Dissertationes Forestales 13

Variation of colour and selected physical and mechanical properties related to artificial drying of sawn silver birch (*Betula pendula* Roth) timber from plantations

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Academic dissertation

To be presented, with the permission of the Faculty of Forestry of the University of Joensuu, for public criticism in auditorium BOR 155 of the University of Joensuu, Yliopistokatu 7, Joensuu, on 10th December 2005, at 12 noon.

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ISSN 1795-7389
ISBN 951-651-114-7 (PDF)

Paper copy printed:
Joensuun yliopistopaino, 2005

Publishers:
The Finnish Society of Forest Science
Finnish Forest Research Institute
Faculty of Agriculture and Forestry of the University of Helsinki
Faculty of Forestry of the University of Joensuu

Editorial Office:
The Finnish Society of Forest Science
Unioninkatu 40A, 00170 Helsinki, Finland
http://www.metla.fi/dissertationes

Möttönen, V. 2005. Variation of colour and selected physical and mechanical properties related to artificial drying of sawn silver birch (*Betula pendula* Roth) timber from plantations. Dissertationes Forestales 13.

Birch is the most important domestic hardwood species for the wood products industries in Finland. In the near future, the wood from silver birch (B*etula pendula* Roth) plantations will broadly increase as a source of raw material of saw and veneer logs. Due to the differences in growth rate and silviculture, the raw material from plantations is likely to have characteristics different from those of the wood harvested from naturally regenerated forests. From the point of view of the wood products industries, however, little is known of the quality of the wood of plantation-grown birch trees. In addition, environmental factors such as growing site, felling season and storage of timber are also known to have an influence on the wood properties, but there is little knowledge of the mechanism of those factors and the possibilities to control them. In the further processing of sawn birch timber, the drying of wood is one of the most difficult phases: discolouration, deformation, moisture content gradient, being typical defects for birch timber produced during drying.

The objective of this thesis was to study the drying behaviour and related wood and timber properties of plantation-grown silver birch for the raw material of wood products industries. The wood procurement season and storage of logs before further processing were studied as a source of variation of wood properties and drying behaviour. To study the variation in wood properties and drying behaviour caused by the drying method, the conventional kiln drying (heat and vent drying) and vacuum drying were used, which are the most common drying methods for sawn birch timber. On the subject of drying method, wood colour, shrinkage, weight density, final moisture content, Brinell hardness and equilibrium moisture content were studied. The role of proanthocyanidins (condensed tannins) and their polymerisation as a chemical background for the discolouration was studied.

Owing to the variation in the wood properties, the drying behaviour was found to differ between the wood procurement seasons. In addition, due to the low temperature used during the first steps of the conventional drying process, the drying conditions in the kiln differed between the processes. The initial moisture content of the wood, basic density and proanthocyanidin content were found to change with the wood procurement season. These changes were consequences of the physiological alterations in birch trees with the seasons and they were found to have an influence on colour, density, equilibrium moisture content and Brinell hardness of wood. The mechanism of the discolouration of wood differed between the drying methods. Regarding the conventionally dried wood, the discolouration was the most intensive for summer-felled wood while the vacuum-dried wood discoloured the most intensively when it was felled in winter. In summer-felled and winter-felled wood the storage of timber as logs increased the discolouration of the wood during drying.

The increase in the use of plantation-grown sawn birch timber will increase the variation of wood properties, which has to be taken into account during the different phases of the further processing.

Keywords: *Betula pendula* Roth, conventional drying, density, hardness, plantation forests, proanthocyanidins, shrinkage, vacuum drying, wood colour, wood drying

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ACKNOWLEDGEMENTS

This study has been funded by the Academy of Finland through the Forest Cluster Research Programme “Wood Wisdom” under the title “Quality of dried wood of cultivated silver birch”, by the Faculty of Forestry of the University of Joensuu, and by Puumiesten ammattikasvatussäätiö. I am grateful to these sources of funding for making this work possible.

I am deeply grateful to my supervisors, Prof. Erkki Verkasalo and Prof. Antti Asikainen, for valuable guidance in all stages of the work. I am likewise most grateful to Ms. Katri Luostarinen, who initially recruited me to research of wood technology, instructed me in the field of wood colour and chemistry, and was the co-author in three papers of my thesis. I gratefully acknowledge Prof. Henrik Heräjärvi for the valuable suggestions in the manuscript and co-operation during several years. Prof. Nasko Terziev from the Swedish University of Agricultural Sciences, Sweden, and Prof. Robert Beauregard from the University of Laval, Canada, are acknowledged for their careful work in reviewing the manuscript and for the constructive suggestions. I also acknowledge the careful and laborious field and laboratory work contributed by Heikki Piipponen, Matti Heiskanen, Leena Kuusisto and Hannu Koivunen. I acknowledge Martti Ruuskanen from UPM-Kymmene Ltd. for providing me the study material, Keijo Silfsten from North Karelia Polytechnic for sawing the logs, and Timo Aavakallio from YTI Research Centre, Mikkeli Polytechnic for carrying out the vacuum dryings. The Faculty of Forestry provided me excellent working facilities. I thank Prof. Olli Saastamoinen and Prof. Matti Kärkkäinen for encouraging me to finish my thesis, David Gritten for correcting the language of this thesis and Teppo Naakka giving me valuable help with the layout of the papers. Many special thanks go to Erkki Järvinen for friendship of many years. Many thanks also to other colleagues at the Faculty of Forestry and to “wood research group”-members at the Chemistry Department. I would also like to thank Prof. Timo Kärki from the Lappeenranta University of Technology for innovative co-operation.

Many special thanks go to my parents, Vieno and Heikki Möttönen, my sisters and brothers and their families, and my parents-in-law for their support and interest. Finally, I would like to express my warmest thanks to my wife Sirja and my children, Markus, Niklas and Melissa for their love, patience and support.

Joensuu, November 2005

Veikko Möttönen

LIST OF ORIGINAL ARTICLES

This thesis is a summary of the following articles, which are referred to in the text by the Roman numerals I-V:

I Möttönen, V. and Luostarinen, K. 2004. Discolouration of sawn birch (*Betula pendula*) timber from plantation forests during drying: Effect of growing site, felling season and storage of logs on discolouration. Baltic Forestry 10(2): 31-38. http://www.balticforestry.mi.lt/

II Möttönen, V. and Luostarinen, K. 2005. Discolouration of sawn birch (*Betula pendula*) timber from plantation forests during drying: The role of proanthocyanidins (condensed tannins) in discolouration of birch wood. Baltic Forestry 11(1): 13-20. http://www.balticforestry.mi.lt/

III Möttönen, V. and Luostarinen, K. 2006. Variation in density and shrinkage of birch (*Betula pendula* Roth) timber from plantations and naturally regenerated forests. Forest Prod. J. (In press). http://www.forestprod.org/

IV Möttönen, V. 2005. Variation in drying behaviour and final moisture content of wood during conventional low temperature drying and vacuum drying of *Betula pendula* timber. Drying Technology. (Accepted). http://www.taylorandfrancisgroup.com/

V Möttönen, V., Heräjärvi, H., Koivunen, H. and Lindblad, J. 2004. Influence of felling season, drying method and within-tree location on the Brinell hardness and equilibrium moisture content of wood from 27-35-year-old *Betula pendula*. Scand. J. For. Res. 19: 241-249. doi:10.1080/02827580410029327

In papers I, II, and III, manuscripts were written jointly by the authors, while V. Möttönen, regarding the plantation-grown birch trees, was solely responsible for collecting the material and analysing the results. In paper V, the materials were collected and the manuscript was written jointly by all authors, while V. Möttönen was solely responsible for analysing the results.

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1. INTRODUCTION

1.1 Background

Hardwood species are important raw materials both in the pulp and paper industries and wood products industries throughout the world. In Finland, the total use of round hardwood timber in wood products industries was 1.73 million m^3 in 2003, including the sawmilling industry (0.22 million m^3) and the plywood and veneer industries (1.51 million m^3) (Peltola 2004). Of the total production of sawn hardwood timber amounting to 100 000 m^3 in Finland, further-processing wood products industries used 84 000 m^3 while 16 000 m^3 were exported.

Silver birch (*Betula pendula* Roth) and European white birch (*B. pubescens* Ehrh.) are the most important domestic hardwood species for wood products industries in Finland. They cover the majority of the use of hardwoods; only 10 000-20 000 m^3 from the total annual consumption of hardwood logs were estimated to be of alder (*Alnus incana*, *A.* glutinosa) (Kärki 2000) and also aspen (*Populus tremula*) (Verkasalo 1999). However, compared to the share of birch trees of the total growing stock volume (15.2%) and to the total production of sawn softwood timber (13.3 million m^3) (Peltola 2004), the production of sawn birch timber in Finland is still relatively small when compared to softwood timber. The main reason for the small proportion of birch in sawing industries is the poor usability of birch as a structural timber: birch is susceptible to decay and its tensile strength is low in relation to the density (Kärkkäinen 2003). In addition, the growing stock of birch is mainly in mixed stands dominated by conifers, which makes the true supply, dependent on the markets of softwood logs and the sorting of sawable birch logs from the timber flow, expensive.

Usually, the two main birch species growing in Finland are considered not to have significant differences of practical importance in wood properties, although there are considerable differences in their growth and yield capacity (e.g., Heräjärvi 2002). At present, main end-uses of sawn birch timber in Finland are in furniture, parquet and edge-glued panel production (Luostarinen and Verkasalo 2000). In addition, smaller amounts of birch are used for decorative and practical items, tool handles and kitchen utensils, as typical examples (Salmi 1987). Both in the furniture and parquet industries, several competitive hardwood species are used that have wood properties rather similar to birch; for example beech (*Fagus sp.*), maple (*Acer sp.*) and ash (*Fraxinus sp.*). The most important competitor of birch in both the furniture and parquet industries in Europe is beech (*Fagus sylvatica*), which is comparable regarding wood colour, density and hardness (Wagenführ 1996).

In furniture production, birch is used as solid wood especially in components of chairs, tables and cabinets (Salmi 1987). In shelf products, solid wood is used less and birch is most often used as a thin veneer coating on the surface of particle board or medium-density fibreboard. Excluding solid-wood parquets, birch is used only for the surface layer of parquet products, while the middle layer is most often cross-glued spruce and the bottom layer is a spruce ply (Koponen 1997). The surface layer of parquet is sawn from dried boards or billets to a thickness of approximately 4 mm by using band-, circular- or frame saws. The surface layer of a single parquet board (approx. 190 mm × 2300 mm) is typically achieved by using three rows of timber strips, although one or two solid looking strips are used as well. Quality requirements for the aesthetic appearance and for the resistance to wear are high especially for the premium quality classes in furniture and parquet products (cf., Auvinen et al. 2002, Forsén and Tarvainen 2003). In this sense, the homogenous colour, the absence of colour defects and the adequate physical properties of wood are extremely important for the raw material used for the birch wood products.

In further processing of sawn birch timber, several factors have effects on the quality of semi-finished and end products. Most of the factors are associated with drying of timber: the entrepreneurs and industries dealing with birch consider the drying of sawn timber to be the most difficult problem in further processing, as concluded by Kivistö et al. (1999). Similar problems were found also in a survey on the Swedish hardwood industries: deformations, discolouration, tension, moisture content variation, checks and collapse were found to be the most frequent difficulties the entrepreneurs are encountering in the hardwood drying (Stenudd 2002).

Regarding the furniture, parquet and edge-glued panel production of birch, the most important problems related to drying are discolouration and deformations of sawn timber. Typically, discolouration appears in the interior of timber, while the surface layer to a depth of 1-5 mm remains light (Luostarinen and Luostarinen 2001). However, the discolouration occurs occasionally in sawn birch and the reasons for the variation in colour are not known precisely. The uneven discolouration reduces the quality of the final product and results in a loss of value due to downgrading and increase in the amount of waste (Luostarinen and Verkasalo 2000). In addition, deformations and their variation in sawn birch timber are large. Deformations mainly comprise uneven shrinkage, warp and twist (Keinänen and Tahvanainen 1995). Reasons for strong deformations are the variations in shrinkage within sawn timber pieces caused by radial differences in density, internal stresses, knots and varying proportions of juvenile wood. Deformations increase the loss of raw material during the further processing after drying. In this respect the importance of drying of sawn timber is emphasised.

Environmental factors, such as growing site, felling season and storage of logs between felling and processing are known to have an influence on the properties of birch wood (Luostarinen and Verkasalo 2000). However, little is known of the mechanism of those factors and the possibilities to control them. In addition, there is a lack of knowledge of the interaction between the drying method and the factors affecting the critical birch wood properties. If the abovementioned factors could be controlled in a proper way, the drying quality of timber could be increased which in turn would increase the profitability of wood products industries using birch as raw material.

1.2 Sources of birch timber in wood products industries

Traditionally, mainly large-diameter logs have been used in the sawmilling industry as the raw material for sawn birch timber (Heräjärvi 2002). However, few hardwood sawmills using large-sized logs have been established during the last twenty years and the older ones that are working use largely outdated technology. Since the 1990s some new hardwood sawmills based on sawing of small-sized birch logs have been established or are in the planning stage (Heräjärvi 2002). The reason for this development is the increasing supplies of small-sized logs from forest thinnings and from abroad (mainly European Russia). Due to the rapid and automated sawing technology in modern sawmills, the small-sized logs are sawn directly into billets for furniture production or they are sawn into boards by the double-cut method to the thickness of 25-50 mm (Luostarinen and Verkasalo 2000). In general, possibilities of affecting the quality of sawn birch timber by sawing method are very limited for small-sized logs (Lindblad et al. 2003).

To date, the main source of birch saw logs has been the naturally regenerated mature silver birch trees from softwood-dominated or pure birch stands on mineral soils. From the point of view of the sawmilling industry, the technical properties of those saw logs have been good especially in the butt log section (Heräjärvi 2001). Simultaneously, the large-diameter, high-quality logs are the main source of raw material also for the veneer and plywood industries, which has contributed to the large demand and high price of birch saw logs.

In the near future, plantations will grow in importance as a source of raw material supply for the mechanical wood industries in Finland, both for softwoods and hardwoods. Silver birch has been planted on a larger scale for almost 40 years in Finland, amounting to the current area of ca. 200 000 hectares (Peltola 2004). The primary objective of planting birch has been to provide raw material for the veneer and plywood industries. Birch plantations have mainly been established on fertile forest regeneration areas and on abandoned agricultural fields (Raulo 1978). The average growth of silver birch on afforested fields corresponds to *Oxalis myrtillus* site type (OMT-type) (Kinnunen and Aro 1996, Saramäki and Hytönen 2004), which is a moist upland forest site type of high fertility (cf., Kuusipalo 1996). Because silver birch grows commonly in natural forests and also on sites of low fertility, it is obvious that the average fertility of plantations is higher than that of naturally regenerated birch forests. Compared with naturally regenerated birch stands, the initial development of birch plantations has been faster and the regeneration has been more secure (Saksa 1998). In addition, the silviculture in the plantation forests is often more intensive than in the naturally regenerated forests, contributing to the higher growth.

Owing to the differences in growth rate and silviculture, the raw material from plantations is likely to have characteristics differing considerably from those of the wood harvested from naturally regenerated forests. Fast-growing trees tend to produce wood that is lower in density than the average trees (Hakkila 1966). Furthermore, it is obvious that the trees harvested from birch plantations will be younger (rotation will be shorter) than those harvested from naturally regenerated forests (Niemistö 1995). In addition, the breeding of the forest plantation material is based mainly on the productivity and external properties of the trees instead of the wood properties (cf., Lepistö 1981). Owing to the shorter rotations, plantation-grown wood is generally known to have a greater proportion of juvenile wood than the wood from naturally regenerated stands (Zobel and Sprague 1998). The role of juvenile wood is, however, little known for the quality and value of birch wood.

Overall, little has been studied about the quality of wood from plantation-grown birch trees from the point of view of the wood products industries. So far, the research of wood quality of plantations in Finland is restricted mainly to softwood species. Especially the poor quality of plantation-grown Scots pine (*Pinus sylvestris*) wood on former agricultural fields (Kontunen-Soppela et al. 1997, Hynönen and Hytönen 1998, Hytönen 1999, Nurmi 2002) has led to doubt as to whether the quality of plantation-grown birch wood is also below that of the quality of wood from naturally regenerated birch trees. Some approximations of the wood quality in plantation-grown birch trees can be made based on the external quality of stems (e.g., Niemistö et al. 1997, Lehtimäki et al. 2002, Lindblad et al. 2003, Saramäki and Hytönen 2004). On average, the stems of plantation-grown birch trees are more forked and crooked than those of naturally regenerated birch trees. The number of knots, especially sound knots, is also greater in the saw log section of plantation-grown birch trees. However, the existence of the external defects on plantation-sites varies, being the lowest on moist and rich mineral soils which are the most suitable for growth of silver birch.

1.3 Drying of sawn birch timber

Drying of sawn timber for high quality is one of the most important challenges associated with further processing of birch wood. Drying in the open air is the traditional way of drying and it is still used to a considerable extent in the wood products industries, especially for the pre-drying of sawn timber (Keinänen and Tahvanainen 1995, Luostarinen and Verkasalo 2000). The through-sawn birch timber, which still has the bark bound on it, is stacked and covered and allowed to dry for several months or up to two years. This procedure usually reduces the development of deformations and produces evenly coloured wood. On the other hand, the slowness of the drying is a disadvantage from the economical point of view as it ties up a great deal of capital to the raw material. In addition, the drying rate is dependent on ambient climatic conditions, which may vary to a large extent within and between years. Usually, sawn timber dries more quickly in spring and early summer than sawn timber going into stacks in late summer, with the drying almost ceasing during the winter (Esping 1996). In all, air drying is a largely uncontrollable drying method for quality and it can be used to dry the wood material down to about 15-20% moisture content (MC) at the lowest, which is, generally speaking, not sufficient for the requirements of the wood products industries using birch.

At present, most of the sawn birch timber is dried artificially; with conventional kiln drying (heat and vent drying) being the most common method. Regarding the drying quality, only batch kilns so far have proved suitable for birch timber to reach the standards required by the joinery industries (Isomäki et al. 2002). The drying processes are controlled mostly by using time-based schedules, which have been developed based on the known average drying properties of wood (Peltoranta 2001). During conventional kiln drying of birch, the low temperature drying (<45°C) is used above the wood fibre saturation point (FSP) in order to avoid the discolouration of wood; even as low as 30°C dry bulb temperature is used during drying above 20% MC (Stenudd 2002). The medium temperature drying (45-95C°) is then used during the rest of the drying process by gradually increasing the drying temperature. The wet bulb depression is kept low in the capillary region of moisture content to avoid checks and casehardening (Isomäki et al. 2002). However, even mild schedules occasionally produce discoloured wood (Luostarinen et al. 2002). The duration of drying birch in a conventional kiln varies between three and five weeks.

During recent years, vacuum drying of sawn birch timber, as being a rapid drying method, has increased markedly in Finland. Vacuum drying is based on the fact that the boiling point of water is substantially lowered when the atmospheric pressure over the wood is lowered; consequently, the water in wood is boiling and is drawn out of the wood (Chen 1997). However, boiling does not occur simultaneously throughout the wood. At the beginning, water boils on the surface of sawn timber and the boiling front retreats inside the wood as drying proceeds (Chen and Lamb 2001). Moreover, contrary to conventional drying, moisture is removed in vacuum drying mainly in the longitudinal direction and it moves in a steam form (Chen 1997). Discolouration of sawn hardwood timber is less with vacuum drying than with other artificial drying methods due to the small oxygen concentration and the short drying time as a result of the lower boiling point of water

(Charrier et al. 1992). The duration of vacuum drying of birch is three to five days. Regarding the drying quality, however, of the selection of suitable process parameters to control the vacuum drying process is extremely important (Ressel 2003). It was found in an industry survey that none of the studied industrial vacuum kilns was capable of controlling drying conditions with acceptable accuracy to meet the demands which the European Drying Group, a network consisting of representatives from European timber trade, timber processing industries, research and education authorities, has set for the exclusive quality class (Källander 2003). Although the drying quality of birch is usually high, similar problems with discolouration to conventional drying occur by using vacuum drying (Lahtinen and Tolonen 2001). In vacuum-dried wood, however, the darkest layer also may appear near the board surface, in addition to the strongly discoloured centre of the board.

The heat transfer to the sawn timber is lower in a vacuum than in the atmospheric pressure; therefore, the use of additional humid air or steam (Ressel 2003) or dielectric field (Harris and Taras 1984, Smith et al. 1994) during drying is essential to keep the continuous vacuum drying process efficient. Radio frequency vacuum (RFV) drying combines vacuum drying with radio-frequency heating (Milota and Wengert 1995). An application of RFV drying called high frequency vacuum (HFV) drying has been under investigation on birch wood at the Lahti Polytechnic, Finland (Auvinen 2001). In this method, the continuous heat transfer to wood is obtained by using a dielectric field. The checking of birch wood is unactual, and the colour remains light and uniform with this rapid drying method; birch wood can be dried in less than ten hours. The disadvantages of the method are the low volumetric capacity of the kiln, the sometimes uneven drying quality due to the varying penetrability of electromagnetic waves through the wood and the high consumption of electricity.

High temperature drying (>100°C) is successfully used for American white birch (*Betula papyrifera*) (Erickson et al. 1984, Larson et al. 1986), but the preliminary results with sawn birch timber in Finland, especially concerning the wood colour, have been inconsistent (cf., Sonninen 2001). Typically, high temperature drying of birch produces strongly red-coloured wood material because of the steaming used to transfer the heat to wood and prevent the casehardening of sawn timber. Steaming is typically used for the colour control with hardwoods, e.g., with beech and walnut (Burtin et al. 2000), giving a reddish colour for the dried wood, but it is not a usable method with sawn birch timber due to the uneven and glaring colour of the end product.

An application of high temperature drying is the compression drying method (Method for... 1963), where the sawn timber is, in modern applications, compressed between perforated aluminium plates during the drying process at high temperature to keep the timber straight (Ressel 2003). Due to the compression during drying, the sawn timber is straight and has an increased density, especially in the surface layer of the boards, leading to the improved surface hardness, strength and net material savings of 15-20 %. Using high temperature drying, sawn birch timber can be dried in a day.

1.4 Wood colour and discolouration

The human eye can detect electromagnetic waves in the visible light region, for the wavelength of approximately 380-780 nm (Hunt 1998). This is a small portion of the electromagnetic waves in space. The range of visible light is seen by the human eye as a spectrum, which is a distribution of colours. The ability to see the spectrum is based on stimulating the retina in the human eye by the specific wavelengths (Hunt 1998). An object absorbs part of a light from the light source and reflects the remaining light. The light reflected from an object is a mixture of light at various wavelengths. The light of a specific wavelength absorbed by the object is caused by chromophores - the side chains of the pigment molecules (Hon and Minemura 2001).

The colour characteristics of wood depend on the chemical components that interact with light. Typical molecules having chromophore bindings in wood are lignin, below the wavelength of 500 nm, and phenolic extractives such as tannins, flavonoids, stilbenes and quinines, above the wavelength of 500 nm (Hon and Minemura 2001). Cellulose and hemicelluloses do not absorb light in the visible region. Due to differences in composition of wood components, the colour of fresh, untreated wood varies between different species, between different trees of the same species and even within a tree. Within a species wood colour can vary due to the genetic factors (Rink and Phelps 1989, Mosedale et al. 1996) and environmental conditions (Phelps et al. 1982, Wilkins and Stamp 1990).

In discolouration, chemical reactions take place in wood, changing the number and type of chromophores. Both microbial and non-microbial factors cause discolouration, i.e., changes in natural colour of wood in sawn timber (Amburgey 1994). Microbial discolourations are caused primarily by mould, sap stain or decay fungi. In addition, bacteria may cause discolourations called “wetwood” in hardwoods (e.g., Ward and Zeikus 1980). Microbial discolourations may already have developed in the living tree as a consequence of diminished resistance to fungi or they may develop in the sawn timber until the moisture content falls below 20%. Prolonged storage of saw logs or sawn timber, especially in summer time, increases the risk of microbial discolouration (e.g. Verkasalo 1993, Corbo et al. 2001). Development of microbial discolouration may be hindered by ensuring that the storage times and the associated physiological conditions of logs and sawn timber are not adequate for microbial infections.

Discolouration in a living tree is generally associated with heartwood formation. Different kinds of polymerisation of phenolic compounds are found to be involved in the process of heartwood formation, e.g., in the woods of ash (*Fraxinus excelsior*) (Frey-Wyssling and Bosshard 1959), walnut (*Junglans nigra, J. regia*) (Burtin et al. 1998) and western red cedar (*Thuja plicata* Donn) (Johansson et al. 2000). However, birch does not develop heartwood at all (Piispanen and Saranpää 2001), or not until the trees become very old (Kärkkäinen 2003). Instead, the discolourations in the pith of the stem and in the dead branches, already typical for birch trees at the age of thirty years, are connected with the microbial invasion (Hallaksela and Niemistö 1998). The darkened wood around the pith is thought to be caused by the stresses of physiological or biological origins, which have increased the number of malformed and parenchyma cells (Pape 2002). Red heart of white birch (*Betula papyrifera* Marsh.) is shown to be an enzymatic oxidation of glycosides and catechin caused by fungi (Siegle 1967). However, the darkened wood around the pith is not necessarily decayed and the timber around the darkened wood is most often suitable for veneer and sawn timber production.

Discolourations caused by the drying process are those which actually occur during drying and are mainly caused by non-microbial factors (Amburgey 1994). Drying temperatures above the fibre saturation point have proved to be important factors for the interior discolouration of initially light-coloured sawn hardwood timber. The critical temperature for discolouration of hard maple (*Acer saccharum*), which should not exceed the average moisture content of sawn timber of 20%, is about 43°C (Smith et al. 2002, Yeo and Smith 2003). However, the same temperature is only high enough to stop the growth of the discolouring fungi but not high enough to kill them (Taylor 1997). During low-temperature drying, the conditions in wood are convenient for enzymatic activity in the living parenchyma cells above fibre saturation point. For example, the highest enzymatic activity related to colour changes of wood was found with Douglas fir sapwood at the temperature of 35°C (Laver and Musbah 1996). As a consequence of the enzymatic activity, the so-called chemical precursors of discolouration are developed (Wengert 1997). Later in the drying process, these precursors react with air and form new oxidised polymers which are typically dark in colour. In the precursor-phase, the discolouring chemicals are colourless and their presence is difficult or impossible to detect. Several pre-treatment methods have been studied to prevent the enzyme related discolouration in both softwood and hardwood sawn timber (Kreber et al. 1994, Kreber and Haslett 1997, Kreber et al. 2001, Schmidt et al. 2001). In general, the drying techniques which are developed to reduce or eliminate discolouration are based more on accidentally discovered methods rather than understanding the causes of discolouration (Taylor 1997).

After lignin, the most common polyphenols occurring in woody plants are proanthocyanidins (condensed tannins) (Haslam 1975). They have several biological activities in plants from toxicity to biological antioxidants, but their main characteristic is that they bind and precipitate proteins. The oxidation and condensation of phenolic extractives of wood are known to produce insoluble coloured compounds, which are seen in wood as discolouration. Luostarinen and Möttönen (2004) found a correlation between proanthocyanidin concentration and colour of birch wood in mature birch trees. Catechin, a precursor of proanthocyanidins, was found in the light-coloured interior of birch boards but not in the surface layer which was strongly discoloured (Asikainen et al. 2001). It is also one of the predominant phenolics present in green birch wood (Hiltunen et al. 2003). Catechin also was supposed to be involved in the discolouration of wood in ilomba (*Pycnanthus angolensis* Exell) (Yazaki et al. 1985), western hemlock (*Tsuga heterophylla*) (Hrutfiord et al. 1985, Kreber and Byrne 1994, 1996) and amabilis fir (*Abies amabilis*) (Kreber and Byrne 1994, 1996).

Microscopic studies have revealed that the discoloured chemicals in wood are concentrated in ray parenchyma cells containing globules from crystalline to amorphous pigments (Bois 1970, McMillen 1975, McGinnes and Rosen 1984, Forsyth and Amburgey 1991, Stenudd 2002, Koch et al. 2003, Straze et al. 2003). These globules subsequently turn dark upon exposure to high temperatures and slow drying conditions (Forsyth and Amburgey 1991). Because of the closeness of wood rays to each other, the discolouration appears to cover the general area (Bois 1970).

Many environmental factors such as solar radiation, moisture and temperature cause weathering or oxidative degradation of wooden products during their normal use; these ambient phenomena can eventually change the chemical, physical, optical and mechanical properties of wood surfaces (Hon 2001). All chemical components of wood are susceptible to degradation by sunlight or ultraviolet light, which typically leads to discolouration, loss of gloss and lightness, and roughening of surfaces. Typically, birch wood darkens and turns yellow even in diffuse light conditions indoors if coatings with ultraviolet protection are not used (Puisten sisäverhousten... 1995). Some newly developed finishes in which the absorbance characteristics are shifted more towards the longer wavelengths may better provide the colour stabilization of wood compared with the standard products (Rogez 2002). With regard to using additional finishes, however, the natural elasticity, which is considered as an advantageous property of the surface layer of wooden products, should be taken into account.

1.5 Physical and mechanical properties of wood related to further processing of birch timber

The suitability of birch as a raw material for the wood products industries is based on the homogeneity and equable structure and colour of wood (Salmi 1987). In relation to the density of wood, also the strength and wearing properties of birch are adequate, e.g., for many furniture and parquet products (e.g., Jalava 1945, Wagenführ 1996, Heräjärvi 2002).

In earlier studies, the average basic density for mature *B. pendula* wood from naturally regenerated stands has been 501 kg m^{-3} (Hakkila 1966) and 512 kg m^{-3} (Heräjärvi 2004). In the same studies, the average basic density of *B. pubescens* was 480 kg m^{-3}. Due to the diffuse-porous structure and low proportion of late wood in both species, the variation in density is low. The most important exception is the fast grown juvenile wood which has lower density than the mature wood and decreasingly in young trees may affect density (see: Zobel & van Buijtenen 1989, Dunham et al. 1999). However, the proportion of juvenile wood and the difference in the properties of juvenile and mature wood is little studied for Finnish birch species. Earlier, basic density of 420 kg m^{-3} (Anttonen et al. 2002) and 429 kg m^{-3} (Sterner and Hedenberg 2003) was measured for *B. pendula* saplings of six and eleven years old, respectively. In accordance with the juvenile effect, the basic density of plantation-grown, young (ca. 30 years old) silver birch trees was found to correlate negatively with the width of the annual ring (Verkasalo 1998).

Environmental factors during the growth of a tree to some extent may affect the wood properties by changing the growth rate of wood. Among hardwoods, response of wood to environmental factors varies for different anatomic types of wood species. In the diffuse-porous wood category, growth rate has very little influence on wood properties (Zhang 1995). Theoretically, wood density should decrease from poor sites to fertile sites, because of the production of larger and more frequent vessels in a matrix of relatively thin walled fibres on high-fertility sites (Zobel and van Buijtenen 1989). However, the basic density of mature birch wood was found to increase with increasing fertility (Hakkila 1966). According to Verkasalo (1998), basic density of young plantation-grown silver birch trees growing on abandoned agricultural fields was lower than that presented in earlier studies for birch trees from naturally regenerated forests. In the same study, the ring width of the birch trees growing on abandoned fields was significantly greater than that of the birch trees growing on forest sites. The relationship between basic density and ring width is strongly affected by the proportion of juvenile wood, which should be taken into consideration (Hakkila 1966).

There exists a high correlation between the basic density and Brinell hardness of birch wood (Kucera 1984, Heräjärvi 2004). According to Heräjärvi (2004) the average Brinell hardness of mature *B. pendula* and *B. pubescens* wood is 23.4 MPa and 20.5 MPa, respectively. Compared to other hardwood species commonly used in the furniture and parquet industries the Brinell hardness of birch is low. However, it is higher than the Brinell hardness of Finnish softwood species (Jalava 1945, Kärkkäinen 2003).

On average, the weight density (at 12-15% MC) of *B. pendula* wood is 630 kg m^{-3} (Wagenführ 1996). The average shrinkage from the green condition to 0% MC of *B. pendula* wood is 5.3% in radial, 7.8% in tangential and 0.6% in longitudinal direction. The rate of drying can affect shrinkage of wood for some wood species (Stevens 1963, Wood Handbook... 1999). Typically, the shrinkage tends to decrease with increased drying rate. In addition, the shrinkage of wood is dependent on the extractive content of wood being the greater the lower is the extractive content (Kärkkäinen 2003).

As a hygroscopic material, wood will give up or take in water vapour from the air surrounding it until it reaches a balance with its environment. The responsiveness of sawn and dried birch wood to ambient relative humidity is a concern because it is in connection with dimensional changes of solid wood both during the further processing and in the end products (e.g., Isomäki et al. 2002). At a given temperature, wood will reach the equilibrium moisture content (EMC) that depends on the relative humidity at that temperature in the physical environment (Keey et al. 1999). The moisture content of wood as a function of relative humidity produces a sorption curve. However, there exists a hysteresis; the desorption curve attained by drying and adsorption curve attained by wetting are not identical, i.e. the moisture content of wood is higher when the equilibrium moisture content is attained by desorption than when it is attained by adsorption. Furthermore, drying of green (saturated) wood produces an irreversible loss of capacity for water or hygroscopicity (Keey et al. 1999). Responsiveness of wood to environmental changes is also dependent on the temperature at which wood is dried.

1.6 The objective of the study

The purpose of this study was, on one hand, to study the basic wood properties and colour of plantation-grown silver birch and, on the other hand, to study the behaviour of that wood during artificial drying. The source of raw material plays an important role in the quality which the end products will have, because the basis of the material properties already exists in the growing stock's wood properties. In this respect, the silver birch trees growing on plantation stands were selected for the source of raw material for this study, because their wood properties are not well enough known and their proportion as raw material of the wood products industries is predicted to greatly increase in the near future. Regarding birch timber, the properties which the semi-finished and end products will have are dependent on the important role of the drying of the wood. Drying induces discolouration and shrinkage in wood and obviously has additional effects on other physical and mechanical properties. Presumably, if the wood properties of plantation-grown birch timber differ from those of naturally grown birch timber, also the response to drying differs. Accordingly, the main objective of this thesis was to study the drying behaviour and related wood and timber properties of plantation-grown silver birch for the raw material of the wood products industries (Table 1).

The reasons for the variation in the wood properties and drying behaviour were studied in more detail in the individual articles. Regarding birch timber, variations in wood properties also can occur due to the wood procurement season, storage and sawing practice. Traditionally, birch trees were only harvested in winter, but the arrangements of modern wood procurement and the process technology of the modern wood products industries call for harvesting timber almost throughout the year. Due to transportation logistics and the need for buffer stocks of timber in production plants, for saw logs it may take several weeks from the felling date, to the moment before they are sawn into boards and dried. The storage of harvested, fresh timber is at risk of an increase in the variation of the properties of the semi-finished and end products. In addition, phenological events and physiological processes which exhibit seasonal pattern in hardwood species are known to have an effect on wood properties. Accordingly, the wood procurement season and the storage of logs before further processing, were studied as a source of variation in the wood properties and drying behaviour of wood.

Table 1. Objectives of the thesis and of the individual articles.

OBJECTIVE OF THE THESIS				
Drying behaviour and related wood and timber properties of plantation grown birch for the raw material of wood products industries				
Behaviour of wood during drying		Basic physical and mechanical properties of wood		
OBJECTIVES OF THE INDIVIDUAL ARTICLES				
ARTICLE I	ARTICLE II	ARTICLE III	ARTICLE IV	ARTICLE V
Variation and mechanism of discolouration of wood during drying	Chemical background for the variation in discolouration of wood during drying	Variation in the density and shrinkage of birch wood	Variation in drying conditions in the kiln, drying behaviour and final moisture content of sawn timber	Mechanical and physical properties of dried sawn timber as raw material for furniture and parquet industries
Differences in discolouration during drying between growing sites, wood procurement seasons and storage periods of logs	Variation of proanthocyanidin concentration of wood between wood procurement seasons in fresh and dried wood and during drying	Density and its variation in fresh and dried wood from plantations and natural regenerations	Differences in drying behaviour (drying time, drying rate) caused by the differences in drying conditions (temperature, relative humidity) and initial moisture content	Variation in Brinell hardness and equilibrium moisture content of wood between wood procurement seasons, drying methods, and within-tree locations
Differences in discolouration between drying methods	Differences in proanthocyanidin concentration between drying methods	Variation in shrinkage between wood procurement seasons and drying methods	Differences in final moisture content of wood caused by the differences in drying conditions and initial moisture content	Interaction between the Brinell hardness and basic density in plantation-grown birch wood
Within-board appearance of discolouration	Connection between polymerisation of proanthocyanidins and wood colour			

To study the variation in wood properties and drying behaviour caused by the drying method, the conventional kiln drying (heat and vent drying) and vacuum drying, which are the most common artificial drying methods for birch wood, were used for the drying of the study materials. On the subject of drying method, wood colour, shrinkage, weight density, final moisture content, Brinell hardness and equilibrium moisture content were studied. Because the wood properties are known to differ after drying in different parts of an individual board, the surface layer and the inner wood of boards were analysed separately regarding wood colour and moisture content during and after drying.

The thesis is a summary of five articles with scientifically verified results, completed with the current knowledge of practice as well as the author's personal research judgements. The articles form an assembly starting from the discolouration of birch wood during conventional and vacuum drying, continuing with the investigation of chemical background of discolouration in the second paper. The third paper deals with the density and shrinkage of wood. The fourth paper approaches the effects of wood properties and drying conditions in the kiln on the drying behaviour and drying result of sawn timber. Finally, Brinell hardness and equilibrium moisture content of wood are discussed in the fifth paper. The objectives of the individual articles in detail are presented in table 1.

2. MATERIALS AND METHODS

2.1 Study materials

The study was primarily conducted and papers I-V were written based on two silver birch (*Betula pendula* Roth) stands of plantation forests located in North Karelia, Eastern Finland (62°18' N, 30°48' E and 62°46' N, 30°39 E). By the site type, the forests were a typical forest regeneration area of high fertility *Oxalis-Myrtillus*-type (OMT) and a typical afforested abandoned agricultural field. On both study sites, the soil type was fine sand, which is an aeolian deposit of postglacial feature (Haavisto 1983). A total of sixty dominant trees were selected as sample trees. From both stands, ten sample trees were felled during each of the three seasons in 1999, on 3-4 June, 16-17 September and 3-4 December (Table 2). Two logs, 2.5 m in length, were cut from each tree. The first log was cut beginning from the butt of the tree. The upper log usually started at the upper end of the butt log. In a few cases, when the diameter of the trunk allowed, the upper log was cut so that the top diameter was set at 20 cm. The logs from the first five trees from both sites were sawn within a few days after felling. The remaining five logs were stored for eight weeks in the open-air in the yard of the sawmill before they were sawn using a Kara-110 circular saw.

In the first phase, the logs were sawn into boards which were 35 mm × 80 mm × 2500 mm in size. From each butt log, two sample boards were selected; one from the vicinity of the pith and the other from near the log surface. Due to the limited size of the conventional drying kiln, each board was further cut into two shorter boards 1200 mm in length with a precision circular cutting saw. The basic material consisted of 120 vacuum dried and 120 conventionally dried sample boards sawn from the lower part (0-1.25 m) and upper part (1.25-2.50 m) of the butt log respectively. In addition, 66 and 102 sample boards, from butt logs and top logs, respectively, were selected for colour measurements presented in paper I.

Table 2. Characteristics of the sample trees and logs by wood procurement season, storage, and stand. Wood procurement seasons and storage of logs: summer (S), autumn (A), winter (W); unstored (0), stored eight weeks (8).

Wood procurement season - storage	Stand	Sample trees			Sample logs	
		N[a]	Mean height, m	Mean $D_{1.3}$[b], mm	Mean top diameter of butt log, mm	Mean top diameter of top log, mm
S – 0	Forest	5	19.2	227	216	192
	Field	5	18.4	209	200	179
S – 8	Forest	5	20.2	237	223	197
	Field	5	17.9	201	191	171
A – 0	Forest	5	19.6	214	201	189
	Field	5	18.3	229	216	192
A – 8	Forest	5	19.8	211	198	185
	Field	5	20.4	230	214	196
W – 0	Forest	5	19.2	208	199	171
	Field	5	20.7	218	206	189
W – 8	Forest	5	20.1	224	210	192
	Field	5	20.1	223	206	192

[a]number of sample trees; [b]diameter at breast height.

For paper V, three additional plantation forests of silver birch, comprising wood materials from commercial first thinnings, were chosen in addition to the two aforementioned plantation forests, which consisted of trees left on site after the first commercial thinning. The total number of boards originating from these forests was 73. In paper III, in which the variation in wood density and shrinkage of sawn birch timber from plantation forests was determined, birch wood from naturally regenerated forests was used as a reference material. This consisted of two mature silver birch stands, one on MT-type (*Myrtillus*-type) and another on VT-type (*Vaccinium*-type) on mineral soils (Luostarinen et al. 2002). The material from the naturally regenerated forests was collected using similar arrangements in respect of wood procurement seasons and wood processing methods. Also the methods for the analyses of wood properties were uniform. Consequently, the total number of boards from naturally regenerated forests was 235.

2.2 Drying experiments

Each of the six sets of sawn timber from the three wood procurement seasons and the two storage periods of logs were dried as separate drying charges always using the same schedule of conventional and vacuum drying for the charges in the comparison. The drying schedules are presented in paper IV. The schedules were moisture-content-based where the course of drying was controlled by the moisture content in the core of the sawn timber. The basic idea in planning the drying schedules for both conventional and vacuum drying processes was to ensure that discolouration of wood would occur to some extent. Simultaneously, the schedules had to be as close as possible to the schedules used in the birch sawmill industries. In other words, the industry-based drying schedules were modified using an elevated temperature level. For comparison of the drying methods for the effects on the properties of dried sawn birch timber, the final moisture content of 5% was used in both drying methods. Similar temperatures during the different processes were not used, because drying at vacuum is thought to yield lighter-coloured birch wood than drying at normal atmospheric pressure. The end-sealing of boards was not used.

Initial and final moisture contents were determined gravimetrically by weighing 20 sample boards before and after the drying process for each conventional and vacuum drying charge. The residual moisture content after drying was determined gravimetrically using small (10-20 g) sub-samples. Moisture content during drying was determined six times at the moisture content levels from 10 to 55%, measured from two separate sample boards at each moisture content level. For the measurements, small sub-samples were cut from the middle of the boards. All the gravimetric analyses of the moisture content, where small sub-samples were used, were carried out separately for the surface layer and inner wood of boards. During the conventional drying, the progress of moisture content and the drying conditions (relative humidity, dry bulb temperature, wet bulb temperature) measured with the sensors of the kiln were recorded in one hourly sequences. The drying conditions and moisture content of wood during vacuum drying could not be recorded.

In paper V, in addition to conventionally and vacuum-dried wood, part of the wood material was dried outside in the open air. In addition, all the dried material in paper V was analysed after conditioning at 20°C temperature and 65% relative humidity according to the respective standard (EN 1534).

2.3 Spectral measurements and chemical analyses of wood

The wood colour was measured using a portable spectrophotometer (Minolta CM-2002) with d/8 geometry (diffuse illumination/8° viewing angle) and a measuring area of 8 mm in diameter. Measurements were made both on fresh and dried boards and always from the freshly planed surface. Three measurements in each sample board were made avoiding knots and other defects and averaged to one recording. The spectrum of reflected light in the visible region (400-700 nm) was measured and transformed to the CIEL*a*b* colour scale using a 2º standard observer and D_{65} standard illuminant. The transformation was carried out automatically by the meter software (Precise Color... 1994). In this three-dimensional coordinates, L* axis represents non-chromatic changes in lightness from an L* value of 0 (black) to an L* value of 100 (white), +a* represents red, -a* represents green, +b* represents yellow and -b* represents blue (Hunt 1998). The colour variables of both surface layer and inner wood of boards, and the difference in colour (ΔE_{ab}*) between them, were determined.

The proanthocyanidins were analysed using the acid butanol assay which is a method based on anthocyanidin production in acid hydrolysis (Porter et al. 1986). Wood samples for proanthocyanidin analyses were taken from fresh wood, during the conventional drying process from wood at moisture contents of 35, 30, and 25% based on the readings of the moisture content sensors in the kiln, and from the conventionally and vacuum-dried boards after the drying processes. Fresh wood samples were taken both from the vicinity of the pith and from near the trunk surface. The samples taken during and after the drying processes consisted of boards from three different radial locations: from the vicinity of the pith, from near to the surface of the log, and from the middle between the pith and surface (III, Figure 1). The chemical samples taken from the boards covered the entire cross-section of the board.

2.4 Analyses of the physical and mechanical properties of wood

The determination of basic density and weight density was based on the volumes of green and dried (5% MC) sample boards. Shrinkage of the wood during drying (from the green state to the target moisture content of 5%) was determined in the tangential and radial direction on the basis of the dimension measurements of the boards. Determination of the volumetric shrinkage was based on the shrinkages in these main directions and the longitudinal direction. The variation in the longitudinal shrinkage during drying was assumed to be small in relation to radial and tangential shrinkage. Hence, the constant longitudinal shrinkage of 0.6% (Wagenführ 1996) was used for the calculation of volume of dried (moisture content of 5%) boards.

Brinell hardness was determined at a constant relative humidity (65±3%) and temperature (20±2°C) according to EN 1534 using FMT-Mec 100 (Matertest). The measurements were made mainly in the radial direction and the distance from the measuring point to the pith was determined. At the same time, the equilibrium moisture content of the wood was determined by the gravimetric method.

2.5 Statistical methods

One-way analysis of variance (Tukey's test) was used to compare means between groups, and Pearson's correlation coefficient was used to examine relationships between the variables in the interest of the study (I, II, III, IV, V). Analysis of variance was split into various analyses according to the study factors: season of harvest, length of the storage period, radial and longitudinal location of wood in the trunk and growing site. Analyses were performed separately for both drying methods. For the conventional drying in paper I, factor analysis was used to study the effect of wood location in radial and longitudinal directions and their interaction on colour co-ordinates. Linear regression analysis was used to study the dependence of Brinell hardness on basic density (V). Regression analysis (dummy variable regression) was also used to analyse the variation in drying behaviour of wood by studying the dependence of weight density on basic density (III).

3. RESULTS

3.1 Effects of wood procurement season, storage, and growing site on discolouration of timber during drying (I)

The colour of green sawn birch timber was always light and significant differences between felling seasons or storage periods were not found. The decrease in yellowness of fresh wood during the storage of logs from summer-felled trees and the smaller yellowness values of fresh wood from autumn- and winter-felled trees seemed to be connected to the variation of the moisture content of the wood.

Of the wood procurement factors, the felling season had the strongest effect on the discolouration of sawn birch timber during drying. The colour coordinates (L*, a* and b*) differed significantly between the felling seasons both in conventionally and vacuum-dried wood; the difference between wood from summer-felled and winter-felled trees being the greatest. The seasonal differences in colour were large especially in the surface layer of the boards.

In conventional drying, discolouration was the strongest in the wood from summer-felled trees where both the surface layer and the inner wood of sample boards darkened intensively. Then, the colour difference between the surface layer and interior of the boards was hardly visible (ΔE_{ab}*=1.9). In the boards from winter-felled trees, the surface layer remained markedly lighter than the interior of the boards. The boundary between the lighter surface layer and the darker interior was gradual; in conventionally dried boards the colour change occurring during the depth of the first ten millimetres.

In vacuum drying the mechanism of discolouration varied from that in conventional drying; the colour of both the surface layer and inner wood of the boards being the lightest and the least red and yellow in the boards from summer-felled trees, and the darkest and the most red and yellow in the boards from winter-felled trees. In addition, the surface layer discoloured more than the inner wood of the boards; the difference in colour between the locations being the greatest in the boards from winter-felled trees.

The storage of logs increased the intensity of discolouration during conventional drying of the wood from summer-felled and winter-felled trees, and during vacuum drying for all materials. The opposite was the effect of the storage period of logs on the discolouration during the conventional drying of wood from autumn-felled trees. In all, the discolouration behaviour of the wood from unstored, autumn-felled trees was similar to that found for summer-felled trees. Respectively, the behaviour of the wood from autumn-felled trees which were stored for eight weeks was similar to that of the wood from winter-felled trees.

In the radial direction, the lightness of the inner wood of the boards increased and the redness and yellowness decreased from wood sawn from the vicinity of the pith towards that sawn from close to the trunk surface. The difference in colour between the radial locations was greater in the upper logs than in the butt logs. In the longitudinal direction, the differences in colour of conventionally dried wood were not significant between the butt logs and upper logs.

No differences in discolouration during drying were found between the two growing sites.

3.2 The role of proanthocyanidins in discolouration (II)

With regard to the felling season, the proanthocyanidin concentration in fresh and conventionally dried wood was the highest for winter-felled trees. The storage of logs increased the proanthocyanidin concentration both in fresh and dried wood especially for summer-felled trees. In vacuum-dried wood, the seasonal differences in and the effects of storage on the proanthocyanidin concentration were small. Compared to fresh wood, the proanthocyanidin concentration increased during the conventional drying and it was always higher in conventionally dried wood than in vacuum-dried wood.

Irrespective of the radial location of the wood, the proanthocyanidin concentration was at the same level in fresh wood but, in conventionally dried wood, it was highest in boards sawn from the vicinity of the pith of the trunk. In vacuum-dried wood the difference between the radial locations was smaller than in conventionally dried wood.

During conventional drying, it was seen that the proanthocyanidin concentration went through three stages linked to the reduction in the moisture content of wood. The proanthocyanidin concentration steadily increased until the moisture content fell to 30%. At 20-30% MC, the proanthocyanidin concentration was constant, but decreased gradually below 20% MC until the target moisture content of 5% was reached.

The correlations between the colour of dried wood and the proanthocyanidin concentration were the highest in the surface layer of boards sawn from unstored logs. In conventionally dried wood, proanthocyanidin concentration correlated positively with lightness and negatively with redness and yellowness of the surface layer. In vacuum-dried wood, the correlations between the proanthocyanidin concentration and the colour of the surface layer of the boards were opposite to those found in conventionally dried wood. Any statistical dependence of colour on the proanthocyanidin concentration could not be detected in wood that was stored as logs for eight weeks. As a whole, the interaction between proanthocyanidin concentration and colour coordinates was opposite, on the one hand, between the surface layer and inner wood of boards of conventionally dried wood and on the other, between the conventionally dried wood and vacuum-dried wood.

3.3 Density and shrinkage of timber during drying (III)

The basic density of birch timber from plantations, 454.4 kg m^{-3}, was significantly lower compared to that from naturally regenerated stands, 507.4 kg m^{-3}. Within a tree, the basic density increased from the wood sawn from the vicinity of the pith towards the wood sawn from near the log surface. Within a 2.4 m butt log, the basic density of timber was significantly higher in the lower half (0-1.2 m) than in the upper half (1.2-2.4 m) of the log.

The seasonal variation in the wood density and in the behaviour of wood during drying was significant. The basic density of timber was the lowest for autumn-felled timber and the highest for winter-felled timber. The difference was significant between winter and the two other seasons. The basic density was 5.9% and 6.1% higher in winter-felled timber than in autumn-felled timber for plantation-grown birch trees and for naturally regenerated birch trees, respectively.

Naturally, the correlation between the basic density of fresh timber and the weight density of dried timber was high ($r = 0.989$). However, according to the dummy variable regression, the dependency of weight density of dried timber on the basic density of fresh timber differed between the timber origins and felling seasons, but it did not differ between the drying methods.

The average volumetric shrinkage of all sawn timber specimens was 12.8% during the drying (from the green condition to the target moisture content of 5%). In radial and tangential directions, the shrinkage was 5.6% and 7.4%, respectively. The shrinkage of the sawn timber from the naturally regenerated stands was greater than that from the plantations.

Regarding the drying methods, the shrinkage of sawn timber was greater in conventional kiln drying than in vacuum drying. Volumetric shrinkage was the greatest in sawn timber from winter-felled trees and it differed significantly from that of summer- and autumn-felled trees for the timber from the naturally regenerated stands, but not for the timber from the plantations.

Both the volumetric and tangential shrinkage of sawn timber correlated very positively with basic density and weight density of dried timber. In addition, a negative correlation was observed between tangential and radial shrinkage.

3.4 Effect of wood properties and drying conditions in the kiln on drying behaviour and final moisture content (IV)

The moisture content of fresh wood was the highest in wood from unstored summer-felled trees (96-111%) (see also paper II, Table 1). It did not differ between autumn-felled (80-88%) and winter-felled trees (78-89%). In all seasons, the moisture content was the highest in wood sawn from the vicinity of the pith and the lowest in wood sawn from near the log surface, the difference in radial direction being the greatest in wood from winter-felled trees. The eight weeks' storage period of logs had an effect on the moisture content only in wood from summer-felled trees, when the wood dried to the level of 62-70% MC.

Despite the same drying schedule, the relative humidity in the kiln differed between seasons during the first steps of the conventional drying process when a low drying temperature was used. In general, during that time, the relative humidity was highest in summer and lowest in winter. Especially, during drying of the eight weeks stored summer-felled wood, the target relative humidity was not reached until the temperature was raised from 42 to 60°C. This was probably because of the humid and warm fresh air taken from the outside atmosphere.

In summer rather than in autumn and winter, due to the higher initial moisture content of the wood and relative humidity in the kiln, the drying time was longer and the drying rate was slower down to 30% MC. For winter-felled wood, however, the drying time was the longest and the drying rate was the slowest below 30% MC. Regarding vacuum drying, the drying time was the shortest and the drying rate was the fastest for summer-felled wood both down to and below 30% MC.

The average final moisture content of the wood was higher in vacuum-dried wood than in conventionally dried wood. In general, the vacuum-dried wood had a lower standard deviation of final moisture content than the conventionally dried wood. The final moisture content of vacuum-dried wood had a positive correlation with initial moisture content and drying rate, and a negative correlation with drying time. The final moisture content of conventionally dried wood neither correlated with initial moisture content nor with drying behaviour variables. In general, the moisture content gradient between the inner wood and the surface layer of boards was smaller in vacuum drying than in conventional drying. Regarding conventional drying, the moisture content gradient was the largest for the boards from winter-felled trees.

3.5 Brinell hardness and equilibrium moisture content of wood (V)

The average Brinell hardness of all specimens was 19.40 MPa, with the average values of 18.04 and 20.05 MPa for woods from unthinned and thinned stands, respectively. Brinell hardness of the wood from winter-felled trees was significantly higher than that of the wood from summer-felled trees. The Brinell hardness correlated positively with the basic density of wood.

The Brinell hardness increased gradually from the pith towards the log surface. Within a distance of 20 mm from the pith it was only 14 MPa, but at a distance of over 60 mm from the pith it was almost 25 MPa. However, the increase of Brinell hardness in the radial direction seemed to decline at a distance of 80 mm from the pith. The wood from the lower part of the butt log (0-1.2 m) had a higher Brinell hardness than that from the upper part of the butt log (1.2-2.4 m).

A within-tree variation was observed, especially in the radial direction, also for the equilibrium moisture content of dried and conditioned (20°C, 65% RH) birch wood. The highest values of equilibrium moisture content were obtained at a distance of approximately 30-50 mm from the pith, decreasing both towards the pith and towards the log surface. The longitudinal variation of equilibrium moisture content was very small, the value decreasing upwards. The equilibrium moisture content of dried birch wood was the highest in the wood from winter-felled trees and the lowest in the wood from summer-felled trees.

4. DISCUSSION

4.1 Reliability, validity and ability of generalisation of the results

The material of this study was collected from forests which were managed in accordance with the current Finnish silvicultural practices for the subjects of initial development and thinning stage. Both birch plantation sites of this study were typical of the southern part of Finland. Also the two naturally regenerated birch stands, which were used as a reference material in paper III, covered the typical growth sites of silver birch. Therefore, the results obtained can be generalised, in the first place, concerning the wood from the properly managed plantation forests of silver birch. However, due to the special characteristics of genetic origin and intensive breeding of silver birch in Finland (Raulo 1981), the generalisation of the results to the other industrially important countries (Sweden, Norway, Russia and the Baltic countries) can be only suggested.

The number of plantation stands (2) and sample trees (60) was, however, small for the purpose of the generalisation of the results. Therefore, the variation found in wood properties and drying behaviour between wood procurement seasons and the storage periods of logs may partly be caused by the uncontrolled natural variation. Larger study materials would have increased substantially the budget of the study and the time required for the different experiments and laboratory analyses. However, the materials enabled systematic comparative studies between the most interesting sub-groups of silver birch timber for felling period, storage time and drying method.

Although the sample trees had reached the dimensions required for sawable timber, in practice, their probable harvesting time would have been twenty to thirty years later. It is to be presumed that the wood properties would change to some extent during this time due to the maturation of wood and the decrease of the proportion of juvenile wood. In reality, the differences in wood properties between the plantation wood and wood from natural birch forests would finally be verified if the tests were repeated at the age of approximately sixty years.

Regarding the drying methods, the results of this study can be generalised for the drying schedules which are quite similar to those used in this study. However, the results provide some additional basic rules for the development of drying schedule according to the material and drying conditions. The drying schedules were not planned so that they would produce the lightest possible birch wood, because the aim of the study was to obtain discoloured wood in order for it to be studied. In this respect, the wood obtained from the vacuum drying in this study was at variance to the wood from the wood obtained in the practical wood industry more than the wood obtained from the conventional drying, since vacuum drying is normally known to produce lighter coloured wood than conventional drying. Therefore, regarding the suitability of different drying methods for sawn birch timber drying in practice, the comparison between the drying methods based on the results of this study is not relevant. In this study, however, the drying methods are compared considering the mechanisms of discolouration in different drying conditions and drying methods.

The variation of relative humidity during the first steps of conventional drying between drying runs creates uncertainty of the extent the changes in the drying behaviour (eg., discolouration, shrinkage) were caused by the differences in the drying conditions or by the differences in the wood's properties. In any case, the variation in relative humidity clearly affected the drying rate during the first steps of the drying process. Similar variation in the drying conditions is likely to exist in conventional drying of sawn birch timber by the industry, as well, as the drying temperature is kept low.

Most drying kilns in the wood products industries are using time-based drying schedules in which the duration of the drying process can be determined based on the initial moisture content of wood in each drying run, but the real time control of the process stages is not possible. In practice, this means that the drying behaviour in time-based kilns differs between drying runs the more the greater the variation in the initial moisture content between drying runs, because the risk for the difference in the drying conditions at the different moisture content levels increases. Therefore, to apply the results of this study to the time-based drying processes would be very complicated.

The evaluation of colour differences in paper I was mostly based on statistical analyses. However, a colour difference which is statistically significant, is not necessarily distinguished by a human observer. Based on the personal opinion of the author, a colour difference (ΔE_{ab}*) of 1.8 was chosen as a limit of an observable colour difference, which is somewhat smaller than those values of 2.5-3 presented in the literature (Hon and Minemura 2001). However, the observable colour difference is obviously wood-species dependent, as well, since lightly tinted shades can be more readily distinguished than deeply saturated shades (Popson et al. 1997).

The fact that the sampling method of proanthocyanidin concentration in paper II was not parallel with the spectral measurements of wood reduces the validity of the results. While the spectral measurements were made separately from the surface layer and inner wood of the boards, the samples taken for the chemical analyses covered the cross-section of the board as a whole. The possible difference in the proanthocyanidin concentration between the different layers of the boards would possibly have given additional information on the variation in colour between the layers and the different mechanism of discolouration between the drying methods.

Density characteristics of wood are typically measured by the water-immersion method from the small wood samples or discs. In paper III, however, the aim was to measure all the physical variables from specimens that are of normal size in sawn timber production.

Therefore, the volumes of sample boards needed for density characteristics were determined based on their space geometry. The volume of the fresh boards was measured always after the overnight storage at +6°C. Evidently, the boards from the winter-felled trees were not thawed throughout at the time of the volume measurement, which might have affected the density results.

Regarding the Brinell hardness in paper V, the interpretation of results would have needed to test the effect of difference in thickness of the specimens on Brinell hardness. The possible effect of thickness of specimens should then have to be taken into account in the statistical processing. However, the indentations were 1-2 mm only, and thus the variation in the thickness of the specimens (15-38 mm) unlikely influenced the results.

4.2 Variation in initial moisture content and drying behaviour of timber

The moisture content of wood has a seasonal variation of up to 40 percentage points in birch timber, ranging from the approximate monthly minimum of 55-60% (dry weight basis) in August, to the maximum of 90-95% in February (Hakkila 1962, Marjomaa 1992). In living trees, the moisture content rises to the highest value in spring just before the bud burst and then gradually decreases until the leaf fall (Burmester 1983). Both increasing (Burmester 1983) and stable (Peterson and Winquist 1960) moisture content of wood during the period between leaf fall in autumn and dormancy in winter has been reported. In this study, the moisture content of wood did not vary much during this period. Most probably, it does not vary either during the late winter, but the increase of the moisture content is faster in spring after the end of the frost period.

In an earlier study, the drying of birch pulp timber was found to be 25-50 kg m^{-3} during the first eight weeks of storage in summer, measured as the decrease in the density of fresh wood (Marjomaa 1992). This result is in accordance with the observations in this study, although the drying of wood is, naturally, dependent on the weather conditions during each storage period. The ambient conditions during the storage enabled the air-drying of logs in summer time, but not in autumn or in wintertime. It should be pointed out, that the most significant decrease in the moisture content and in the weight density occur in the log ends while, in the middle part, both the physiological, biological and visible morphological as well as physical and mechanical changes are small (e.g., Verkasalo 1993). Obviously, this causes additional within-log variation in wood properties and makes further processing more difficult. Although the loss of dry matter due to the storage has been found in birch timber (Pekkala and Uusvaara 1980), the period of eight weeks is probably only long enough for the infection of decaying fungi, which appears as the change of colour in the log ends (Verkasalo 1993, Luostarinen et al. 2002).

The within-tree variation in the moisture content of birch wood was also obvious. Based on the earlier studies, moisture content at its highest in the middle of the trunk (Burmester 1983), except during the spring when it is highest in the surface wood of the lower parts of the trunk (Peterson and Winquist 1960). In this study, the moisture content of wood was highest in the boards sawn from the vicinity of the pith for the trees felled during any season.

Differences in drying time and drying rate were obvious between the sawn timbers from trees felled during different seasons when the moisture content of wood was above 30%. The initial moisture content (which has been found to be an important factor for example for the distribution of final moisture content of Scots pine wood (Salin 2002)) decisively affected the drying time during conventional drying. Above 30% MC, drying time and drying rate were influenced also by the drying conditions in the kiln. They could be dissimilar for the different drying runs due to the variation in the environmental conditions outside the kiln, and the variation in the initial moisture content of wood, although the set-up of each drying schedule was the same. The variation in the amount of moisture in the fresh air taken outside the kiln, seemed to affect the relative humidity in the kiln at the low temperatures which are used during conventional kiln drying at above 20% MC of wood. In addition, according to Esping (1996), the increase in the initial moisture content of wood decreases the wet bulb depression and increases the drying time during the first steps of the drying process.

The variations between the sawn timber from trees felled during different seasons in drying time and drying rate below 30% MC, indicated differences in those wood properties which affect the migration of water in wood both in the conventional drying and in the vacuum drying. According to Sehlstedt-Persson (2001), the moisture diffusion coefficient of Scots pine and Norway spruce decreases with increasing density and increasing amount of extractives. In addition, it is possible that the fast drying of the surface layer of boards from winter-felled trees hindered the drying of the inner wood of the boards by decreasing the moisture migration properties in the surface layer.

Regarding the final moisture content of wood, which is an important criterion of drying quality for sawn timber (Salin 2002, Welling 2004), the vacuum-dried sawn timber had a smaller standard deviation of moisture content than the conventionally dried sawn timber. Also the gradient of moisture content between the inner wood and surface layer of boards was the smallest in vacuum-dried wood. In conventionally dried sawn timber, the gradient of final moisture content between the inner wood and the surface layer of boards was the highest in boards sawn from winter-felled trees. Obviously, this was the result of the premature drying of the surface layer of boards from winter-felled trees, which sustained a high gradient of moisture content until the end of the drying process.

4.3 Proanthocyanidin concentration in wood

Seasonal variation in non-structural carbohydrate reserves has been reported in the stem wood of sessile oak (*Quercus petraea* (Matt.) Liebl.) and beech (*Fagus sylvatica* L.) (Barbaroux and Bréda 2002), sugar maple (*Acer saccharum*) (Wong et al. 2003) as well as for *B. pendula* (Piispanen and Saranpää 2001). For *B pendula*, the smallest total amounts were found for bud burst and early wood growth from spring until mid-summer. Notably, however, in the leaves of *B. pendula*, there exists a large annual variation of phenolic compounds (Laitinen et al. 2000). During the late summer and early fall, the soluble carbohydrates are accumulated in the xylem ray tissues. During the leafless period, starch is stored for the metabolic processes and for primary growth in spring. During cold months, soluble sugars increase when starch is hydrolysed due to the low temperature (Wong et al. 2003). The seasonal variation of carbohydrates in wood is due to plants maintaining respiration during a cold period in winter, building leaves and supporting new growth in spring, and providing the energy expended in making adaptive responses to different kinds of stresses (Barbaroux and Bréda 2002). A similar pattern of seasonal fluctuation was observed in this study for the soluble proanthocyanidin concentration in fresh wood. Additionally, the storage of timber as logs contributed to the higher proanthocyanidin concentration. In fresh wood, it increased during the eight weeks' storage period most significantly for the summer-felled trees, which was obviously due to the adequate temperature for enzyme-catalysed synthesis of phenols (cf., Laver and Musbah 1996).

The within-tree variation in the proanthocyanidin concentration in fresh wood was not found in this study. This result was unexpected, because the content of soluble sugars was found to decrease from the cambium towards the pith in an earlier study (Piispanen and Saranpää 2001), and the content of methanol extractives was found to decrease from the inner sapwood towards the outer sapwood in fresh silver birch wood (Mononen et al. 2004).

In this study, during the conventional warm-air drying process, drying of wood induced the synthesis of proanthocyanidins down to 20-30% MC. Synthesis of proanthocyanidins is probably a reaction of wood against the stress caused by the removal of water and the increase of temperature in living parenchyma cells and it is favoured by moist and warm conditions (e.g., Botha et al. 1981). It is also possible that the macromolecular compounds present in wood decompose during drying into soluble compounds of lower molar mass (Mononen 2004). The initial proanthocyanidin concentration in the fresh wood was at the same level irrespective of the radial location, but proanthocyanidins were synthesised most in the boards sawn from the vicinity of the pith and least in the boards sawn from near the trunk surface. Obviously, due to the higher initial moisture content of boards sawn from the vicinity of the pith, the drying process above 30% MC was longer for those boards, and the synthesis of proanthocyanidins continued for a longer period. The increase of drying temperature during the last steps of the drying process contributed to the polymerization of the proanthocyanidins to insoluble form. Below 20% MC, the concentration of proanthocyanidins decreased steeply remaining, however, in dried wood at a higher level than in undried wood. Also the difference in proanthocyanidin concentration between the boards from different radial locations, which developed above 30% MC, remained until the end of the drying process.

In vacuum-dried wood, which was dried at higher temperatures than the conventionally dried wood, the concentration of proanthocyanidins was markedly lower than in undried wood. The same result was obtained in an earlier study on mature birch wood from naturally regenerated forests, which, in addition, had a higher proanthocyanidin concentration after drying in room conditions than after conventional drying (Luostarinen and Möttönen 2004). The sample preparation and drying conditions have been found to affect the polyphenol concentration of the plant foliage material; for example, the smallest amounts of (+)-catechin concentrations were found in willow leaves after heat-drying at 60 and 90°C (Julkunen-Tiitto and Sorsa 2001), and the highest condensed tannin concentrations were found in conifer foliage material after freeze-drying (Yu and Dahlgren 2000). For willow leaves also, both the concentrations of (+)-catechin and condensed tannins showed higher values after freeze-drying than fresh or room drying (Julkunen-Tiitto and Sorsa 2001).

4.4 Discolouration of timber during drying

When comparing the results of this study with earlier studies on discolouration of wood during drying, the layer in which the colour measurements have been carried out should be taken into account. Seasonal differences in the discolouration of the surface layer of hard maple (*Acer saccharum* Marsh.) timber during drying were studied by Smith and Herdman (1996). They also observed the lightest and the least red colour for winter and autumn felling seasons when drying timber with low-temperature and low humidity schedules. In the study of Luostarinen et al. (2002), in which the colour values of birch wood from mature, naturally regenerated birch trees were measured from the inner wood of split-sawn boards, the highest lightness and the lowest redness was observed for the boards from winter-felled trees. Whereas in this study on birch wood from plantations, the lightness of conventionally dried wood did not differ between the woods from summer- and winter-felled trees, and the redness of the inner wood of boards was the greatest in the boards from winter-felled trees. Furthermore, no favourable effect of storage of the logs on wood colour was found in this study. The main reason for the different results between the wood from natural stands and plantations was probably in the differences in wood properties.

The seasonal variation in the discolouration during drying could not be connected directly to the seasonal variation in the proanthocyanidin concentration in fresh birch wood. For conventional drying, the marked differences in the discolouration between the felling seasons were observed in the surface layer of boards while the colour of the inner wood varied less. Discolouration of the surface layer of conventionally dried boards was greatest for summer-felling when the proanthocyanidin concentration of both undried and dried wood was lowest. Correspondingly, in vacuum drying, the discolouration was greatest both in the surface layer and in the inner wood of boards for winter-felling, when the proanthocyanidin concentration of undried wood was highest.

The principal reason why the difference in colour between the surface layer and inner wood of conventionally dried boards varied between the wood procurement seasons was the variation in drying time, especially during the first steps of the drying processes. Obviously, drying at low temperatures produces the precursors of discoloured compounds the more the longer the drying proceeds above the fibre saturation point; the precursors are then discoloured by oxidation during the last steps of the drying process, below the fibre saturation point (cf., Koch et al. 2003). The longer drying time above 30% MC for the summer-felled wood than for that of the autumn-felled or winter-felled wood had the greatest influence on the drying of the surface layer of the boards. On the other hand, the quick drying of the surface layer of boards from winter-felled trees, which was observed through the development of the moisture content gradient in boards during the first steps of the drying process, caused the colour of the surface layer to remain very light.

Also the minor contrasts in the discolouration between the boards from the different radial locations was most probably due to their variations in initial moisture content of wood which lead to the difference in drying time. The difference in colour between the radial locations may also occur in an individual piece of sawn timber (Sundqvist 2002*a*).

The colour variation between the layers of conventionally dried boards also differed between storage periods in autumn, when the weather conditions turned from autumn to winter. During the course of this study, this happened, when a decrease was observed in the daily mean temperature from +10°C to -3°C. Accordingly, the drying conditions in the kiln differed between the drying charges in autumn. Possibly, some migration of water from the cell wall tissue to the cell cavities occurred during the storage, which is typical in wood at temperatures below 0°C (Skaar 1988).

The freezing of wood has been found to have an effect on the drying process which, based on the drying experiments with artificially frozen wood, remains in wood from a few days to a number of weeks after the freezing treatment (Erickson 1968, Ilic 1999). It is evident that the natural freezing of wood was the main reason for the light and less red surface layer in the boards from winter-felled trees. The relocation of water through freezing may affect the drying process, at least in the surface layer of boards, as the water is removed more easily from the cell cavities than from the cell wall tissue. In the wood from winter-felled trees, the restrained drying of the inner wood of boards below 30% MC was probably to some extent caused by the faster drying of the surface layer.

In this study, the combination of relatively high temperature and the low drying force that was already used in the beginning of the vacuum drying process was the reason for the darker and more reddish colour of vacuum dried wood compared to that of conventionally dried wood, although vacuum drying is normally known to produce light-coloured wood. The risk of drying defects is high in vacuum drying when the chosen process parameters are unsuitable (Ressel 2003). The low proanthocyanidin concentration in vacuum-dried wood, which did not differ between the trees felled during the different seasons, showed that these colourless phenolic compounds polymerised to insoluble discoloured substances during drying. Seasonal variation of phenolic compounds, which was seen as changes in the proanthocyanidin concentration in fresh wood, probably had an effect on the discolouration. However, it is obvious that the main reason for the seasonal variation in the discolouration was the difference in drying time, owing to differences in the related wood properties. Parallel to the changes in the physical and chemical properties of wood (e.g., basic density, extractive content), the moisture migration properties of wood were obviously different during drying (cf., Sehlstedt-Persson 2001).

The moisture content at which the condensation of the colourless phenolic compounds to the discoloured compounds occurs is related to the increase in the availability of oxygen for the condensation reaction (cf., Koch et al. 2003). The largest change in the availability of oxygen during drying takes place at the fibre saturation point. However, as the fibre saturation point is dependent on several factors and cannot be specified at certain moisture content (Kärkkainen 2003), the critical moisture content at which the discolouration begins during drying may vary. In hard maple, the critical phase was found to be when the moisture content of wood is at or above fibre saturation point (Yeo and Smith 2003). Consequently, elevated temperature and the presence of air are important components for the development of discolouration. Based on the colour measurement during drying, Luostarinen et al. (2002) concluded that the discolouration of birch wood starts when the moisture content of wood is about 30% and the wood reaches its lowest lightness at 18-20% MC. This corresponds well with the moisture content of 23.5% which, according to Koponen (1985), is the fibre saturation point for birch wood at 40°C. According to Stenudd (2004), both the capillary phase, when moisture content is above fibre saturation point, and the diffusion phase have effects on the final colour of silver birch wood after drying and, during the capillary phase the drying time is more important than the drying temperature. Also Sundqvist (2002*b*) found that, when subjected to heat treatment at 60-90°C, time is more important for the discolouration than temperature. A similar conclusion can be drawn based on the results of this study: the longer the time above fibre saturation point during drying the stronger is the discolouration. Although the drying-related discolouration becomes visible in birch wood below 30% MC, the chemical precursors of the discoloured compounds are mainly developed during drying above 30% MC (cf., Wengert 1997). However, the temperature is important below fibre saturation point (Stenudd 2004), but in this phase the variation in the critical wood properties (e.g., density, extractive content) may also affect the drying rate and discolouration.

When birch wood is dried at low temperature, the initial moisture content of the wood and the absolute humidity of fresh air, which both vary annually, are the decisive factors concerning the time of drying above fibre saturation point. The high concentration of phenolic extractives in wood only has an effect on the discolouration during prolonged storage and drying above 30% MC. However, as the discolouration may occur also during drying at room temperature (Luostarinen and Luostarinen 2001), the critical temperature where the precursors of the discolouration are developed obviously varies as well. Evidently, the synthesisation of precursors is accelerated by temperature. In this study, this was seen as an intensive discolouration in vacuum-dried wood. However, it is obvious that regardless of the temperature, if the drying would be fast enough, birch wood could be dried with remarkably less discolouration (cf., Stenudd 2003). On the other hand, the thickness of the sawn birch timber is normally relatively large (≥ 38 mm) making the drying of the inner parts of the boards so long lasting that the variation in discolouration inevitably occurs during conventional kiln drying.

The variation in colour between the surface layer and the inner wood of the boards occurred in a different way in the two drying methods. It is obvious; that the higher dry bulb temperature of 60-82°C during the drying process was the main reason for the more intensive discolouration during the vacuum drying. However, it is unclear why the surface layer discoloured more than did the inner wood of the boards during vacuum drying. One hypothesis is the role of low-molecular sugars and nitrogenous compounds which, in sawn Scots pine (Terziev 1995) and radiata pine (Kreber et al. 1998) timbers, are known to migrate to the surface of the boards when high dry bulb temperatures are used during drying. However, this is an unlikely reason in relation to the vacuum drying in which the moisture moves mainly in the longitudinal direction (cf., Chen 1997). It is also possible that, in this study the drying conditions were favourable for strong discolouration of the surface layer; the drying force was relatively low and the drying temperature was relatively high at the beginning of the vacuum drying process. Unfortunately, real time data on the ambient drying conditions during the vacuum dryings were not recorded.

Differences in the discolouration of timber were not found between growing sites in this study. In an earlier study, the growing site and its fertility, for the natural habitats of birch trees, were found to have only a minor effect on the discolouration of birch wood during drying (Luostarinen et al. 2002). However, as the differences in fertility between growing sites affect growth rate and, hence the ring width, the ratio between light-coloured early wood and dark-coloured late wood varies with the level of fertility.

4.5 Physical and mechanical properties of wood

Both the wood from plantations and the wood from naturally regenerated forests showed seasonal variation in basic density for silver birch. The result is in accordance with earlier findings by Peterson and Winquist (1960); the basic density of birch wood is higher in the winter half of the year than in the summer half of the year. Also Burmester (1983) found an increase in birch wood density during the frost period in winter, and a decrease to the minimum at the time of the bud burst. However, when comparing the basic density values between summer-felled and autumn-felled wood, this study found none of the gradual increase in density during summer found by Burmester (1983).

Based on the between-season difference in the concentration of soluble carbohydrates in birch wood (Piispanen and Saranpää 2001), the variation in dry density caused by the difference in extractive content could be 1-2%. The relative difference of 5-6% in the density of wood between the seasons which was observed in this study, cannot therefore be explained by the seasonal fluctuation of storage carbohydrates only (cf., Burmester 1983), but by the season-dependent physiological changes as a whole. The seasonal changes in the extractive and moisture contents and in the temperature, caused changes in the mass and volume of fresh wood. In addition to the increase in extractive content of wood, the coldness shrinkage of wood at the temperatures below 0°C might have increased the basic density of wood in the winter-felled trees. Coldness shrinkage is a result of the migration of water from wood tissue to the ice crystals in cell cavities (Skaar 1988). It can also be seen as changes in the dimensions of wood (Kübler 1962, Leikola 1969).

The variation in the density between the seasons was emphasised in dried wood, due to the difference in the drying behaviour between seasons. Obviously, owing to the higher extractive content of wood in the winter-felled trees and the shrinkage of fresh wood due to the cold, the physical properties altered in a way that lowered the drying rate of wood below fibre saturation point. Consequently, the deceleration of drying especially below 30% MC lead to the increase in shrinkage of wood from winter-felled trees.

The significance of the variation in density between the wood procurement seasons, which was found in this study, is as such presumably quite low for the quality of the wood products. However, the variation in wood properties, including the initial moisture content, extractive content and wood density, had an effect on the behaviour of the wood during drying. This was seen as a variation in discolouration, shrinkage and gradient of final moisture content of the wood. It is essential to take the variation of the wood properties into account during the further processing of sawn timber. In practice, this would possibly mean that the wood properties were taken into account in more detail in drying schedules. Furthermore, as the variation of the wood properties of the sawn birch timber will increase with the supply of plantation grown timber, the sawn timber should be sorted more specifically according to the wood properties before further processing (cf., Welling 2004).

In this study, the basic density of silver birch wood from plantations was found to be significantly lower than that of wood from naturally regenerated silver birch forests or the basic density for mature silver birch as presented by Hakkila (1966), Wagenführ (1996), and Heräjärvi (2002). Similar findings of lower density of wood for plantation-grown birch trees have been presented by Velling (1979) and Verkasalo (1998). Also Dunham et al. (1999) found a 10% difference in the density between fast-grown and slow-grown birch wood. The within-tree variation in the density was observed as the density increased from the pith to the bark and decreased from the base of the trunk upwards. These results correspond well with the results of Hakkila (1966) and Heräjärvi (2002). However, the radial change in density was clearly larger in plantation-grown birch trees than in naturally grown trees, which resulted in the proportion of juvenile wood being higher in plantation-grown trees. In this study, the effect of a lower density of plantation-grown wood was shown as a lower hardness of wood compared with the results obtained for mature, naturally regenerated birch wood (Kucera 1984, Heräjärvi 2004).

According to Heräjärvi (2004), the density of birch wood does not increase outwards in the outermost wood (distance more than 100 mm from the pith); close to the stump height, the density may be even smaller than within the distance of 50-100 mm from the pith. Obviously, the decrease in density in the outermost wood is related to the maturation of the trees. It should be pointed out that due to the sawing pattern, the outermost wood was not included in this study.

The effect of drying rate on wood shrinkage was seen in this study as a greater shrinkage of conventionally dried wood compared to that of vacuum-dried wood. A similar difference between the same drying methods was obtained for sawn red oak timber by Harris and Taras (1984). Stevens (1963) found that the increase in drying rate decreased the shrinkage of beech wood. He also found that an increase in temperature affected shrinkage increasingly if slow drying was used, but decreasingly if fast drying was used. In addition to the difference in drying rate between the drying methods, the difference in drying rate between the felling and storage seasons also had an effect on shrinkage in this study. On the whole, the drying rate below fibre saturation point seems to have an effect on shrinkage of silver birch wood. Regarding the shrinkage, the conclusion is that the increase in drying rate improves the drying quality of sawn birch timber.

Previous research has found that drying temperature may have an effect on the equilibrium moisture content of wood when high temperatures (>100°C) are used (Edvardsen and Sandland 1999, Sehlstedt-Persson 1995, 2000). Consequently, the hygroscopicity of wood decreases and the dimensional stability increases with the increasing drying temperature. In this study, the equilibrium moisture content was also different in air-dried (20°C) and artificially dried (65 and 82°C) wood. Based on the difference in the equilibrium moisture content, the dimensional stability of wood also may vary between the radial locations.

5. CONCLUSIONS

In European wood products industries, the light and uncoloured birch wood is considered to be the most suitable for the products which are finished with clear or shaded varnishes. The uncontrolled colour variation increases the need for sorting and matching of raw material and, at worst, the discolouration of wood during drying alone may cause the rejection of an entire batch of sawn timber. In this study, the discolouration of birch wood during drying appeared both as a phenomenon of darkening and reddening of wood and as a difference in colour between the surface layer and inner wood of the boards. The uneven colour within a board is a problem when the timber is processed further by planing or resawing, and the machining exposes contrasting surfaces. For the support of further processing, additional research is needed on the acceptable discolouration and colour variation on the markets of wooden products. Furthermore, it is well known that the stability of colour in birch wood products in use is poor, especially when exposed to UV-radiation. However, to date the research information on the colour stability of birch wood surface in use is limited.

Obviously, the discolouration of birch wood during drying is mainly as a result of oxidative polymerisation of phenolic compounds. However, the seasonal and within-tree variation of the chemical and physical properties of wood complicates the control of colour during drying. It is obviously impossible to define any exact critical temperature for the discolouration of birch wood during drying, because it would be dependent on the wood properties and ambient drying conditions. To obtain the minimum variation in colour of dried sawn birch timber, it would be essential to be able to pre-sort the timber into batches according to the initial moisture content of the wood. Furthermore, regardless of the drying method, the drying schedules in every batch should be adjusted according to the initial moisture content of the wood. However, a uniform final colour is probably difficult to obtain for birch woods with different initial moisture contents. In all cases, the adequate control of colour during drying of sawn birch timber requires experimental research data and practical experience from the kiln operator.

To keep the quality of sawn birch timber uniform, the common practice used in the wood procurement is to avoid harvesting birch timber between the bud burst in spring and the leaf fall in autumn. This kind of action seems reasonable on the basis of the results of this study, if the objective is to obtain conventionally dried birch timber which has a light surface layer. In any case, the fresh wood should not be stored during a period of warm weather because of the chemical processes which may produce the precursors of the discoloured compounds. The storing of timber during a frost period is obviously not harmful regarding the wood colour. Therefore, the snow storage, which is commonly used by the wood products industries, is evidently a reasonable method to replace the wood harvested during summer.

High lightness and low redness values of birch wood colour together with a moderately short drying time obviously are not possible to achieve by the conventional warm-air drying method without causing a variation in colour between the different layers in the boards. The uneven colour of the boards is further emphasised when the boards are thick. The further lowering of temperature excessively increases the drying time and would approach the time taken for air-drying. In practice, vacuum drying is known to yield light-coloured birch timber in a relatively short drying time. This is presumed to be as a result of low oxygen concentration in the drying kiln. The results of this study indicate that the discolouration of birch wood during vacuum drying is also related more to the drying time than to the oxygen concentration in the kiln.

From the point of view of the wood products industries, additional research is required to optimise the drying quality as a function of drying costs. Additional research is needed also on other drying methods which are faster and perhaps more economical than the conventional kiln drying and the vacuum drying, e.g., high temperature drying and compression drying. In addition to the experimental research of drying behaviour of wood with different drying methods, the ability to use simulation models on discolouration would make it easier to find the solutions to the problem of discolouration.

Based on the results of this study, the density and the Brinell hardness in plantation-grown birch wood are significantly lower than for those in birch wood grown in naturally regenerated forests. The reasons for the lower values in those properties are the higher growth rate and young age of the cambium producing the wood cells (Bhat 1980). This can be considered in part to be a consequence of the breeding of plantation material during the 1960s when greater emphasis was placed on the quantity of the wood over the quality. The plantation-grown birch trees already achieve the size of saw logs at the age of forty to sixty years, which is up to forty years earlier than that of birch trees from natural regeneration. The difference in the density obviously will have an effect on the properties of birch wood products, which must be taken into account when raw material for the mechanical wood manufacturing industry is processed. Probably the mixed use of the plantation-grown and naturally grown birch timber during the further processing would be unreasonable. In addition, the radial variation in the density in plantation-grown material requires pre-sorting of material prior to or during the sawing. Due to possible differences in dimensional stability, the sorting of sawn raw material according to radial location prior to further processing seems to be reasonable. On the other hand, the radial variation in the value of wood in itself calls for the optimisation of bucking the stems (Heräjärvi 2002) and setting the sawing patterns in order to maximise the utilisation of the densest and the hardest wood near the log surface.

In addition, to retain the quality of birch products at the present level new production technology should be introduced into the wood products industries. Some possible uses include the utilisation of the drying technology which increases the wood density (compression drying) or the newly presented polyurethane finishes (Al-oxide finishes), which are able to increase the hardness of the surfaces of the wood products.

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