated by the preservative. Figure 54 and Figure 55 show exemplarily the distribution of the wood preservatives 1 over the sleeper cross section for standard sleepers and sleepers with mechanical pre-treatment at distances of 300 mm, 800 mm and 1300 mm from the end grain.

Figure 54: Penetration of the water-based wood preservative 1 in standard sleepers at distances of 300 mm; 800 mm and 1300 mm (from left to right)

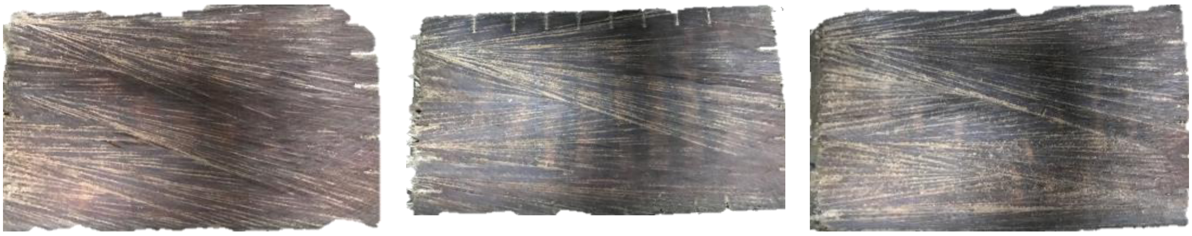


Figure 55: Penetration of the water-based wood preservative 1 in standard sleepers at distances of 300 mm; 800 mm and 1300 mm (from left to right)

In general, the amount of preservative absorbed during a vacuum pressure process depends on the volume of air space and the density of the impregnated wood species, respectively. The maximum retention of oily products for wood species with a density of 400 kg/m³ is about 700 kg/m³, while for species with a density of 800 kg/m³ approximately about 400 kg/m³ can be reached. The same will obtain with water-based preservatives, except the retention will increase to a certain extent by additional solution uptake by the cell walls (Anonymous 1979). Thus, Beech sleepers with average gross densities between approximately 730-745 kg/m³, should reach retentions around 455-470 kg/m³.

The use of two water-based wood preservatives for the impregnation of Beech sleepers led to average retentions of 498.6 kg/m³ (preservative 1) and 521.5 kg/m³ (preservative 2), which correspond with the general calculation of Anonymous (1979). Furthermore, the retentions also corresponded with results made by Schulz (1987b), using a water-based CCB preservative, showing retentions between 410 kg/m³ to 550 kg/m³. Likewise, Pfabigan et al. (2017) found similar results impregnating Beech sleepers with two copper-amine-based wood preservatives. Average retentions of 422 kg/m³ (preservative 1) and 455 kg/m³ (preservative 2), at a mean gross weight of 747 kg/m³, were achieved. Therefore, the reached retentions can be considered being the amount of preservative possible, entering the porous structure of Beech during the impregnation by vacuum pressure processes.

The sleepers showed unimpregnated parts of the sleeper cross section where red heartwood appeared. Unlike, the sapwood like tissue of Beech, which is categorised as easy to impregnate, red heartwood is categorised as very hard to impregnate (EN 350 2016). Tyloses are formed during the formation of red heart wood. These are bag-like protrusions formed by parenchyma cells. They grow into the lumen of adjacent vessels and can, under certain circumstances, lead to a complete occlusion of the vessels. This prevents the impregnation and homogeneous distribution of preservatives (Zycha 1948). In regard of railway sleepers, the amount of red heartwood is strictly limited regarding its dimension, position over the sleeper cross section and its characteristics (EN 13145 2011). Fluid flow within wood is, as stated before, controlled by the continuity of the wood's porous structure. Hardwoods have a structure, owing a large variety of tissue types and are therefore more complex than softwoods (Kumar and Dobriyal 1993). The variation in size and distribution pattern of structural tissues is considered to be the main cause of variation in flow/penetration patterns, even within a species (Greaves 1974).

Regarding preservative penetration and distribution, Pfabigan et al. (2017) found, based on chemical copper analysis, a sufficient distribution in longitudinal and transverse direction for the tested wood preservatives. The required minimum uptake of the preservatives was achieved or respectively even exceeded, at all distances from the end grain.

3.6.3.2 Influence of different gross weights on the retention and penetration of water-based wood preservatives

Increasing the gross weight of Beech sleepers led to a decrease in average retention using a water-based wood preservative. While sleepers with gross weights between 800-830 kg/m³ and 830-860 kg/m³ showed average retentions above 400 kg/m³ (466.2 kg/m³ and 435.5 kg/m³), sleepers with gross weights of 860-900 kg/m³, 900-930 kg/m³ and 930-1100 kg/m³ showed average retentions below 400 kg/m³ (381.8 kg/m³, 355.7 kg/m³ and 306.5 kg/m³) (Figure 56).

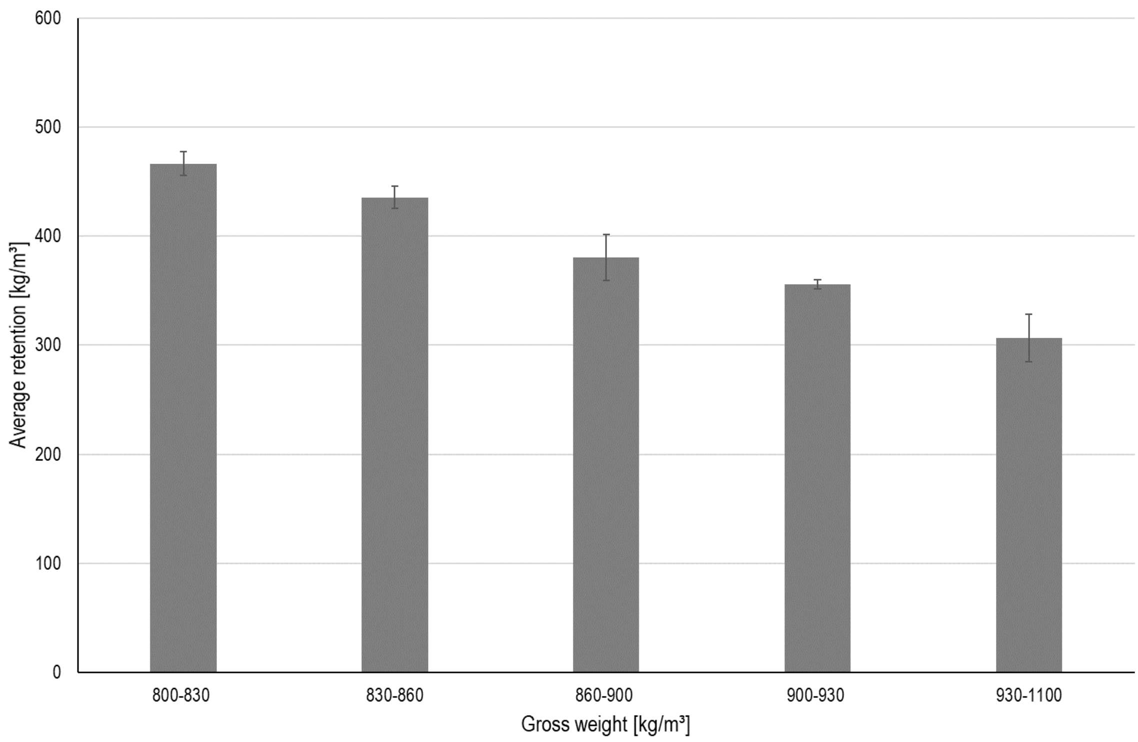


Figure 56: Average preservative retention [kg/m³] for Beech sleepers impregnated at different gross weights [kg/m³] with a water-based wood preservative

The visual analyses of the preservative penetration showed that a complete penetration of the sleeper cross section is generally possible at all distances from the end grain (300 mm, 800 mm and 1300 m) and even at all gross weights. Nearly all specimens showed wet spots, especially at 800 mm and 1300 mm from the grain. Specimen 9.6 with a gross weight of 921.9 kg/m³ showed unevenly distributed, unimpregnated parts of the cross section at all distances. Likewise, specimen 9.12 with an average gross weight of 921.8 kg/m³, showed not impregnated parts at the lower centre of the cross section at all distances. Even at a gross weight of 1012.4 kg/m³ and a retention of 280.1 kg/m³ a penetration of the complete cross section was possible (Figure 57).

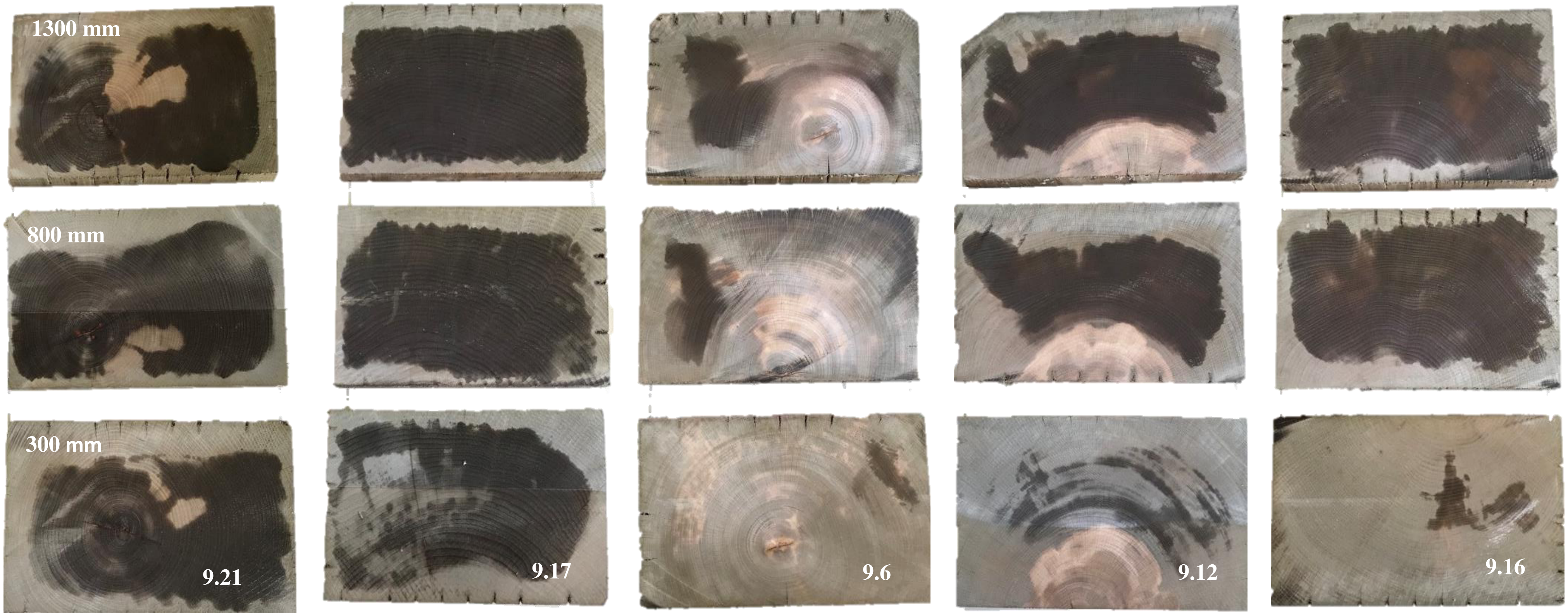


Figure 57: Preservative retention and penetration of Beech sleepers impregnated with a water-based preservative at different gross weights:(9.21) Gross weight: 827.5 kg/m³, retention 449.3 kg/m³; (9.17) Gross weight: 857.1 kg/m³, retention 421.6 kg/m³; (9.6) Gross weight: 891.3 kg/m³, retention 349.5 kg/m³; (9.12) Gross weight: 921.8 kg/m³, retention 350.4 kg/m³; (9.16) Gross weight: 1012.4 kg/m³, retention 280.1 kg/m³

Increasing gross weight led to decreasing preservative retention. The gross weight of wood itself is defined as quotient of pure wooden mass and volume including all porous spaces and the present water content (Langendorf 1988). Green wood contains water-saturated cell walls and lumens, which are filled to different extents with liquid water, water vapour or both at the same time. During drying, liquid water is released and the cell walls arrive the transition state between a saturated and an unsaturated state, which is called fiber saturation point. Since fibers are not saturated with water, but the cell wall is, the term cell wall saturation (CWS) would be better (Brischke and Alfredsen 2020). Underneath CWS in the hygroscopic range (between 0 and 30% moisture content) wood adsorbs water molecules in the cell walls by interaction with hydroxyl groups and is bound by hydrogen bounds (Fredriksson 2019). Nevertheless, the maximum amount of cell bound water is not reached in absence of already existing capillary water (Brischke and Alfredsen 2020). The more completely or partially filled lumina and intercellular spaces are present, the less preservative can be taken up during impregnation and the retention decreases.

Visually, a complete penetration of the sleeper cross section seems to be possible even at gross weights of above 1000 kg/m³. Still wet parts of the cross sections reinforce this statement but also show an underestimated re-drying duration for sleepers impregnated with water-based preservatives. Nevertheless, a visually complete appearing penetration of the cross section will not automatically assure a sufficient protection against wood destroying organisms. Unlike oily wood preservatives, water-based wood preservatives are, as the name implies, water-soluble. The water-soluble toxic ingredients are able to break free from the water carrying them and diffuse into the still existing water. High wood moisture contents result in high diffusion rates of the water-soluble ingredients. In extreme cases, the concentration of the wood preservative is decreasing to an extent, where a sufficient protective effect is no longer possible, even though the part of the wood has been impregnated (Leiße 1992). Therefore, a chemical analysis of the single preservative components, as carried out by Pfabigan et al. (2017) for copper, is mandatory to ensure the sufficient preservative distribution.

While not impregnated parts are either caused by existing red heartwood (specimen 9.12), other not impregnated parts could not be directly distinguished (specimen 9.6). Formed tyloses may be the cause, since Zycha (1965) found also unimpregnated areas other than heartwood, blocked by tyloses, while evaluating creosote treated Beech sleepers.

3.6.4 Conclusions

Beech sleepers have been impregnated using two different water-based, chromium-free wood preservatives. Based on the results, following conclusions were drawn:

- The impregnation of sufficiently seasoned Beech sleepers according to DIN 681811 (2007) resulted in similar average retentions using two different water-based, chromium-free wood preservatives. The results were comparable to earlier attempts using chromium containing water-based preservatives.

Parts of the results show differences to the impregnation using oily wood preservatives like creosote as well as the alternative oily wood preservative. Considering these results, following conclusions were drawn:

- A mechanical pre-treatment by incising as well as alternative drilling pattern did not influence the retention of both water-based preservatives.
- A visually homogeneous penetration of the complete cross section was possible at all distances from the end grain of the sufficiently seasoned sleepers. Furthermore, the penetration was visually not improved by both types of mechanical pre-treatment.
- While increased gross weights resulted in decreasing retentions of a water-based wood preservative, a complete penetration of the cross section was visually still possible.

Other results showed parallels to creosote or the alternative oily wood preservative. Based on these results, the following conclusion was drawn:

- Existing red heartwood was not completely penetrated by the water-based preservatives, but penetration was slightly improved in the areas around the incising slits.

Since a complete penetration of the sapwood like tissue of Beech sleepers was possible even at increased gross weights, using water-based, chromium-free wood preservatives, the following pursuing conclusions were drawn:

- A chemical analysis regarding the distribution of the single preservative components is inevitable in future tests, since the impregnation of big dimensions like sleepers, may result in preservative gradients with increased gross weights.
- Based on the visibly successful penetration of the complete sleeper cross section, a double impregnation using water-based wood preservatives followed by the alternative oily wood preservative seems reasonable.

3.7 Double impregnation of incised Beech sleepers using a water-based preservative and an oily wood preservative and the influence of incising on preservative penetration

3.7.1 Introduction

Reaching a complete penetration of the sapwood like tissue of Beech sleepers with an alternative oily wood preservative was not possible using empty- as well as full cell processes. Likewise, a modification of empty cell processes including a pre-heating of the sleepers or an alternating (pulsation) fluid pressure did not improve penetration (Chapter 3.2). An improvement of penetration was only possible to a certain extent, by using the alternative oily wood preservative in combination with an alternative drilling pattern (Chapter 3.5). The impregnation of water-based preservatives however, led to a complete and homogenous penetration of the sleeper cross section (Chapter 3.6).

A double impregnation of Beech sleepers is intended to achieve a complete penetration using a water-based wood preservative. Using oils in a second treatment will obtain a hydrophobic surface, reducing water uptake as well as check formation during outdoor application (Treu et al. 2011). The included biocides from the alternative oily wood preservative will additionally increase the efficacy of the peripheral area against wood-destroying organisms.

A combination of water-based wood preservatives and mostly creosote, formally known as dual treatment or double treatment, has already been considered and carried out during the past. Also Beech sleepers were subjected to double impregnation for a certain period in the past. The Austrian State Railways successfully used a chlorine solution and creosote, while the German Reichsbahn used a combination with fluorosodium solution on an experimental basis between 1938 and 1939. Unlike the Austrian State Railways, impregnation with the fluorosodium solution took place as second step after the impregnation with creosote (Peters 1950). A further approach for preserving track and bridge sleepers/timbers using dual treatment technologies is combining water-soluble and diffusible borate-based treatments with oily preservatives like creosote or copper naphthenate (Lloyd et al. 2018, Kim and Lloyd 2018).

But not only railway sleepers have been impregnated by using a double impregnation during the last decade. Fenske (1940) discussed a double treatment of wooden poles using first water-based preservatives, followed by an impregnation with creosote at retentions of 60 kg/m³ or even less. Another modification of the double impregnation of wooden poles is the method developed by Poulain. By placing the autoclave vertically after salt impregnation, only the butt is impregnated a second time with creosote (Mörath 1950). For the protection of marine piles against the attack of marine borers, a double impregnation using copper, chromium and arsenic containing water-based wood preservatives in combination with creosote was also suggested (Resch and Parker 1982). Furthermore, structural elements like wooden bridges are also dually treated. In the first step, the single lamella of the later formed glulam elements are impregnated using water-based preservatives. Afterwards, the final elements are impregnated with creosote and transported to the construction site, where the bridge is erected (Mahnert and Hundhausen 2018, Ekeberg 2010). Another combination includes water-based preservative systems and a subsequent treatment in modified natural oils at elevatored temperatures. This process is referred to as royal process and was developed about 40 years ago (Häger 1980).

In the case of a double impregnation using water-based, chromium-free preservative followed by the alternative oily wood preservative, it is not only the time of the first impregnation that is decisive. Oily preservatives are not water-soluble and can be stopped by existing water in cell lumen or cell walls (Leiße 1992). Incising can also influence the penetration of wood preservatives by increasing the transverse surfaces of the treated product. The penetration of fluids in axial direction is much more effective than in radial and tangential direction. Thus, there is an improvement in penetration in the area of the incision (Morris et al. 1994, Morrell et al. 1998). This results in a better penetration and distribution of the preservatives, especially in refractory wood species. With regard to the penetration of alternative oily wood preservatives for the impregnation of railway sleepers, the influence of incising has not been further investigated by now in European wood species. Especially for sleepers made of Beech. Therefore, the following objectives have been set:

- Evaluation of incising regarding its influence on the penetration depth and retention of an alternative oily wood preservative at different gross weights after impregnation using a water-based, chromium-free wood preservative
- Determination of the optimum time for the second impregnation with an alternative oily wood preservative during a double treatment in order to achieve the required retention and distribution to ensure a homogenous penetration of the fringe area of the sleepers

3.7.2 Materials and methods

3.7.2.1 Impact of incising on the preservative penetration depth and retention at different gross weights

In order to investigate the impact of incising on the penetration depth and retention of an alternative oily wood preservative, test specimens of error-free Beech (40 (ax.) x 40 x 80 mm³) were cut and afterwards sealed from five sides in two steps (SIKA Unitherm Top W & SIKA PU sealing compound, Stuttgart, Germany). The unsealed radial surface (40 x 40 mm²) was left untreated in a first collective (collective 1), while in collective 2 an incising-mark (20 x 20 x 3 (L x D x W) mm³) was pressed in centrally. After following impregnation with a water-based, chromium-free wood preservative in a vacuum pressure process (60 min -0.85 bar; 120 min 8 bar), the collectives 1 and 2 were each divided into groups of ten test specimens each and dried to different target gross weights (Table 29).

Table 29: Target gross weights to be achieved for 2nd impregnation with the alternative oily wood preservative

Target gross weights [kg/m³]					
1100	1000	950	900	850	800

After reaching the target gross weights, the test specimens were impregnated with the alternative oily wood preservative using a Rüping-process (air pressure 20 min 3 bar; fluid pressure 100 min 8 bar; post-vacuum -0.80 bar approx. 720 min). Finally, the retention in kg/m³ was determined in accordance to Eq. (2). Furthermore, the penetration of the alternative oily wood preservative was evaluated visually on the split test specimens. Therefore, the specimens have been split in the direction of the incising slit.

3.7.2.2 Study on the impregnability of Beech sleepers at different gross weights

To investigate the influence of the gross weight of impregnated Beech sleepers using a double impregnation, 36 Beech sleepers with an average gross weight of 786 kg/m³ (42) were first impregnated with a water-based wood preservative in a vacuum/pressure process (180 min 0.95 bar; 480 min 9 bar). After impregnation, the sleepers were divided into six groups of similar average gross weight [kg/m³], stacked in accordance with DIN 68811 (2007) for seasoning outdoors. Six different target gross weights were defined as starting points for a second impregnation of the sleepers with the alternative oily wood preservative. The sleeper collectives were then weighed weekly in bundles of six to monitor the average gross weight. When a bundle reached the previously defined gross weight, the respective collective was prepared for impregnation. For this purpose, all sleepers were first weighed individually in order to determine the subsequent retention of the alternative oily wood preservative in accordance to Eq. (2). The impregnation of the sleepers was carried out using a Rüping-process (air pressure 20 min at 3 bar, fluid pressure 100 min at 8 bar, post-vacuum -800 mbar approx. 720 min). After impregnation and weighing, the sleepers were cut at a distance of 300 mm, 800 mm and 1300 mm from the end grain and the penetration of the alternative oily wood preservative was visually evaluated.

3.7.3 Results and discussion

3.7.3.1 Influence of incising on the retention and penetration behaviour at different gross weights

Incising had a positive effect on the penetration depth and retention of the alternative oily wood preservative for test specimens in laboratory scale. However, the gross weight did neither significantly affect the preservative penetration nor the retention (Figure 58 and Figure 59). The specimen collectives without incising all showed a penetration depth between 10 and 15 mm. In comparison to the specimens without incising, the specimen collectives with incising showed a penetration of the alternative oily wood preservative twice as deep across all gross weights. Again, the penetration depth was not influenced by the different gross weights (Figure 59).

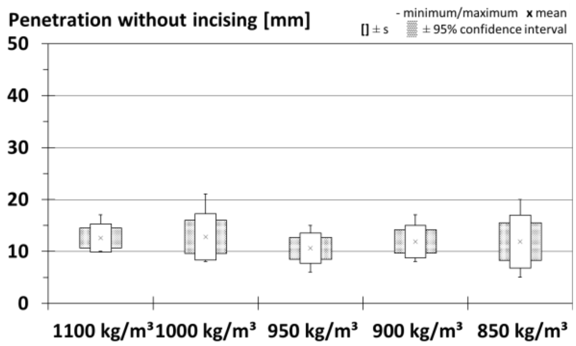


Figure 58: Penetration depth of the alternative oily wood preservative in mm in specimens without incising

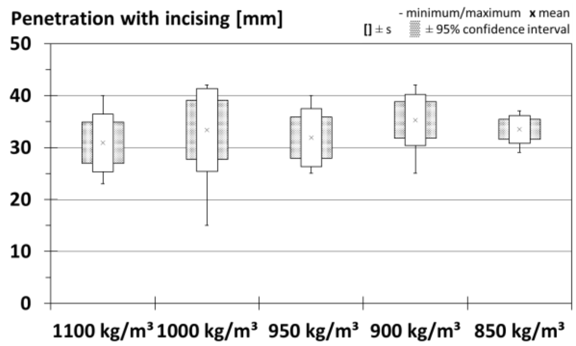


Figure 59: Penetration depth of the alternative oily wood preservative in mm in specimens with incising.

While the average retention at all gross weights for specimens without incision was 46.5 kg/m³, it was 72.0 kg/m³ for specimens with incision (Figure 60 and Figure 61).

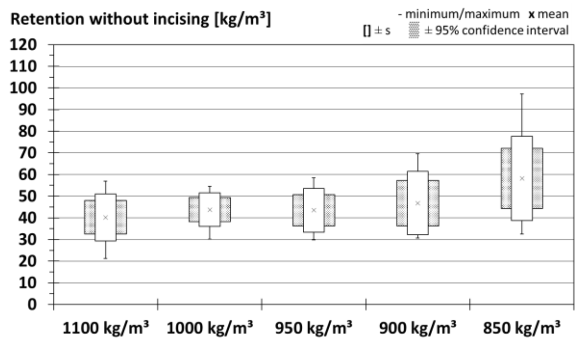


Figure 60: Retention of the alternative oily wood preservative in kg/m³ for specimen <u>without</u> incising

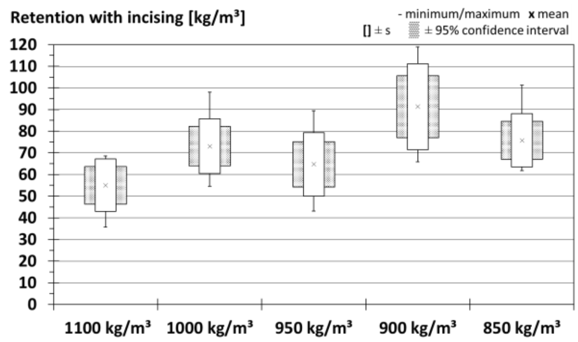


Figure 61: Retention of the alternative oily wood preservative in kg/m³ for specimen <u>with</u> incising

The penetration of fluids into wood takes place primarily in longitudinal direction (Côté 1963). Fluid movements in transverse direction are generally more difficult (Murmanis and Chudnoff 1979). Punching in the incising marks creates new axial surfaces, which enables longitudinal penetration. Penetration up to the depth of the incising mark is facilitated and thus simultaneously leading to an improved uptake of the preservative. The missing influence of the gross weight on the uptake of the preservative can be explained by the dwell time of the specimens in the oil during the pressure phase. This may have resulted in drying of the upper layers and therefore led to a balance between the gross densities.

3.7.3.2 Double impregnation of Beech sleepers

The retention of the alternative oily wood preservative increased with decreasing gross weight, respectively re-drying of the water-based impregnated sleepers. While an average gross weight of 1123 kg/m³ still resulted in a negative average uptake of the alternative oily wood preservative (-1.7 kg/m³), the retention subsequently increased to approx. 20 kg/m³. From an average gross weight of 950 kg/m³ an increase in the average retention up to 30 kg/m³ was occurring, but remained comparable at further decreasing gross weights (Figure 62).

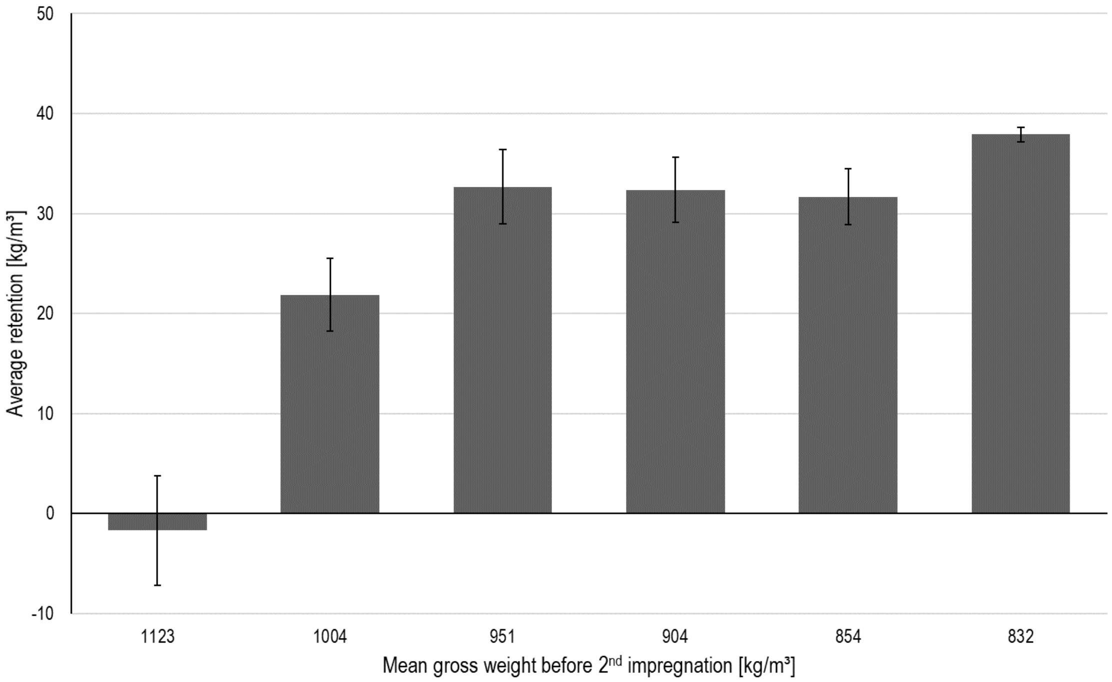


Figure 62: Average retention of the alternative oily wood preservative after 2nd impregnation at different gross weights

Figure 63 shows exemplarily the influence of the decreasing gross weight on the retention as well as the penetration of the alternative oily wood preservative. While at a gross density of 1114 kg/m³ the penetration of the alternative oily wood preservative was still inhomogeneous and insufficient, it improved to a closed homogeneous envelope treatment at a gross weight of 965 kg/m³.

Figure 63: Penetration of the alternative oily wood preservative in sleepers at different gross weights (1114 kg/m³; 979 kg/m³; 965 kg/m³) at 300 mm, 800 mm and 1300 mm

The required degree of seasoning (moisture content) before the second impregnation was of great importance for the quality of the impregnation with the alternative oily wood preservative. The negative retention of the alternative oily wood preservative for sleepers with an average gross weight of 1123 kg/m³ can be explained by a weight loss during the second impregnation. The quantity of water, released during impregnation, exceeded the amount of absorbed alternative oily wood preservative. The sleepers became lighter. Broese von Groenou and Bellmann (1958) made similar experiences during the creosote impregnation of wet Beech sleepers. Since oily products are not water-soluble, free water or aqueous preservatives act as an impassable barrier in the cell cavities and prevent the penetration of oily preservatives. The areas to be impregnated should have a MC below fiber saturation, ideally less than 20 % (Leiße 1992). From a gross weight of 950 kg/m³, moisture levels required by Leiße (1992) have most likely been reached in the peripherical areas of the Beech sleepers, because penetration of the alternative oily wood preservative is possible. Since there is no considerable increase in the retention despite the decreasing gross weight, the retention and penetration depth can be further modified by means of optimisation of the impregnation parameters.

3.7.4 Conclusions

Based on the results evaluating the influence of incising on retention and penetration of the alternative oily wood preservative in Beech sleepers, following conclusion was drawn:

- The mechanical pre-treatment of Beech by incising has a positive effect on the penetration depth and retention of the alternative oily wood preservative in the area of incising marks.

Regarding the double impregnation of Beech sleepers, the following conclusion was drawn:

- It became evident that before the second impregnation with the alternative oily wood preservative, a re-drying of the sleepers to a target gross weight of $\leq$ 950 kg/m³ is necessary to reach a homogeneous distribution of the alternative oily wood preservative in the peripheral area of the sleepers.

4 General discussion

The main objective of this thesis was to implement a process optimisation of the commonly used wooden railway sleeper made of Beech, to strengthen and ensure its further use as part of the track superstructure. Therefore, 2 major optimisation steps have been evaluated regarding their potential for improvement:

1. A mechanical pre-treatment by incising to improve seasoning speed, check formation, dimensional stability and preservative penetration
2. Optimisation of the impregnation process regarding a complete and homogenous penetration of the sleeper cross section

The results can be summarised as follows:

Incised Beech sleepers showed an improvement by reduced check formation during seasoning and by positively influenced penetration depth and retention of the alternative oily wood preservative in the areas of the incising slits. An improvement in seasoning speed as well as dimensional stability during seasoning could not be reached due to the applied incising.

The use of common impregnation processes and various modifications did not result in complete penetration of the cross section, excluding the end grains. A major influence of longitudinal preservative penetration as well as a reduced penetration in transversal direction in Beech became evident. After adapting the already existing drilling pattern, an improvement in preservative penetration was reached. Still, it was not possible to ensure a complete homogeneous penetration of the sleeper cross section, since areas between the single boring holes remained unimpregnated. As a complete penetration of the cross section is the essential point for an optimal impregnation process, a second approach using water-based preservatives was made. The impregnation using water-based preservatives showed a complete and homogenous penetration of the sleeper cross section, even above fiber saturation. Therefore, a combination with the alternative oily wood preservative using a dual treatment seemed reasonable and was evaluated. An additional protection of the peripheral area by the alternative oily wood preservative could be achieved at gross weights about 950 kg/m³. The supplementary use of the alternative oily wood preservative not only improves the fungicidal effect, but also makes the surface more hydrophobic. Negative aspects of the water-based wood preservative, such as increased hygroscopy of the impregnated wood and the associated increased conductivity of the sleeper, can also be mitigated.

The following chapter will discuss the overall results and give a broader view about the single optimisation steps and especially discuss their effects on the future of the wooden sleeper made from Beech.

4.1 Process optimisation by incising

Mechanically pre-treating wooden sleepers by incising is a commonly carried out processing step for wooden sleepers at least in the United States. At first, only refractory wood species were incised, but today nearly all sleepers are incised to either increase preservative penetration or mitigate seasoning defects (Webb and Webb 2016). However, incising of wooden sleepers, regardless their wood species, have never become a commonly carried out processing step in Europe, even though positive effects were found by Franciosi (1956 and 1967) evaluating incised Beech sleepers.

4.1.1 Check formation and dimensional stability

Evans (2016) reviewed the scientific works on effects of incising on the checking of wood for different products including sleepers, concluding incising is clearly able to reduce the checking of sleepers made from most wood species. Solely being less effective for some oak species or refractory softwoods like western hemlock or spruce (Evans 2016). Therefore, a check inhibiting effect was also expected by incising of freshly sawn Beech sleepers. The present results verified decreased check lengths, - widths and depths on the upper broad side as well as on both narrow sides (Chapter 2.1). This positive effect of incising on the check formation during seasoning of Beech sleepers was also found by Harkom (1932) as well as Franciosi (1956).

Next to check formation, dimensional stability is also a major aspect of quality after seasoning of freshly sawn wood. Deformations may occur during seasoning of Beech sleepers until reaching the required moisture content for impregnation. Sleepers show particularly warping in the vertical direction (bow) or in the horizontal direction (spring). Especially bowed sleepers can influence the track accuracy. Based on steadily increasing speeds up to 200 km/h, the track accuracy became more and more important and also became the requirements towards the dimensional stability of the sleepers (Schulz 1971a). A positive influence of incising on the dimensional stability of Beech sleepers during seasoning was evaluated, but did not occur (Chapter 2.1). Even with applied incising approximately five percent of the sleepers were culled due to deformation. This value is consistent with either the work of Schulz (1971a), who found approximately three percent sleepers showing extensive deformation after seasoning, as well as

Werner (2008), who also assumes around three percent. Comparable studies regarding the influence of incising on the dimensional stability of railway sleepers in particular were not found in the literature. Likewise, the influence on dimensional stability in general. Assumptions can be made in regard of not effected tension wood, but however have to be investigated in further examinations.

Nevertheless, not only incising is able to reduce the formation of checks. Other mechanical pre-treatments like profiling or kerfing are also known to reduce the checking of wood in different applications. Cheng (2010) summarizes the results from scientific works carried out by various authors. While profiling is mostly applied to deckings, kerfing is used in products like post or poles. Helsing and Graham (1976) found a reduction in check size for pressure treated Douglas-fir poles. Since checks still developed at the base of the kerf, they suggested that kerfing might concentrate drying stresses. Thus, kerfing could also be considered as a mechanical pre-treatment to reduce checking of Beech sleepers. A possible influence on the dimensional stability has yet to be determined in further investigations.

4.1.2 Seasoning speed

Incising may have an impact on the drying rate, if freshly sawn wood is mechanically pre-treated. However, it is additionally influenced by the wood species and therefore has to be assessed case by case (Suttie 2002). The presented results have shown, that incising of Beech sleepers had no influence on the seasoning speed as well as the moisture distribution across the sleeper cross section (Chapter 2.1). Franciosi (1956) also found no significant influence of incising on the drying speed of railway sleepers made of Beech. As a probable cause, he considered an eventually accelerated drying during the first month of seasoning, which might be diminished by the long drying period of more than 7 months. Since the sleepers have been weight monthly during the examination period, this theory can be excluded. During the whole seasoning time no considerable difference in average gross weight was determined. Various authors also found no definite influence on the drying rate or ultimate dryness of railway sleepers, either before or after air-drying (Harkom 1932, Perrin 1978) or even at dimensions bigger than railway sleepers (Lee et al. 2016). Others like Thompson (1971) found a positive influence of incising on the drying rate evaluating dimensional lumber (2x4 inch), but solely while using a kiln dryer. Simpson (1987) on the other hand found a positive influence of laser incising on the drying time of hard maple heartwood but also in fairly small specimens (1 x 1 x 0.5 inch) and with the help of a kiln dryer. By using various incising patterns, a reduction in drying time up to 70 percent was reached. Unfortunately, both approaches cannot be transferred on railway sleepers without further ado. Based on their big dimensions the seasoning of sleepers by using a kiln dryer is not cost efficient (Schulz 1969).

4.1.3 Preservative penetration

The success of chemical wood preservation is depending on preservative retention and penetration (Leiße 1992). The penetration depth indicates how deep the active substances enter the wooden structure (Scheiding et al. 2016). Incising is used to improve penetration of wood preservatives, especially for refractory species (Winandy 1996, Ruddick 1986). For many years it is utilised primarily for large timbers like railway sleepers and utility poles (Morell et al. 1998). In contrast to refractory wood species, the incising of Beech sleepers revealed no influence on the retention and penetration of water-based, chromium-free preservatives. Otherwise, the retention and penetration of the alternative oily wood preservative was considerably influenced by incising during the second impregnation. In the area of the incision a higher retention as well as deeper penetration was found (Chapter 3.7). For refractory wood species like spruce, incising is known to improve the penetration of water-based preservatives (Schulz 1971b). For easy penetrable wood species like Beech, the improvement in penetration seems to be neglectable, based on their high natural permeability. In case of oily preservatives, Franciosi (1956) found no significant difference between the retention of incised and not incised Beech sleepers impregnated with creosote. Nevertheless, an improved penetration in the area of the incisions became apparent after cutting the sleepers. Incising is known to increase the amount of exposed transversal areas. Exposed longitudinal surfaces are way more receptive for potential preservative penetration compared to radial or tangential surfaces (Morris et al. 1994). Since oily wood preservatives like creosote show a primary penetration in longitudinal direction (Peters 1950), an improvement by means of incising becomes apparent.

4.1.4 Potential of incising as process optimisation for Beech sleepers

Despite the positive effects on the check formation during seasoning of sleepers, incising as a mechanical pre-treatment has not prevailed in Europe as a standard procedure. Even though for other applications like wooden poles, the incision by perforation of the ground line level has become a pre-treatment being described in the EN 14229 (2010).

Incising is an additional process step during the production of sleepers. Of course, on the one hand, adding a processing step into a running production process will result in supplementary work load and additional costs. But on the other hand, by reducing the number of checks during seasoning, the number of sleepers that have to be culled due to check formation will be reduced. The appearance of ordinary drying checks is generally desired (Conners 2008) and in practise, a common visual sign for sufficiently dried wood. Nevertheless, sleepers that show fewer checks during the customer's inspection additionally appear to be of higher quality and strengthen the trust in the product.

Improving preservative retention and penetration will prolong the service life of the wooden sleeper. A prolonged service life will furthermore reduce maintenance costs, which are very important considering the provision of the track superstructure (Rastl 2013).

The acceleration of seasoning speed would have been an additional advantage in many points of view. In terms of quality, a reduction in seasoning duration could have reduced the risk of fungal infestation of the untreated sleepers, especially while Beech- and Scots pine sapwood are both categorised as less durable according to EN 350 (2016). Solely the heartwood of Scots pine is categorised as moderate to little durable against the attack of wood destroying fungi. Furthermore, a reduction of seasoning duration would simplify the stock keeping. Still to this day, it is of utmost importance to have adequately seasoned sleepers in stock for intense construction projects at the earliest in spring- and summertime like Schulz (1969) stated many years ago. Since Beech sleepers need at least 6-8 months for proper seasoning, sleepers, delivered in the prior year, have to be still in stock to supply these construction projects, which again increases the risk of fungal infestation. This can only be counteracted by storing already impregnated sleepers until suitable orders are placed. The dimensions of track sleepers are varying, based on customers' needs. Often different lengths and also different cross sections are requested even from the same customer. To prevent the exposure of untreated wood, all mechanical processing steps like planning of the chairing area and drilling the boring holes should be carried out before impregnation (Webb and Webb 2016), but these are directly correlated towards the requested sleeper dimensions. This means, a wide range of differently processed impregnated sleeper types have to be in stock with a proper chance of not being requested for specific construction projects. This would rather complicate stock keeping, since large storage areas are needed.

Based on the positive influence of incising on check formation as well as preservative retention and penetration in the area of the incisions, the quality of standard wooden sleepers made from Beech can be improved. Therefore, the named aim of study can be considered as successful. Due to the positive aspects of incising, the potential of this mechanical pre-treatment should be further used in Europe. Since European oak and Scots pine are also used in Europe in addition to Beech, the influence of incising should still be specifically investigated in more detail for these wood species. Oak in particular offers great potential to be positively influenced by incising due to its slow drying rate (Trübswetter 2009) and its heartwood content. In addition to an acceleration of the drying speed, an improvement of the preservative penetration in the area of the incision is also possible here. There is also the potential of reducing the formation of checks. The same applies to sleepers made from Scots pine.

4.2 Process optimisation by impregnation of alternative wood preservatives

At the beginning of this thesis, the process optimisation for Beech sleepers using an alternative oily wood preservative promised to be unproblematic. This misleading conclusion was made, because Beech is defined as easy to penetrate by fluids (although with high variability), respectively by wood preservatives (EN 350 2016) as well as the fact, that Beech sleepers are impregnated with creosote for more than 100 years.

4.2.1 Impregnation using an alternative oily wood preservative

Today, the impregnation of railway sleepers is exclusively carried out by using empty cell processes in accordance with DIN 68811 (2007). Empty cell processes ensure the recovery of excessive preservative from the porous structure and prevent from later bleeding (Leiße 1992). Based on the low natural durability of Beech (DC 5) (EN 350 2016), a full penetration of the cross section is necessary to ensure a sufficient protection against wood destroying organisms. The impregnation of Beech with an alternative oily wood preservative using different empty cell processes (Rüping, Lowry, double Rüping) resulted in average retentions between 50-150 kg/m³. Against expectation, a full penetration of the specimen cross section was not possible for all carried out processes at all reached average retentions. Nearly all specimens showed a rather inhomogeneous penetration pattern even at retentions above 100 kg/m³ (Chapter 3.2). In contrast to Richardson (2003), who found an improved creosote penetration for Scots pine poles with increased pressure duration, an increase in pressure did not result in improved penetration of the sleeper cross section. In case of creosote the normal Rüping-processes were also not able to ensure complete penetration of the sleeper cross section (Schulz 1965). Zycha (1965) found no correlation between retention and distribution. On the other hand, a clearly positive influence of the retention on the distribution of creosote was shown in practice. Still, based on the inhomogeneous wooden structure of Beech, irregularities occurred, where small retentions resulted in complete penetration of the cross section, but also high retentions resulted in incomplete penetration (Schulz 1964a). Schulz (1964a) also stated, that from a scientific point of view, each sleeper has to be seen as an individuum and it is necessary to harmonize sleeper collectives, which can be reached by modifying the impregnation process by pre-heating of the sleepers (Schulz 1965).

By pre-heating the sleepers during a double Rüping-process, Schulz (1965) and Schulz and Broese van Groenou (1967) reached an improved creosote penetration. The main effect can be traced back on a combination of moisture redistribution and reduction, increased temperature of the wood and especially viscosity (Schulz 1965), since the penetrating wood preservative will no longer cool down, entering the wooden structure (Richardson 1980, Schulz 1987a). Unlike creosote, the alternative oily wood preservative showed no improvement in penetration and distribution, even though the specimens have been pre-heated either with different heating devices or a carried out pulsation process. Again, average retentions higher than 100 kg/m³ were reached, resulting in an inhomogeneous penetration of the specimen cross section (Chapter 3.2). Based on poor heat conductivity of the treated wood (Richardson 1980), an insufficient heating of deeper layers of the specimen cross sections, can be discussed being one cause for the insufficient penetration. But moreover, compressed air inside the specimens due to penetrating preservative (Liese 1951) or an applied initial air pressure by the Rüping-process, was identified as most probable cause.

Empty cell processes are designed to remove air from the porous structure during the first process step, so no present air will be compressed and resist penetration of the entering solution during the pressure phase (Richardson 1980). Retentions up to 277 kg/m³ can be reached using creosote (Schramm 1952). Therefore, an improved penetration and distribution of the alternative oily wood preservative should have resulted, but could only be achieved in one specimen, with actually comparable retention. Although this result seems contradictory at first, it is again consistent with Schulz (1965) stating that the retention is not necessarily an indicator of sufficient penetration.

Wood, but also wood preservatives, are complex materials. The way in which liquids penetrate a porous structure depends on a number of variables. It partly depends on the interaction of the liquid with the pore walls and the pore structure, but more importantly on the pressure gradient under which the liquid is subjected (Hösli and Bariska 1980). Since various commercially used empty- and full cell processes, as well as their modifications, did not result in a complete penetration of the specimen cross section, a hindering effect of remaining and compressed air was detected as possible cause for insufficient penetration (Chapter 3.2). Reinforced by the statement of Richardson (1980), that a complete penetration using empty cell processes is not possible, since trapped air will always obstruct penetration, the need of pressure gradient determination arose even more. The results of the carried out pressure evaluations during the impregnation with the alternative oily wood preservative showed nearly complete aeration of the cross section during the pre-vacuum of the empty cell process. Furthermore, no pressure compensation in the middle of the cross section was found during the pressure phases of a vacuum pressure process and a Rüping-process (Chapter 3.3). Comparable results depending pressure gradients were found by Hösli and Bariska (1980) during the impregnation of Beech sleepers with creosote using a double-Rüping-process. During the first and second pressure phase, also no pressure compensation was reached in the middle of the sleeper cross section, leaving zones of the sleeper cross section unimpregnated by creosote. Likewise, measurements of pressure gradients have been carried out during the impregnation of Scots pine poles using empty cell processes and different types of creosote (WEI B and WEI C). Bergman (2003) also found no pressure compensation during the pressure phases. A full sapwood penetration was also not given for all poles. Slowly increasing pressure can be caused by various factors. Increased viscosity of the penetrating preservative due to cooling as well as remaining oil- or water-droplets are named by Hösli and Bariska (1980). These remained droplets have to be pressed through barriers like ladder-shaped openings or pits, causing substantial obstruction of the penetrating preservative.

4.2.2 Essential influence of the longitudinal direction on penetration of the alternative oily wood preservative

Viscosity is considered one of the most important factors for the penetration of oily preservatives like creosote (Hösli and Bosshard 1979, Schulz 1987a). By increasing the temperature of creosote, the viscosity is decreased and the penetration of the wooden structure is improved (Willleitner and Dieter 1984, Schulz 1987b). In contrast to creosote, the viscosity did not influence the penetration of the specimen cross section of Beech and Scots pine sapwood, weather being impregnated with three different hydrophobic carrier substances or mixtures with biocidal components (for Beech) (Chapter 3.1). A complete penetration of the cross section was only possible by means of the longitudinal direction for Beech, while for Scots pine sapwood, a complete penetration was also possible excluding the penetration in longitudinal direction. A great impact of the longitudinal direction on preservative penetration for Beech was mentioned by various authors even in case of creosote (Peters 1950, Schulz 1964a). However, this does not only apply for the impregnation of oily products. The impregnation of other solutions also showed a major influence of the longitudinal direction on uptake and penetration of Beech. Larnøy et al (2005) found a major influence on the longitudinal direction impregnating Beech with different chitosan-based solutions, while Tondi et al. (2013) also found nearly complete penetration of Beech in longitudinal direction using tannin solutions. Comparable results to Tondi et al. (2013) were found during the microscopic analysis of the penetration pathways of two hydrophobic carrier substances in Beech and Scots pine sapwood (Chapter 3.1). Beech was penetrated in longitudinal direction via vessels and fibers, while less penetration seemed to occur within the wood rays. Scots pine sapwood was penetrated in longitudinal direction via the lumen of late- and earlywood, but also through resin canals. Different authors (Behr et al 1969, Liese 1951, Bosshard 1965) found comparable results during the examination of penetration pathways of creosote or pentachlorophenol in Beech and Scots pine sapwood.

Transversal penetration of Beech by creosote on the other hand was defined as insufficient (Peters 1950, Schulz 1964a). Under exclusion of the longitudinal direction, the impregnation with different hydrophobic carrier substances (Chapter 3.1) and the alternative oily wood preservative led to incomplete penetration of the specimen cross section (Chapter 3.2). Based on these results, conclusions were made confirming these statements. Likewise, the delaying influence on pressure compensation of the air-pressure during a Rüping-process (Chapter 3.3) gave additional indication. Analysing the influence of the longitudinal and transversal direction on the penetration of the alternative oily wood preservative (Chapter 3.4) substantiated the previously made assumptions. The results clarified the impeded transversal penetration and essential influence of the longitudinal direction on the penetration of the alternative oily wood preservative. It became clear, that if a complete penetration of the sleeper cross section is desired, it cannot be achieved without supporting the potential of the longitudinal direction by further optimisation steps.

4.2.3 The necessity of further process optimisation

Beech sleepers are equipped with an additional drilling pattern since 1940 to improve creosote penetration, especially in the middle section of the sleeper. The pattern is located in the centre of the sleeper bottom and was first consisting of four, later of eight diagonally arranged holes. By creating new penetration pathways in longitudinal direction, the penetration of creosote was further improved, reducing the proportion of not penetrated areas (Schulz 1964). As well as for creosote, a hindered transversal penetration was found using the alternative oily wood preservative (Chapter 3.4). Therefore, an adjusted drilling pattern was developed for the impregnation with the alternative oily wood preservative, to improve the penetration of the cross section by supporting the longitudinal penetration. Whereas for creosote only one centred drilling pattern is sufficient to improve the penetration, an improvement of the penetration for the alternative oily wood preservative could only be achieved by applying two drilling patterns. Insufficient penetration from both grain sides were thereby diminished and penetration could be considerably improved at retentions of approximately 90 kg/m³ (Chapter 3.5). According to Schulz (1964a), the causes for this are different and usually cannot be clearly analysed, while insufficient penetration from the grain side is mostly caused by disruptions in anatomical structure, intergrown knots, partial red heartwood or strong tylosis. Furthermore, strips of not impregnated wood remained between each hole. This is also known from impregnation with creosote (Zycha 1965). Even though a big improvement was made regarding the penetration of the cross section, the result was still not satisfactory. Since the penetration of the complete cross section was the main focus during process optimisation and was not reached by solely using the alternative oily wood preservative, an impregnation using water-based preservatives was considered.

Beech sleepers had already been impregnated with water-based wood preservatives during the last century. It was primarily used when creosote was not available in times of need (during both world wars) (Seekamp 1950). Nevertheless, a single impregnation using solely water-based wood preservatives never really found acceptance. Trials using a CKB-based preservative led to average retentions between 410 and 550 kg/m³ (Schulz 1987b). Comparable retentions of approximately 500 kg/m³ were reached during the carried out research by using two commercially available copper-based preservatives. Both preservatives showed a complete penetration of the sleeper cross section (Chapter 3.6). Similar retentions of copper-based preservatives were also found by Pfabigan et al. (2017). Nevertheless, distribution gradients may occur based on either product dimension or moisture content before impregnation. Differences in concentration between a penetrating solution and the existing wood moisture content will be equalized by diffusion (Klüppel and Mai 2013). On the one hand, the biocidal components will be distributed deeper into the wood, but on the other hand diffusion can also be able to dilute the solution up to concentrations below the biocidal efficacy. This applies especially for increasing moisture contents and increasing product dimensions (Leiße 1992). Slight gradients of preservative retention in longitudinal and transversal direction were proven by Pfabigan et al. (2017) via copper analysis. Nonetheless, for all sleepers in this trial, the required preservative retentions were achieved or even exceeded. However, a complete impregnation of the sleeper cross section and the resulting protection against the attack by wood-destroying organisms is only one important aspect regarding the use of alternative wood preservatives. In addition to its high biocidal efficacy, creosote also has a hydrophobic effect (Küch 1967, Halank 1959), which is the opposite for water-based preservatives for example alkaline copper quaternary (ACQ), chromated copper arsenate (CCA) or disodium octaborate tetrahydrate (DOT) (Zelinka and Glass 2010). By decreasing the water uptake due to hydrophobic substances, check formation as well as degradation by fungi can be reduced (Treu 2006). Therefore, an additional hydrophobicity of the sleeper is helpful to further increase the quality. This can be carried out using the alternative oily wood preservative in a following second impregnation.

The use of a double impregnation for Beech sleepers has been carried out likewise during the last century. Here, the unsatisfactory penetration of creosote in Beech sleepers was one of the deciding factors for the use of a double impregnation as well (Peters 1950). Re-seasoning the sleepers to an average gross weight of ≤ 950 kg/m³resulted in a retention of approximately 30 kg/m³ showing a closed homogeneous envelope treatment (Chapter 3.7). Requested additional creosote retentions of 110 kg/m³ (Austrian State Railways) and 75 kg/m³ (Deutsche Reichsbahn) after the double impregnation of Beech sleepers, were considerably higher, compared to the retention of the alternative oily wood preservative with approximately 30 kg/m³.

4.2.4 Potential of process optimisation by alternative wood preservatives/ double impregnation

The use of wooden sleepers as part of the track superstructure decreases more and more due to the application of concrete sleepers. Nevertheless, the use of wooden sleepers is still favourable in special areas of application (Pfabigan and Reitbauer 2020) and also ensures the existence of companies directly associated with the production of wooden sleepers. Namely sawmills and impregnation plants.

The results of this thesis show, that in case of Beech sleepers a complete penetration of the cross section by an alternative wood preservative can only be reached with an additional impregnation using a water-based preservative. A complete and homogenous penetration of the sleeper cross section is consequently one of the most critical values, because each replacement of sleepers creates excessive costs. Therefore, the highest economic efficiency can only be achieved if the largest possible collective of sleepers shows a common service life without outliers with lower quality (Zycha 1965).

This can be reached by the implementation of a double impregnation. Compared to the impregnation with creosote, a double impregnation of Beech sleepers requires additional processing steps as well as the use of two different preservatives systems respectively in nearly all cases two impregnation plants. On the one hand, this could be seen as a possible limitation, since not every impregnation plant has these technical prerequisites. On the other hand, other producers do, which can therefore also be seen as a unique selling point.

Not only the additional impregnation with a water-based wood preservative, but also the time needed for re-seasoning before the second impregnation have to be mentioned as additional processing steps. Re-seasoning will result in additional storage durations and storing costs and prolong the production duration.

Concludingly it can be said, that double impregnated Beech sleepers offer great potential to serve as a replacement for the currently used creosote impregnated sleepers. Additional costs due to further processing steps are still neglectable compared to occurring replacement costs.

Consequently, there is further potential for the use of the alternative oily wood preservative. As already mentioned, in Europe sleepers made from European oak and Scots pine are also used. Therefore, an impregnation of sleepers made from these wood species has to be considered more closely in the future. It needs to be clarified in particular, whether any additional impregnation using water-based preservatives will be necessary, as in the case of Beech.

5 Literature

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