Density determination of tropical hardwoods with the Resistograph

By

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Abstract

This research focused on the question whether it is possible to predict the density of tropical hardwoods with acceptable accuracy based on drill resistance measurements. To assess the feasibility, the influence of the characteristics of the drill resistance measurement tool; the Resistograph® and the wood species have been investigated. With respect to the measurement tool, drill sharpness, feed speed and rotation rate were examined. For the wood samples, the influence of extractives, moisture content, drill direction and density were investigated. It was found that the influence of drill sharpness cannot be ignored and a calibration procedure was developed. No significant difference in drill resistance was observed between drilling in radial and tangential directions; however, drilling in the longitudinal direction resulted in a significant higher drill resistance. Moisture content influences the drill resistance; however, the effect is small and not statistically significant, it can usually be ignored. The influence of extractives on the drill resistance most likely depends not only on the mass fraction of extractives but also on the sort and the composition of the cell wall. Meranti has a typical density within the range 350 to 860 kg/m^3. With an appropriate calibration procedure, it is possible to predict the density of meranti with 95% confidence to an accuracy of ± 70 kg/m^3

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1. Introduction

The timber industry in the Netherlands is not a market dominated by a few large companies. The market consists of many small (family) companies; that produce a wide variety of wood products; some companies are more specialised whereas others produce a variety of products. The products produced in timber industries vary from windows and doors to stairs and even complete garden houses. Timber industries usually obtain their wood from large timber trade companies. Who import their softwoods from countries in the east from the tropics for hardwoods. The imported wood species and especially the species used as structural timbers are strength graded; either based on visual grading or machine strength grading. Ravenshorst (2015) investigating strength grading of tropical hardwoods found that strength and stiffness of clear (defect free) wood is related to density. In further processing of the imported woods, density plays an important role; especially in drying. The resistance against diffusion increases with the density of wood and therefore the drying time as well (density is not the only parameter influencing the drying time, but that is outside the scope of this study). As a result: upon drying a batch of wood with large density variations the drying time of the most dense wood pieces are governing.

Strength grading and drying already illustrates the importance of wood density in the timber industry, but density is also related to the natural durability of wood. Zeller (1917) investigating the physiology of fungi found that for pine (heartwood) there is a relationship between density and durability. Research of Ghanaian hardwoods reveals an indirect relationship between density and durability (Antwi-Boasiako & Atta-Obeng, 2009), this is an indirect relationship since both density and durability are related to the vessel to fibre ratio.

Although a relationship between density and durability holds for a specific wood species, such a relationship usually does not exists between different wood species. The Dutch certification body KOMO (**K**euring en **O**nderzoek van **M**aterialen voor **O**penbare werken) prescribes a minimum density of 450 kg/m^3 for meranti based on a study of T.N.O. (Houtinstituut T.N.O., 1977) which showed a relationship between density and durability for meranti. This minimum density is based on the global density, meaning the average density of a piece, which may differ from the local density, which is a representative of the conditions at a certain position in the piece.

The minimum density required by KOMO brings us to the actual problem: how to determine the density of a certain piece of wood in a construction? Determination of the wood density prior to construction is not that difficult, with known dimensions and a balance the density can be evaluated easily. But when a piece of wood is part of a construction, additional requirements arise: damage to the wood piece should be limited and the testing should take place on location.

The Resistograph is a machine developed for tree-ring detection in European woods, the working principle is as follows, a thin needle, with a head similar to a spade drill, bores into the wood and meanwhile the drill resistance is measured. This machine was initially applied for tree-ring detection, but soon the possibility to detect decayed wood and holes was discovered. Several authors investigated the possibility to use the Resistograph to relate drill resistance to density. For softwoods a linear relationship between density and drill resistance is accepted.

The question arises whether the problem being described above (measurement of the density of a piece of timber in a construction) could be solved with the Resistograph. The Resistograph is a fast method, can be used in-situ and its use causes only little damage to the test piece, but can the Resistograph also determine the density of a tropical hardwood piece with ± 50 kg/m^3 accuracy? This question is the basis of the present study. Related to the main research question are the sub-questions: if the Resistograph represents the local density, how can this be related to the global density? What properties of the Resistograph drill influence the drill resistance, and how do they influence the drill resistance? It is also important to have a closer look at the material, how the material properties influence the drill resistance.

This thesis starts with a background investigation (chapter 2) in wood machining in general and the accompanying energy consumption. A background study is also presented on the process of drilling wood and the influence of the machine and drill bit on the drill resistance. There is a background study performed on the properties of wood and how these influence the drill resistance. Following this background study the most important parameters are selected for further research (chapter 3). For the machine these parameters are rotation rate and feed velocity (together determining the chip thickness) and sharpness of the drill bit. Related to the material several parameters are investigated, first the influence of density on the drill resistance which is the main research question. Second comes the extractives, is there a spread in the results caused by a different mass fraction of extractives? Third is moisture content which influences mechanical properties, so likely also the drill resistance, but to what extent? Last is the drill direction; when drilling a certain sample that is usually coated, the drill direction is not clear, does the direction influence the drill resistance? In the results (chapter 4) the influence of the different parameters on the drill resistance described. The discussion (chapter 5) and conclusion (chapter 6) clarify and explain the results; providing a strong basis for density determination of tropical hardwoods with a Resistograph.

2. Background

A literature study was performed before the actual tests, this literature provides a background for the experiment and investigations as well as a guide for the results, discussion and conclusion. A detailed literature investigation resulted in only a few studies into the process of wood drilling, some studies regarding the Resistograph and a number of studies into the wood cutting process. This data is all combined and the possible consequences for drill resistance and density are analysed.

This chapter will start with an outline of the structure and properties of tropical hardwoods, followed by a short description of the wood species examined in this work. Then the process of cutting wood is described since a lot of research is done into wood cutting and this likely contains valuable information for resistance drilling. Also sawing is treated; subsequently the factors arising during cutting and sawing are related to drilling. Finally the wood properties influencing the drill resistance are presented.

2.1 Tropical hardwoods

Not all timber is the same, to make the assessment more complex: two pieces from the same tree can also show significant variations (Figure 1). How variability influences the drill resistance is considered in this subsection.

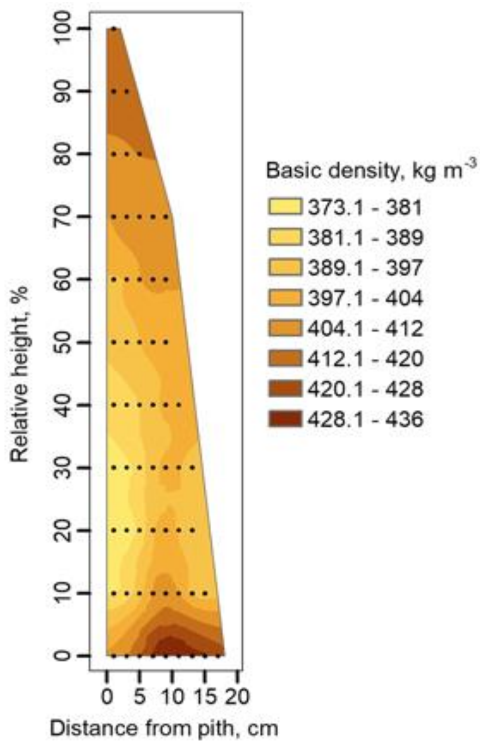

Figure 1 Density variation in a tree trunk (Liepiņš`, 2017), note: the pith on the left is the centre of the tree trunk

For wood there is an established classification system. There are two broad classes, angiosperms and gymnosperms[1]. Usually gymnosperms are classified as softwoods while angiosperms are classified as hardwoods. One should be aware that this classification says nothing about either biological durability nor hardness. The group of angiosperms can be subdivided into temperate and tropical hardwoods. The temperate hardwoods are usually deciduous and tropical hardwoods are usually evergreen. This study focusses on the tropical hardwoods and therefore the focus will be on the anatomical features of these species. In this section, first the global or

[1] (bamboo and some other monocots are not considered since they are actually a grass instead of wood).

large scale is presented and then the smaller or local scale and finally microscopic features are considered.

2.1.1 From tree to timber

Trees grown in tropical forests are so called evergreen trees; that means that the annual rings, visible in temperate hardwoods and softwoods, are not present. Instead of these, sometimes growth rings are visible corresponding to dry and wet seasons. A cross-section of a trunk is shown in Figure 2.

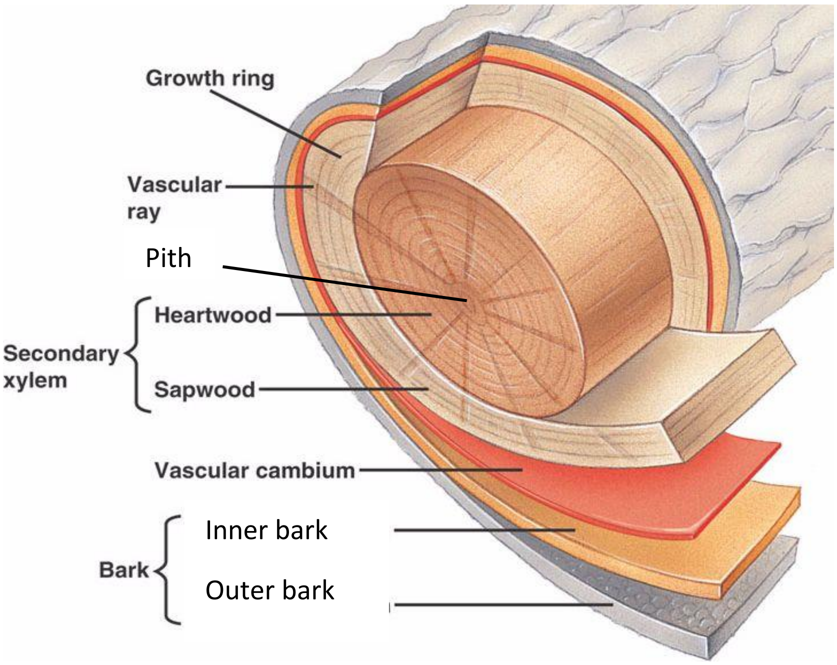

Figure 2 Hardwood stem with definition of the different wood features, adapted from (Pearson education, 2011).

From the outside to the inside the first barrier is the outer bark, a layer of dead material protecting the tree. Inside of this is the inner bark, transporting the glucose and other organic substances resulting from photosynthesis, down the tree and at all levels in the trunk (Desch & Dinwoodie, 1996). The cambium are the cell layers (only a few layers thick) where the actual growth takes place. Due to division of the cells in the cambium, wood and bark are formed. The remaining part of the trunk is divided into sapwood, heartwood and the pith. Sapwood is the living part of the stem, the sapwood conducts water, provides support and stores reserve substances. However these substances are also nutrients for fungi and insects which explains the lower biological durability of sapwood relative to heartwood. Heartwood is by definition the part of the tree which no longer contains living cells (Wagenführ, 1989). The function of heartwood is to support the tree (Taylor, Gartner, & Morrell, 2002). At the centre of the stem the pith is encountered which conducts water in the first year, however when growth continues already in the second year the water conduction takes place in the newly formed layers and the pith dies (Wagenführ, 1989). Verheyden et al. (2004) studying *Rhizophora mucronata* reports low vessel density for the wood formed during rainy season and a high vessel density wood formed during the dry season. These differences are visible in a transverse cross-section as a growth ring; however not all tropical species have growth rings or they are hardly visible, this is especially the case for wood from tropical forests with a constant climate.

2.1.2 Microscopic structure

The microscopic structure of the sapwood and heartwood are especially interesting for this study, the structure consists of:

1. Tracheids
2. Vessel elements
3. Parenchyma cells
4. Fibres

these are all shown in Figure 3.

Tracheids are the main sap conductors in softwoods, although in hardwoods they are rare. In some hardwoods two types exists, vascular and vasicentric tracheid's. The tracheids differ from vessels in having closed ends and many bordered pits[2]. Tracheid's have thick lignified cell walls (Campbell, 2009)

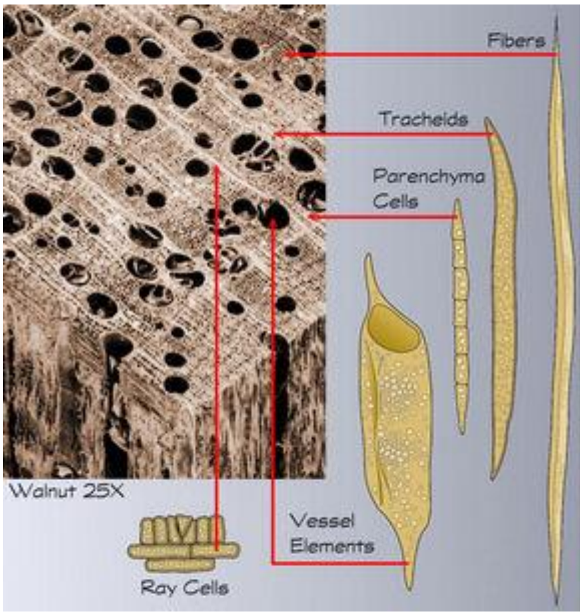

Figure 3 components of hardwood (Engler, 2009).

Vessels are the sap conductors of hardwoods; a vessel is actually the result of numerous connected vessel members (of 0.2-1.3 mm in length and 0.005-0.5 mm diameter). In sapwood the vessels are usually open, however upon hardwood formation the vessels are plugged with tyloses from an adjoining ray or vertical parenchyma cell (Tsoumis, 1991). A vessel cross-section, as seen in the transverse plane, is usually described by the term pore. The distribution of pores in a growth ring is usually used for wood species recognition. Vessels have thick, lignified cell walls (Campbell, 2009).

Parenchyma cells are the storage cells of the hardwoods, they run both in the direction from pith to bark (ray parenchyma) and longitudinally (axial parenchyma). The parenchyma cells have a length of about 0.1-0.22 mm and a width ranging from about 0.01 to 0.05 mm, rays in hardwoods are composed entirely of ray parenchyma cells. (Tsoumis, 1991). Parenchyma cells have thin and flexible cellulose cell walls (Campbell, 2009).

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[2] Pits are for exchanging fluid with adjacent cells.

Fibres do not exist in softwoods, their main function in hardwoods is mechanical support of the living tree. Fibre wall thickness varies considerably between species and even in a piece, wall thickness immediately influences the density and through density the mechanical properties (Desch & Dinwoodie, 1996). Fibres are usually between 1 and 2 mm long and have a diameter of 0.01 to 0.05 mm (Tsoumis, 1991). Fibres have extremely thick cell walls (Campbell, 2009).

2.1.3 Molecular structure

The basic building blocks of wood are cellulose, hemicellulose and lignin with a dry density (dry density of cell wall) of approximately 1450 kg/m^3 (Kellog & Wangaard, 1969).

In Figure 4 several wood cells are shown, the cells are separated by the middle lamella immediately surrounding the primary layer which is thin. Then the thickest part is the secondary wall (S1,S2 and S3), S1 is the outer layer, in this (thin) layer the fibrils are arranged in two distinct spirals with a pitch of from 50˚ to 70˚ to the vertical axis (Desch & Dinwoodie, 1996) . The S3 layer which is the innermost layer has an arrangement similar to the S1 layer and is the same thickness or even thinner (Tsoumis, 1991). The S2 layer is the thickest layer, in this layer the microfibrils are arranged at an angle of 10˚ to 30˚ to the vertical axis. This secondary layer is 60-70 µm thick (Tsoumis, 1991). This S2 layer mainly causes the strong anisotropic strength properties of wood (high tensile strength parallel to the grain direction).

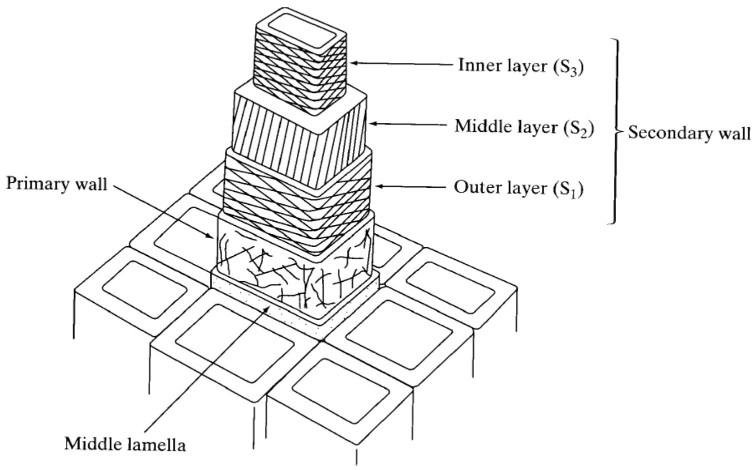


Figure 4 Cell wall schematically (Desch & Dinwoodie, 1996).

The building block for the cell walls are microfibrils. A microfibril consists of a crystalline core of cellulose, surrounded by a layer of low crystallinity of hemicellulose and cellulose. At the outside is an amorphous layer of lignin (Desch & Dinwoodie, 1996). 'Cellulose is a high-polymer chain molecule with very high tensile strength' (Blaß & Sandhaas, 2017), these cellulose chains are mainly arranged parallel with the microfibril length. The tensile strength of a microfibril perpendicular to the length is governed by intermolecular forces like hydrogen bonds, whereas the tensile strength parallel is governed by covalent bonds (which are stronger). Since in a trunk the microfibrils are mainly arranged parallel to the vertical axis, the strength in this direction is higher compared to the radial directions. For a deeper view into this topic the works of Tsoumis (1991) and Wagenführ (1989) are recommended.

After describing the structural features of tropical hardwoods, one constituent remains, the extractives. Extractives are not part of the wood substance but deposits in cell walls and cell lumina. In tropical hardwoods the mass fraction of extractives can be up to 20% of the oven dry mass (Tsoumis, 1991). Extractives include fats, oils, resins, sugars and tannins. Resins are sometimes used for their friction increasing properties (violin bows, handball), whereas oils are known for their lubricating effects.

2.1.4 Tropical wood species investigated

The wood species used in this study are briefly described below. For this description and the pictures, information from delta-intkey.com (Richter & Dallwitz, 2009) are used. The wood species, meranti, sapele and merbau are described. For the other wood species considered, only some notable features are presented. For these, the website www.wood-database.com compiled by Eric Meier has been employed. Pictures are shown of the transverse, tangential and radial plane respectively (defined in Figure 5)

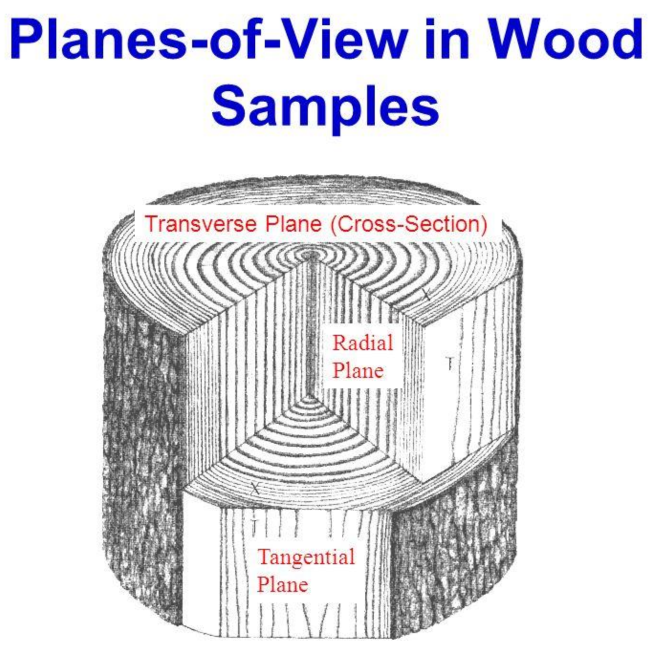


Figure 5 Planes-of-view visible in a tree trunk. (Lilley, 2007)

Dark red meranti

Dark red meranti (Figure 6, Figure 7 & Figure 8) is well known in the Netherlands for its application in window and door frames. Most frames are made of this wood species. Meranti is a collective name for different wood species of the Shorea family.

Dark red meranti is a diffuse porous wood species with vessel diameters of 155-295 µm.

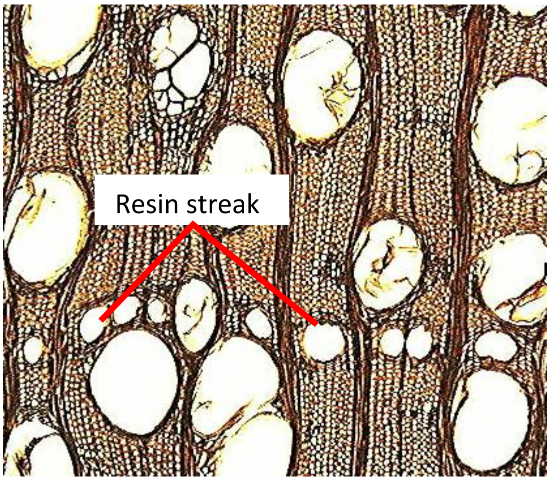


Figure 6 Meranti transverse plane.

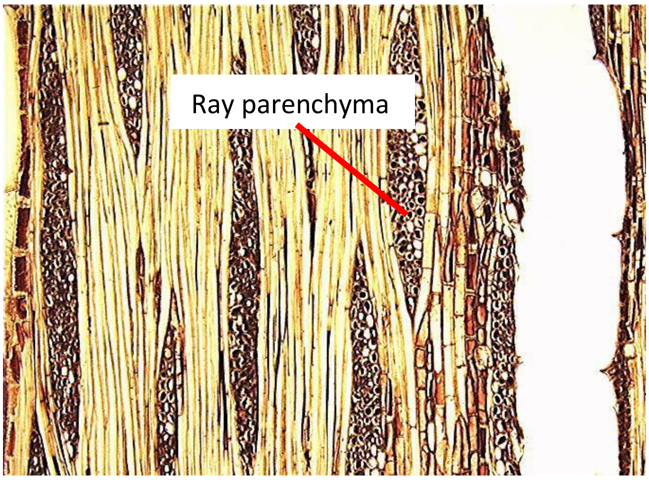


Figure 7 Meranti tangential plane.

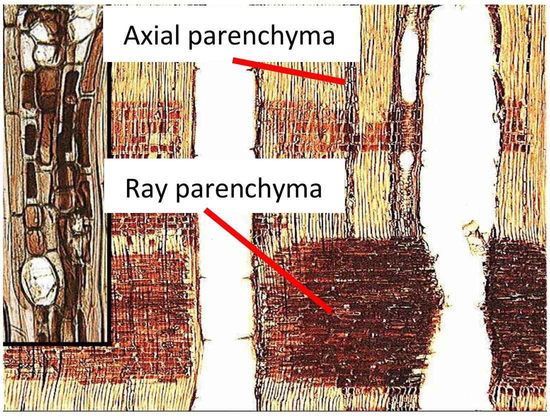


Figure 8 Meranti radial plane.

There are few axial parenchyma, although the ray parenchyma are present, visible in Figure 8 and between fibres in Figure 7. Rays are between 500 and 1000 µm high. Some thin walled tyloses (outgrowth of the cell wall) are present in the vessels. The fibres have a medium/thick cell wall. A characteristic feature of dark red meranti is the white resin streaks in tangential series (Figure 6).

Sapele

Sapele (Figure 9, Figure 10 & Figure 11) is also used for door and window frames and for doors.

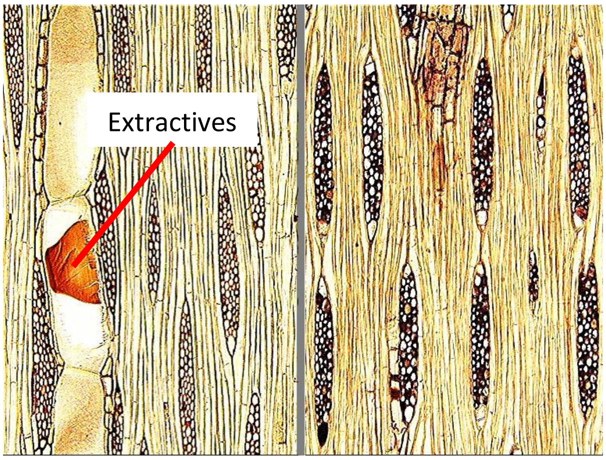


Figure 9 Sapele tangential plane.

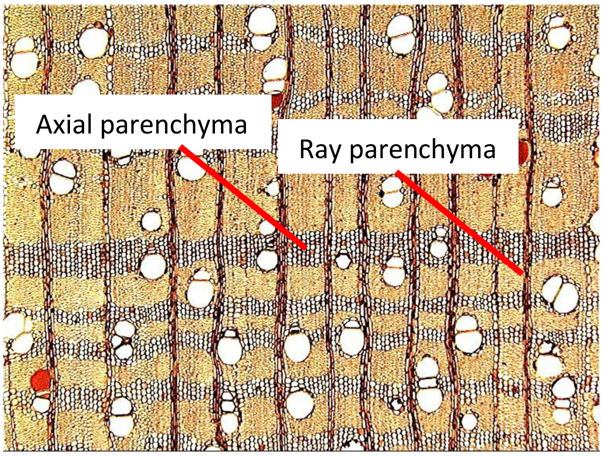


Figure 10 Sapele transverse plane.

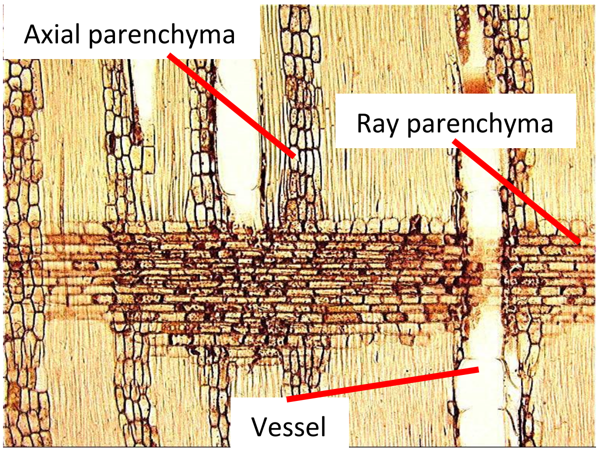


Figure 11 Sapele radial plane.

Sapele, unlike meranti, is from a single species. Sapele is a diffuse-porous wood species, with approximately 9-17 vessels per mm^2 where the average diameter is between 90 and 200 µm. fibres have a medium wall thickness. Axial parenchyma are grouped and lie in circular bands around the pith (Figure 10), ray parenchyma seem slightly smaller compared to meranti, approximately 500 µm high. Some reddish brown extractives are visible in the vessels (Figure 9). Sapele is known for its interlocked grain (considered in a trunk; the grain spirals around the longitudinal axis of the trunk but the direction changes or reverses for successive growth layers).

Merbau

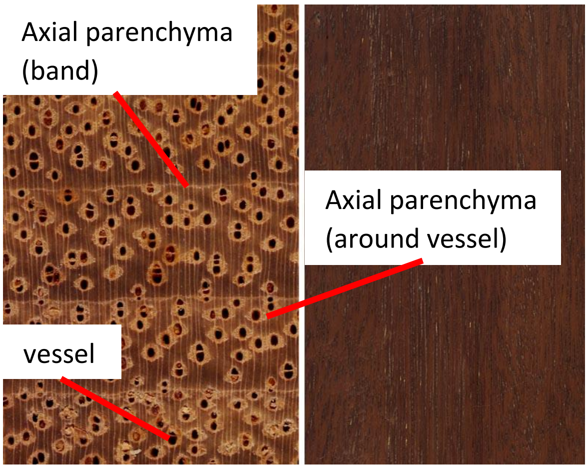


Figure 12 Merbau transverse plane.

Figure 13 Merbau tangential plane.

Merbau (Figure 12, Figure 13 & Figure 14) is known for its water-soluble extractives (gums), leaching when exposed to rain. Merbau is a diffuse porous wood, with a vessel diameter between 120-280 µm and approximately 2-5 vessels per mm^2. White, yellow and dark reddish deposits are present in the vessels. The fibres have medium to very thick cell walls. Axial parenchyma are present both in circular bands around the pith and around the vessels (Figure 12), in the axial parenchyma mineral inclusions are present. The rays (ray parenchyma) have a height comparable with the width of the vessels. Merbau is often used for doors.

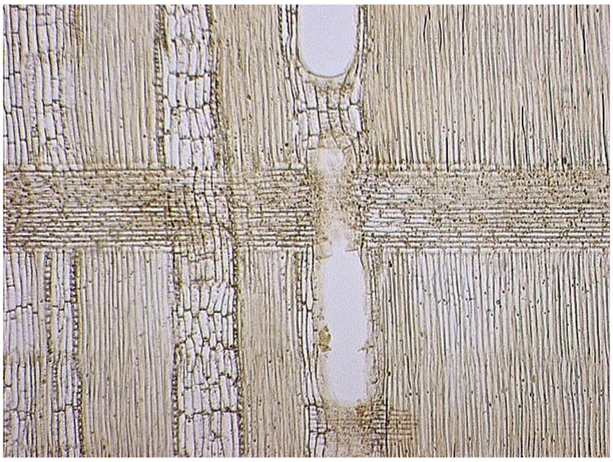


Figure 14 Merbau radial plane.

Other wood species examined in this study are: sapupira/angelim pedra, tatajuba and jarrah. Sapupira is known for its irregular grain and also contains resins, furthermore there is a difference in hardness between the parenchyma and fibre tissue. Jarrah has interlocked grains and sometimes gum pockets are present. Tatajuba has also interlocked grains and a high silica content.

2.2 Background on cutting of wood

Before explaining the process of wood drilling it is useful to have a closer look at wood machining in general to relate this information to the process of wood drilling.

In order to describe the cutting mechanism first two terms need to be defined, oblique and orthogonal cutting. Orthogonal cutting is described as cutting with the cutting-edge perpendicular to the cutting direction. In oblique cutting the tool cutting edge has an angle, of less than 90˚ with the cutting direction (see Figure 15). For true orthogonal cutting two additional requirements have to be fulfilled: the requirement that the tool is wider than the workpiece and the requirement that the tool does not pass the previously machined surface (Astakhov, 2010). The latter is mainly important for steel (due to plastic deformation and accompanying work hardening below the tool).

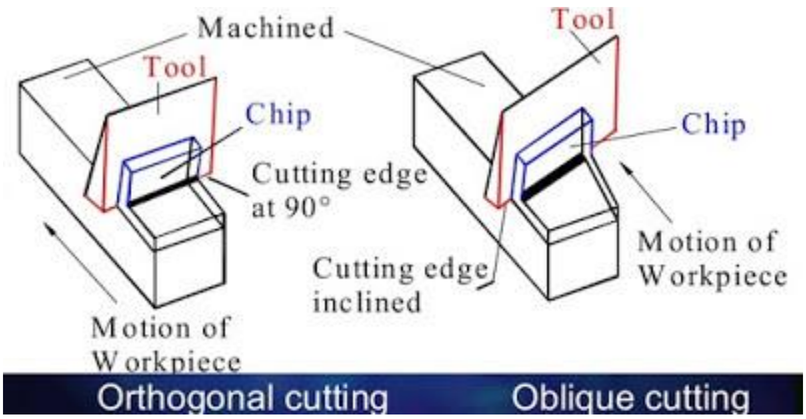


Figure 15 Difference between orthogonal and oblique cutting (orthogonal cutting and oblique cutting, 2016).

Furthermore the cutting direction can be described according to the work of McKenzie (1961). who defined two angles; the angle between the cutting edge and the grain and the angle between the velocity vector and the grain direction (longitudinal direction). Figure 16 shows examples of the McKenzie cutting angles.

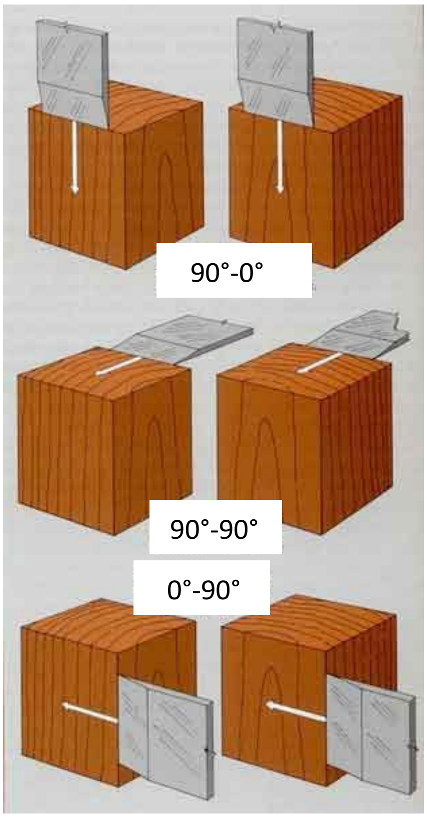


Figure 16 McKenzie cutting angles (Hoadley, 1980).

Reineke (Kollmann & Côte, 1984) explained the energy consumption of sawing by the following steps: (I) fibre severance and internal friction, (II) side shearing from kerf wall which depends on chip thickness, (III) chip formation and associated friction; (IV) chip breakage and its associated friction, and finally (V) the chip removal and associated friction which also depends on chip thickness. The energy of fibre severance (first step) decreases with a sharper cutting edge.

Drilling cannot easily be classified. The cutting mechanism of the main cutting edge can be regarded as orthogonal cutting since the velocity vector of the main cutting edge is normal to the cutting edge (if ignoring the feed velocity which is, especially far from the centre, small compared to the tangential velocity). However the two additional requirements; not passing a previously machined surface and the tool wider than the material are not fulfilled. The tip cutting edge is described by orthogonal cutting as well since the tip cutting edge is perpendicular to the velocity vector. Close to the centre the assumption that the tangential velocity is large compared to the feed velocity does not hold, there oblique cutting takes place. In Figure 17 the velocity vector is shown for the main cutting edge, closer to the centre this tangential velocity (v) is smaller according to equation (1).

$$v = \omega * r, \qquad (1)$$

where ω is the angular velocity and r is the distance to the centre. The feed velocity is the same for the whole drill bit. Thus far from the centre the tangential velocity dominates while at the centre the feed velocity is the main velocity component.

Attempts to define the McKenzie cutting angles for the main cutting edge during drilling is difficult; it depends on the drill direction and on the position at the cutting edge (at the outer edge the feed velocity can be ignored while at the centre the tangential velocity is zero). If assuming drilling perpendicular to the grain and neglecting the feed velocity, the cutting direction can be evaluated. Upon rotation the main cutting edge (marked red in Figure 17) has a varying angle with the grain. The angle with the grain in the position shown in Figure 17 is 90˚ (perpendicular to the grain), upon rotation this angle decreases to 0˚ (parallel to the grain) and

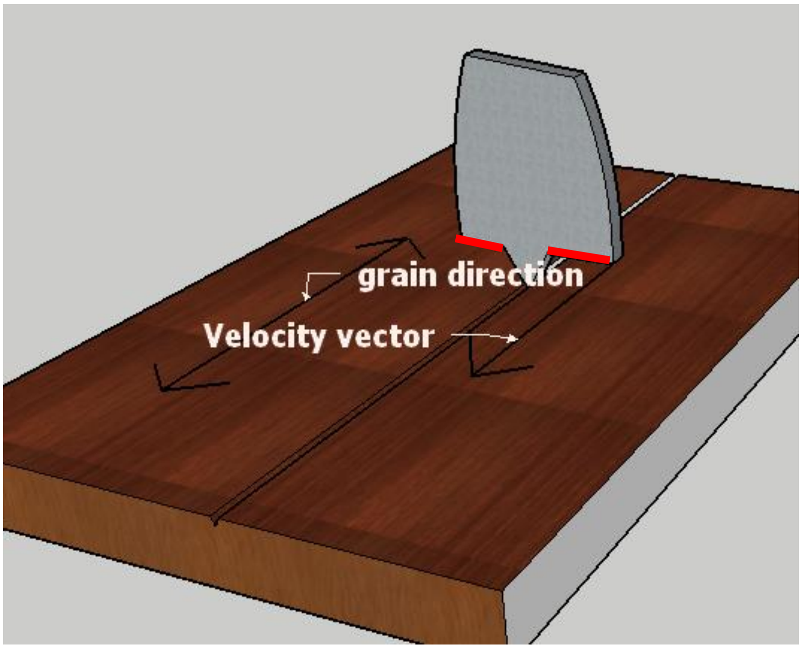


Figure 17 Illustration of the drill bit, indicating the main cutting edge (red), the grain direction and the velocity vector. The velocity vector is drawn at the outer edge; therefore only the tangential velocity is considered, the feed velocity (pointing into the material) is small compared to the tangential velocity and ignored here.

then increases[3] again to 90˚. The angle between the velocity vector and the grain direction (Figure 17) is initially 0˚ (parallel) and upon rotation this increases to 90° (perpendicular) and then decreases again. From this it is clear that drilling cannot easily be classified and therefore not easily compared to other wood machining techniques.

For drilling the energy consumption consists of the same components as in case of sawing; however side shearing from kerf wall is not a constant but changes during rotation since shearing fibres parallel to the grain requires only a fraction of the energy of shearing fibres perpendicular to the grain (Jeronimidis, 1980). According to Reineke the severance energy decreases with a sharper cutting edge.

Prior to McKenzie, Franz (1958) did important work on chip formation in wood cutting. Describing three possible chip types: Type I, the wood splits ahead of the tool by cleavage; type II is continuous wood failure in the chip along a line from the cutting edge to the wood surface and type III is the result of compression and shear failure in the wood ahead of the cutting edge (see Figure 18).

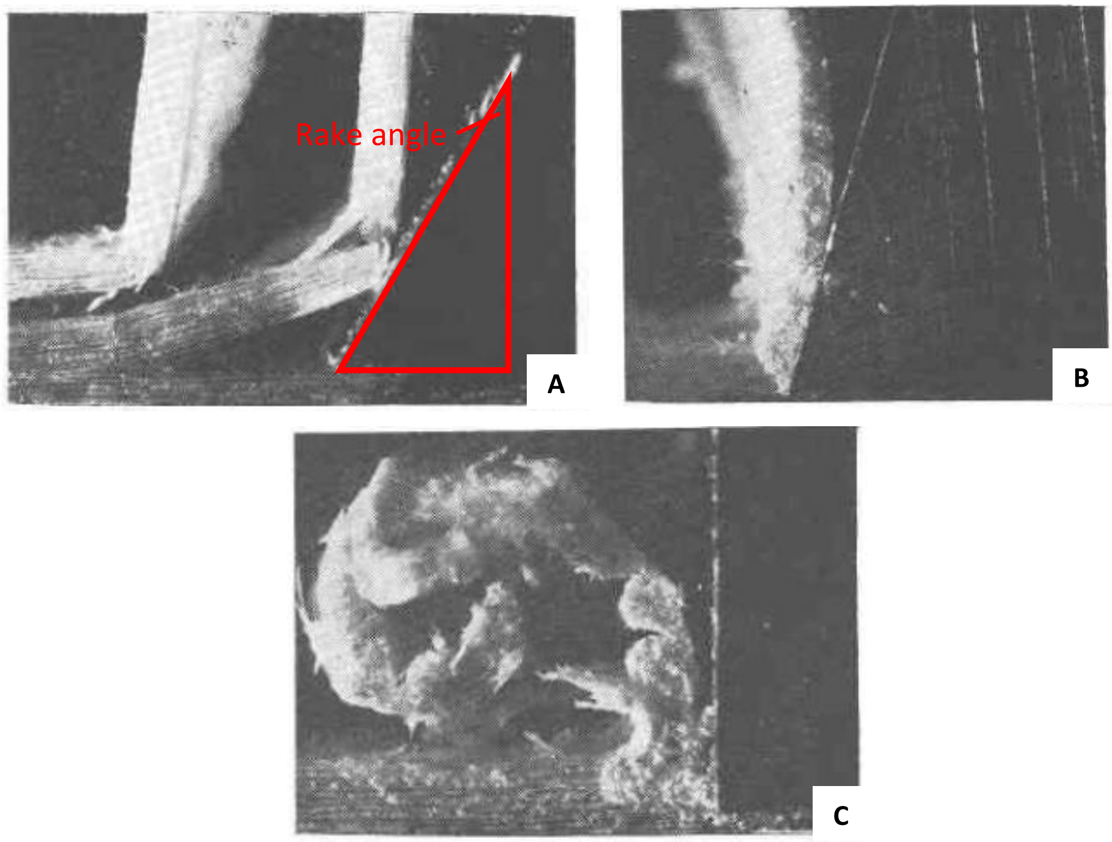


*Figure 18 Different chip types: type 1 (**A**), type 2 (**B**), type 3 (**C**) the tool is in the right of the respective figures. The different chip types are obtained by changing the rake angle, approximately 35° at **A** to approximately 0° at **C** (Franz, 1955)*

[3] Due to symmetry of the drill bit defining an angle of -90° or 180° does not make sense since it is the same as 90° or 0° respectively

A small and even negative rake angle favours the formation of a type III chip. Franz also mentioned that type III chip does not flow up the tool face but causes compression of the wood ahead of the tool, until the compressive forces becomes critical and bending upwards occurs. The formation of chip type III upon drilling is favourable since dulling of the edge does favour the formation of chip type III (Woodson & Koch, 1970). This means that dulling of the needle drill's edge does not result in the formation of a different chip type, although some reservation is required since the chip analysis holds for orthogonal cutting with free edges, which is not the case in drilling (note that the main cutting edge has one free edge at the centre due to the drill tip). It is expected that the non-free edge favours the formation of a type III chip since this edge hinders splitting.

McMillin & Woodson (McMillin & Woodson, 1972), investigated the chip formation upon drilling southern pine with a spur machine bit. They stated that while drilling in the longitudinal direction the action of the main cutting edge approximated orthogonal cutting. The chip types encountered belonged to McKenzie type II (different from the above-mentioned Franz type II) meaning failure perpendicular to the grain and parallel to and below the tool path (Wyeth, Goli, & Atkins, 2009). In cross-grain boring the chip formation was more difficult to identify and depend on the cutting direction relative to the grain. But at low moisture contents the chips were mainly of the Franz II type. The study of McMillin and Woodson seems to contradict the assumed Franz type III chip formation as is expected, but two important differences were present. Firstly the machine bit was equipped with a spur, meaning that there are two free edges and secondly the slightly positive rake angle of the machine bit compared to the negative rake angle of the Resistograph needle (Figure 19). The influence of the rake angle is clear from Figure 18 while the non-free edge at least hinders splitting.

Figure 19 Machine bit (2) and spade drill (3) similar to a Resistograph drill bit. (Wood magazine, 2002)

In conclusion drilling cannot be classified as either oblique or orthogonal cutting, the McKenzie cutting angles varies from 0˚-90˚ to 90˚-0˚ for the main cutting edge, the energy consumption is expected to vary during rotation, being highest when cutting in the 0˚-90˚ direction, since the fibres at the kerf wall are broken whereas upon cutting in the 90˚-0˚ direction the fibres at the kerf wall are separated. The chips formed upon drilling are most likely Franz type III chips and this will not change with dulling of the cutting edge. However, dulling of the cutting edge can still lead to a higher torque since dulling leads to a more negative rake angle and by that, a larger compression force component resulting in a higher torque.

2.3 Resistograph

For this study, the Resistograph R650-SC of the German company Rinntech was used. The Resistograph is in short a machine that measures the resistance upon drilling. In this section the Resistograph and its different components are described. After a short summary of the historical development, the machine and the influence of the machine on the measurements is discussed.

2.3.1 History

The basics of resistance drilling in wood go back to 1984 when two German engineers (Kamm and Voss) developed a drill that recorded the resistance of a thin needle drilling into wood. The first recording mechanism was based on a scratch pen connected to a spring-loaded gear box which scratches on wax paper during drilling.

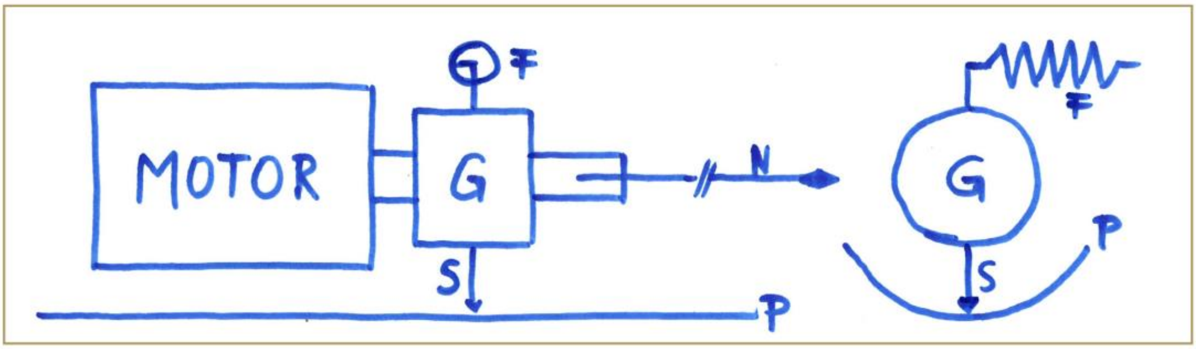


Figure 20 "Sketch of an early resistance drill from 1984: a scratch pin (S) was fixed at a spring (F) loaded gear box (G) between motor and needle (N), creating a 1:1-scaled resistance profile on a wax-paper strip (P)" (Rinn F. , 2012).

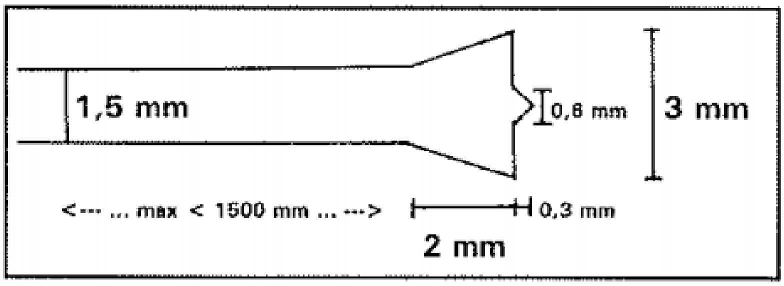


Figure 21 Dimensions of Resistograph needle drill (Rinn F. , 1994).

However due to resonance effects, this approach did not work properly, and the application of dampers led to the appearance of plateaus and introduced a stimulus threshold[4]. The mechanically recorded profiles were unreliable and due to mentioned shortcomings led to systematically to unreliable results (Rinn F. , 2012). The two German engineers switched to an electric recording mechanism (Germany Patent No. DE3501841A1, 1985). In 1988 the

[4] The mentioned stimulus threshold means that when the difference in drill resistance between two different positions was below a certain minimum nothing was recorded. A plateau is likely due to the same effect.

University of Hohenheim and Heidelberg invested whether the proposed method was suitable for recognition of earlywood and latewood in a tree ring[5] (Rinn F. , 1988). Rinn founded the Rinntech company which commercially exploited the drill resistance method and further developed the method (Rinn F. , 2011).

2.3.2 Drill bit

The drill bit of the Resistograph is the key point of the Resistograph. The drill bit has a specific geometry, comparable with a spade drill. Figure 21 shows the drill bit and its dimensions, which is used by many researchers (Acuña, et al., 2011) (Morales-Conde, Rodríguez-Liñán, & Saporiti-Machado, 2014).

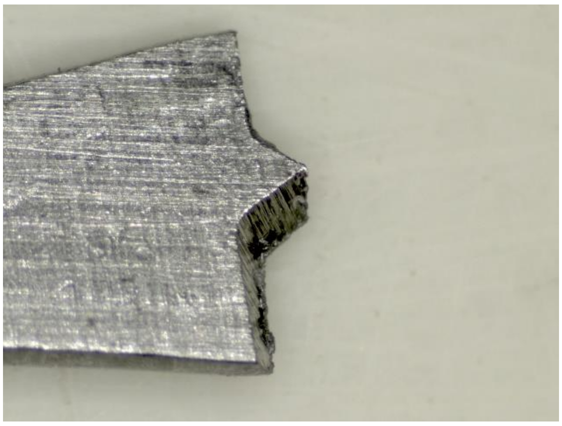


Figure 22 Microscopic picture of Resistograph drill bit (top view).

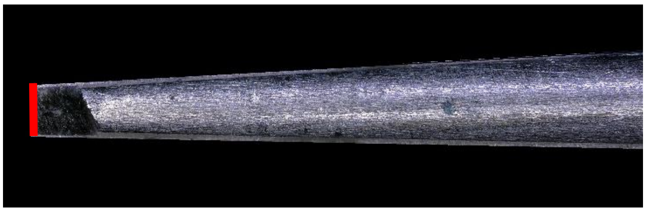


Figure 23 Side view of Resistograph needle drill.

The description in Figure 21 is unsatisfactory especially since it does not show the actual three-dimensional structure of the drill tip. Figure 22 and Figure 23 show confocal microscopic pictures of the needle.

The needle drill geometry is specified according to the work performed by Zhao and Ehmann (2002), (2010). Their extensive analysis of the spade drill is used as background for the analysis of the needle drill. The global definition of the spade drill is shown in Figure 24. In general the spade drill can be divided into different parts, namely the tip, blade and the shank. In the following section the three parts of the needle drill are investigated.

Tip

The function of the spade drill tip is to centre the drill bit. The top part of the drill bit (marked red in Figure 23) is the so-called chisel edge, the length of the chisel edge influences the thrust force (Zhao & Ehmann, 2005). The tip cutting

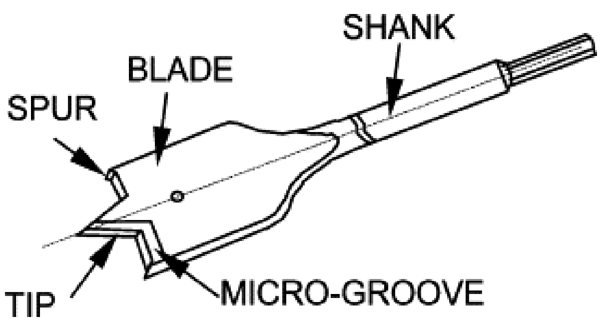


Figure 24 The spade drill bit (Zhao & Ehmann, 2002).

[5] focusses on softwoods

edge point angle, ρ (Figure 25) is defined as the sharpness of the chisel edge viewed from a plane parallel to the drill bit. In the same figure the tip height e and tip width w are shown.

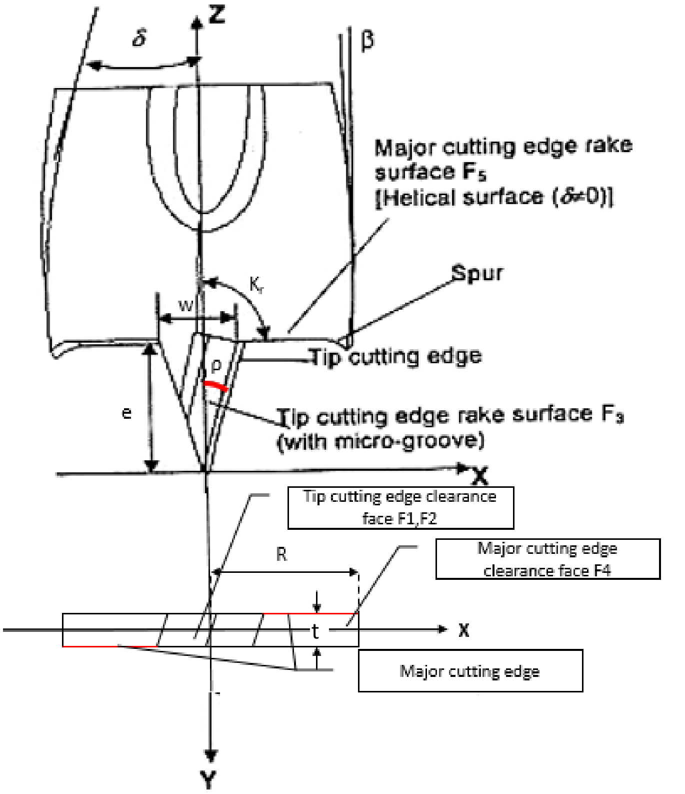


Figure 25 geometry of spade drill, adapted from (Zhao & Ehman, 2003).

Blade

The blade is flat, although it increases slightly in thickness away from the tip. The blade is the major cutting edge with radius R (marked red in Figure 25), and spade drill bit thickness t at the major cutting edge, the drill bit has a flat front, meaning that the semimajor cutting edge point angle k_r is 90 degrees. The needle drill has a taper angle to minimize friction between bit and hole wall, with an approximate spade drill taper angle β. The cutting-edge definition also requires the clearance angle (static definition) and the rake angle (Figure 26) between the drill blade and the cutting surface; in case of the Resistograph drill bit the rake angle is slightly negative. The Resistograph drill has no spur, no microgroove nor a curved base.

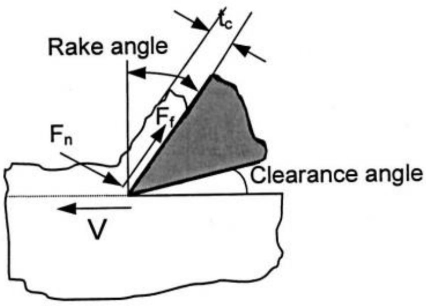


Figure 26 Chip removal model (Zhao & Ehman, 2003).

Shank

The shank is a 1.5 mm thick needle, the length depends on the Resistograph version since versions of 420 mm up to 600 mm (or even longer) are available.

2.3.3 Motor and Battery

The Resistograph series 6 is equipped with two motors, a direct current motor for needle rotation, and a feeding motor with constant speed (Rinn F. , 2012). The needle rotation motor is a Maxon DCX direct current motor.

2.3.4 Accuracy

Little investigation is done into the measured quantity, and the literature is even contradictory in some instances. A number of sources mention that the torque is registered (Morales-Conde, Rodríguez-Liñán, & Saporiti-Machado, 2014). Conversely (Acuña, et al., 2011; Tseng & Hsu, 2008) mentioned that percentage of energy consumed by the motor is presented as the drill resistance. Others only mention the registration of the drill resistance without clarifying how drill resistance is defined (Bouffier, Charlot, Raffin, Rozenberg, & Kremer, 2008). The differences can be due to the different machines used, as mentioned in section 2.3.1. The first drills were based on torque measurements, later they switched to electronic recording of the motor power consumption (Shan et al., 2017). At least for the Resistograph used in this study the R650-SC, it is mentioned that the Resistograph measures the electronic power consumption of the direct current needle rotation motor, and this is proportional to the mechanical torque (if the motor acts linearly (Rinn F. , 2012)). In the same article Rinn mentioned that only the needle rotation motor is used for the resistance values, the feeding motor did not contain significant additional information. The raw values from the Resistograph are presented as [rel], it is likely that this is relative to the idle power consumption.

The rotation rate (ω) is, in case of a direct current-motor, the sum of the no load speed minus the speed decrease due to the resistance (R) as is visible in equation 2.

$$\omega = \frac{V}{k_t} - \frac{TR}{k_t^2} \qquad (2)$$

If voltage (V), rotation rate (ω) and the motor constant (k_t) are constant; torque (T) and resistance (R) are direct related according to equation 3.

$$C = -TR \qquad (3)$$

Since torque is directly related to current (i) according to equation 4 and power (P) (energy consumption per unit time) is equal to the product of current (i) and voltage (V) (which is constant), power is a direct measure of the torque (equation 5 and 6).

$$T = k_t i \qquad (4)$$

$$P = iV \qquad (5)$$

$$T = k_t \frac{P}{V} \qquad (6)$$

According to the product specification (Rinntech, 2014), the drill records the resistance with 12 bit accuracy and 100 measurements per mm drill advancement.

2.4 Influence of machine parameters

It is important to know what features of the Resistograph influence the results, why and to what extent. In this section, the sharpness, geometry, feed rate and rotation rate are discussed.

2.4.1 Sharpness & geometry

The definition of sharpness is quite arbitrary, Figure 22 in section 2.2.2 shows the drill under microscope, a woodworker would probably say that an edge like that shown is not sharp. Sharpness is relative, a tool being sharp for a certain chip thickness is blunt for smaller chips. (Atkins, 2009). Blunt edges in wood cutting give additional friction forces, due to compression of the wood at the cutting tip, which recovers and results in friction at the clearance surface. This behaviour is referred to as 'clearance face rubbing' (Atkins, 2009). Figure 27 shows the process of clearance face rubbing.

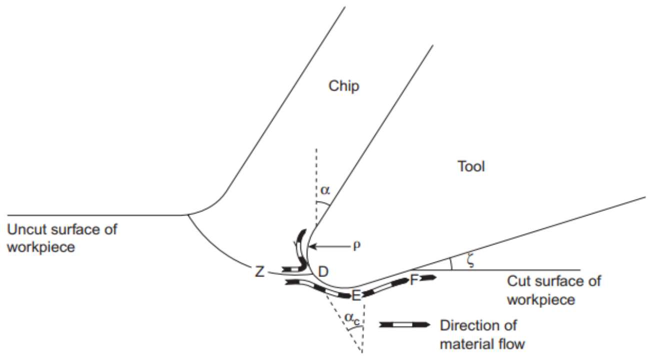


Figure 27 Clearance face rubbing Illustrated here for steel however also applicable for wood (Atkins, 2009).

Cristóvão, (2013) investigated the machining properties of wood and found that tool wear (measured either as nose width, edge radius or edge recession on the rake or clearance face) is increased by silica inclusions in wood and, to a lesser extent, ash content[6]. A higher moisture content also leads to a higher wear rate, whereas extractives decrease the wear rate, possibly due to lubrication effects. Darmawan et al. (2012) found additional wear due to acidity (caused by extractives) causing corrosion. These differences could be related to the type of extractives. Hernandes (2010) investigated the influence of drill sharpness on the drill resistance and found a higher resistance and an increased standard deviation for the eroded drill. However, in this study the drill bit was eroded with a stone, this means that the drill geometry was different (tip is completely missing). Rounding of the edges can result in a smaller hole diameter, so the conclusions are of limited relevance.

Related to the geometry, Zhao and Ehmann (2002) found that the chisel edge (see Figure 23) of a spade drill generates a relatively large thrust force and a very small torque. Since the Resistograph records the power consumption of the needle rotation motor (as a measure of drill resistance), the influence of dulling of the chisel edge

[6] Non-combustible components in wood

hardly leads to an increased drill resistance. From experiments of Zhao and Ehmann (2002) with spade drills with a 25.4 mm radius and a 6.6 mm wide tip, the torque for the main cutting edge was approximately two to three times higher than the torque due to the drill tip. The thesis of Zhao (2010) showed that torque depends on the rake angle, an increase in rake angle leads to a decrease in torque, Cristóvão (2013) found this behaviour also for cutting.
The Resistograph drill bit is equipped with a taper edge, to reduce the friction forces with the wall of the bore hole. In the borehole some friction occurs on the needle due to compression of the drill chips, the needle occupies 25% of the available space (Eckstein & Sass, 1994). However the friction, although important for inspection of tree trunks, is assumed to be less important for inspection of door and window frames since boreholes are less than 100 mm deep. Furthermore the effect seems more pronounced in wet wood and less in dried wood, which is probably the result of the water in the lumen of wood cells (bore residue has a higher density leading to a higher contact pressure with the needle) and the higher coefficient of friction for wet wood (Koubek & Dedicova, 2014).

From the data of Li et al. (2014) it can be concluded that the torque does not scale with radius squared (area) nor with diameter (perimeter) of the drill bit, most likely the torque is related to the amount of material removed and the diameter as a measure for the perimeter. Since the force is the sum of the force required for cutting of the fibres at the edges and that required for removing the chip.

2.4.2 Feed rate

The mechanistic model developed by Zhao & Ehmann (2003) and the accompanying results give a good view of the importance of feed rate on the torque. Their plot of torque as a function of feed-rate (Figure 28) showed that the torque does not depend linearly on the feed rate, although the drill type best matching the Resistograph drill bit (LNG15) behaves in a more or less linear manner.

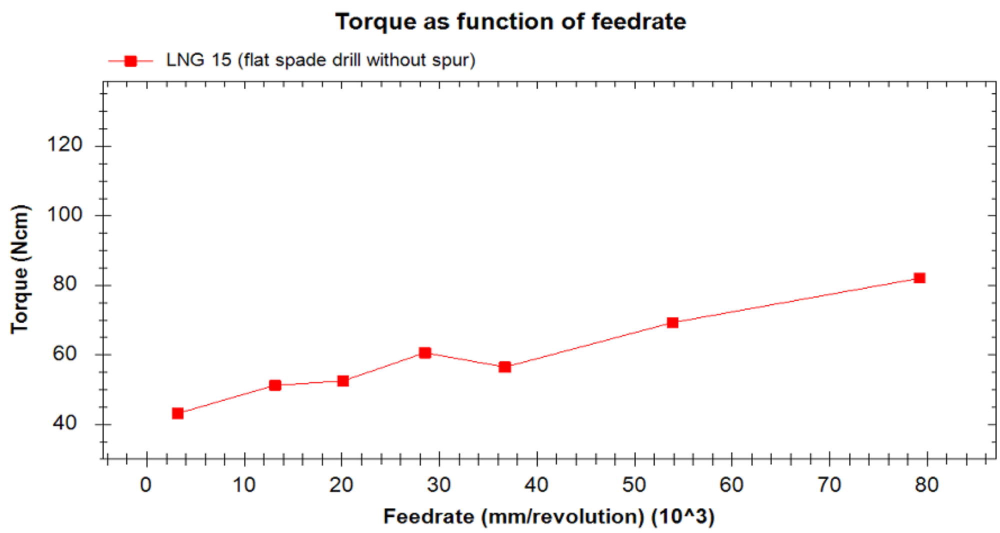


Figure 28 Torque as function of feed rate (Zhao & Ehmann, 2002) (adapted in order to increase the visibility).

Zhao and Ehmann (2002) found that with higher feed rate, clearance face rubbing has substantial influence on both torque and thrust force.

Podziewski and Górski (2012) performed an experiment in which they drilled plywood with varying feed rate but constant spindle speed of 6000 rpm. Varying the feed rate between 0.1 and 0.7 mm/revolution they found a linear increase of torque and thrust (feed force) with increasing feed rate.

2.4.3 Rotation rate

McMillin & Woodson (1972) when drilling southern pine with a spur machine bit found that the torque was unrelated to spindle speed when chip thickness was held constant. They measured at 1200, 2400 and 3600 rpm. Torque does depend on the chip thickness. Zhao & Ehmann (2002) showed with their mechanistic model that the torque depends more or less linearly on the rotation rate if the feed rate is kept constant, see Figure 28. The drill bit most closely matching the Resistograph drill bit is the LNG15 (this is a flat spade drill bit without spur although equipped with a micro groove to improve the rake angle). Both these sources point to the fact that not just rotation rate but more specifically the combination of rotation rate and feed rate (chip thickness) has a clear influence on the torque, although doubling of the chip thickness does not lead to a doubled torque. This is clearly visible in Figure 29 (the slope is not, the red line is the drill bit comparable with the Resistograph drill bit whereas the green line is the line of constant specific cutting work (work per volume chip removed). If assuming that the specific cutting work (P) is constant, equation 7 becomes equation 8.

$$P = T\omega, \qquad (7)$$

where T is the Torque and ω the rotation rate

$$T = \frac{C}{\omega}, \qquad (8)$$

where C is a constant; a doubled rotation rate leads to a halved torque; which is represented by the green line in Figure 29.

Grönlund (2004) showed that an increase in chip thickness results in a decrease of the specific cutting work (work per volume chip removed); this agrees with Figure 29. In order to illustrate this consider a short example: a certain material is resistance drilled and has a drill resistance x. if now another material with a higher drill resistance is drilled, the drill resistance is $x + dx$. This dx is the additional drill resistance due to the higher drill resistance of the material; but the increased efficiency (due to a larger chip thickness) makes this dx smaller and lowers therefore the distinctiveness of the resistance drill.

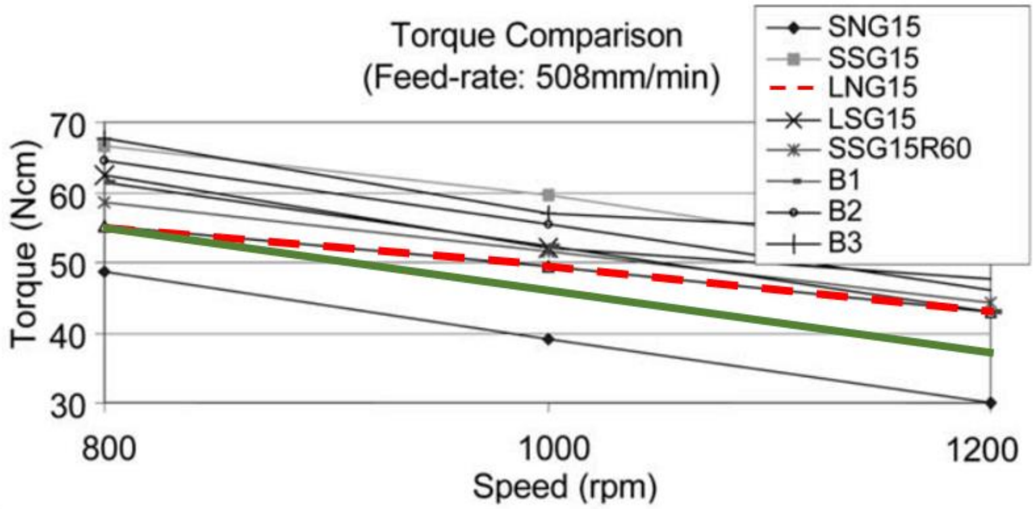


Figure 29 Torque versus rotation rate for a Feed-rate of 508mm/min extended with line of constant specific cutting work (green) adapted from (Zhao & Ehmann, 2002).

Several processing parameters influence the measured drill resistance but sharpness of the cutting edge is most important for this research, since this is influenced during the drilling process whereas other parameters are not adjustable. In the manual of the Resistograph, it is stated that for hardwoods the drill should be replaced every 100 drillings (Rinntech, 2014). For the chip thickness (influenced by the rotation rate and feed velocity) the smaller the variation the better.

2.5 Influence of material properties

It is clear that local wood conditions influence the drill resistance; however the local composition is unknown and it is not easily possible to relate the local composition to the measured resistance. Nevertheless some conclusions can be drawn: Especially in wood with large rays (radial drilling direction) or large vessels (longitudinal drilling direction) these elements may act as 'pre-drilled holes' and hence influence the drill resistance. The drilling direction determines the angle between micro fibrils and drill direction and therefore influences the resistance, however this effect is less clear in wood with interlocked grain for example. The mass fraction and composition (oils vs resins) of extractives is likely to influence the drill resistance. The influence of the thickness of the cell walls, as is reflected in the density of wood, on the drill resistance is the basis of resistance drilling. The thickness of the cell walls solely is not a good measure of the drill resistance since vessels for example that have a thick cell wall but a large diameter have a low average drill resistance. However drilling resistance represents the resistance at a particular location. It is possible that with a wood species containing many grouped (thin walled) parenchyma cells, like sapupira, the location will influence the drill resistance.

After discussing the microstructure of wood, the wood species examined in this study are presented. The influence of different wood properties on the drill resistance, starting with extractives followed by moisture content, drilling direction and density. Finally some remarks are made on the influence of shaft friction.

2.5.1 Extractives

In section 2.3.1 the influence of extractives on wear behaviour is treated. Little literature on the influence of extractives on wood machining is available. McKenzie and Karpovich (1968) investigated the frictional behaviour of wood. Their research showed that greasy woods have a lower friction coefficient, even on rough steel. Meanwhile experience gained with drilling oregon pine with resin pockets showed a significant increase of drill resistance and clogging on the drill bit. It is most likely that not just the mass fraction of extractives but especially the sort is of importance. Gums and resins differ in the fact that resins are insoluble in water and gums are soluble. The mass fraction of extractives present in the wood species varies between different species, and even within trees. Meranti contains several percent of extractives while merbau easily contains around 20% extractives. Sometimes Silica crystals are present which have a fast dulling effect on the drill bit (Cristóvão, 2013).

2.5.2 Moisture content

Wood moisture content largely defines its attractiveness to fungi but also has a large influence on the mechanical properties of wood; therefore it is important to see what the effect of moisture content is on the drill resistance.

The wood-water relationship cannot be described by a single behaviour from 0 to 100% moisture content (mc); rather it involves two successive and to some extent simultaneous behaviours. The stages are explained starting from dry wood, with 0% moisture content up to ‘green wood’ after felling with a moisture content exceeding 100%. In dry wood the cellulose chains are close together and therefore the intermolecular bonds are strong due to hydrogen bonds and van der Waals forces. This results in a strong, stiff and brittle material. If dry wood is placed in a humid environment, it absorbs moisture, which moves between the cellulose chains, forming hydrogen bonds with the OH- groups of the cellulose. This absorption results in swelling of the chains and weaker intermolecular forces between the cellulose chains. Therefore the wood has a lower strength, but an increased toughness. At a certain moisture content, the fibre saturation point (FSP) is reached where the moisture is no longer absorbed in the cell walls (cellulose chains) but entrapped in the cell lumen. The fibre saturation point does not occur at a unique value of the moisture content but represents a transition region. Filling of the cell lumen does not further impact the mechanical properties (Blaß & Sandhaas, 2017). Only the density changes since the air is replaced by water. Free water is actually a second material in the timber piece.

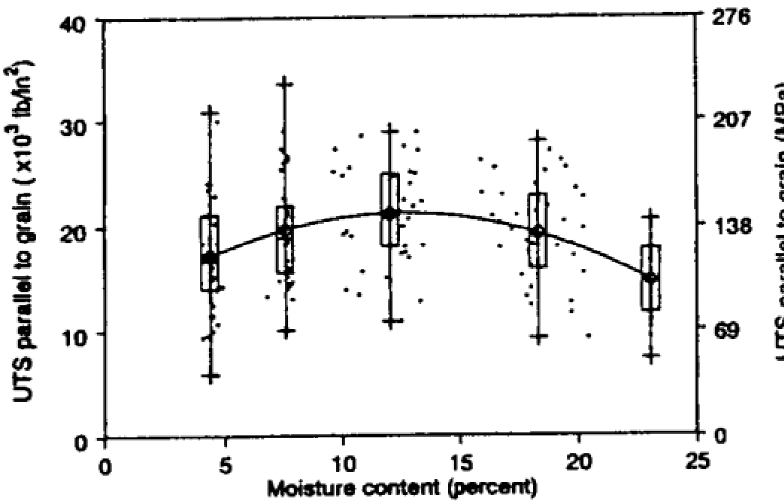


Figure 30 Ultimate tensile strength parallel to the grain versus moisture content (Kretschmann & Green, 1996).

Drilling means breaking and shearing off of fibres, an increasing moisture content up to the fibre saturation point, should result in a lower drill resistance since the bond strength weakens. However at really low moisture contents, brittleness of the wood can results in a lower energy consumption due to brittle fracture. At higher moisture contents there can be an increase in resistance due to increased friction. Higher drill resistance especially above fibre saturation point is also found by Lin et al. (2003); however from this study no conclusions could be extracted about the region 5%-25% moisture content. Furthermore the density of the specimens varies, which makes conclusions even more difficult.

Walach et al., (2015) found that the drill resistance is higher for wood at the fibre saturation point[7] compared to air-dried wood[8]. According to Kretschmann and Green (1996) all mechanical properties showed a decrease upon increasing the moisture content from above 12% (which is approximately the equilibrium moisture content at 20˚C and 65% relative humidity) to the fibre saturation point. An example of this behaviour is shown in Figure 30 which presents the relationship between the ultimate tensile strength and the moisture content. Below 12% moisture content some properties do increase (ultimate compressive stress, shear strength parallel to the grain and modulus of elasticity in compression perpendicular to the grain) while others flatten or even decrease. This is explained with a lowered fracture toughness. These data support the theory of increased brittleness at lower moisture contents as stated above.

Cristóvão investigating the machining (sawing) properties of wood reported that moisture content had a large influence on the cutting force. Generally cutting forces decrease with increase in moisture content, although this seems not to hold for high density woods (Cristóvão, 2013). McMillin & Woodson (1972) drilled southern pine with a spur machine bit and recorded thrust and torque, and the relationship of these with moisture content. They found a maximum torque between 5 and 10% moisture content. Although the torque was more dependent on moisture content parallel to the grain compared to perpendicular to the grain, as shown in Figure 31. Kivimaa (1950) evaluating the cutting force in Finnish birch found a maximum cutting force between 10 and 13% moisture content.

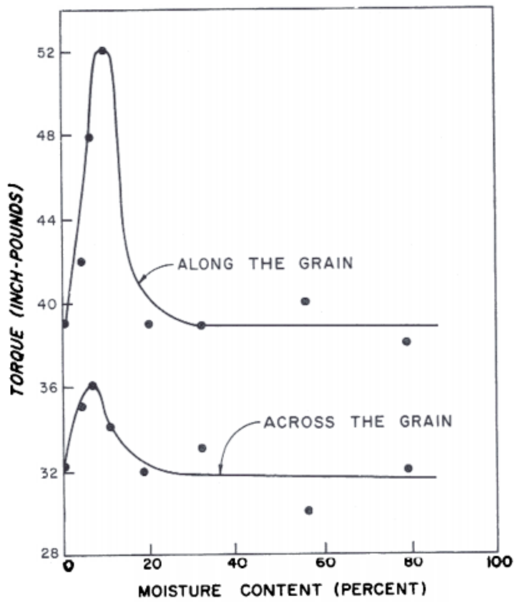


Figure 31 Influence of moisture content on torque upon drilling (McMillin & Woodson, 1972). Along the grain is parallel to the grain whereas perpendicular to the grain is the same as across the grain.

2.5.3 Drill direction

The drill direction influences the measured drill resistance as found by several researchers (Hernandes, 2010) and (McMillin & Woodson, 1972). However these reports also point out that the difference between radial and tangential drilling is

[7] Approx. 30% mc for the tested wood specie (beech)

[8] Approx. 18% mc

relatively small. McMillin & Woodson separating radial and tangential directions (Figure 32) did not find significantly different torques nor thrust forces in drilling southern pine with a spur machine bit. In drilling parallel to the grain a higher torque was measured compared to drilling perpendicular to the grain (see Figure 31) (McMillin & Woodson, 1972). Upon drilling parallel to the grain the wood fibres have to be severed in their strongest direction (fibres are broken instead of separated). In the remaining part when mentioning 'perpendicular to the grain' no distinction is made between the radial and tangential directions.

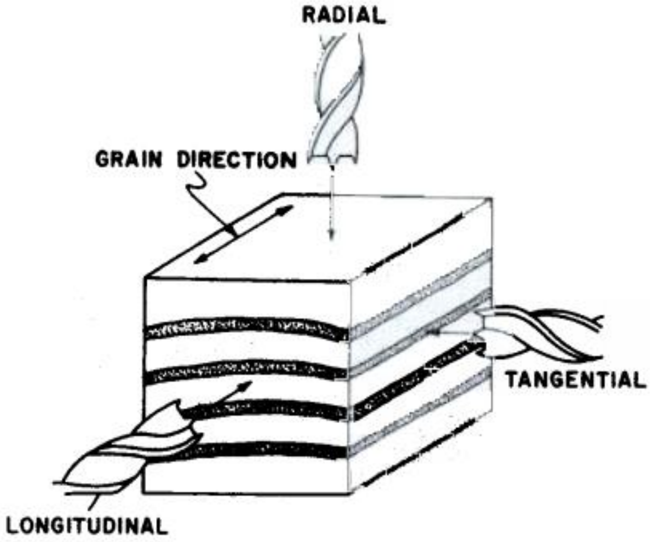


Figure 32 definition of radial, tangential and longitudinal drill direction according to Woodson and McMilling (1972)

2.5.4 Density

The main question of this study is: whether a relationship between density and drill resistance exists for tropical hardwoods. An important question then is whether there are indications pointing to such a relationship. There are, numerous studies, especially related to the Resistograph or the IML-Resi (similar machine from another company), that have proven a relationship between density and drill resistance for softwoods. In general it seems to depend largely on drill bit geometry since Woodson & McMillin (1972) did not find a significant relationship between torque and specific gravity for a machine bit although they found a relationship for the ship auger bit (machine bit has a spur contrary to the auger bit, meanwhile the auger bit has a slightly larger rake angle). Kivimaa in investigating the cutting forces in cutting Finnish birch (air dried) found an approximate linear relationship between specific gravity and cutting force (Kivimaa, 1950). The studies of Kivimaa and Woodson & McMillin, to a certain extent, support all the work done in later studies relating the density to the drill resistance. Currently it is accepted in the literature that the density and drill resistance (of the Resistograph) are related for softwoods. However there is still no clear agreement on how accurate the density predictions are and only limited studies have been done with tropical hardwoods.

Some studies relating density and drill resistance find an R^2 value (as a measure of how well a regression line fits the data, 0.8 for example means that 20% of the variance cannot be explained by the model) around 0.45 where others find values in the range of 0.9 (Shan et al., 2017). Hernandes (2010) found a non-linear relationship whereas others found a linear relationship. To some extent these differences can be due to the use of inaccurate machines and measurement techniques as is believed by Rinn[9]. The different accuracies may also be due to different conditions (moisture content, wood species and local or global density).

2.5.5 Shaft friction

Shaft friction, especially for deeper cuts is a factor that cannot be ignored. Woodson & McMillin (1972) found that "clogging masks normal torque and thrust associated with the cutting action". Although their research was on drilling of southern pine (softwood) with an auger or machine bit, the results likely also apply to hardwoods. The design of the spade drill with the thin shaft does not result in chip clogging, the dust is compacted leading to friction on the needle. The space for the bore dust is 25% less due to the volume of the shaft (Eckstein & Sass, 1994). The shaft friction is not investigated in this research since the drilled depth is small compared to the drilled depth in tree diagnosis and other wood inspection applications.

[9] Stated both in his article (Rinn F. , 2015) and in email conversation with the author of this work.

3. Materials and Method

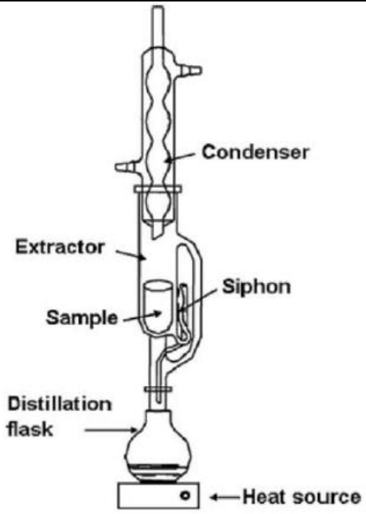
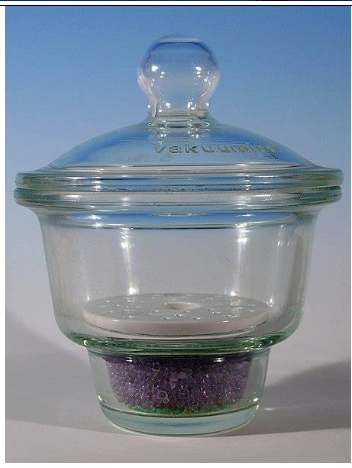
Several materials and items of equipment have been used in this study, an overview of which is given in this section. The approach employed to get the desired results is then described, divided into subsections, concerning influences related to the machine and machine properties and the factors related to the material.

3.1 Materials and Equipment

In Table 1 below an overview is given of the equipment used. The most important machines are shown.

Table 1 Materials and equipment.

Apparatus	description	Image / details
Rinntech R650SC Resistance drill	Drills a small needle like drill bit into the material and registers the energy consumption of the rotational motor as function of the position.	
Climate chamber	Climate at 20°C and 65% relative humidity	The laboratory where this research is performed is climatized at this climate
Climate boxes	Smaller boxes with a fan and a saturated salt solution (above this salt solution is a constant climate)	Accuracy of relative humidity ±1%
Calliper Mitutoyo SHR/350	Accurate measuring dimensions, accuracy 0.05 mm	
Balance	Different types used	Accuracy 0.01 g or 0.001 g
Furnace	Electrical heated furnace calibrated to 110°C	Accuracy ± 2°
Wooden blocks	Test pieces retrieved from multiple companies	Wooden blocks, usually intended for door and window frames the different the sample number and some properties are presented in the following tables

Soxhlet extraction apparatus	Heat source heats the distillations flask, the solution evaporates, condenses at the condenser, drips at the sample. This process continues until the siphon is filled, and the extractor is emptied by suction due to the siphon. This process repeats	
Test setup	Wood specimen and Resistograph fixed to table to avoid motions disturbing the results	
Desiccator	Filled with dried silica to cool down after oven drying and prevent water adsorption. Also used after vacuum impregnating with water (without silica) to allow the water to distribute in the sample.	
Tachometer	To determine the rotation rate of the Resistograph, accuracy (±75 rpm)	
Sheet of 6 mm thick polyethylene and other plastics	For the calibration procedure and relationship with density	Thicker sheets would give more likely clogging and accompanying heating up of the chips and probably melting.

The most important machine used throughout this study is the Resistograph. The resistance drill used is described in detail in section 2.3. A feature of this machine used in this study and not described in section 2.3 is the depth setting. This makes the machine automatically reverses when the depth is reached. In Figure 33 the Resistograph is shown with the different components, not clearly visible are the guides to avoid buckling of the drill bit.

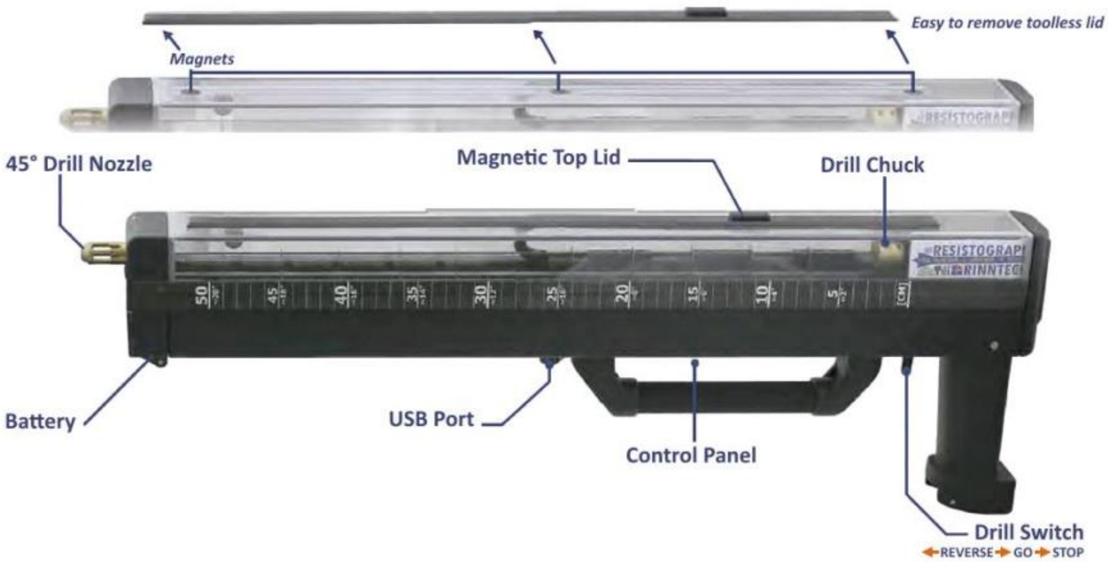


Figure 33 Figure showing all the different components of the Resistograph drill (Rinntech, 2014).

Also of importance is the test setup, by clamping both the machine (inside the test setup) and the sample to a table, no motions (which likely influence the drill resistance) are possible.

3.2 Method

The methods used for the different research subtopics are discussed below. First the approach related to the Resistograph: drill sharpness, rotation rate and feed velocity is discussed. Followed by the approaches related to the material: moisture content, extractives content and drill direction. Finally the relationship between drill resistance and density is discussed. The density at $x\%$ moisture content (ρ_x) is calculated according to equation 9 and the moisture content (mc) according to equation 10.

$$\rho_x = \frac{m_{at\ x\%\ mc}}{V_{at\ x\%\ mc}} \qquad (9)$$

$$mc = \frac{m_{at\ x\%\ mc} - m_{dry}}{m_{dry}} 100\%, \qquad (10)$$

so moisture content is based on the mass ($m_{at\ x\%\ mc}$) and the oven-dry mass (m_{dry}). The oven-dry mass is the mass after oven-drying for 24h-48h (till mass is constant)

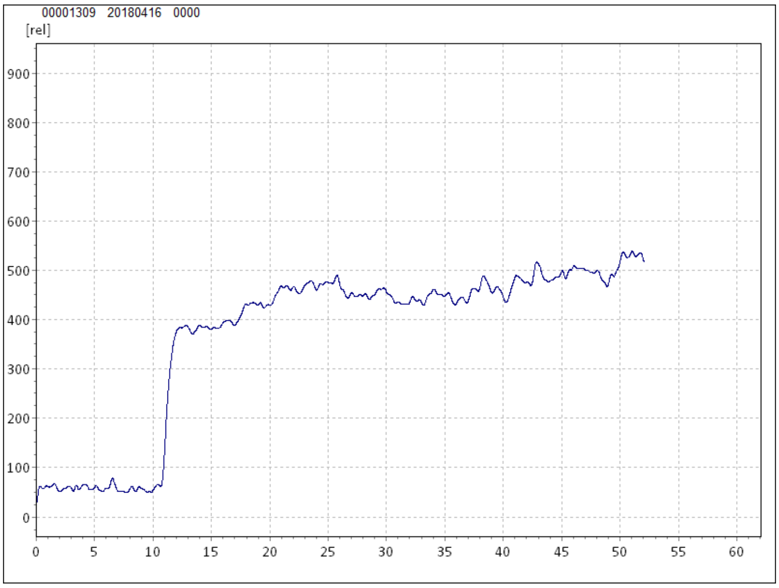


Figure 34 Typical Resistograph resistance profile with depth at the x-axis and drill resistance, measured relative to the idle speed on the y-axis.

In general all experiments with the Resistograph are performed in the test setup as shown in Table 1.

The drilling depth is set to 50 mm, except for the drillings in polyethylene and other plastics which are 6 mm thick. The mean drill resistance is calculated as the mean of the profile from the point that the main cutting edge enters the sample until the moment that the tip leaves the material or until the end[10]. In Figure 34 a typical Resistograph profile is shown, with the measured quantity [rel] on the y-axis and the depth on the x-axis. Here the mean is calculated as the mean value from 13 mm to the end of the profile. In the following subtopics when the aim was to compare different blocks with as much as possible the same properties, the approach of paired samples is used. This means that the samples are slices of the same block but from a different location, lengthwise (Figure 35). By thus selecting the blocks, the grain direction is usually the same, grain orientation is the same and growth conditions were similar. Furthermore the wood pieces are selected to be defect free.

[10] In the case of a blind hole

3.2.1 Influence of the drill bit sharpness

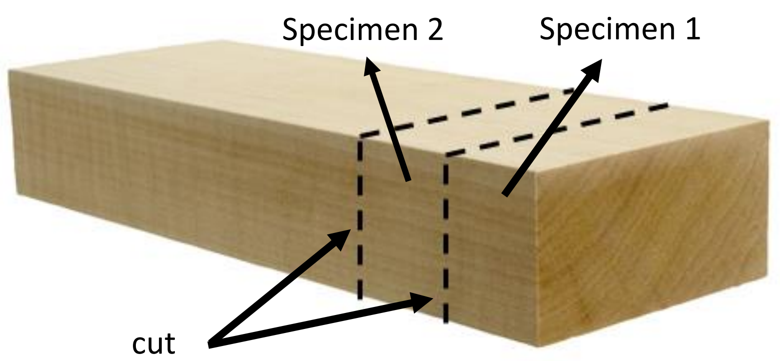


Figure 35 Paired samples illustrative.

To analyse the influence of drill sharpness on the drill resistance an isotropic material is required. Since wood is an anisotropic and non-homogeneous material drilling in a certain piece of wood at a random location is unsuitable for calibration. Therefore plastics, which are (compared to wood) isotropic and homogeneous are used for calibration. A six millimetre thick polyethylene sheet is used for calibration since it has a constant resistance and gives repeatable results. For calibration successive drillings of 50 mm in meranti are followed by a calibration in polyethylene to see if there is an increase of drill resistance with dulling of the drill bit. Additionally the drill bit diameter was measured and the borehole was investigated. To check whether dulling on polyethylene has the same effect as on meranti the same procedure is done with calibration in meranti (although stated above that drilling at a random location is unsuitable for calibration, after applying the procedure of paired specimens the variability is small)[11].

3.2.2 Influence of rotation rate and feed velocity

The rotation rate cannot be set with the Resistograph; therefore only the actual speed is measured and how it changed with changing drill resistance. To measure this a piece of dark tape was attached to the Resistograph chuck, and a tachograph was installed to measure the rotation rate. Then different materials were drilled and the rotation rate was measured. Furthermore the chip thickness of a polyethylene chip, which has a continuous chip, is measured for comparison. The feed velocity cannot be directly influenced and is therefore only analysed, this is done during drilling in different materials. The feed velocity was analysed with a video camera.

3.2.3 Influence of extractives

Testing of the influence of extractives on the drill resistance is not simple since it is difficult to isolate this property. An attempt was made to remove extractives from a block of wood; however, this method only succeeded in removing a small amount of the extractives present. Therefore the approach was changed to remove extractives

[11] It is important to note that the approach of paired specimens requires that the drill location and drill direction in the paired samples are the same.

from shavings. The shavings were obtained from the transverse face of the sample to fulfil the requirement of paired samples. First the shavings of some different wood species; meranti, merbau, sapele and sapupira were analysed. Later on several pieces of meranti of similar density were also analysed (see Table 2). The procedure is shown in the flowchart in Figure 36. After the different steps (conditioning, resistance drilling, oven drying) the mass was determined, the filter tube was also oven dried and its dry mass determined.

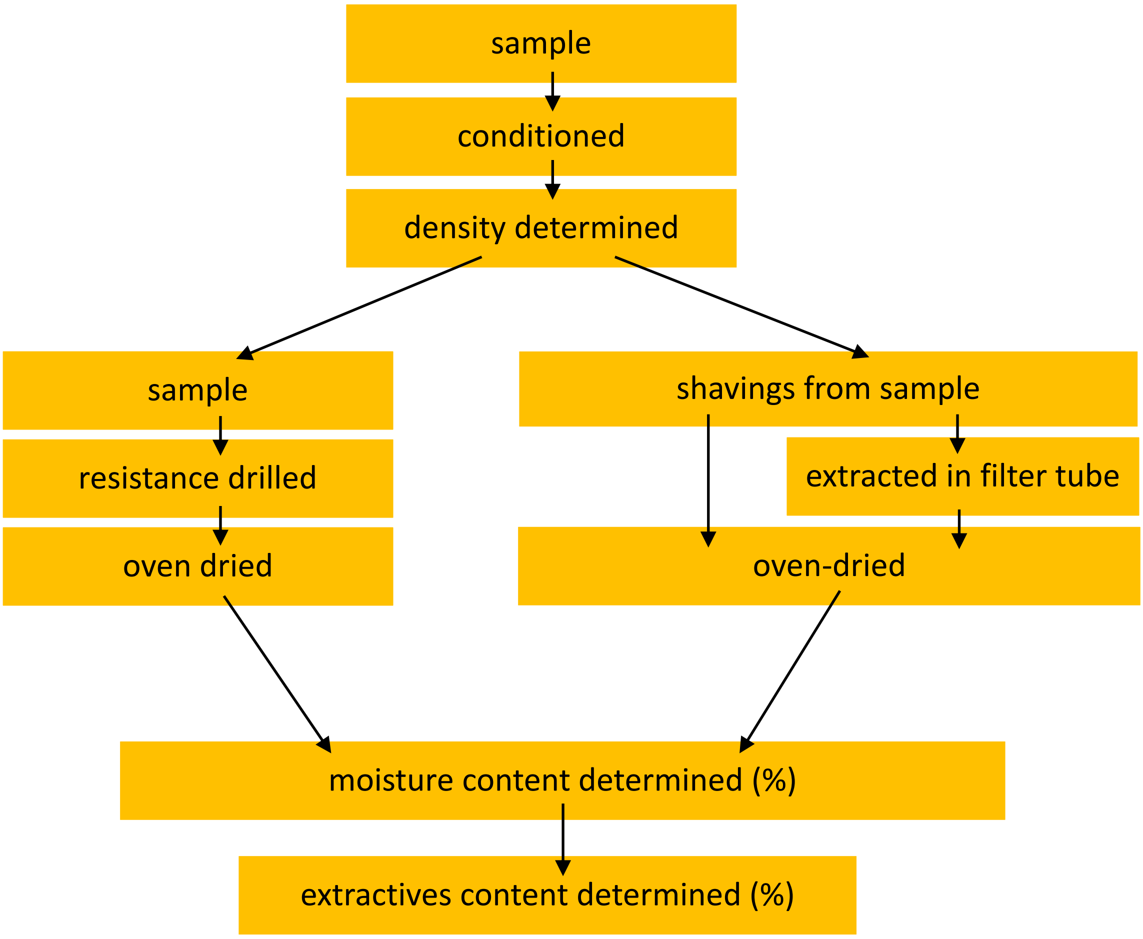


Figure 36 Flowchart of the approach to determine the influence of extractives on the drill resistance

The extraction was mostly done according to ASTM D1105-96 (ASTM, 2001). The extractions were done in a soxhlet extraction apparatus, first with an ethanol-toluene mixture, followed by ethanol and finally with distilled water. In between the extractions (overnight) The samples were stored in a fume cupboard to allow the solvent to evaporate. In the soxhlet extraction apparatus the heated solution (in the distillation flask) evaporates, condenses on the condenser, drips on the samples in the extractor. After the samples are fully submerged and the solution completely fills the extractor, the extractor is emptied by the siphon into the distillation flask. Then the process starts again from heating of the solution to siphoning, for ethanol-toluene and ethanol this process takes place on average five times an hour for six hours. Due to the higher specific heat of water, the process for water only takes place on average two times an hour, therefore this process is continued for twelve hours. The mass fraction of extractives removed is calculated according to equation 11.

$$mass\ fraction\ extractives = \frac{m_b - m_a}{m_a} 100\%, \quad (11)$$

where m_b is the oven-dry mass before extraction (mass of sample minus mass of the moisture in the sample), m_a is the oven-dry mass after extraction.

Each sample is drilled multiple times, the mean drill resistances of these measurements (obtained as explained in section 3.2) were averaged to form the average mean drill resistance.

Table 2 Samples, examined for the determination of the influence of extractives, and their density at 20°C and 65% humidity.

Sample name	Density [kg/m^3]	Wood species
A-06-Me.1	634	meranti
A-12-Me.1	643	meranti
A-12-Me.2	648	meranti
A-09-Me.1	649	meranti
A-15-Me.1	653	meranti
A-09-Me.2	658	meranti
A-57-Me.3	605	meranti
A-36-Sa.3	682	sapele
A-02-Mr.3	923	merbau
A-01-Sap.3	671	sapupira

3.2.4 Influence of Moisture content

The extent of the influence of moisture content on the mechanical properties of tropical hardwoods is not clear from the literature. In order to investigate the influence of the moisture content it is important to isolate this property as much as possible. Therefore again paired specimens were used (see section 3.2) of different wood specie (Table 3). These paired specimens were conditioned in different climates, either in a climate chamber or closed boxes with a saturated salt solution and a forced air flow. The sample just above fibre saturation point reached their moisture content by vacuum impregnation with water for two hours, followed by storage in a desiccator (with xylene[12]) to allow the water to redistribute through the

[12] To prevent wood from decay

material and avoid drying. In the flow sheet (Figure 37) the approach is shown schematically. Each sample is resistance drilled three times to obtain a mean drill resistance for the particular block.

Table 3 Samples, examined for determination of the influence of moisture content, and their density at 20°C and 65% humidity.

Sample name	Density [kg/m^3]	Wood specie
A-25-Me	797	meranti
A-44-Me	651	meranti
A-96-Me	796	meranti
A-97-Me	664	meranti
A-19-Sa	570	sapele
A-01-Mr	877	merbau
A-01-Ta	772	tatajuba

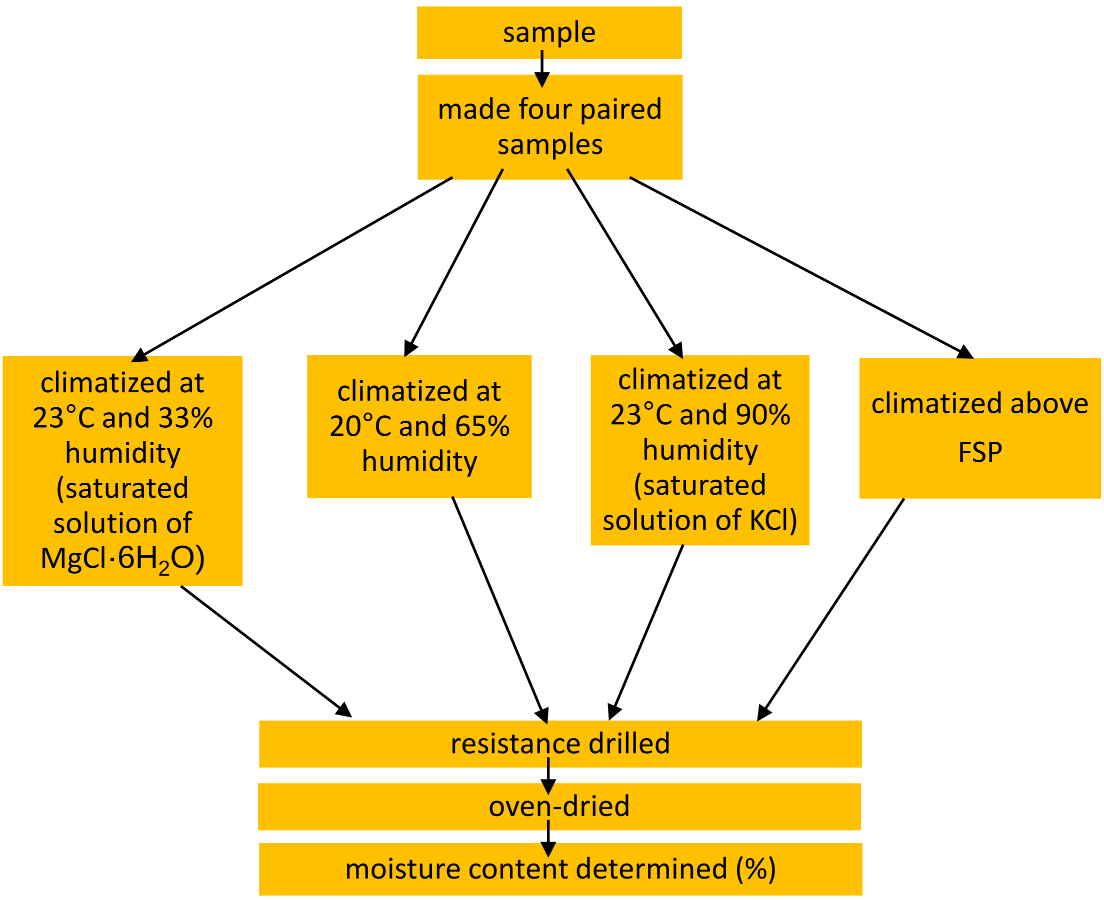


Figure 37 Flowsheet showing the approach used for the determination of the influence of moisture content on the drill resistance.

As is visible in Figure 37, after conditioning the samples are resistance drilled (usually 3 times), the samples conditioned at 23°C and 33% humidity are resistance drilled (3 times) again after oven drying (this is the drill resistance at 0% moisture content). To get the different climates, boxes with a continuous air stream over a saturated salt solution are used. It is important to note that different wood species have a different equilibrium moisture content for a certain climate. It is also important to bear in mind that moisture content is based on density rather than volume, that means a piece of meranti with 12% moisture possibly contains less water than a piece of merbau with the same dimensions and a moisture content of 8%.

3.2.5 Influence of drill direction

The drill direction is often not clear, especially for painted window and door frames, therefore it is necessary to find out to what extent the drill direction influences the drill resistance. Directions relative to the tangential direction (3 conditioned meranti samples) and relative to the grain direction (2 conditioned meranti samples) where evaluated (Table 4). The angles β with the grain and θ with the tangential direction are defined in Figure 38**Fout! Verwijzingsbron niet gevonden.**, β is the angle between the fibre direction and a plane spanned by the tangential and radial direction. Θ is the angle relative to the tangential direction. When drilling relative to the tangential direction (varying θ), β is 90°, upon drilling relative to the grain direction (varying β), θ is not defined.

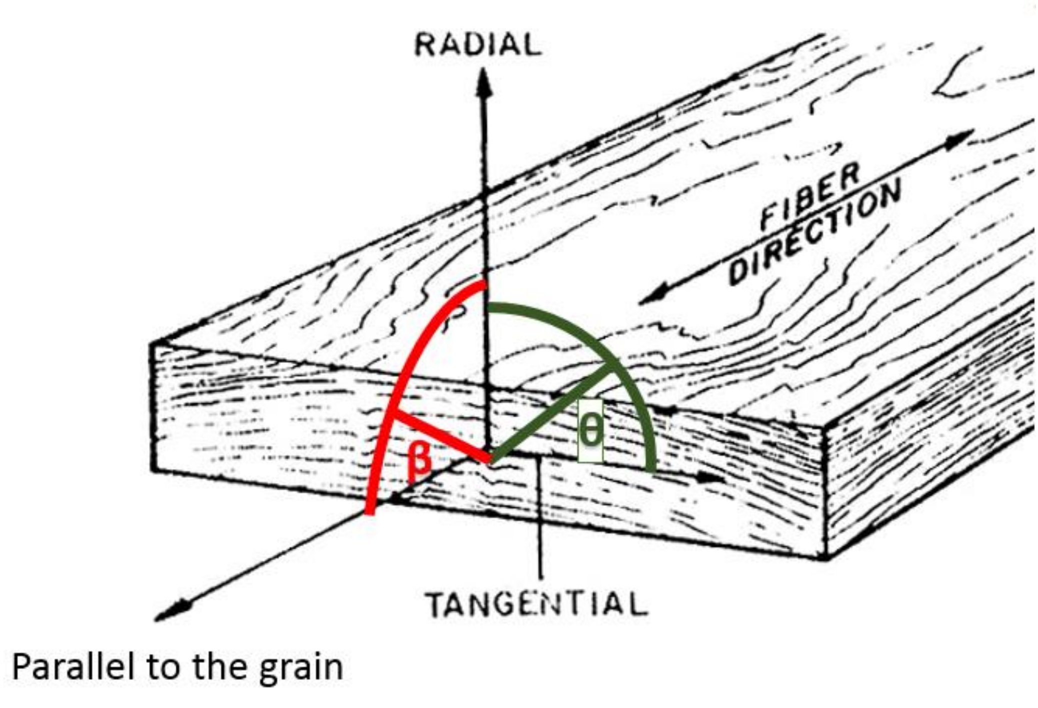


Figure 38 Definition of drilling angles β relative to the grain direction and θ relative to the tangential direction.

For the drill direction relative to the tangential direction; drillings were performed at angles θ of 0°, 30°, 45°, 60° and 90° (see Figure 40). If necessary a flat surface was sawn (perpendicular to the drill direction) to make sure the drill bit was not deflected due to flank contact before the drill tip enters the material.

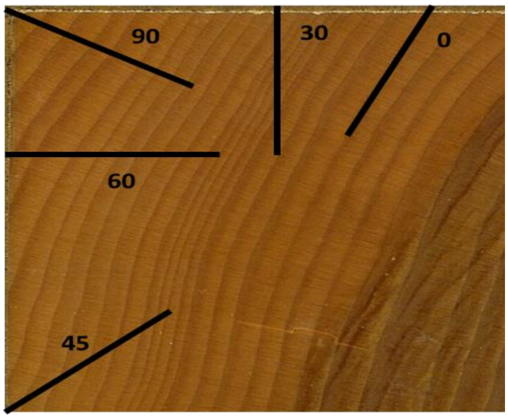


Figure 39 (Transverse plane) drilling direction relative to tangential direction, angles θ represent the angle relative to the tangential direction (tangential direction means parallel with the growth rings).

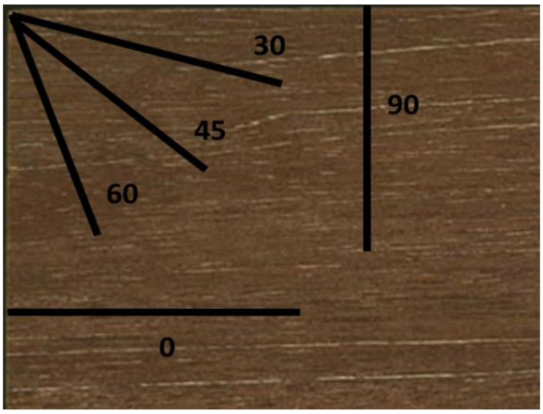


Figure 40 (Radial or tangential plane) drilling direction relative to the grain shown are the angles β where 0° is parallel to the grain and 90° perpendicular to the grain.

For the samples relative to the grain direction; drillings were performed at angles β of 0° (parallel to the grain), 30°, 45°, 60° and 90° (see Figure 40). It is difficult to establish the principle of paired samples for these tests, since with a different drill direction the principle is by definition not fulfilled. After the drillings the actual angle with the grain or tangential direction was measured.

Table 4 Samples examined to determine the influence of the drill direction on the drill resistance

Sample name	Density [kg/m^3]	Wood specie
Relative to the grain		
A-21-Me	581	meranti
A-22-Me	Not determined	meranti
Relative to the tangential direction		
A-19-Me	750	meranti
A-20-Me	753	meranti
A-24-Me	Not determined	meranti

3.2.6 Influence of density

Density can relate to the local density as presented by the Resistograph, but in this study the possibility to relate the drill resistance with the global density has been examined. Seventeen conditioned[13] pieces of meranti of varying density were cut into two. In all these 34 pieces, three drillings were performed, the positions were selected such that the drillings were in different growth rings at different positions and thus are representative for the piece examined. The mean drill resistance of these three drillings was averaged. After thus having made one dataset the pieces were drilled again (with a slightly duller drill) to see whether the results were repeatable. Furthermore different samples of other wood species were drilled and these samples were also conditioned. Finally some drillings were done in plastics to check whether the relationship with density is universal, only applicable to wood or does not exist at all. The plastics examined are shown in Table 5.

Table 5 Drilled plastics with their density

Material	Density [kg/m^3]
Nylon	1144
Foam PVC	475
POM Delrin	1414
Hard PVC	1431
Polycarbonate	1193
Plexiglass	1178
Polyethylene	964

The samples used for the influence of wood density on the drill resistance are in appendix A, here 'Me' in the sample name indicates meranti, 'Mr, Ta, Sa, Ja and Sap' indicates merbau, tatajuba, sapele, jarrah and sapupira respectively.

[13] At 65% humidity and 20°C, the Equilibrium Moisture Content (EMC) at this climate is approx. 12%

4. Results

In this chapter the results of the experiments are shown, starting with the results related to the Resistograph: geometry, sharpness, rotation rate and feed velocity. Then the results related to the wood properties are presented, the most important of which is the relationship with density; also the influence of moisture content, extractives and drill direction are described. Throughout this chapter, boxplots are used for data representation.

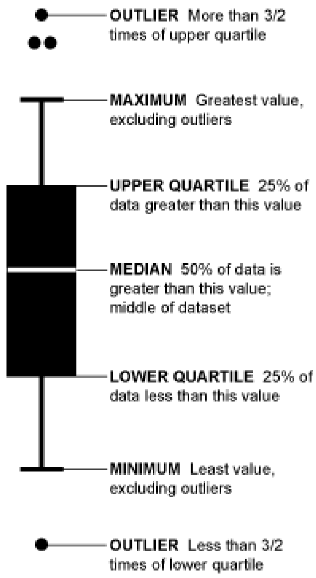


Figure 41 Boxplot (Yau, 2008)

The boxplot consists of a minimum, lower quartile, median, upper quartile and a maximum. Sometimes there are outliers present, Outliers are values that are by definition more than 3/2 times the distance between upper and lower quartile away from either the lower or upper quartile. The box (between lower quartile and upper quartile) gives an indication of where 50% of the data will be. In Figure 41 a boxplot is shown and explained.

4.1 Drill dimensions

The dimensions of the drill bit as measured according to section 2.2.2 are given in Table 6.

Table 6 Dimensions of the Resistograph drill bit.

Tip cutting edge point angle (ρ)	32,5˚
Tip height (e)	0.5 mm
Tip width (w)	0.6 mm (makes a hole of approx. 0.8 mm)
Drill bit taper angle (β)	8˚
Drill bit thickness (t)	0.5 mm
Drill bit radius (R)	1.5 mm
Semimajor cutting edge point angle (k_r)	90˚
Chip thickness (t_c)	Depends on feed velocity and rotation rate
Rake angle (γ)	-2.17˚
Clearance angle (α)	25˚

4.2 Sharpness of the drill bit

A drill bit does not remain sharp during successive drillings; therefore a photograph of the drill bit was made after usage. The pictures are shown in Figure 42 where the initial drill bit with a burr from production is visible (**A**). After one drilling in meranti, the burr is removed (**B**). From the successive figures (**A**-**F**) it becomes clear that the outer edge (flanges) round somewhat resulting in a smaller diameter, and from the light reflection at the main cutting edge it is also clear that this edge dulls. This dulling can also be seen in Figure 42 (**G-I**) with a side view of the drill bit.

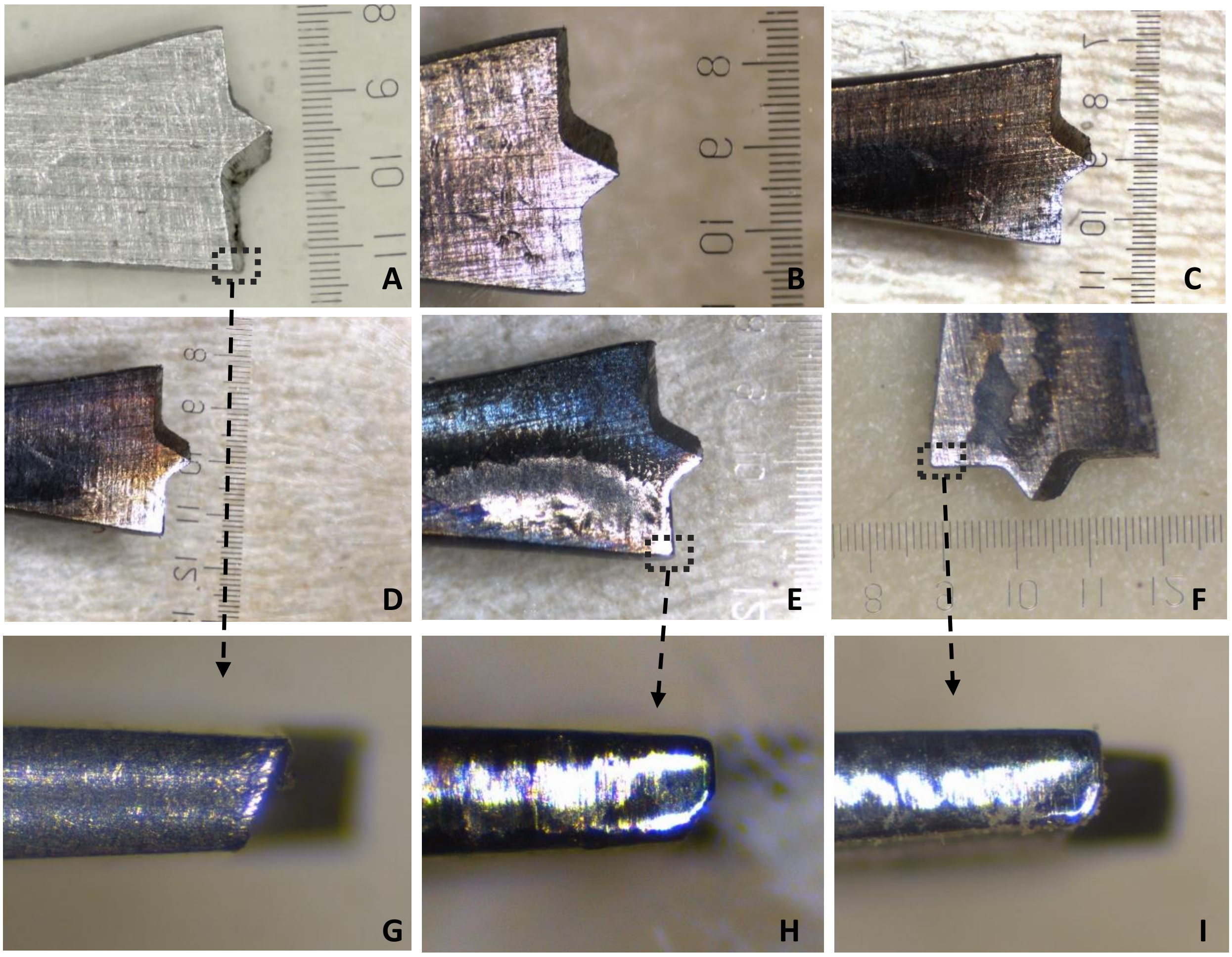


*Figure 42 (**A**) Initial drill bit with burr visible, (**B**) after 5 drillings (**C**) after 50 drillings (**D**) after 90 drillings (**E**) after 90 drillings of 40 mm and 50 drillings of 60mm (**F**) after 90 drillings of 40mm, 60 drillings of 60mm and 5 drillings in bamboo (85mm), 10 drillings in wet Angelim de Campina (70mm) (**G**) side view of initial drill bit (**H**) side view of **E** (**I**) side view of **F**.*

The nose width initially is in the order of 50 µm (analysed with imageJ) and increases up to nearly half the drill bit thickness (250 µm). The drill bit diameter (Figure 43) was analysed from the pictures with ImageJ. It was found that the drill bit diameter decreases (Table 7), this result is supported by measurements with a digital calliper (1.2% decrease in diameter).

Table 7 Drill bit diameter as defined in figure 43.

Distance drilled before measurement	Diameter
Initial	3.09 mm ± 0.01
0.05 m	3.08 mm ± 0.01
0.25 m	3.08 mm ± 0.01
0.75 m	3.08 mm ± 0.01
1.25 m	3.07 mm ± 0.01
2.25 m	3.08 mm ± 0.01
3.75 m	3.08 mm ± 0.01
7.00 m	3.06 mm ± 0.01
7.25 m	3.06 mm ± 0.01

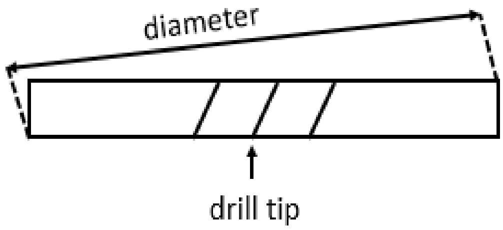


Figure 43 Definition of the drill bit diameter.

It is important to investigate the influence of dulling on the drill resistance, which was tested by drilling into climatized blocks of meranti followed by a calibration after approximately 25 drillings with the depth set to 50 mm (Figure 44). The calibration was performed by measuring the drill resistance of a reference material, either a piece of polyethylene or a conditioned piece of meranti (drilled parallel to the grain or perpendicular to the grain). In Figure 45 the mean drill resistance versus the drilled distance is plotted. The drilled distance is thus the sum of the drilled depth in meranti in between the calibrations. It is visible that the slope for polyethylene and meranti along the grain are steeper compared to meranti across the grain. For meranti across the grain, the slope of the calibration curve is approximately 3 m^{-1}, meaning that the relative drill resistance increases by 3 [rel[14]] every meter drilled. The overall influence of sharpness largely depends on material and drilled distance. For meranti after drilling 5 metres the influence is roughly 3%.

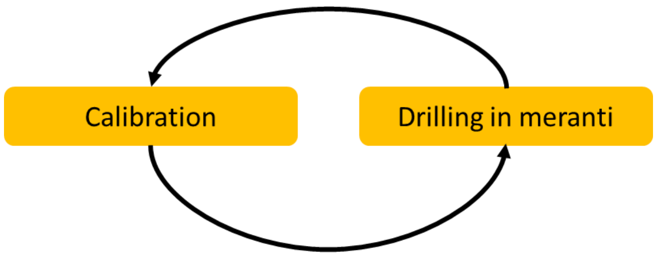


Figure 44 Procedure to test the influence of dulling on the drill resistance.

[14] The manufacturer represent the drill resistance with [rel], a measure of the energy consumption of the continuous rotating motor, relative to the idle power of the motor.

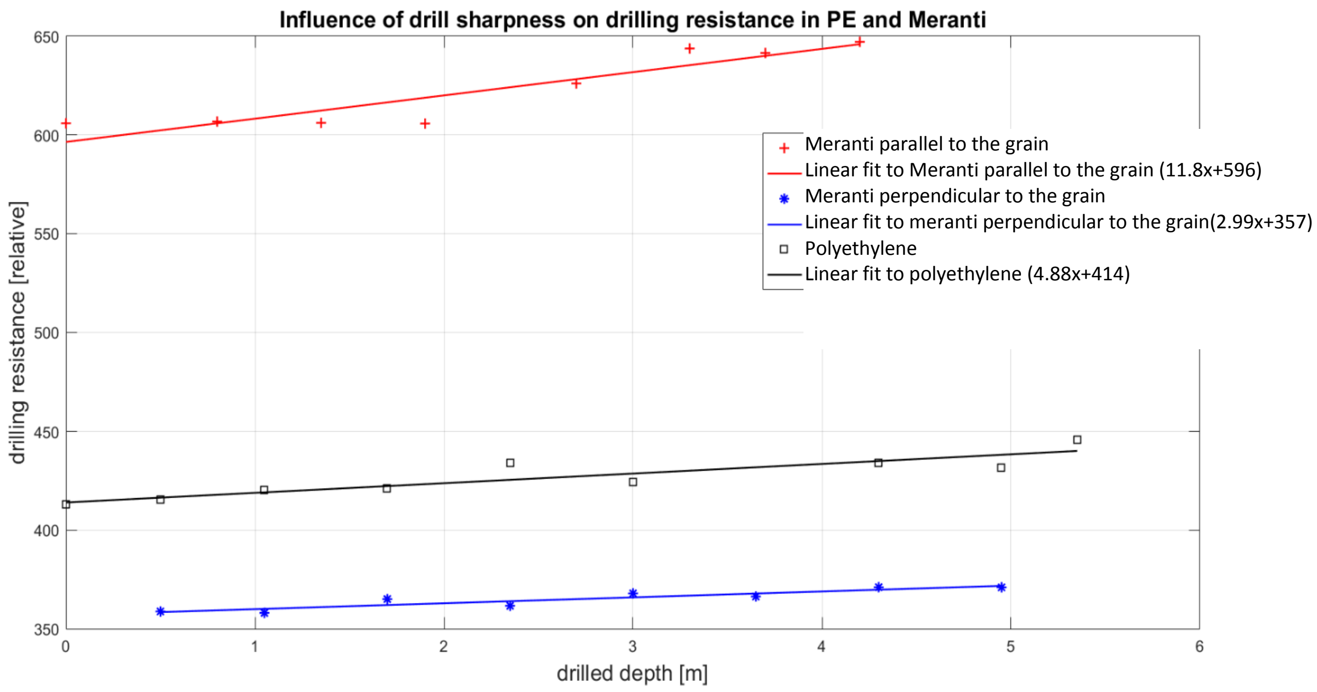


Figure 45 Influence of drill bit sharpness on the drill resistance in polyethylene and meranti (parallel and perpendicular to the grain).

To know what part of the drill bit is responsible for the increased drill resistance and to check whether the theory (stating that it is mainly the main cutting edge) is correct; the main cutting edge of a dulled drill bit was re-sharpened with a hand file. This re-sharpening resulted in a decrease of the drill resistance in polyethylene, honing of the main cutting edge with a whetstone decreases the drill resistance in polyethylene further (around 430 [rel] before and around 360 [rel] after honing). Removing of the drill tip (sanded) did not increase the drill resistance significantly (less than 1% in polyethylene according to Table 8) whereas the thrust increased noticeable[15].

Table 8 Influence of removing the drill tip on drill resistance.

	Drill resistance in PE	Number of measurements
Drill bit	470.3 [rel]	2
Drill bit with tip removed	471.3 [rel]	2

During testing two unexpected points arose (1) there exists some difference between the initial needle drills, in polyethylene several new drill bits showed a resistance

[15] Not measured but noticed upon drilling.

difference up to approx. 5% (see Table 9); and (2) for calibration in polyethylene, the spread increases with dulling of the cutting edge.

Table 9 Variation of new drill bits in drilling polyethylene.

	Drill resistance in PE	Number of measurements	Number of drill bits tested
Initial drill bit	408.9 ± 11.1[rel]	5	3

Figure 46 (**A**) shows two opened bore holes; left is drilled with the new sharp drill bit and right after approximately 180 drillings of 50 mm depth. The surface of the hole drilled with the eroded drill bit is slightly rougher. Pictures taken from the drill entry revealed upon evaluation a slightly decreased borehole diameter (**B**), approximately 3.25 mm for a sharp drill bit and approximately 3.2 mm for an eroded drill bit (analysed with ImageJ). The sawdust (**C**) collected from the boreholes do not show a consistent size nor shape. The chips from the eroded needle drill do not differ visible from the chips of the sharp needle drill.

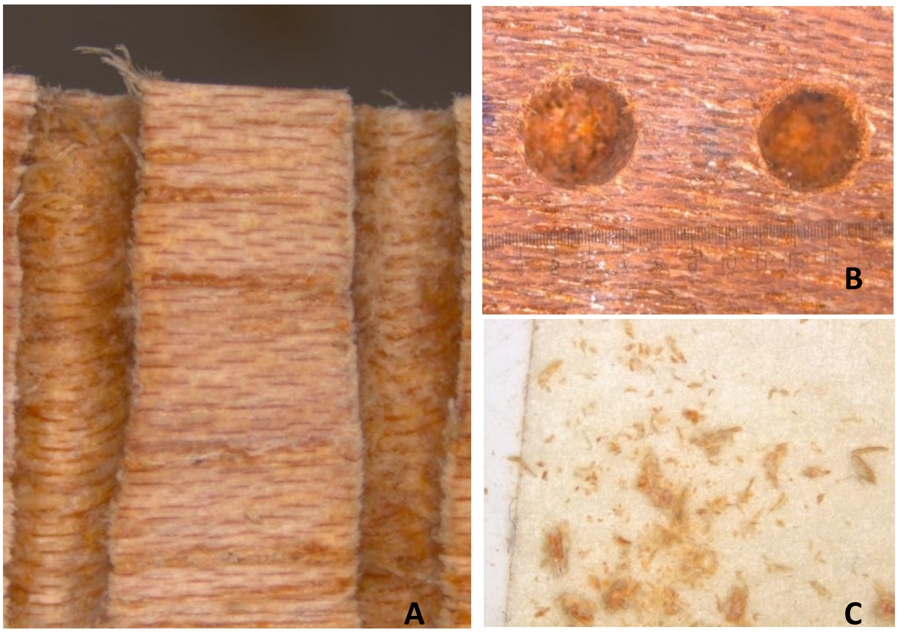


*Figure 46 (**A**) Opened borehole with sawdust removed, sharp left and eroded right (**B**) Bore entry (sharp left eroded right) (**C**) Chips collected from borehole.*

4.3 Rotation rate and feed velocity

Evaluation of the influence of the drill resistance on the rotation rate is tested with plastics of different densities. Figure 47 shows that the rotation rate decreases with increasing drill resistance. The difference in rotation rate is around 5% between high plexiglass or polycarbonate and foam. The no load speed is approximately 12000 rpm. Regarding the feed velocity, initially there is some scatter in the result, this is obvious at the start; then the feed velocity is fairly constant as is visible in Figure 48. The feed velocity does not change much with drill resistance. it is fairly constant at approximately 7.4 mm/sec.

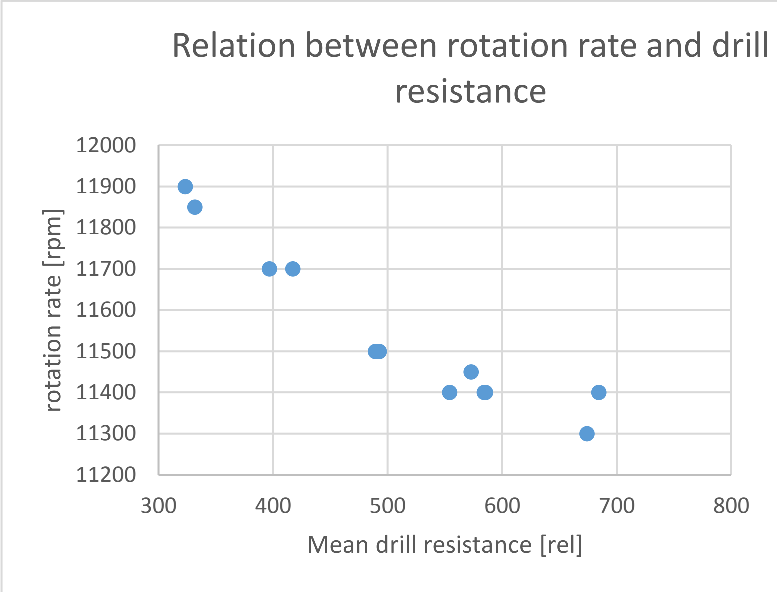


Figure 47 Change of rotation rate with drill resistance; upon drilling sheets of plastic with different densities.

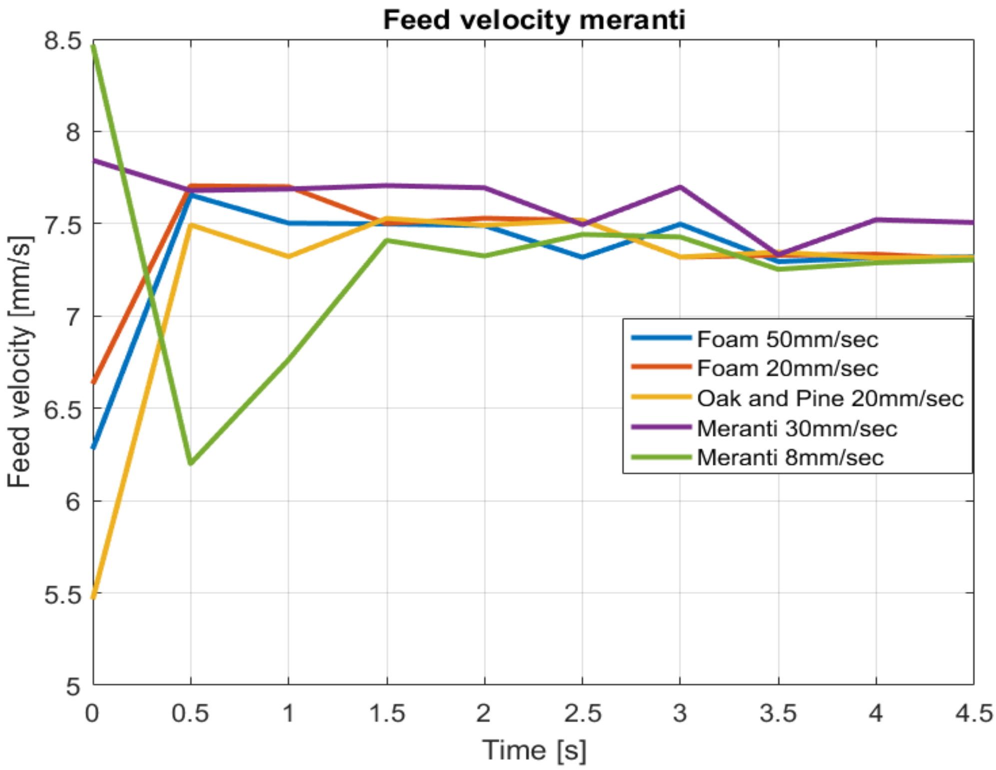


Figure 48 Feed velocity upon drilling different materials. In the legend the feed speed as set on the machine is shown, however this does not influence the actual feed speed as is clearly visible in the graph.

4.4 Influence of density

Establishing a relationship between density and the drill resistance is the aim of this study. As is shown in Figure 49 such a relationship is to a certain extent present for plastics. A certain increase in drill resistance is visible with increasing density but this does not result in a clear trendline. Some plastics, more specifically: PVC sheet, plexiglass and polycarbonate showed some melting and corresponding clogging upon drilling. If we ignore these, a more linear relationship arises; however nylon lies outside this line. The plastics and corresponding densities are shown in Table 5 in section 3.2.6.

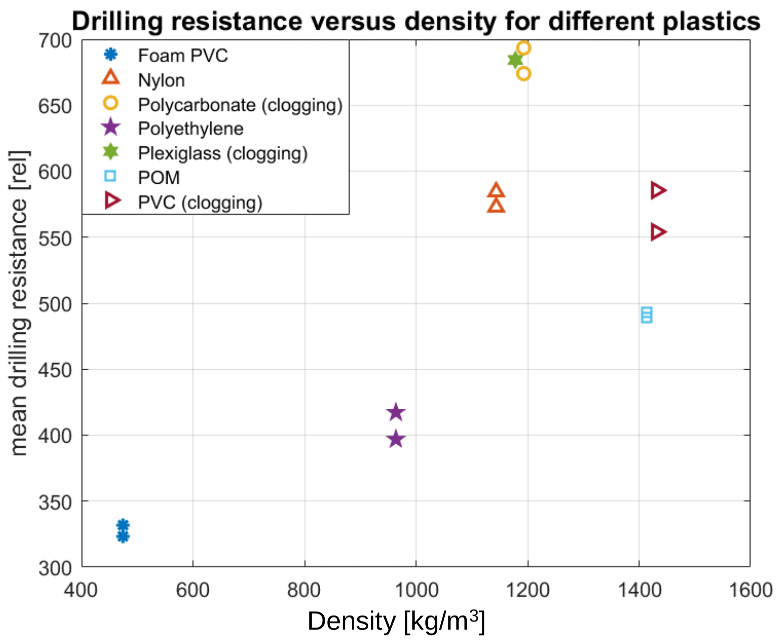


Figure 49 Mean drill resistance for different plastics

To obtain the relationship between drill resistance and density for meranti, 34 conditioned meranti pieces of known density were drilled. In Figure 50 the mean drill resistance, corrected for the sharpness of the drill, (a detailed explanation about the

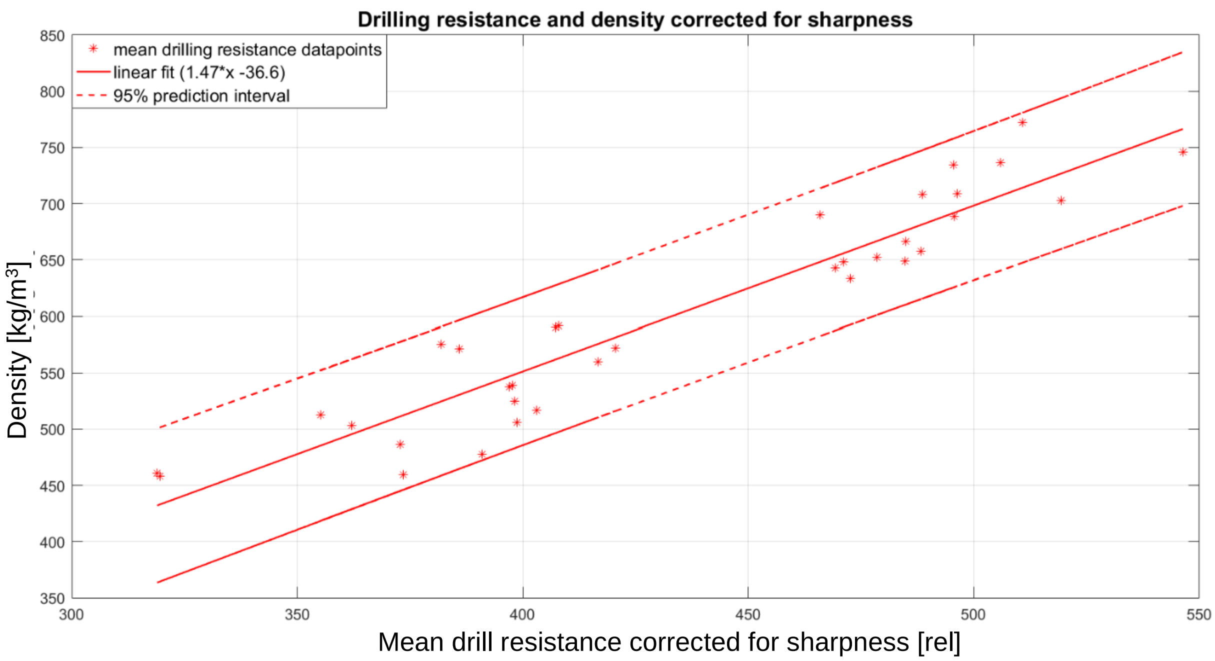


Figure 50 Mean drill resistance of conditioned meranti pieces corrected for sharpness versus density. The red line is the linear regression line.

correction for sharpness is given in section 5.1.2) is plotted as function of the density [kg/m^3]. Each datapoint in Figure 50 represents the mean drill resistance of 3 measurements. A Linear least squares regression is performed which results in equation 12

$$Density = 1.47x - 36.6, \qquad (12)$$

where x is the mean drill resistance.

Also shown in Figure 50 is the 95% prediction interval, which gives a 95% possibility a new measurement will be inside this region. The 95% prediction interval is given in equation 13:

$$\hat{y}_0 \pm t_{n-p}^{a/2} \hat{s}_e \sqrt{1 + \frac{1}{n} + \frac{(x^* - \hat{x})^2}{(n-1) * s_x^2}} \qquad (13) \qquad \text{(Leininger, 2013)}$$

where $\hat{y}_0$ represents the estimated response value for x^* based on the linear regression, t is the statistical value to correct for sample size and needed accuracy (95% prediction interval or 99%). $\hat{s}_e$ represents the standard deviation of the residuals, $\hat{s}_x$ is the standard deviation of the x-values. $\hat{x}$ is the average x-value and n is the number of samples.

After applying the linear least squares regression to the drill resistances obtained and plotting the corresponding calculated density against the measured density, Figure 51 is obtained. Figure 51 shows the same dataset as Figure 50 but this time the density, calculated based on the linear regression line, is plotted on the x-axis.

It is visible that the 95% prediction interval has approximately 70 kg/m^3 offset from the linear fit.

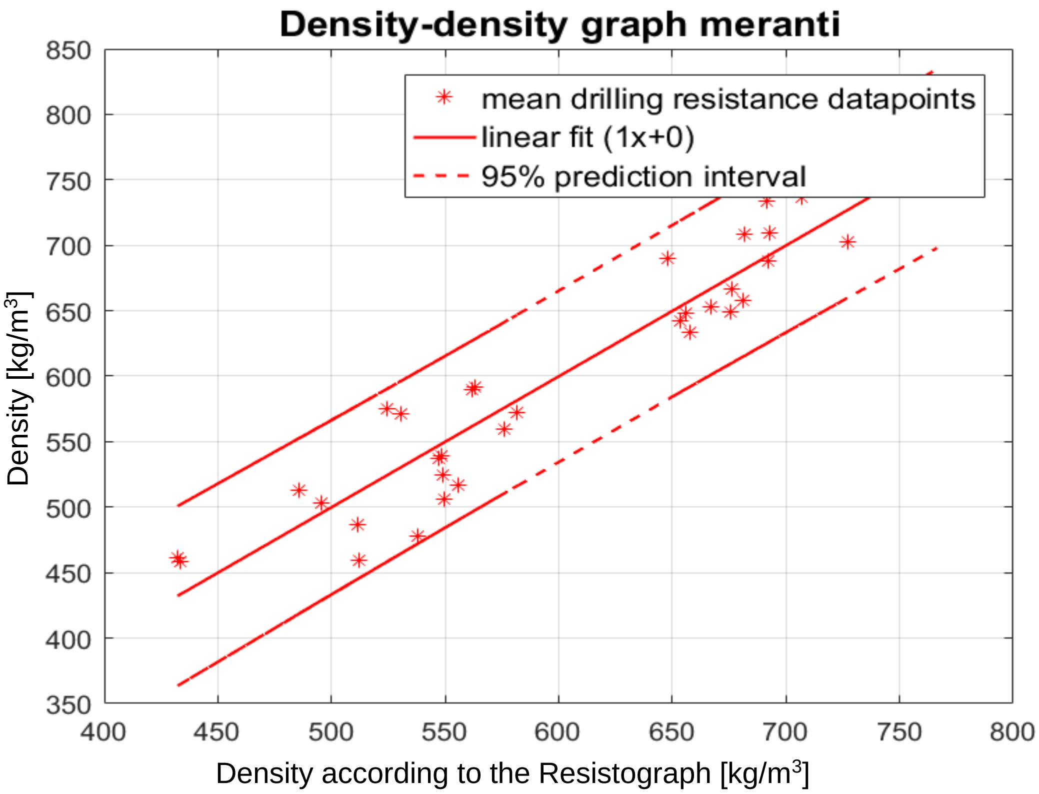


Figure 51 Calculated density versus the density obtained by measuring the dimensions and mass.

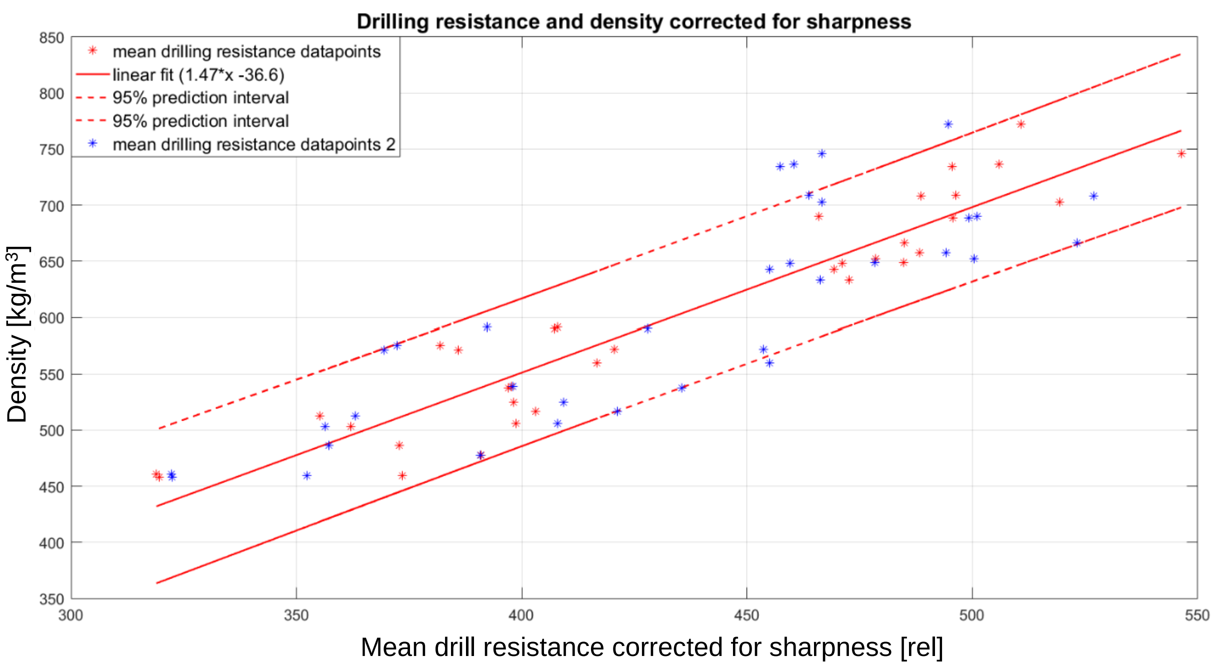


Figure 52 Verification of the regression and prediction interval, data 1 and 2 are the same samples, but drilled with a different drill bit sharpness.

The samples were drilled again for verification. For this second dataset the needle drill was less sharp. The mean drill resistance for the first and second dataset are plotted with red and blue stars respectively in Figure 52. The scatter of the mean drill resistance is larger in the second dataset where more than 5% of the new drillings lie outside the prediction interval. In this second test the mean drill resistances were again corrected for sharpness. The regression lines for the second dataset is given by equation 14.

$$1.37x + 11 \qquad (14)$$

This seems different from the regression line obtained for the first dataset however, the lines are close to each other and the maximum distance between both regression lines is 14 kg/m^3.

To check whether other wood species behave similarly to meranti and follow the same regression line; some other wood species were tested and their drill resistance (corrected for sharpness) is plotted as a function of the density with the calibration line of meranti in Figure 53 andFigure 54. The blocks were conditioned.

For tropical hardwoods (Figure 53) it is clearly visible that sapele is comparable to meranti, merbau has a lower resistance compared to meranti, but tatajuba, sapupira and jarrah have a higher drill resistance.

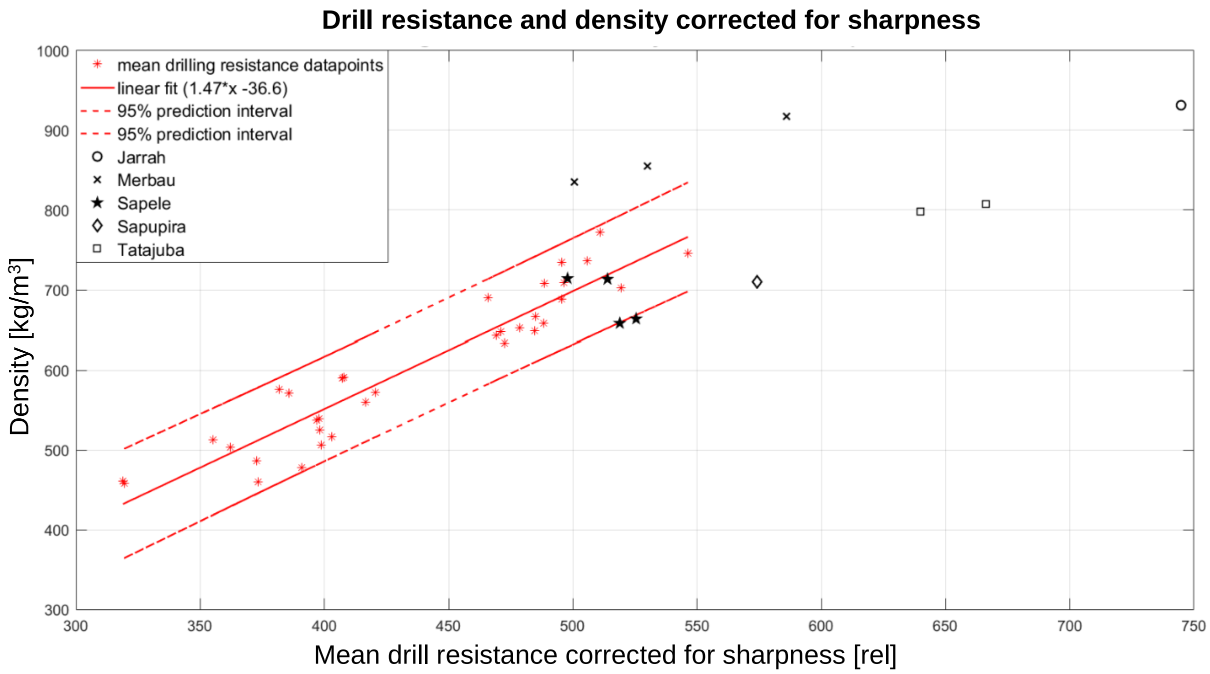


Figure 53 Drill resistance of other wood species compared to meranti, each mark in the graph represents the mean drill resistance of multiple drillings (usual three) in one sample.

Some European woods are close to the calibration curve obtained for meranti as is clearly visible in Figure 54; although oak, robinia and redcedar deviate from the calibration line. One sample of pine also deviates, however this sample is sapwood.

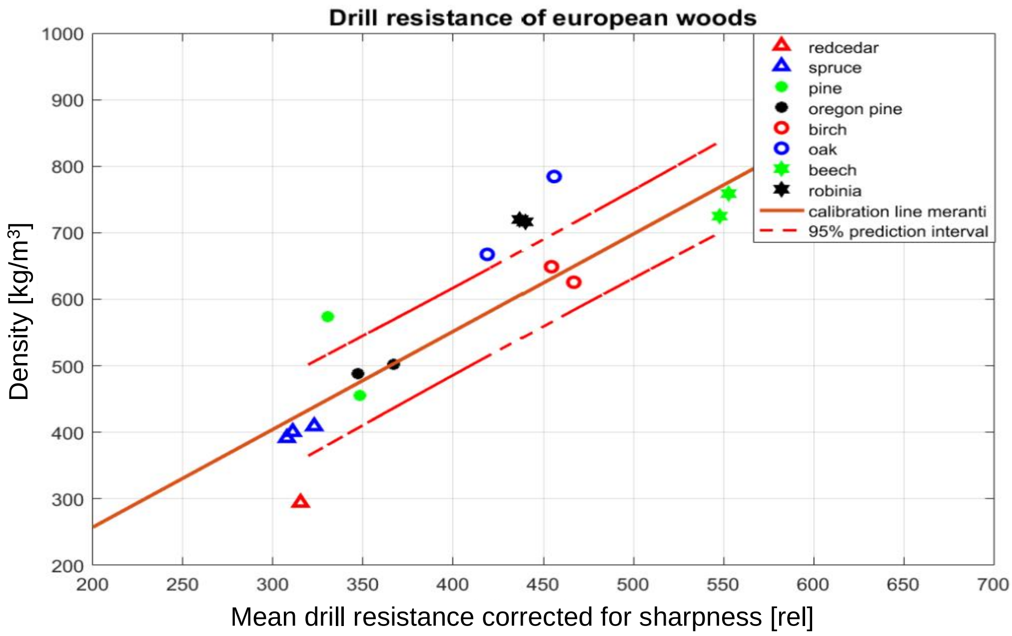


Figure 54 Drill resistance of conditioned European woods plotted with the calibration line and prediction interval of meranti. Each mark in the graph represents one sample, and is the mean drill resistance of multiple (usual three) drillings in that sample.

4.5 Influence of extractives

To investigate the influence of extractives on the drill resistance it is important to isolate this influence as much as possible. The samples used are conditioned samples of meranti. In Figure 55 the deviation from the expected drill resistance is plotted as a function of the mass fraction of extractives; in Table 10 the conditions of the specimens are presented. As is visible, the samples have similar densities. There are six samples used of four different meranti blocks.

In Figure 55 and Figure 56 the quantity on the y-axis is calculated according to equation 15

$$Dev = \frac{(R_m - R_c)}{R_c} 100\%, \qquad (15)$$

where Dev is the deviation from the expected drill resistance. R_m is the mean drill resistance, and R_c is the resistance as expected if it was a meranti piece, so calculated based on density according to the regression line obtained in Figure 50. From Figure 55 it is evident that the influence of extractives (for meranti) is small and it cannot be clearly concluded whether it increases, decreases or does not influence the drill resistance. The different samples deviate from the expected drill resistance, however there is no clear pattern and the spread is large.

Table 10 Samples, respective mass fraction extractives (% of dry mass), density and number of measurements used for Figure 55

Sample name	Mass fraction extractives [%]	Number of measurements	Density
A-06-Me.1	3.8	2	633
A-12-Me.1	5.0	3	642
A-12-Me.2	4.9	3	647
A-09-Me.1	6.3	3	648
A-15-Me.1	11.6	3	652
A-09-Me.2	5.1	3	658

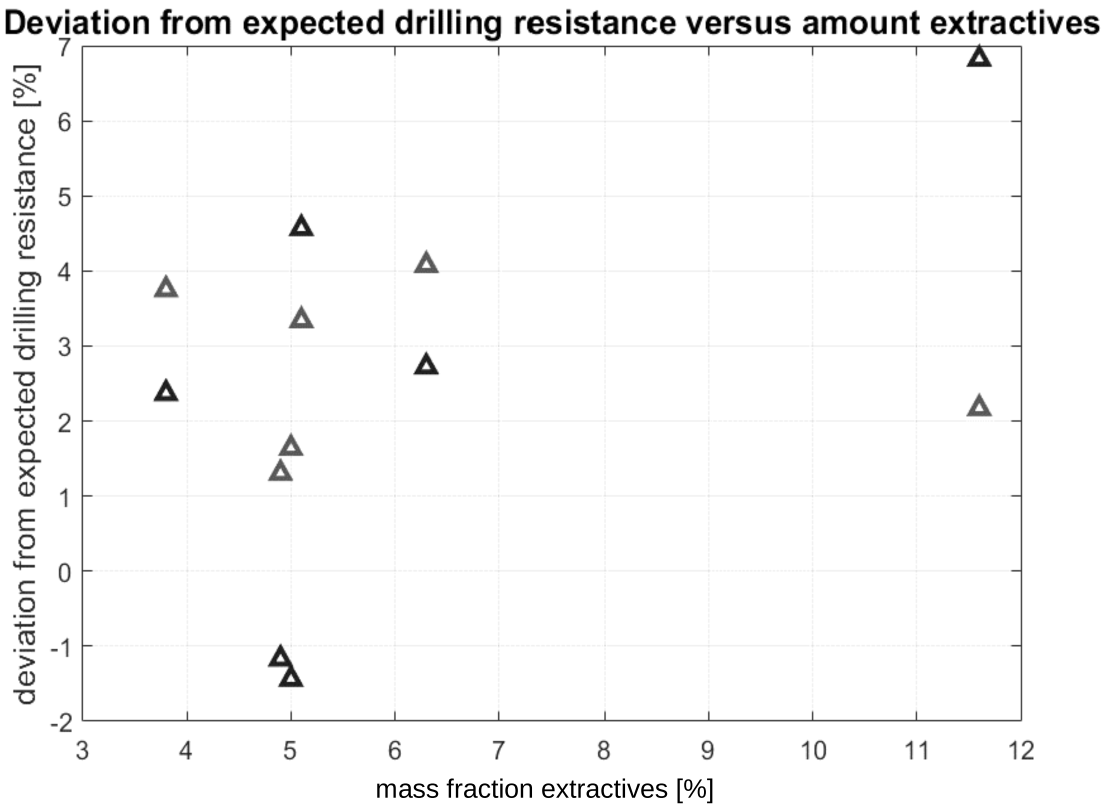


Figure 55 Influence of mass fraction extractives (% of dry mass) on drill resistance for meranti each datapoint is the mean drill resistance of one drilling in a sample.

In the results of Figure 55 only meranti samples are used, therefore the difference in mass fraction extractives is small. To broaden this, other wood species with a higher extractives content were selected: conditioned samples of merbau, meranti, sapele and sapupira. In Figure 56 the deviation from the expected drill resistance is plotted as a function of the mass fraction extractives. The density and mass fraction extractives of each specimen (of Figure 56) are shown in Table 11.

Table 11 Samples, respective mass fraction extractives (% of dry mass), density and number of measurements used for Figure 56.

Sample name	Mass fraction extractives [%]	Number of measurements	Density
A-57-Me	8.9	2	597
A-36-Sa	8.3	2	685
A-02-Mr	22.8	3	923
A-01-Sap	12.1	2	671

In common with tropical wood species, there is no clear relationship between the mass fraction extractives and the drill resistance. Sapupira has a high mass fraction extractives and shows a high drill resistance (more than 15% higher than the expected drill resistance) whereas merbau has over 20% extractives and a low drill resistance (around 15% lower than the expected drill resistance).[16]

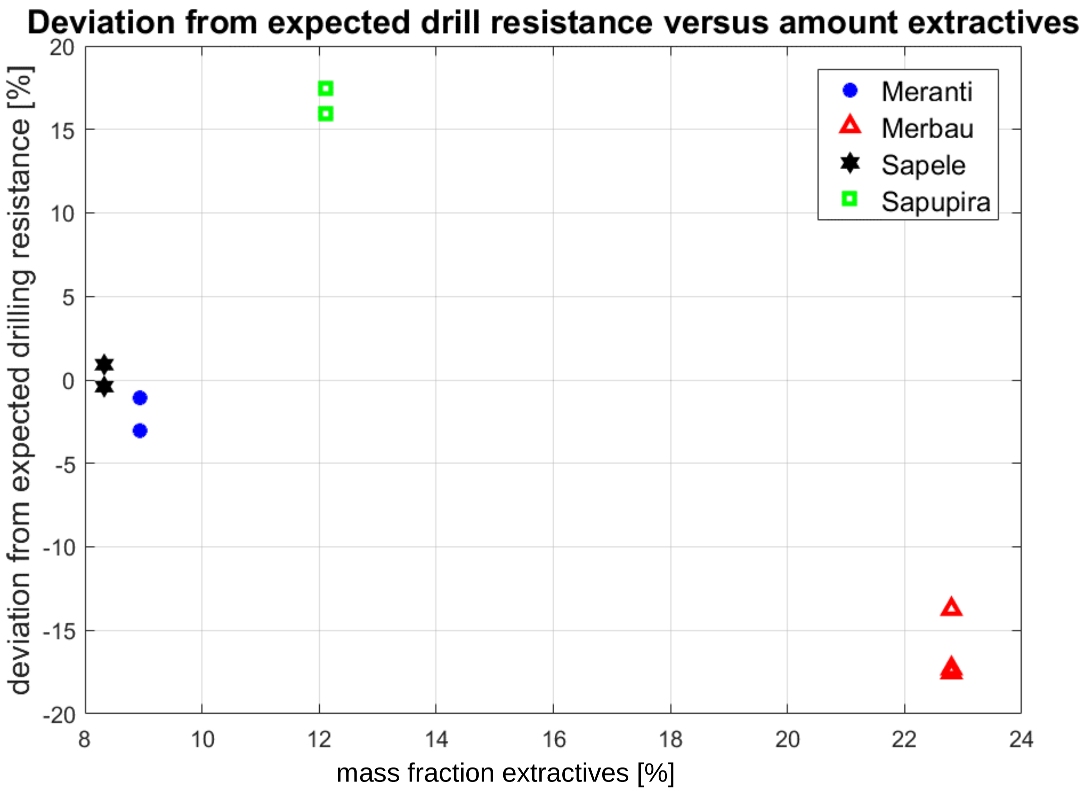


Figure 56 influence of the mass fraction extractives (% of dry mass) on the drill resistance for different tropical wood species.

4.6 Influence of moisture content

The influence of moisture content reveals a general pattern. In Figure 57 the medians of all results are shown with the spread presented in a boxplot. In order to create a boxplot the moisture contents are grouped in bins. The quantity on the y-axis is calculated according to equation 16.

$$Difference = \frac{R_{x\%\,mc} - R_{8\%\,mc}}{R_{8\%\,mc}} 100\%, \qquad (16)$$

[16] The deviation from the expected drill resistance of merbau and sapupira is also visible in Figure 53

where R indicates the mean drill resistance and mc is the abbreviation for moisture content. The value obtained represents the deviation in percent of the drill resistance from a chosen reference point (mean drill resistance at 8% moisture content).

In general following the median (Figure 57) there is an increase of drill resistance from 0 to approx. 12% mc, then the drill resistance decreases between 12% and approximately 20% mc. The samples conditioned above the fibre saturation point give a less clear picture. The deviation in the results is large not only between wood species, but also between different samples of the same wood species. For some samples conditioned above fibre saturation point, the extractives moved to the surface (Figure 58).

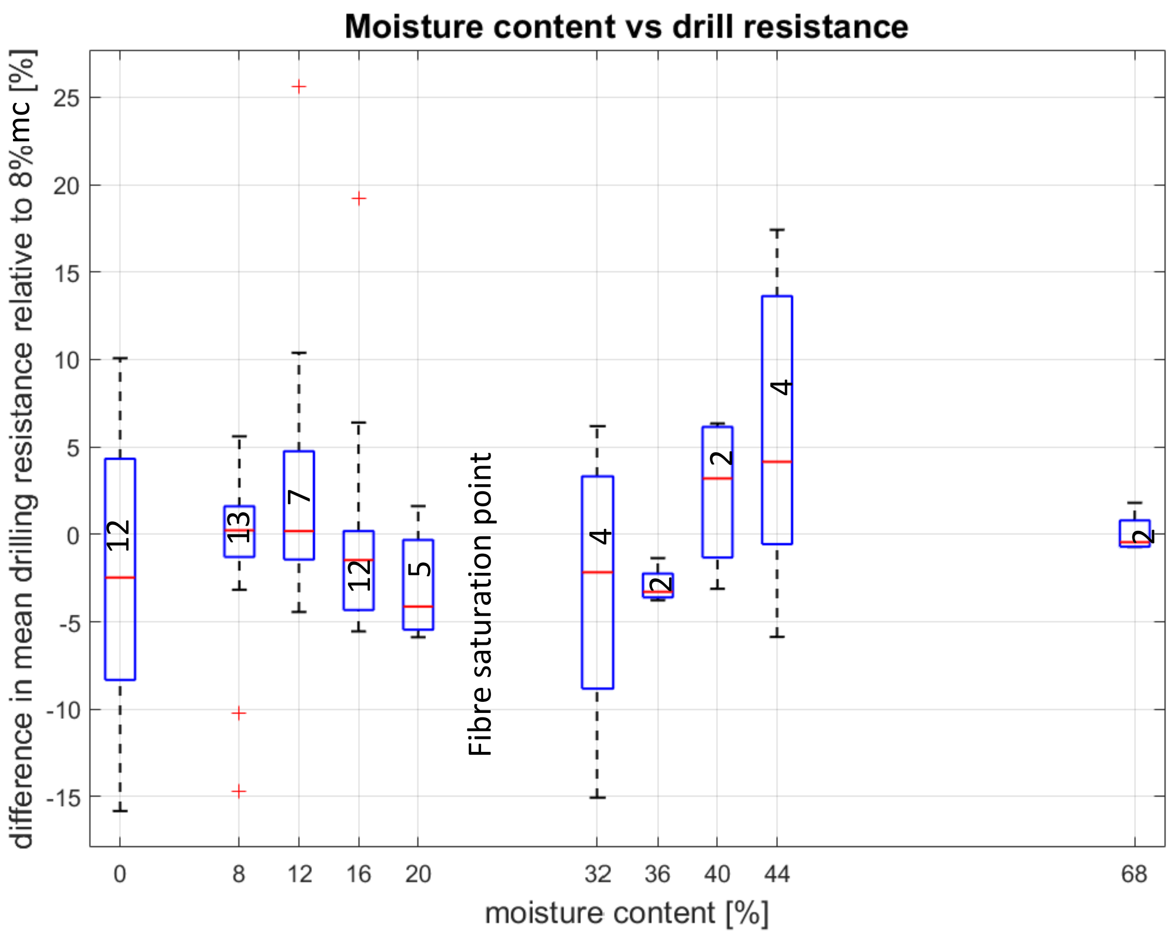


Figure 57 Influence of moisture content on drill resistance, the numbers in the boxes indicate the number of measurements between the higher and lower quartile..

Especially the oven-dried samples and those above the fibre saturation point at 32% and 44% moisture content have large deviations. The number of samples and the number of measurements in each bin is given in Table 12.

Table 12 Number of samples and number of measurements for Figure 57

Moisture content of bin	No of samples in the bin	No of measurements
0%	7	24
8%	7	29
12%	4	16
16%	6	25
20%	2	9
32%	2	8
36%	1	4
40%	1	4
44%	2	8
68%	1	4

Figure 58 extractives moved to surface (above)

In Table 13 the equilibrium moisture content (EMC) for the samples subject to different climates are shown, (above fibre saturation point and after oven-drying there is no EMC and the moisture content is given). In the sample name, 'Me' are meranti samples whereas 'Sa, Mr and Ta' are sapele, merbau and tatajuba respectively.

Table 13 Samples and their respective moisture content

Sample name	EMC at 23°C and 33% relative humidity	EMC at 20°C and 65% relative humidity	EMC at 23°C and 90% relative humidity	mc above fibre saturation point	mc after oven-drying
A-25-Me	8.4	13.9	16.7	44.6	0
A-44-Me	8.3	14.5	18.0	43.3	0
A-96-Me	8.5	15.1	18.1	34.5	0
A-97-Me	8.1*	11.0	14.5	40.9	0
A-19-Sa	9.7	14.3*	16.5	66.1	0
A-01-Mr	8.6	9.9	12.6	30.1	0
A-01-Ta	8.3	11.0	14.8	32.0	0

The values in Table 13 marked with a '*' are not considered further since the condition of paired specimens was not met, or a little defect (small knot) was found in the sample.

As is visible in Figure 57 that the drill resistance changes with moisture content, especially in the region from 8% to 20% moisture content, but the question arises as to whether this difference is significant? A pooled T-test can be used to access significance if it can be assumed that the data is normal distributed and the samples are independent. First an F-test is applied to check if the variance between the two series correspond, followed by a T-test, the statistics used in this chapter are based on de Brouwer and Langen (1996)[17]. Each F-test starts with a null hypothesis given in equation 17.

$$H(0):\ s_1^2 = s_2^2, \tag{17}$$

where s_1 and s_2 are the standard deviation of the first and second series respectively (equation 18)

$$s = \sqrt{\sum \frac{(x_i - \bar{x})^2}{n-1}}, \tag{18}$$

where n are the number of samples, x_i the individual measurement and $\bar{x}$ the mean of the measurements. The F-test is in equation 19.

$$F_{n_1-1,n_2-1} = \frac{s_1^2}{s_2^2} \tag{19}$$

If F is larger than a critical value (for the number of specimens and confidence interval) than the null hypothesis is rejected, and the pooled T-test cannot be used. A non-pooled T-test is then required.

Table 14 Calculation of F-test whether variances are statistically different.

	8% mc	20% mc
Mean μ	-0.15 [%]	-3.13 [%]
Standard deviation s	4.06	2.61
Number of samples n	29	9
$F_{critical}$ 95% confidence interval	3.9 (Heagerty, 2004)	
$F_{29,9}$	$4.06^2/2.61^2=2.43$	

Since $F_{29,9}$ is smaller than $F_{critical}$ the pooled T-test can be applied.

For the pooled T-test the first step is a null hypothesis; the means of 8% equals the mean at 20% moisture content (equation 20).

$$H(0): \mu_1 = \mu_2 \tag{20}$$

[17] The rectification of the article is also considered

The alternative hypothesis is that mean at 8% is larger than the mean at 20% (equation 21), this results means a one-sided interval.

$$H(1) : \mu_1 > \mu_2 \qquad (21)$$

So the null hypothesis is this time that the averages of the two series are equal. The pooled T-test is based on the pooled standard deviation (s_p) (equation 22)

$$s_p = \sqrt{\frac{((n_1 - 1)s_1^2 + (n_2 - 1)s_2^2)}{(n_1 + n_2 - 2)}} \qquad (22)$$

The pooled T-test is given by equation 23. If the pooled t value is larger than a critical (student's) t; the null hypothesis is rejected with 95% confidence in favour of the alternative hypothesis.

$$t_{n_1+n_2-2} = \frac{|\bar{x}_1 - \bar{x}_2|}{s_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \qquad (23)$$

Table 15 calculation of the T-test for the hypothesis that the means of the first and second series are equal.

	first series 8% mc	Second series 20% mc
Mean $\bar{x}$	-0.15 [%]	-3.13 [%]
Standard deviation s	4.06	2.61
Number of samples n	29	9
Pooled standard deviation (s_p)	4.71	
Degrees of freedom	36	
$t_{critical}$ one tailed 95% confidence interval	1.69 (San Jose State University, 2007)	
t_{36}	1.65	

Since according to Table 15, t_{36} is smaller than $t_{critical}$ the null hypothesis cannot be rejected, meaning that the assumption that the drill resistance at 8% equals the drill resistance at 20% cannot be rejected with 95% confidence.

4.7 Influence of drilling direction

The influence of the orientation of the wood piece relative to the drilling direction has been studied. The differences in mean drill resistance for different angles relative to the tangential direction is shown in Figure 59. The difference in mean drill resistance (Div_{dir}) is calculated according to equation 24 and is relative to the resistance in the tangential direction.

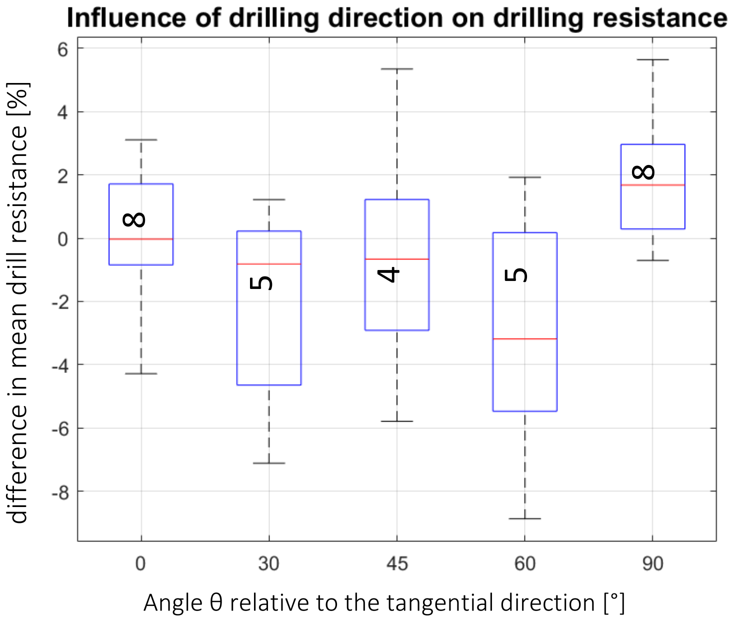


Figure 59 Influence of drill direction relative to the tangential direction on the drill resistance. The numbers in the figure indicate the number of measurements in a box

$$Div_{dir} = \frac{R_{a^\circ} - R_{0^\circ}}{R_{0^\circ}} 100\%, \qquad (24)$$

where R is the mean drill resistance. The drill direction (tangential or radial) does not have a significant influence on the drill resistance. The drill resistance seems to be smaller for θ is 60°, this effect is due to one specimen (A-19-Me).

Table 16 Samples and number of drillings for figure 52

Sample name	No. drillings at θ = 0°	No. drillings at θ = 30°	No. drillings at θ = 45°	No. drillings at θ = 60°	No. drillings at θ = 90°
A-19-Me	7	7	3	7	8
A-20-Me	7	4	3	4	6
A-24-Me	3	0	3	0	3

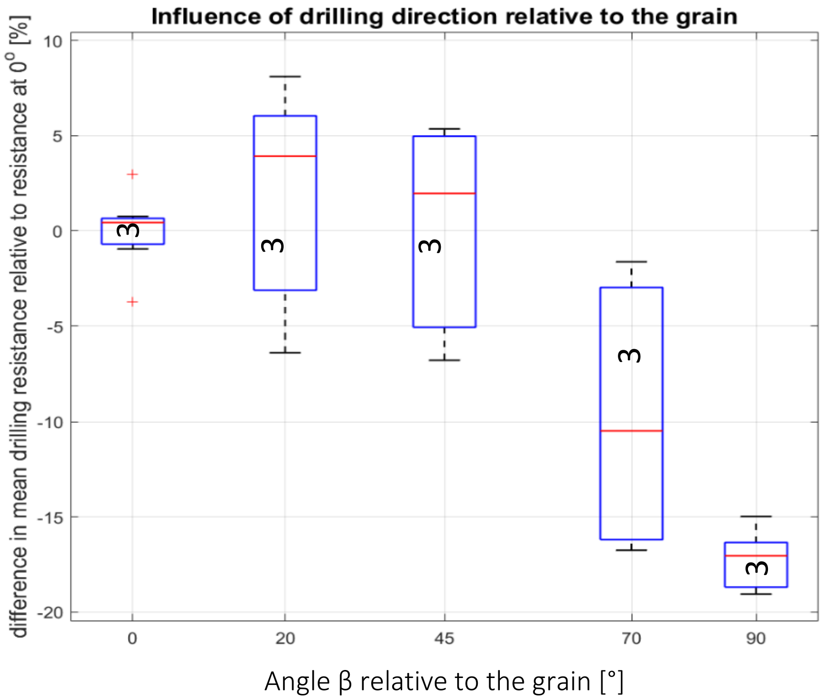


Figure 60 Two conditioned pieces of meranti drilled multiple times at different angles (β) relative to the grain direction. The numbers indicate the number of measurements in a box.

For two specimens also multiple drillings were performed at a specified angle to the grain. Figure 60 shows the relative mean drill resistance versus angle relative to the grain direction ($Div_{dirgrain}$), calculated according to equation 25.

$$Div_{dirgrain} = \frac{R_{grain\ a°} - R_{grain\ 0°}}{R_{grain\ 0°}} 100\%, \qquad (25)$$

where R is the mean drill resistance. The y-axis shows the percentage difference between the drill resistance at a certain angle and the mean drill resistance at an angle 0° to the grain

Clearly drilling parallel to the grain has a high drill resistance, whereas drilling perpendicular to the grain has the lowest drill resistance. At intermediate angles the drill resistance does not follow a linear relationship between 0 and 90 degrees. In Table 17 the number of drillings in each box of the boxplot (Figure 60) are presented.

Table 17 Specimens and the number of drillings at the different angles relative to the grain as used in Figure 60.

Sample name	No. drillings at β = 0°	No. drillings at β = 30°	No. drillings at β = 45°	No. drillings at β = 60°	No. drillings at β = 90°
A-21-Me	3	3	3	3	3
A-22-Me	3	3	3	3	3

5. Discussion

In this chapter the results are discussed in terms of the influence of parameters on the drill resistance and how the observed results can be explained. First the results related to the Resistograph: drill bit sharpness, rotation rate and feed velocity are covered, followed by those related to the material: extractives, moisture content, drill direction and density. This chapter ends with the combination of the different parameters.

5.1 Influence of drill bit sharpness and calibration procedure

In this section first the results related to drill bit sharpness and its influence on the cutting process and the drill resistance are discussed, then the proposed calibration curve is explained.

5.1.1 Influence of drill bit sharpness

From Figure 42 showing the drill bit appearances it is visible that successive drillings results in rounding of the outer edges, as well as dulling of the main cutting edge. Several processes take place simultaneously:

- rounding of the outer edges giving a smaller diameter and thus less resistance
- dulling of the main cutting edge, resulting in a more negative rake angle and thus a higher drill resistance (section 2.3.1)
- additional resistance due to clearance face rubbing of the reduced clearance angle (section 2.3.1)

That the chip formation (Figure 46) did not change with dulling can be explained by the fact that the initial chip is already of type 3 (see section 2.1). Another reason can be that the chip thickness (approximately 19 µm see section 5.2) has the same order of magnitude as the initial nose width (NW in Figure 61) (approximately 50 µm see section 5.2) so the rake angle does not change much with dulling and therefore the cutting process remains substantially unchanged (see Figure 61).

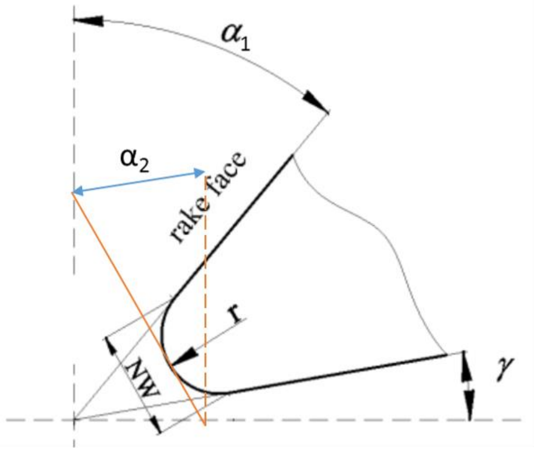


Figure 61 Drill parameters, Clearance angle γ, rake angle α_1, effective rake angle for a thin chip α_2 and nose width NW adapted from (Cristóvão, 2013)

Polyethylene is suitable for calibration although the increase in drill resistance due to dulling in polyethylene is roughly twice as fast compared to meranti perpendicular to the grain. In between measurements, it is important to keep the drill bit clean from burned wood and extractives.

From drilling a second time in the same samples with a duller drill bit it became clear that the spread in the drill resistance is larger (Figure 52). Therefore it is important that a sharp drill bit is used.

Sharpness clearly influences the drill resistance and to obtain reliable drill resistances not only should the drill bit be replaced on a regular basis (after approx. 5 m drilled depth) but also the drill resistances should be adjusted for the decrease in sharpness. The adjustment for sharpness is explained in section 5.1.2, this adjustment is done based on the slope of the calibration in Meranti across the grain and the drill resistance in polyethylene.

5.1.2 Calibration curve

The least squares linear fit for meranti is established in Figure 50 where the drill resistance is adjusted for dulling of the cutting edge. In this section how this adjustment is done is explained. The line obtained to correct for sharpness is named the calibration line.

In this research, the initial drill resistance of the fresh and sharp drill bit in polyethylene is 415 [rel]. This point is used as a starting point, for further calibrations. With the first dataset it was found that the drill resistance in polyethylene increased by approx. 25 [rel] after 5 m drilling whereas the resistance in Meranti was increased by approx. 15 [rel]. The dataset was again drilled to see if the results are comparable. When drilling the second time, the initial drill resistance in polyethylene was approximately 450 [rel]. After drilling the samples again, the mean drill resistance of all samples the first and second time were compared. These mean drill resistances differ by 12 [rel], this clearly indicates that the calibration line in meranti agrees with the actual increase in resistance (15 [rel] and 12 [rel] increase respectively); since the increase predicted by the calibration line and the measured increase closely agree.

It is assumed that dulling is a linear process and thus the total increase is as a linear increase subtracted from each drilling. In equation 26 the calibration procedure for meranti is as follows:

$$R_c = \frac{(415 - R_i)}{2} + R_m - 3l, \qquad (26)$$

where l is the drilled length in meters R_c is the drill resistance corrected for sharpness, R_i is the initial drill resistance in polyethylene and R_m is the mean drill resistance of the sample. The initial part of this equation is universal, the remaining part depends on the speed with which the drill bit dulls. It is possible to adjust the last part based on the final resistance in polyethylene, establish a straight line for polyethylene and keep in mind that the increase of drill resistance in polyethylene (PE) is twice as fast as it is in meranti. This results in equation 27.

$$R_c = \frac{(415 - R_i)}{2} + R_m - \frac{(R_f - R_i)N_{total}}{2n_i}, \quad (27)$$

where R_f is the final drill resistance in polyethylene, N_{total} is the number of drillings in between the initial and final drilling in polyethylene and n_i is the number of the individual drilling to be corrected.

Two important rules should be kept in mind:

1. Make sure the drill bit is not warm when drilling polyethylene
2. Make sure the drill bit is clean from burned wood and the removal of the chips is not hindered at the drill head.

It is not possible to determine whether this calibration curve is applicable for other machines since variation between machines has not yet been investigated.

Although the influence of dulling is usually small, since it is a known and predictable influence, it should be included in the results.

5.2 Influence of rotation rate and feed velocity

Tests reveal (Figure 47) that the rotation rate decreases with increasing resistance, this means that the chip thickness increases with increasing resistance. An increase in chip thickness results in a more efficient cutting process (section 2.3.2 and 2.3.3). This is also clear from Figure 62; lowering the rotation rate gives an increase in torque, but a smaller increase than would be expected from the line of constant specific cutting work (green line in Figure 62). So the cutting process is more efficient for a lower rotation rate (a thicker chip results in a smaller net cutting surface). This effect is also expected to be present in the Resistograph; however the extent of this effect could not be determined since the machine does not allow manual adjustment of the rotation rate, furthermore accurate measurement of the torque was not possible. The variation in rotation rate is small at around 5% (very little resistance was observed in foam compared to high resistance in polycarbonate or plexiglass). With an average rotation rate of 11500 rpm and a feed velocity of 7,4 mm/s the chip thickness (t_c) can be calculated according to equation 28.

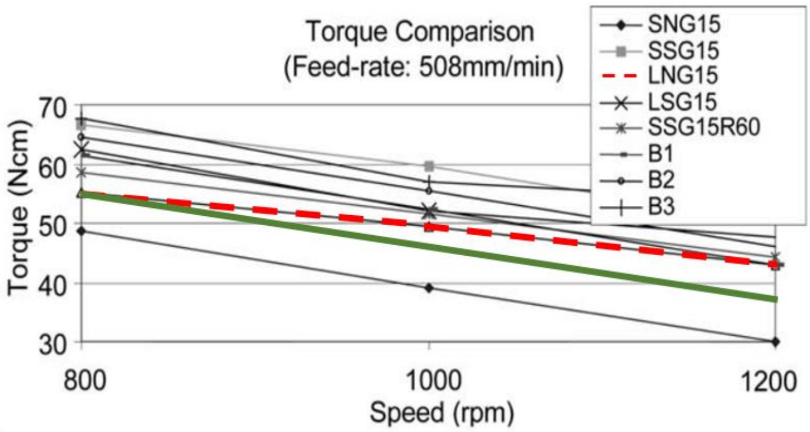


Figure 62 Torque versus speed (green: constant specific cutting work line, red: measurement) adapted from Zhao and Ehmann (2002)

$$t_c = \frac{60}{2}\frac{V_{feed}}{rpm} = \frac{60}{2}\frac{7{,}4}{11500} = 19{,}3\ \mu m \qquad (28),$$

where the factor ½ is included to correct for the second cutting edge and V_{feed} is the feed velocity.

The feed velocity is fairly constant (Figure 48) which agrees with information retrieved from the literature (section 2.2.3). However the feed speed could not be changed with the machine settings. The theory above on rotation rate together with the background information explains why the feed velocity should not be altered: changing the feed velocity changes the chip thickness and therefore the cutting efficiency, as is visible in Figure 63 (doubling of the chip load does not lead to a doubled torque).

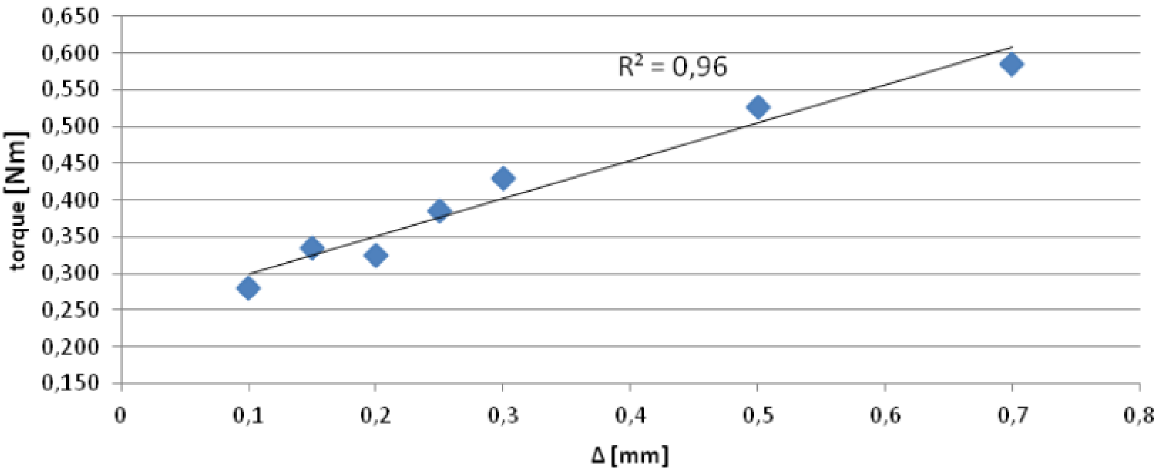


Figure 63 Torque and feed per revolution (PODZIEWSKI & GÓRSKI, 2012)

5.3 Influence of density

From the results (section 4.4) it is clear that density influences the drill resistance. Both in plastics and in wood the drill resistance increases with density. In plastics it is evident that other parameters also play a role, this is also the case for wood, as can be seen in the results (Figure 57) on moisture content. If moisture content increases, density also increases but the drill resistance does not. The influence of other parameters is also visible when drilling different wood species, it is not possible to establish a calibration curve with sufficient reliability for all tropical hardwoods. Figure 52 clarifies that this would lead to a large deviation and would make the prediction accuracy unacceptable. Some wood species with a similar structure as meranti, like sapele, follow the linear least squares fit obtained for meranti. Others with a different structure or either having more extractives or different sorts of extractives deviate from the least squares fit obtained for meranti.

In Figure 50 and Figure 52 the prediction interval is shown, it is important to note that this interval is only valid if a sharp drill bit is used. It is found that with dulling of the edge the spread increases. The linear relationship with density does not agree with all literature (section 2.5.4), Hernandes (2010), found a non-linear line according e^x although others present a linear relationship (Brashaw, 2013). The results obtained in this study do not give any evidence for non-linear behaviour, also there is no theory found in the literature supporting a non-linear relationship. A possibility is that the results of Hernandes are obtained with an older version of the Resistograph. Furthermore a non-linear response could be the result of the motor behaviour, the linear least square fit obtained for meranti has a value of -36.6 for zero resistance which is an impossible value (meaning a negative drill resistance), and clearly indicates that some non-linearity is expected.

Some spread in the results is expected since there is always some variation in the results, especially due to the inhomogeneity of wood. The calibration line for meranti can also be used for other wood species provided their structures are similar to meranti. Species with more abnormalities show a larger deviation, these include merbau, robinia and redcedar with a lot of extractives, oak with a characteristic anatomy (large rays), and sapupira which contains resins. For jarrah and tatajuba it is difficult to explain if and why they deviate, the calibration line is not actually evaluated for their density. Summarizing, the calibration line obtained is not universal for all wood species but could be used for those species which are sufficiently similar to meranti and do not have one of the above mentioned abnormalities.

5.4 Influence of extractives

From the investigation into the influence of the mass fraction of extractives on the drill resistance it is not possible to draw conclusions about a direct influence of extractives. There seems to be no or only a weak correlation between the expected drill resistance and mass fraction of extractives in meranti (Figure 55). Investigating the mean drill resistance from different tropical wood species (Figure 56) indicates that merbau has a much lower drill resistance, as expected based on its density, whereas tatajuba has a much higher resistance. There could be an explanation based on the fact that extractives contribute largely to the density but are not a structural element (however it could also be due to the different structure of the wood species). It is possible that this process is again a combination of two processes which are interconnected: one process is the drill resistance due to the presence of extractives, which depends on the sort and mass fraction of extractives. The second process being the drill resistance due to the cell walls.

The influence of the sort of extractives is obvious if resins and oil are compared, where the first has a lubricating effect the second is known for its stickiness. It is also likely that the location of the extractives influences the drill resistance, for example if the extractives are grouped together in canals rather than evenly distributed in the cell walls? During drilling, the combination of the location with the type of extractives and heat due to drilling; can lead to sticking of the chips and combusted material to the drill bit, in general this was observed for the more dense wood samples.

The second process mentioned above being the drill resistance due to the cell walls, is the only process for wood without extractives. Hundred percent of the mass fraction contributes to resistance due to cell walls. When extractives are present the mass fraction of the cell walls decreases; for a wood species with 10% extractives only 90% of the density belongs to the cell wall material. Thus the drill resistance should decrease with increasing mass fraction of extractives. Furthermore the drill resistance due to the cell wall is influenced by the orientation of the microfibrils (more specifically the orientation of the crystalline cellulose fibres). These vary and are different for different wood species but also within a single species.

These two processes are connected and they influence each other, since the extractives usually are in the cell walls and cannot be investigated separately.

The actual mass fraction of extractives removed from the species are in agreement with observations reported in literature (Malik, Santoso, Mulyana, & and Ozarska, 2016), (Yamamoto & Hong, 1989)

5.5 Influence of moisture content

The influence of moisture content on the drill resistance in Figure 57 shows a similar pattern to the results obtained by McMillin and Woodson (1972). In this research (Figure 57) tropical hardwoods are used of a different species drilled with the needle drill (similar to the spade drill). McMillin and Woodson in their research used a machine bit on southern pine which is a softwood. Furthermore the maximum drill resistance, found at around 12% moisture content, agrees with the results of Kivimaa (1950). Kivimaa investigated the influence of moisture content on the cutting force of Finnish birch, although cutting differs from drilling, drilling has certain features in common with cutting as discussed in section 2. This evaluation demonstrates that the behaviour found in their research is not limited to temperate wood species but seems to hold for tropical hardwoods too. The fact that the oven-dried state differs considerably for the different species can be explained by the side-effects of heating in the oven. Above the fibre saturation point the values show significant scatter, this is similar to the results of McMillin and Woodson (1972), who assume a constant drill resistance above the fibre saturation point. However since the drill resistance is the sum of the drill resistance due to water and the resistance due to the cell walls a slight increase of the drill resistance above the fibre saturation point is expected. Besides; drilling in green wood has a high drill resistance[18]. Since the volume of a

[18] Information retrieved from colleges at SHR using the Resistograph in green wood.

wood block above the fibre saturation point does not increase further, a higher moisture content also results in less space for the chips and thus increased friction of the chips on the needle drill. From the boxplot in Figure 57 the influence of moisture content above the fibre saturation point on drill resistance is not clear. Below the fibre saturation point, the boxes usually contain several specimens and the box represent all samples, however above the fibre saturation point the moisture contents differ a lot and thus a box contains only one or two samples. This gives more scatter and an unclear view of the actual influence above fibre saturation point.

The maximum drill resistance is found at around 12% moisture content, which is likely to be the result of two processes taking place simultaneously. Below 12% moisture content the energy consumption decreases with decreasing moisture content due to increased brittleness (explained in section 2.5.2). Simultaneously with an increasing moisture content the cellulose chains are further apart and the bond strength decreases, although the toughness increases. It is likely that the competition between these two processes leads to a maximum drill resistance at around 12% moisture content. It is important to note that the density increases with increasing moisture content (Kollmann & Côte, 1984). Since the drill resistance does not increase, this clearly shows that drill resistance is not related to density alone.

Although the literature and present results show a similar behaviour, and there is evidence for this behaviour, the question is whether the results are significant given the spread of the individual results; therefore a T-test was performed. This indicates that there is not enough statistical evidence that the mean drill resistance at 8% moisture content is higher than the drill resistance at 20%.

5.6 Influence of drill direction

Drawing direct conclusions from the data obtained on drill direction is difficult, especially since the principle of paired samples as used throughout this study does not hold here since the different directions also means that different material is sampled. This combined with a small number of samples cannot lead to a strong conclusion; however, the difference in drill resistance between the tangential and radial direction does not seem to be significant (Figure 59), which also agrees with the data obtained by Hernandez (2010) as explained in section 2.5.3. If the sample over the cross section has a more or less homogeneous structure, the cutting process is the same for radial drilling, tangential drilling and drilling in between these directions. However when in the tangential direction bands of parenchyma (with thin cell walls) are present and the drill mainly follows this band of parenchyma, it is likely that the drill resistance for the tangential direction is lower compared to the radial direction.

For drilling parallel to the grain, the number of samples is again small; however the samples show the same trend: a high drill resistance when parallel to the grain which decreases with increasing angle θ (Figure 60). The fact that drilling perpendicular to the grain has a smaller resistance is also found by Mcmillin and Woodson (1972) as described in section 2.5.3. The intermediate region is more interesting. The rapid increase when deviating from cutting perpendicular to the grain can be explained by the more or less immediate change in cutting process. When drilling perpendicular to the grain (θ = 90°), the wood fibres are separated along their axis and cut at the sides of the hole. When drilling at an angle, (other than 90°) to the grain direction, the wood fibres are no longer separated along their axis but slanted which to some extent involves cutting of the wood fibres along their strongest direction. Calculating the area of the drill bit perpendicular to the grain at all angles, the area of the main drill head perpendicular to the grain is given in equation 29.

$$area_{\perp\, with\ grain\ direction} = \pi D^2 \sin(\beta), \qquad (29)$$

where D is the diameter of the drill and β the angle with the grain. This results in a sinusoidal function and not a linear function. This sinusoidal function changes slowly around an angle (β) of 0° to the grain direction and rapidly around 90°. This explains why (in Figure 60) a small deviation from drilling parallel to the grain (for example β = 5°) has little influence whereas a deviation from the angle perpendicular to the grain (for example β = 85°) has a pronounced effect on the drill resistance.

Since the angle with the grain has a significant influence on the drill resistance, it is expected that for certain wood species with pronounced grain patterns (spiral grain or interlocked grain for example) the drill resistance will be influenced by this since the surface is usually not perpendicular to the grain.

5.7 Combined influence

After discussing the influence of the respective parameters, it is important to know which parameters should be taken into account and to what extent these parameters influence the drill resistance. Summarizing the above results: drill direction relative to the tangential direction (angle θ) can be neglected, from Figure 59 it is clear that this has little or no influence. The mass fraction of extractives most likely influences the drill resistance; however, no relationship could be established; furthermore the effect of extractives is taken into account with the prediction interval (since the samples used for establishing this prediction interval have a varying mass fraction extractives). Feed velocity and rotation rate cannot be adjusted and their influence is therefore present in the graph on density. Two parameters remain, first the drill direction relative to the grain direction (angle β): The calibration is obtained at an angle of 90° relative to the grain and is therefore only suitable for drillings done in that direction, for a different angle a different linear fit and prediction interval should be used.

Moisture content is more complex and results (Figure 57) indicate a small influence. The influence of moisture content in the range 8-16% (which is a common moisture content for indoor and outdoor) is relatively small (mean values differ less than 3%). For moisture contents exceeding 16% the influence increases. Statistical tests were performed to determine whether this increase is due an actual different mean value. These tests showed that the probability that the difference is due to the spread in the results is too large to conclude that the mean values are different. Summarizing, a relationship between drill resistance and density can be established for meranti and similar structured wood species when the drill direction is perpendicular to the grain and the moisture content lies in the range 8-16%.

How accurately this relationship with the density can be established is a logical question. The answer depends on the application. The prediction interval established represents the region within which a new measurement[19] with a probability of 95% will fall. But if someone tests several blocks and needs the average density, the standard deviation of this average density is given by equation 30. Assuming a normal distribution and that the measurements are independent.

$$s_{mean} = \frac{s}{\sqrt{n}}, \qquad (30)$$

so the standard deviation of this average equals the standard deviation of the individual measurement divided by the square root of the number of frames tested and decreases with increasing number of blocks.

[19] Multiple of several measurements representing the global drill resistance.

6. Conclusion and recommendations

The main conclusions are pointwise below in section 6.1 whereas section 6.2 contains recommendations for further research.

6.1 Conclusions

The main conclusions of investigating the influences of machine and material properties on the drill resistance is in short statements below

- It is possible to determine the global density of a piece of meranti and other wood species with a similar structure, with the Resistograph, with an accuracy of 70 kg/m^3, fast and with only little damage.
- The drill direction relative to the grain (β = 90° and θ varies) does not influence the drill resistance and thus the density of a coated piece of wood can be determined as well as an uncoated piece.
- The drill bit sharpness, especially of the main cutting edge, does influence the drill resistance, therefore a correction for sharpness should be applied. The drill bit should be replaced after 5 m of drilling (in meranti) since accuracy is worse for a dull drill bit.
- The moisture content influences mechanical properties of wood and does also influence the drill resistance however, the influence is not statistical significant.
- The drill direction relative to the grain (varying β) does influence the drill resistance, the area of the drill bit perpendicular to the grain corresponds with the drill resistance.
- Extractives influence the drill resistance, however this feature is of little importance since within a single wood species there is no clear relation between amount of extractives and drill resistance. Likely, especially with large amounts of extractives, the drill resistance decreases due to fewer cell wall material.

6.2 Recommendations for further research

Although this research revealed numerous properties which influence the drill resistance, further research should be done to find out why different wood species have a different drill resistance. More specifically, the following questions arise:

- What is the influence of the different types of extractives on the drill resistance?
- How is the drill resistance influenced by the microfibril angle?

- Does the chemical composition of the wood influence the drill resistance (Hemicellulose, cellulose and lignin content)?
- What is the influence of moisture content on the drill resistance especially above 16% mc, and does this depend on wood specie?

The influence of microfibril angle on the drill resistance is especially important, since currently the orientation of the grain angle is a limiting factor in strength grading, so if it is possible to predict the grain angle with the Resistograph a new application field comes up.

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Appendix A

Samples used for determination of the influence of density on drill resistance.					
Machine	SHR/001	SHR350	SHR/350	SHR/350	
Sample name	mass [g]	lenght [mm]	height [mm]	width [mm]	density [kg/m3]
A-06-Me.1	278,11	114,02	34,2	112,55	634
A-06-Me.2	260,56	114,02	29,4	112,9	688
A-07-Me.1	255,92	165,7	27,53	95,08	590
A-07-Me.2	363,72	165,3	40,2	95,08	576
A-08-Me.1	177,23	94,78	74,72	33,56	746
A-08-Me.2	176,31	94,85	74,58	33,95	734
A-09-Me.1	379,43	184,2	71,23	44,58	649
A-09-Me.2	405,66	184,1	71,27	47,01	658
A-10-Me.1	315,62	140,78	94,94	33,3	709
A-10-Me.2	323,59	140,6	94,95	34,5	703
A-11-Me.1	147,77	94,85	34,08	77,3	591
A-11-Me.2	141,09	94,95	33,8	76,9	572
A-12-Me.1	308,11	144,6	71,22	46,55	643
A-12-Me.2	299,37	143,88	71,28	45,05	648
A-13-Me.1	178,69	103,25	34,7	95,05	525
A-13-Me.2	185,78	105,06	33,25	94,98	560
A-14-Me.1	310,8	180,65	95	33,7	537
A-14-Me.2	337,01	181	95,05	34,25	572
A-15-Me.1	339,14	163,4	71,22	44,66	653
A-15-Me.2	359,53	161,2	71,22	46,98	667
A-39-Me.1	329,19	150,3	71,25	66,87	460
A-39-Me.2	314,86	150,11	67,03	64,3	487
A-38-Me.1	446,44	155,91	62,04	66,92	690
A-38-Me.2	409,1	156,35	66,85	55,25	708
A-49-Me.1	190,21	108,82	69,07	49,99	506
A-49-Me.2	235,33	108,48	68,99	60,88	516
A-18-Me.1	395,22	124,99	73,14	58,72	736
A-18-Me.2	430,45	125,91	73,07	60,58	772
A-50-Me.1	149,99	114,05	70,6	39	478
A-50-Me.2	118,47	113,95	70,85	27,21	539
A-53-Me.1	189,14	92,75	71,98	61,82	458
A-53-Me.2	173,98	93,49	72,05	56	461
A-59-Me.1	119,42	69,91	60,61	56,03	503
A-59-Me.2	102,86	69,82	51,24	56,07	513
.1 is closest to the pith					
A-20-Sa.1	201,5323	70,2	71,07	56,63	713
A-20-Sa.2	211,79	69,85	71,18	59,64	714
A-02-Mr.1	556,35	71,86	63,3	143,02	855

A-02-Mr.2	553,81	72,97	63,18	143,83	835
A-32-Sa.1	279,83	80,16	71,08	74,02	663
A-32-Sa.2	251,3	80,38	66,88	71,03	658
A-1-Ta.1	44,7483	66,53	23,08	36,51	798
A-1-Ta.2	80,4764	66,58	40,92	36,59	807
A-05-Mr	52,959	80,53	40	17,92	917
A-01_Ja	740,39	150,34	44,58	118,6	931
A-02-Sap	163,76	167,88	69,47	19,78	710
beech rad	90,29	118,59	49,25	20,37	759
birch rad	79,04	118,9	40,7	26,11	626
oregon pine rad	92,23	118,63	74,07	21,5	488
pine spint rad	60,34	120,1	51,1	21,59	455
spruce rad	63,57	100,99	70,09	21,95	409
robinia rad	246,39	120,36	79,09	35,95	720
oak rad	124,78	101,49	86,93	21,19	667
redcedar	44,37	118,55	50,71	25,08	294
beech tan	121,87	118,56	65,92	21,51	725
birch tan	63,82	119,63	39,89	20,61	649
oregon pine tan	76,44	118,38	65,83	19,53	502
pine tan	55,62	120,39	51,7	15,57	574
robinia tan	57,74	119,98	35,87	18,73	716
oak tan	145,5	101,5	89,88	20,33	785
spruce tan	90,6	150,59	69,83	22	392
spruce rad 2	66,13	107,35	70,06	21,95	401

rad means quartersawn
tan means flatsawn