METSÄNTUTKIMUSLAITOKSEN TIEDONANTOJA 807, 2001
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Factors affecting the knottiness, twisting and mechanical properties of pith enclosed round and sawn timber of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) from thinnings in Southern Finland

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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 B1 of the University, Yliopistokatu 2, Joensuu, on June 15, at 12 o'clock noon.

JOENSUU RESEARCH CENTRE
2001

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The primary aim of the study was to find out factors affecting the mechanical properties and twisting of pith enclosed round and sawn Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) timber produced from small-size thinning wood. The effects of age i.e. number of annual rings, ring width, density, moisture content, knots, defects, form and size of the specimen, wood processing, origin of timber and tree species were studied. In addition, factors affecting knot properties in round and sawn timber were studied. The characteristics of timber produced from thinnings are discussed in order to determine the possible obstacles to utilise pith-enclosed timber from thinnings in constructions. The testing of mechanical properties were performed in order to determine the characteristic strength and modulus of elasticity of small diameter round timber in accordance of EN 384 (1995) and EN 408 (1995) standards. Therefore, special attention was given to the applicability of EN standards for round timber. Issues to be studied and discussed included adjustment factors, strength classes and grading. The purpose was to provide scientific information for the development of international standards for small-sized round timber.

Experimental studies, i.e. measuring twisting after seasoning, testing modulus of elasticity and strength in bending and compression parallel to grain, were performed on full-size pith enclosed pine and spruce timber. The EN standards 338 (1995), EN 384 (1995), EN 408 (1995) and EN 518 (1995) were used for the test procedure of mechanical properties. The studied twisting material comprised 400 test specimens (pine 225, spruce 175). The material to test mechanical properties comprised 500 specimens in total (pine 275, spruce 225) both for compression and bending. The diameter and moisture content of the specimens ranged between 50 mm to 180 mm and 10 % to 22 %, respectively. Test results were first tabulated and further investigated by graphs. There after, correlation and regression analyses were performed for the effect of age, density, ring width, cross grain, knots, moisture content, diameter of specimen, origin of timber, processing methods and form of specimen, and tree species on the properties of knots, mechanical properties and twisting of timber. Interactions between variables were also studied.

The results for pine and spruce showed that sawing results in higher knot area ratio, knot sum per circumference, than machine rounding. The mechanical properties of sawn timber suffer due to the higher knot area ratio compared to round timber. The change in the thickest knot quality from dead measured over bark to sound measured after wood processing depended on the amount of processed wood and the diameter of knot i.e. the knots which had changed from dead to sound were regularly larger over bark than those which had remained dead.

Regression analyses for mechanical properties and twisting confirmed that age i.e. number of annual rings affect these properties. Young pith-enclosed timber with an age of below 20 years had about 50 % higher twisting than older specimens. Results also indicated that moisture content and age had an interaction. The interaction indicated that moisture content had a greater effect on the mechanical properties and twisting of young, pith-enclosed timber than older timber. For more than 20 years old pith-enclosed timber, the effect of

juvenile wood was lower than those of younger. The mechanical properties of pith enclosed timber were about double at the age of 30 years compared to an age of 10 years.

For pith enclosed timber, the relationships between compression and bending strength were remarkably lower than that given by the EN 384 standard. For bending strength, both a negative and positive the size effect was observed. The direction of the size effect was also dependent on the age, diameter and ring width of timber. Round form was stronger and stiffer in bending than in sawn form, but any differences in compression were not found between forms and processing methods. The mechanical properties of pine and spruce could be considered similar, providing the specimens have similar physical properties, except density. At the same density, spruce was stronger and stiffer than pine. In general, modulus of elasticity and strength of pine and spruce timber can be considered similar, providing the specimens have the same physical properties and wood characteristics, other than density. At the same ring width, pine had higher density than spruce.

The external properties of log affecting inner knot characteristics in small-sized pine and spruce, such as knot sum and quality of knots was found in this study. Therefore it would be useful to study, whether these relationships could be used for determination on sawing or peeling sets in the wood industry. Profitable utilisation of small-size thinning wood is difficult because a great number of pieces have to be processed to yield one cubic meter end product and the losses due to drying deformations in further refining are obviously about double compared to wood from large logs. For example, planing of dried sawn timber produced from small-size thinning wood gives lower volumetric yields compared with sawn timber from final cuttings. The use of thinning wood should be avoided in complex and high-quality constructions exposed to humidity variations in order to avoid drying deformations. The stabilisation methods to prevent drying deformations of timber are now even a more interesting matter to study and develop than had been traditionally thought. Round form had better strength and modulus of elasticity in bending compared to rectangular form. Therefore it would be beneficial to develop a structural system, where round small-size timber can be used as load bearing material. Finally, mechanical properties of tested timber, in particular grade A and B round timber met the requirements of EN standards for structural timber i.e. properly dried and graded round thinning wood can be used in load bearing structures.

Keywords: *Picea abies, Pinus sylvestris,* bending strength, compression strength, density, drying deformations, juvenile wood, knots, mechanical properties, modulus of elasticity, physical properties, round timber, sawn timber, twisting.

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PREFACE

This paper is based on sub-studies of a European Union (EU) project titled Small Diameter Round Timber for Construction, which came under the EU's fourth framework programme (EU – Fair Programme CT95-0091). The aim of the project was to develop structural systems in which thinning wood can be used in a round form and thereby create new markets for dried, quality and strength graded small diameter round wood. This study was carried out to investigate factors affecting selected physical and mechanical properties of round and sawn spruce (*Picea abies)* and pine (*Pinus sylvestris*) timber from thinnings in Southern Finland.

All studies introduced in this paper is based on author's work in EU-project. The following persons and organisations contributed to the collection of the test results and gave valuable comments and advice in analyses and writing the paper:

- Employees (professors, assistants and other staff) at the Faculty of Forestry, University of Joensuu, Finland.
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CONTENTS

ABBREVIATIONS AND APPLICATION OF TERMS

Terms used are defined as follows in this paper:

- Basic density: oven dry weight per green volume. It expresses in kilogram how much wood substance there is in one green cubic meter of wood. (Blass et al. 1995).
- Density: the weight and volume of wood at specific moisture content. The wood shall be tested at temperature 20 °C and relative humidity 65% which corresponds with most wood species moisture content of 12%. (Blass et al. 1995, EN 384 standard 1995).
- Specific gravity: the ratio of the dry weight of a given volume of wood to the weight of an equal volume of water at 4 °C. (Zopel and van Buijtenenn 1989).
- Branch: external branch existing in a tree.
- Knot: internal branch existing in timber.
- Over bark: measured on a log with bark.
- Under bark: measured on a processed log i.e. timber.
- Sound knot: a knot without rot that has an anatomical contact with the stem wood of at least 75% of its circumference. (Sahatavaran kaupallinen…1999).
- Dead knot: a knot that does not meet the requirements of a sound knot.
- Log: a piece of timber with bark, crosscut from a stem.
- Timber: processed log i.e. debarked, machine rounded or sawn wood
- Redwood: pine species
- Whitewood: spruce species
- Juvenile wood: Wood formed close to the pith is defined as juvenile wood. It is characterised by gradual changes in wood properties from pith outwards.
- 5-percentile: value for which the probability of obtaining lower values is 5 per cent (EN 384 standard 1995).
- Characteristic value: value that corresponds to the defined fractile of the statistical distribution of a timber property. For strength properties, modulus of elasticity and density the fractile is the 5-percentile. For the modulus of elasticity the mean value is also a characteristic value (EN 384 standard 1995).
- Modulus of elasticity: the hypothetical stress by which a rod would be extended to double its initial length (Kollman and Côte 1968). Basically, it measures resistance of material to deformations.
    - $E_{c,\,0}$: modulus of elasticity in compression parallel to the grain (kN/mm^2).
    - $E_{c,\,0,\,mean}$: characteristic value of the population for the modulus of elasticity in compression parallel to the grain (kN/mm^2).
    - E_{m}: modulus of elasticity in bending (kN/mm^2).
    - $E_{\mathrm{m,\,mean}}$: characteristic value of the population for the modulus of elasticity in bending (kN/mm^2).

- Strength: the stress, which breaks the specimen into rupture (Saarelainen 1981).
    - $f_{c,0}$: compression strength parallel to the grain (N/mm^2).
    - $f_{c,0,0.05}$: 5-percentile value of the sample for compression strength parallel to the grain (N/mm^2).
    - $f_{c,0,k}$: characteristic value of the population for compression strength parallel to the grain (N/mm^2).
    - f_m: bending strength (N/mm^2).
    - $f_{m,0.05}$: 5-percentile value of the sample for bending strength (N/mm^2).
    - $f_{m,k}$: characteristic value of the population for bending strength (N/mm^2).
- Mechanical properties: the term in this study concerns modulus of elasticity and strength in bending and compression parallel to grain.

The following variables are used and abbreviated as follows in this study:

- A: cross-sectional area (mm^2).
- a: age (years) i.e. number of annual rings from pith to surface, measured at or close to the failure point.
- a_1: distance between a loading position and the nearest support in a bending test (mm).
- b: deviation on timber surface (mm/m) caused by twisting.
- B: multiplier of independent variable in a regression model.
- c: circumference of the specimen (mm), measured at or close to the failure point
- C: crook (mm) measured between 50 to 250 cm from the base of the specimen according to bending direction, convex (+) or concave (-).
- d: diameter of the specimen (mm), measured at or close to the failure point.
- h: height of the specimen (mm), measured at or close to the failure point.
- F: load (N) in the mechanical test.
- f_i : forest code number.
- G: cross grain (mm/m).
- I : second moment of area (mm^4) for the calculation of modulus of elasticity in bending.
- KAR: knot area ratio (%). In this study the KAR is same as knot sum per circumference (ks/c), measured at or close to the failure point.
- k_h: size adjustment for the bending strength (EN 384 standard 1995).
- ks: knot sum (mm), measured at or close to the failure point.
- ks/c = knot sum per circumference (%), measured at or close to the failure point.
- ks/d: knot sum per diameter (%), measured at or close o the failure point.
- l_1: gauge length for the determination of the modulus of elasticity (mm).
- m: length of machine processed circumference of timber (mm).

- mk: diameter of the thickest knot (mm), measured at or close to the failure point.
- mk/d: diameter of the thickest knot per diameter of specimen (%), measured at or close to the failure point.
- n: number of observations
- ob: over bark.
- ρ_0: basic density calculated by oven dry mass per green volume (kg/m^3).
- ρ_{12}: density at 12% moisture content (kg/m^3) at or close to the failure point.
- $\rho_{12,\ 0.05}$: 5-percentile value of the sample for density at 12% moisture content (kg/m^3).
- $\rho_{12,\ k}$: characteristic value of the population for density at 12% moisture content (kg/m^3) in accordance with EN 384.
- p: processing method.
- Q: correction factor in logarithmic regression models (Equation 24).
- r : annual ring width (mm), measured at or close to the failure point.
- r^2: degree of determination
- S: tree species, pine = 0, spruce =1.
- s: length of sawn circumference of timber (mm), measured at or close to the failure point.
- s/c: length of sawn circumference per total circumference (mm), measured at or close to the failure point.
- s.d.: standard deviation
- s.e.: standard error of the mean
- ss: sawn (plane) surface in compression and tension zone, sawn = 1, other = 0
- t: average taper (mm/m), to measure the conical shape of specimen.
- T: absolute value of twisting of timber (^{0}/m), measured from green state to specific moisture content.
- u: moisture content, mass of water per dry mass of wood (%), measured at or close to the failure point.
- ub: under bark i.e. after wood processing.
- W: section modulus (mm^3) for the calculation of strength in bending.
- w_i: deflection or deformation (mm).
- X_1: reduction in circumference per circumference over bark (%).
- X_2: sawn circumference per total circumference under bark (%).
- X_3: diameter of the thickest knot over bark per circumference over bark (%).
- $\overline{x}$: mean value

1. INTRODUCTION

1.1 THE THINNING WOOD PROBLEM IN FINLAND

The rapid changing of the structure and quality of Finnish forest resources began after World War II. Rebuilding of Finland needed construction material and war imdemnities to the Soviet Union had to be paid in commodities, such as timber and paper products. During the fifties and sixties Finland cut more timber than what was then the annual growth. Since then the annual growth has continuously been greater than the annual removal of wood. Simultaneously, during the period of large cuttings, great efforts were made in the silviculture and forest management. In particular, the regeneration and silviculture of young forests have been intensive resulting in high annual growth. Now, in the very begin of 21 st century, Finnish forest industries will come to the situation where they have to utilise wood from intensively managed thinning forest on a large scale. Despite the low stumpage price so far, the forest industries have utilised thinning wood much less than could be possible based on available resources. Problems related to the utilisation of thinning wood are large. These problems include the small recovery of timber in harvesting, high harvesting costs, low yield and effectiveness in pulping and sawmilling. In addition, for many end uses, the timber and wood properties is inferior compared to wood from final cuttings. (Hakkila et al. 1995, Metsätilastollinen vuosikirja 1999, Reunala et al. 1999, Boren 1999).

The low utilisation rate of thinning wood increases the unmanageability of young stands resulting in a lack of large saw logs and also reducing the average size of stems for the future harvest (Maa- ja metsätalousministeriö 1988). According to silvicultural recommendations the volume of first thinnings in Finland should be more than 200 000 ha/a, but at present only 100 000 ha are harvested. According to the 8th national forest inventory (1986-1992) the greatest amount of first thinnings, 100 000 ha annually, to occur are presently in Southern Finland. About 60 000 ha is dominated by pine and rest by other tree species, which correspond to 4,0 million and 3,8 million cubic meters of timber, respectively. (Hakkila et al. 1995).

The present high utilisation rate of mature forests, the high forest conservation rate and increasing utilisation of wood decrease the sustainable cutting possibilities for mature forest. Therefore, the utilisation rate of thinning wood may increase in the mechanical wood industry in Finland. (Reunala et al. 1999). In order to maintain and improve the competitiveness of Finnish mechanical wood industry the characteristics and potential of thinning wood have to be known. Comprehensive studies related to drying deformations and mechanical properties of thinning wood, in particular for round timber, have not yet been made in Finland. However, branchiness and knots of thinning wood were studied by Wegelius (1939), Heikinheimo (1953), Hakkila et al. (1972), Uusvaara (1974, 1981, 1985), Kellomäki and Tuimala (1981), Pietilä (1989), Lemiux et al. (1997), Mäkinen and Colin (1998) and Mäkinen et al. (2000), whilst strength grades of sawn timber produced from thinning wood were studied by Uusvaara (1974, 1981, 1985).

1.2 WOOD CHARACTERISTICS OF PINE AND SPRUCE

In softwoods, like Scots pine and Norway spruce, conducting and mechanical functions are performed by a single type of cell, each unit of which is known as a tracheid. These cells are hollow, needle-shaped units usually varying from 2.5 mm to 5.0 mm in length. There are differences in the thickness of cell walls and in the size of cell cavities. Thin-walled earlywood is formed at the beginning of a growing season and thick-walled latewood is formed later. The quality of softwoods depends largely on the proportions of earlywood and latewood (Kollman and Côte 1968). According to Hakkila (1968), the density of latewood is 2.4 – 3.0 and 1.9 - 2.8 higher than earlywood for pine and spruce, respectively. Softwoods contain also other cells and tissues, such as ray cells and resin canals, which also influence the utilisation of wood.

The walls of wood cells are composed of mainly tree groups of structural substances, which can be classed as framework, matrix and encrusting materials. The framework substance is cellulose, which occurs in the form of microfibrils. Hemicelluloses are incorporated into the cell wall as the matrix substances and encrust cell. The lignin works as a skeleton (Zimmermann 1964).

In Fig. 1 cell wall organisation is presented diagrammatically for a typical coniferous tracheid (Zimmermann 1964). The middle layer of the secondary wall (S_2), contributes mostly to the bulk of the cell wall material in addition to its physical properties. Therefore, the orientation of microfibrils of the S_2 layer is an important matter influencing on wood properties; normally the orientation of microfibrils of the S_2 layer varies between 10° to 30° depending on the source of the cell, earlywood or latewood. The orientation of microfibrils in other cell wall layers are randomly arranged in the thin primary wall (P), whilst in the outer layer (S_1) in the secondary wall the orientation is between 50° to 70° from the cell axis and the inner layer (S_3) secondary wall the orientation is between 60° to 90°. The effect of microfibril angle of the S_2 layer on mechanical properties of wood is great; the lower the angle, the higher the mechanical properties (Bodig and Jayne 1982).

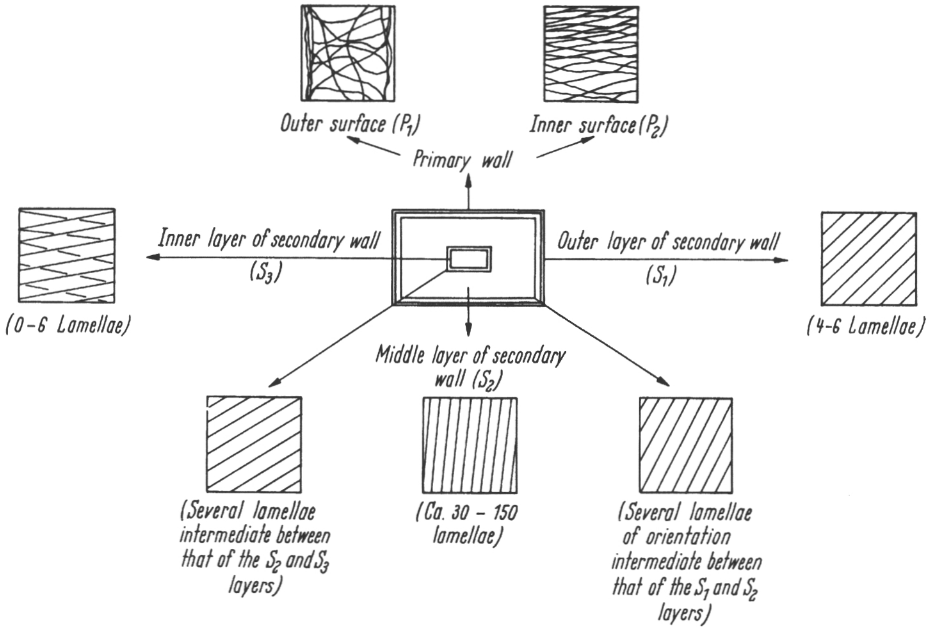


Fig. 1. Cell wall organisation represented diagrammatically for a typical coniferous tracheid. (Zimmermann 1964).

The young outer part of tree is known as sapwood, which conducts flow of water in trees. As the cells grow older, they stop functioning physiologically. This inner part of the tree is known as heartwood. In most species heartwood is darker in colour due the incrustation with organic extractives (Blass et al. 1995). Kellomäki (1981) studied the dependence of heartwood diameter on log top diameter in Scot pines in Finland and found that the proportion of heartwood increased linearly with the increasing top diameter of logs. For top diameters of 11 and 20 cm over bark, the heartwood percentage from the top diameter was about 45 % and 55%, respectively. According to Hakkila (1968), the percentage of heartwood of Scots pine increase logarithmically with increasing age.

The moisture content, when the cell wall is saturated, but no free water exists in the cell lumen, is termed the fiber saturation point (Blass et al. 1995). Trendelenburg (1939) concluded that the fiber saturation point varies with the structure and chemical composition of woods as follows:

1. Coniferous woods without significantly coloured heartwood, such as fir and spruce, and the sapwood of coniferous species with distinctly coloured heartwood, such as pine, white pine and larch, have a high fiber saturation point from 30 to 34%.
2. Coniferous woods with distinctly coloured heartwood:
   - With moderate content of resin such as pine, larch and Douglas fir have a fiber saturation point from 26 to 28%
   - With a high content of resin they have a fiber saturation point from 22 to 24%

The formation of heartwood begins at the age of 30 to 40 years in Scots pines and the share of heartwood increases with increasing age. Therefore, in particular for Scots pine, the fiber saturation point of juvenile wood is significantly lower for old trees than in thinning wood (Lappi-seppälä 1952). Consequently, the formation of heartwood can reduce the effects of juvenile wood. A similar idea has also been presented for Norway spruce by Saranpää (1994). Kärkkäinen (1981) showed that the resin content of Scots pine and Norway spruce is respectively 3.2% and 1.3 %. According to Hakkila (1968) the resin content of Scots pine heartwood (5.1 %) is higher than sapwood (3.0 %) but the difference between sapwood and heartwood is negligent for Norway spruce (average 1.6 %). In addition, Jalava (1933a) showed that shrinking in heartwood is about 7% less than in sapwood, which can affects deformations whilst drying. Hillis (1984) concluded that the extractives present in heartwood might stabilize the warp-prone juvenile wood core.

Many researchers, for example Spurr and Hyvärinen 1954, Erickson and Arima 1974 and Bendtsen and Senft 1986, have reported that low density and poor fiber characteristic are mostly related to age of the wood, not growth rate. Juvenile wood formed close to the pith is characterised by gradual changes in wood properties from pith outwards. Saranpää (1994) concluded that the properties of juvenile wood varied with the height of the stem. Most researchers agree that the first 5 to 20 annual rings from pith are juvenile wood, depending on the tree species and property studied. Compared to mature wood, the juvenile wood of conifers is characterized by low density, shorter and thinner tracheids, more tracheids per unit area, larger microfibril angle, lower transverse shrinkage, considerably higher longitudinal shrinkage, lower strength and modulus of elasticity, lower percentage of latewood, more compression wood, thinner cell walls, larger lumen diameters, lower cellulose and higher hemicellulose and lignin content (Wardrop 1951, Zopel and McElwee 1958, Zopel et al. 1959, Zopel et al. 1966, Bendtsen 1978, Danborg 1994b, Erickson and Arima 1974, Olesen 1977, Pearson and Gilmore 1980, Hillis 1984, Bendtsen and Senft 1986, Schaible and Gawn 1989, Shivnaraine and Smith 1990, Schneider et al. 1991, Zhou and Smith 1991, Kretschmann and Bendtsen 1992, Yngvesson et al. 1993, Saranpää 1994, Ormarsson 1995, Perstorper 1994, Ranta-Maunus 1999, Sauter et al. 1999).

Reaction wood in softwoods is called compression wood and is recognizable in logs through the presence of eccentric growth rings and a more gradual transition between earlywood and latewood than in normal wood. This is made apparent by the lower contrast between these zones and can be seen because in compression wood zone earlywood cells have thicker walls than usual. Compression wood has a considerably higher density than normal wood, but it is nevertheless lower in impact and tensile strength, on a density basis. In compression wood the orientation of microfibrils in the S_2 layer is about 45° from cell axis. Therefore upon seasoning, compression wood zones generally shrink more longitudinally and less transversely than normal wood. Longitudinal shrinkage in normal wood is practically negligible (0.1...0.9%) while it has been known to reach 6 to 7% in compression wood. (Kollman and Côte 1968).

The spiral grain of Scots pine is typical for softwoods. The direction is first left hand side and the angle of spiral grain is very low but reaches a maximum value between the ages of 15 to 20 years. Later the angle of spiral grain diminishes gradually and between the age of 60 to 80 years the direction of spiral grain changes to right the hand side. The spiral grain of Norway spruce is not as systematic as pine. Certainly, the general trend is an increase in age but more gently than with Scots pine. However, the spiral grain has been reported to change very rapidly, and even the direction may change. (Viitaniemi 1988a, Viitaniemi 1988b).

Annual ring width and density correlate negatively. The reason for this is that absolute amount of summerwood is somewhat constant year to year for Norway spruce, in particular. The absolute amount of summerwood varies greatly for Scots pine (Mikola 1950). In Fig. 2. the correlation between basic density and ring width for Scots pine, Norway spruce and Common birch is presented (Hakkila 1966). At similar ring width, the basic density of Scots pine is higher than that of Norway spruce. The smaller the ring width the smaller the difference.

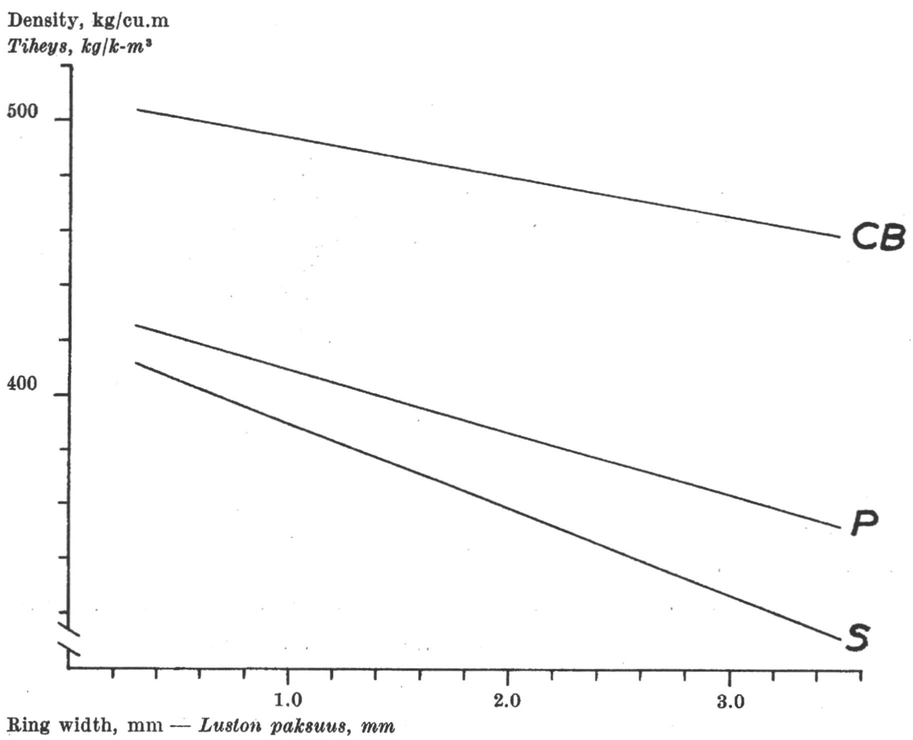


Fig. 2. Correlation between basic density and ring width for Scots pine (P), Norway spruce (S) and Common birch (CB). (Hakkila 1966).

The density of Scots pine increases from the pith outwards (Jalava 1945, Hakkila 1966). Hakkila (1966) concluded that for Scots pines (age 41-80 years) the density difference between the surface and pith varies from 19 to 96 kg/m^3 so that the density difference between pith and surface decreases from butt to top.

The density of Norway spruce decreases from the pith outwards at first but then it begins to increase slightly towards surface. From butt to top the density of spruce decreases only slightly and might even increase closer to top. (Hakkila 1966, Jalava 1945).

Normally, Scots pine has fewer branches than Norway spruce. In general, Scots pine has 3 – 5 and spruces 5 – 6 branches in each whorl (Western 1971, Ager 1972). In addition, Norway spruce has intermediate branches. (Wegelius 1939, Boutelje 1966, Hakkila et al. 1972, Lehtonen 1978). According to Lehtonen (1978), the volume percentage of the Scots pine knots was 0.8 – 4.3 % ($\bar{x}$= 2.0 %) and that of Norway spruce knots 0.5 – 2.0 % ($\bar{x}$= 1.2 %). According to Hakkila and Rikkonen (1970), the volume percentage of Norway spruce knots was 0.6 % in pulpwood and 0.8 % in saw logs. The basic density of the knot wood exceeded that of the stemwood by 351 kg/m^3 in Scots pine and 490 kg/m^3 in Norway spruce. The density of the wood surrounding the knot was slightly lower than that of the knots and slightly higher than that of the knot-free stemwood. The average density of Norway spruce and Scots pine stemwood with knots was 5.4 % and 2.1 % higher than that of stemwood without knots. The branches had small diameters: the mean cross-sectional branch diameter for the Scots pine was 15 mm and for Norway spruce 11 mm. The cross-section of the branch deviated from circular form both in Scots pine and Norway spruce. At a similar vertical diameter of knot, the Norway spruce had a higher knot volume than Scots pine.

Table 1 shows mean values of specific gravity, bending and compression strength and modulus of elasticity at moisture content 12 % for small clear wood specimens of Scots pine and Norway spruce as reported by Jalava (1945). Although Scots pine has about 9 % higher specific gravity than Norway spruce, the modulus of elasticity of spruce is in compression 4 % and in bending 8 % higher than those of pine. For compression strength, Scots pine is 5 % stronger than Norway spruce whilst in terms of bending strength the difference is negligent.

Table 1. Mean values of specific gravity, bending and compression strength and modulus of elasticities at moisture content 12 % reported by Jalava (1945) for small clear wood specimens of Scots pine and Norway spruce.

Species	Specific gravity	$E_{c,0}$ (kN/mm^2)	$f_{c,0}$ (N/mm^2)	E_m (kN/mm^2)	f_m (N/mm^2)
Scots pine	0.484	13.6	47.5	12.7	85.8
Norway spruce	0.445	14.1	45.2	13.7	85.7

1.3 FACTORS AFFECTING KNOT PROPERTIES OF TIMBER

Kärkkäinen (1986) presented diagrammatically the knot zones of Scots pine and Norway spruce (Fig. 3). Norway spruce has the longer sound knot part and shorter dead knot and knot free part than Scots pine. According to Kärkkäinen (1972), the width of branches of Norway spruce is somewhat dependent on stem height: the southern side of the stem has more knots than the northern side. In addition, the breast height of Norway spruce stem correlates positively with the amount of knots. According to Ager (1972), the sum of branch diameters of Scots pine and Norway spruce depended on the diameter of the stem at breast height. Regularly, at same breast diameter, Scots pine had a greater branch sum than Norway spruce.

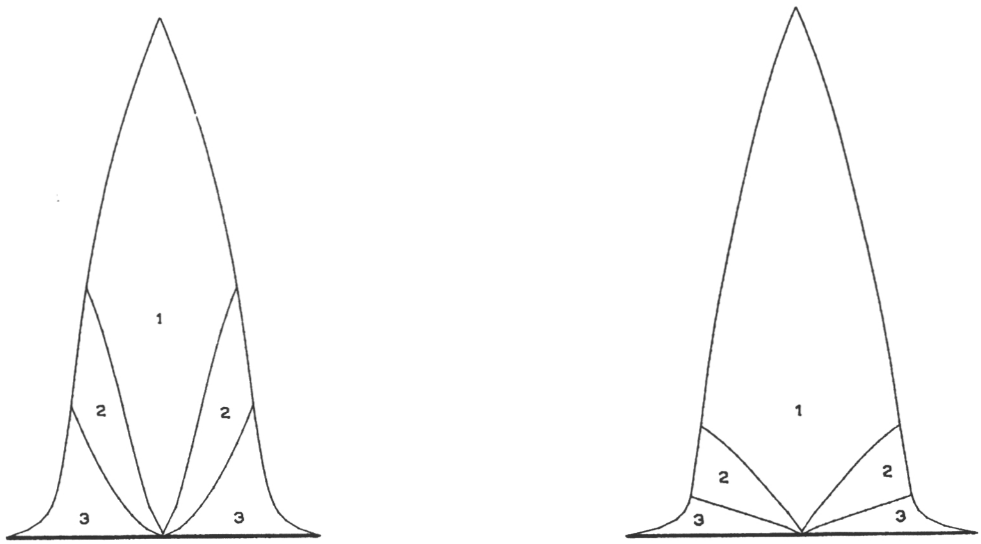


Fig. 3. Longitudinal section of Scots pine (left) and Norway spruce (right) with breast height diameter of 27 cm. 1 = part with sound knots, 2 = part with dead knots, 3 = knot free part of stem (Kärkkäinen 1986).

The proportion of knots of Loblolly pine from the total volume can be estimated by the cross-sectional area or diameter of branches and their number (von Wedel et al. 1968). Heikinheimo (1953) reported, that the cross section area of branches on the surface of Scots pine stems varied from 45% to 60 % at the age of thinning. The diameter of the largest knot of Scots pine correlates with the knot sum of the log (Heiskanen (1954a). Further, Heiskanen (1965) reported that the diameter of the largest knot in Scots pine butt logs depends on the age of the stem and the breast height diameter. The wider the annual rings the larger the amount of knots in the stems. In addition, Heiskanen (1954b) reported that annual ring width correlates well with the presence of inner knots in Scots pine. According to Heikinheimo (1953) branchiness and knot properties of thinning pine are affected by stand properties. In dense forests, branches can not be pruned naturally so effectively. Mäkinen (1999) concluded that the knot diameters of Scots pines are affected by stand properties and in particular crown base. Pietilä (1989) reported that Scots pine have a clear, approximately linear, positive correlation between inner knot diameter and visible knot diameter. The knots of Scots pine achieved their maximum diameter at the distance of 4 – 5 cm from the stem pith. The mean diameter of the knots were 14 mm and the average number of the knots per whorl was in 5.2.

Uusvaara (1974) concluded that the knot diameter at different heights on the stem increases with the width of annual rings at different ages. Uusvaara (1985) compared the quality of stems and sawn goods from plantation grown and naturally grown pine stands. Plantation grown Scots pines had thicker knots and longer dry knot zones. A clear positive correlation was found between the diameter of the thickest stem knots in butt logs and annual ring width near the pith. The quality of centre-sawn goods from butt logs depended mainly on annual ring width close to the pith. The percentage of the u/s grade, which is the best quality timber, decreased with increasing ring width. However, the u/s percentage increased with increasing ring width in boards sawn from a longer distance from the pith in naturally grown pines. According to Mäkinen and Colin (1998), the large branches of a specific whorl of Scots pine had a greater probability of being alive than smaller ones in the same whorl. The properties of the stand affected this probability. According to Kellomäki and Tuimala (1981) with a stand density of Scots pine of 2500 stems per hectare the branch cross-sectional area in a Scots pine was only about one third of a stand with 1800 stems per hectare.

Mäkinen et al. (2000) concluded that the diameter of a Norway spruce branch is closely related to age and tree size. The probability of a branch being alive diminished towards the base of the stem and had a reverse S form. Stand properties affected the knot properties of spruce. According to Lemiux et al. (1997) the knot of Norway spruce grows in diameter up to half of its length, after which it stabilizes. Colin and Houllier (1991) studied the branchiness of Norway spruce in north-eastern France. The maximum size of branch depended on the relative distance from the growth unit to the top of the stem, and on general descriptors of the stem.

1.4 FACTORS AFFECTING DRYING DEFORMATIONS OF TIMBER

Cracks are longitudinal openings at weak points in the wood caused by stresses produced in differential shrinkage. They usually extend across the growth rings. In general, warp in timber is any deviation from a true or plane surface with special forms of warp being bow, cup, twist and crook (Kollman and Côte 1968). Warping of a board is caused by differences in longitudinal shrinkage in different parts of the board (Kollman and Côte 1968, Skaar 1988). Many of the common drying defects can be related to shrinkage and the internal stresses that accompany it. Internal stresses are caused by unisotropic shrinking and swelling and are intensified by casehardening and improper piling. (Kollman and Côte 1968).

The removal of free water, the water contained in the cell lumens, does not initiate shrinkage. Shrinkage begins when drying proceeds below the fiber saturation point, when the absorbed water is removed from the cell walls. Shrinkage and swelling is not the same in different grain directions. The greatest dimensional change occurs in a direction tangential to annual rings, from the green to the oven-dry 3.5 to 15.0%. Shrinkage from the pith outwards or radially is considerably less than tangential shrinkage, from the green to the oven-dry 2.4 to 11.0%. The difference between radial and tangential shrinkage is explained by a restraining influence of the wood rays in radial direction and as far as coniferous woods are concerned, by a different helical arrangement of fibrils in radial and tangential cell walls. In the radial cell walls of the trachdeids of conifers there are 50 to 300 pits and in their vicinity the fibrils are deflected from their normal course (Kollman and Côte 1968). Kärkkäinen and Marcus (1985) discovered that the volumetric shrinkage of Norway spruce correlated positively with density. In addition, Jalava (1933a) concluded the same for Scots pine for radial and tangential shrinkage.

The longitudinal shrinkage of normal wood from the green to the oven-dry condition ranges between 0.1 and 0.9%. Wood from the centre of the tree (juvenile wood) and reaction wood exhibit a high longitudinal shrinkage. In addition, there is a substantial difference in longitudinal shrinkage between earlywood and latewood from the same growth ring. In general, tangential and radial shrinkage is also higher in the heavier woods. The higher the density of the wood, the greater is its volumetric shrinkage or swelling (Kollman and Côte 1968). Longitudinal shrinkage is lower for high-density wood than low-density wood. For example Siimes (1938) concluded that longitudinal shrinkage of Scots pine from green to oven dry are 0,28% and 0,13% at the dry weight densities of 300 kg/m^3 and 500 kg/m^3. A possible reason is that the microfibril angle is greater in earlywood than latewood and therefore earlywood shrinks more than latewood (Kennedy and Ifju 1962, McMillin 1973). A high-density wood contains a greater portion of latewood and therefore it shrinks longitudinally less than lighter wood. Ollinmaa (1959) concluded that a longitudinal shrinkage of Norway spruce is 0.3% in normal wood and 2.4% in compression wood. The microfibril angle in normal wood of Scots pine and Norway spruce ranged between 24° and 27° and in compression wood between 34° and 40°. This and an abnormally thick S_1 layer explained a great longitudinal shrinkage of compression wood. Jalava (1933a) reported that the longitudinal shrinkage of Scots pine containing compression wood could be up to 5.9 %. Danborg (1994a) concluded that the longitudinal shrinkage of Norway spruce increases with increasing ring width and that top-log boards shrink less than but-log boards. Saranpää (1994) concluded similarly with Norway spruce: Longitudinal shrinkage was the highest (about 2.4 %) close to the pith and decreased to about 0.2% in the outer rings. Kärkkäinen and Marcus

(1985) discovered that the longitudinal shrinkage of Norway spruce decreases with an increase in density. Kuusela (1983) summarised reasons of unisotropic shrinking and further reasons of drying deformations (Fig. 4).

Fig. 4. The summarised reasons for unisotropic shrinking and consequencies for drying deformations (Kuusela 1983, reproduced by Tarvainen and Hukka 1997).

Boards cut from near the pith of the log warp more than sideboards. Krempl (1970) concluded that the twisting of board increases with the increasing spiral grain of wood and reduces from pith outwards. Ormarsson (1995) reported that when pith was located at the mid-point of the board cross section, only small cup deformation and the zero bow and crook deformations were measured for the Norway spruce, but large twisting values were obtained. In addition, twisting of pith enclosed timber decreased with the increasing size of timber.

Danborg (1994a) concluded that the smaller the dimension of the board the larger is the twist. Furthermore, if boards are sawn as outer boards they twist less than boards of the same dimension sawn along the pith. In addition, the twist increases with increasing grain angle. Ormarsson (1995) studied how stick location in the cross-section of Norway spruce timber has an affect on drying deformations. In Fig. 5 and 6 illustrate the geometry of experimental sticks and their location in the timber log and deformation of the experimental and simulated sticks of wood. The centre stick has a large twist deformation and the twist decreases markedly with distance from the pith, despite the fact that the spiral grain is assumed to be same for all the sticks.

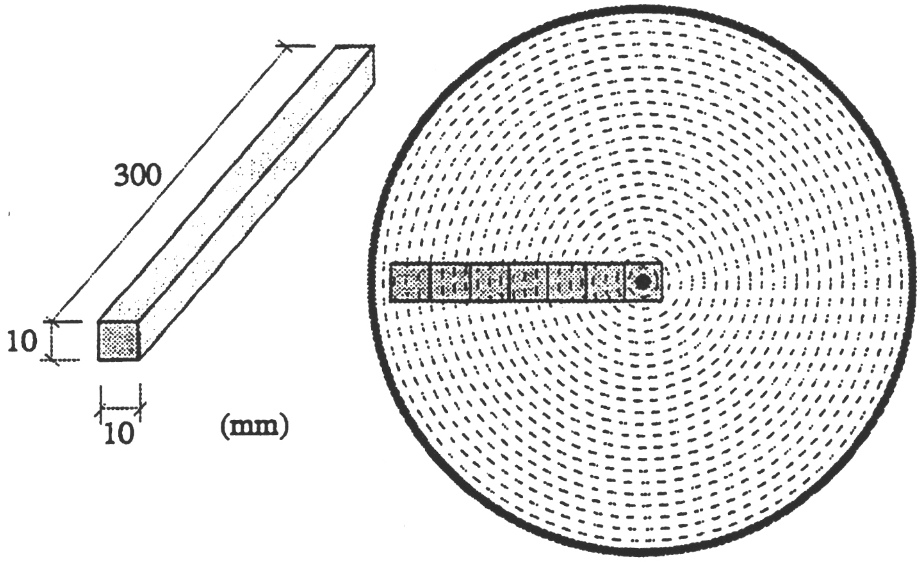


Fig. 5. Geometry of experimental sticks and their location in the timber log (Ormarsson 1995).

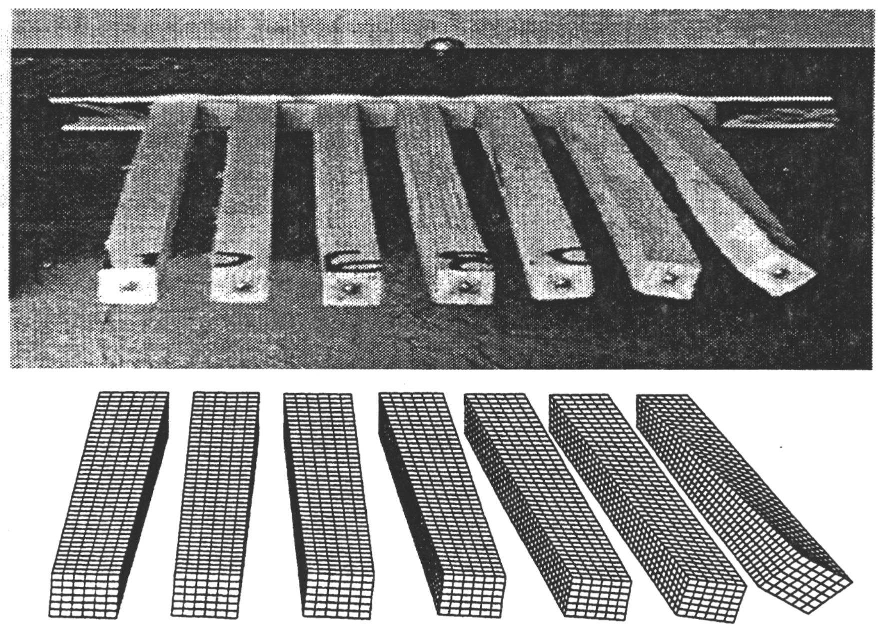


Fig. 6. Deformation of experimental and simulated sticks of wood. (Ormarsson 1995).

Ormarsson (1995) studied how the spiral grain affects the drying deformations of Norway spruce timber. He concluded that the twist and bow deformation increases with increasing spiral grain angle. Wu and Smith (1998) concluded that the twist of Loblolly pine tends to increases as specific gravity decreased, and juvenile wood content and ring width increased. The drying temperature did not affect twisting during drying.

Perstorper (1994) concluded that the twist and crook of Norway spruce timber are larger for pith-associated wood than wood from the outer part of the stem. Twist decreased much more rapidly with the distance from pith compared with crook. Crook was larger in the butt log than in the top log whilst twist and bow appeared not to vary longitudinally. Twist was highly correlated to the distance between pith and centroid of the stud cross section. The ratio of grain angle to pith distance was the best parameter for twist prediction. The presence of compression wood increased bow and crook significantly. Heartwood formation in the juvenile core of the butt log did not diminish warp propensity since the thinning wood contained only a minor amount of heartwood.

Juvenile wood contains more lignin and hemicellulose than mature wood. A low or reduced hemicelluloses content has been associated with the high dimensional stability of timber (Hillis 1984). The extractives, chemical composition and physical organisation of skeletal cell wall affects water-vapor sorption by wood (Wangaard and Granados 1967).

1.5 FACTORS AFFECTING MECHANICAL PROPERTIES OF TIMBER

Wood is basically a series of tubular fibers or cells cemented together. The source of strength in solid wood is the wood fiber. Generally, cellulose is responsible for strength in the wood fiber because of its high degree of polymerisation and linear orientation. For anisotropic material, like wood, the mechanical properties vary with respect to the three mutually perpendicular axes of the material i.e. radial, tangential and longitudinal (Winandy and Rowell 1984). The microfibril angle of S_2 layer in the cell has a great affect on the mechanical properties of wood. Bendtsen and Senft (1986) studied relationships between the strength and modulus of elasticity of wood fibers and the angle between the fibril and fiber axes for cottonwood and loblolly pine. Wolfe (2000) reproduced results in order to compare the relative effect of fibril angle on the bending strength and modulus of elasticity (Fig. 7). A decrease in a fibril angle from 35 to 10 degrees resulted in about a fourfold longitudinal strength and modulus of elasticity. Cave (1968) concluded a similar effect of fibril angle on the longitudinal modulus of elasticity for softwoods.

In addition, Bendtsen and Senft (1986) comprehensively studied the relationships between the age and the mechanical and anatomical properties of cottonwood and Loblolly pine. The cell length, specific gravity and mechanical properties increased whilst fibril angle decreased with increasing age. The average mechanical properties of juvenile wood ranged from 47% to 63% of those for mature wood in Loblolly pine and from 62% to 79% in cottonwood. The age of demarcation between juvenile and mature wood varied by species and property, ranging from 13 to 20 years. Fig. 8 shows the change in bending strength and modulus of elasticity with regards to tree age relative to 30 years (Bendtsen and Senft 1986, reproduced by Wolfe 2000).

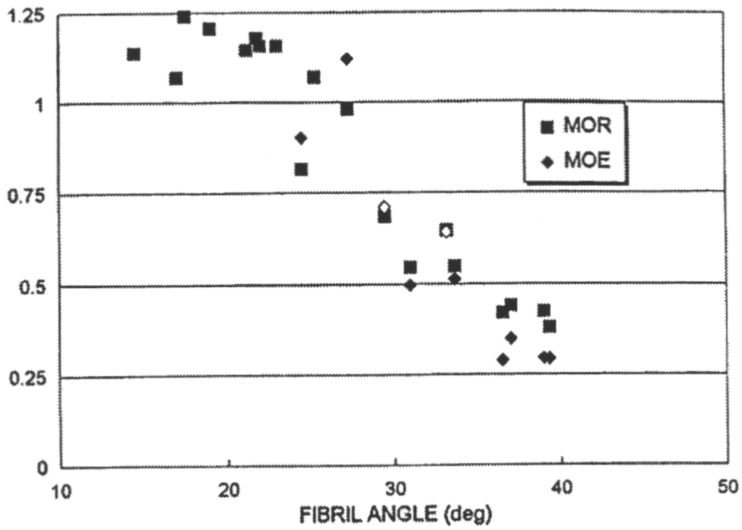


Fig. 7. Relative effect of fibril angle on bending strength and modulus of elasticity (Bendtsen and Senft 1986, reproduced by Wolfe 2000).

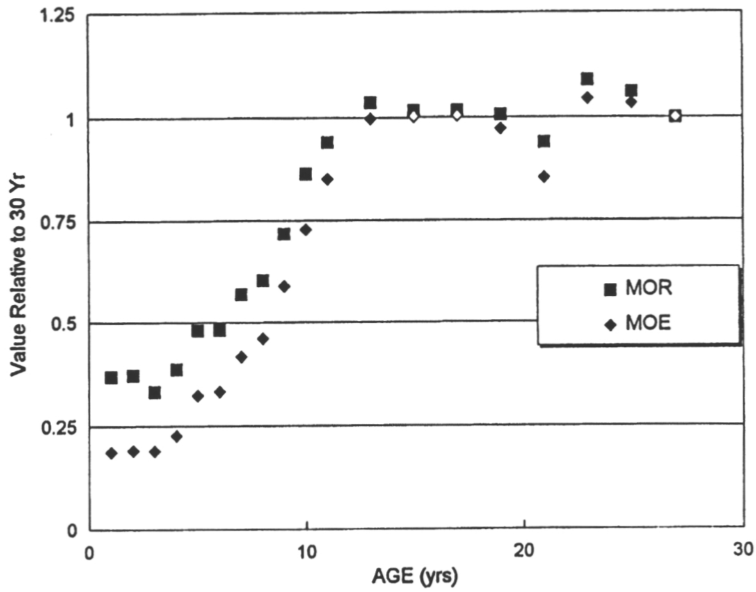


Fig 8. Change in bending strength (MOR) and modulus of elasticity (MOE) with regards tree age relative to 30 years (Bendtsen and Senft 1986, reproduced by Wolfe 2000).

Ormarsson (1995) studied how the location of the stick in a cross-section of Norway spruce timber affects the modulus of elasticity. The geometry of experimental sticks and their location in the timber log are shown in Fig 5. The longitudinal modulus of elasticity of sticks increased from pith outwards. In general, juvenile wood has a great negative effect on the mechanical properties of wood. Leban and Haines (1999) showed that the modulus of elasticity of a hybrid larch could be predicted by age, rings per centimetre and density. They also concluded that prediction could be made also without using density as a factor. Nakai et al. (1994) concluded that the modulus of elasticity in 50 to 60 year old Sugi (Cryptomeria japonica D. Don) is 1.4 to 1.6 times higher than that measured in 20-year-old specimens. Cade and Choong (1969) reported that veneer cut from smaller diameter bolts of Southern pine (Pinus sp.) has lower tension strength than veneer produced from larger diameter logs. Zhou and Smith (1991) observed that the modulus of elasticity and bending strength of white spruce decreased with an increase in warp or juvenile wood percentage. Schneider et al. (1991) concluded that the linear relationships between specific gravity and the mechanical properties of Caribbean pine were better for outer wood than for the core wood. The core wood was also weaker than the outer wood. Pearson and Gilmore (1980) concluded similarly for loblolly pine.

Siimes (1967) concluded that the higher the density of wood the greater the absolute increase in strength and modulus of elasticity. This increase is accelerated by decreasing moisture content. For small clear wood specimens of Scots pine Verkasalo (1992) obtained a high linear correlation between the modulus of elasticity in relation to specific gravity (0.90) and ring width (0.91). According to Kärkkäinen and Hakala (1983) and Kärkkäinen and Dumell (1983) the strength of Norway spruce even with density considered is greater for slow-grown trees than fast-grown trees. Kärkkäinen and Hakala (1983) showed that boards sawn from slow-grown small size Norway spruce logs had a greater strength than boards from fast-grown, large size, Norway spruce logs. Kärkkäinen and Dumell (1983) reported that for Norway spruce the bending strength had a positive linear relationship with density. However, correlation between density and growth ring width was only –0.318, even though the model was curve linear and the difference between the areas was taken into account. Therefore, the relationship between bending strength and ring width was not linear. Ollinmaa (1960) found in his study that the high resin content in the base of Scots pine trees caused the lower compression strength parallel to grain than when the prediction was based on density assumed.

The mechanical properties of wood are dependent on moisture content. An increase in moisture produces lowered strength and elasticity values. This effect is partly explained by cell wall swelling, whereby less cell wall material per unit area is available. More important, however, is that water, when penetrating the cell wall, weakens the hydrogen bonds responsible for holding together the cell wall. Moisture variations above fibre saturation point have no effect on mechanical properties, since such variations are related to free water in the cell lumens. (Blass et al. 1995).

Siimes and Liiri (1952) concluded that the effect of moisture content on bending and compression strength was linear from fiber saturation point to the 8 % moisture content for small clear wood specimens. A 1% change in moisture content causes about a 2.0 N/mm^2 change in bending and compression strength (Fig. 9). Covington and Fewell (1975) reported that the drying of European redwood and whitewood from green to dry condition (15%) increased the average modulus of elasticity by about 8 %.

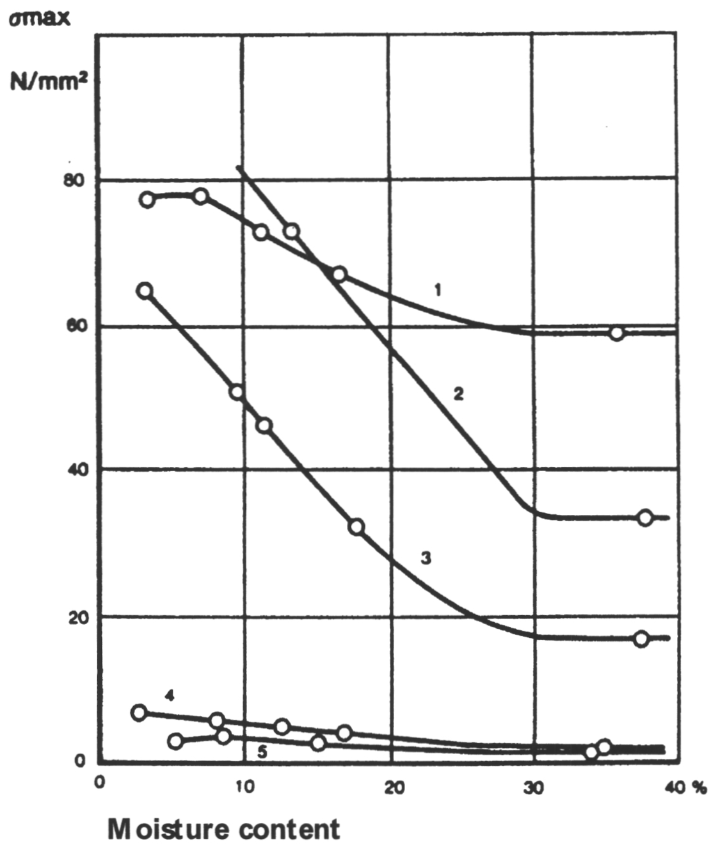


Fig. 9. The effect of moisture content on the strength of small clear wood of Scots pine. 1 = tension II, 2 = bending, 3 = compression II, 4 = compression ⊥ R+T and 5 = shear (Siimes and Liiri 1952, reproduced by Saarelainen 1981).

For some mechanical properties, the influence of moisture content is less significant for timber containing defects than for clear wood. (Kollman and Côte 1968, Madsen 1975, Hoffmeyer 1978, Gerhards 1982, Madsen et al. 1980.) Fig. 10 shows the results of an investigation for sections of timber 50 * 150 mm of spruce (Hoffmeyer 1978). The effect of moisture content on compression strength is high and it is quite independent on timber quality, since the relative strength differences stay almost constant throughout the whole range of percentile values. For tension strength, the effect of moisture content is only modest. Bending strength represents a mixture of compression and tension behaviours, and at the timber quality level corresponding to the 5-percentile, bending strength is only very slightly affected by moisture. However, Barrett and Lau (1991) observed, that the effect of moisture content on the compression strength of Douglas-fir structural lumber is dependent on strength level. The higher the strength is the greater the effect of moisture. In addition, the effect of moisture content seemed to be similar for hemlock, spruce, pine and fir. Madsen (1975) observed similar phenomena for bending strength and the modulus of elasticity. Madsen et al. (1980) reported that timber at the 5-percentile level does not gain strength as it dries out, if anything, it looses strength.

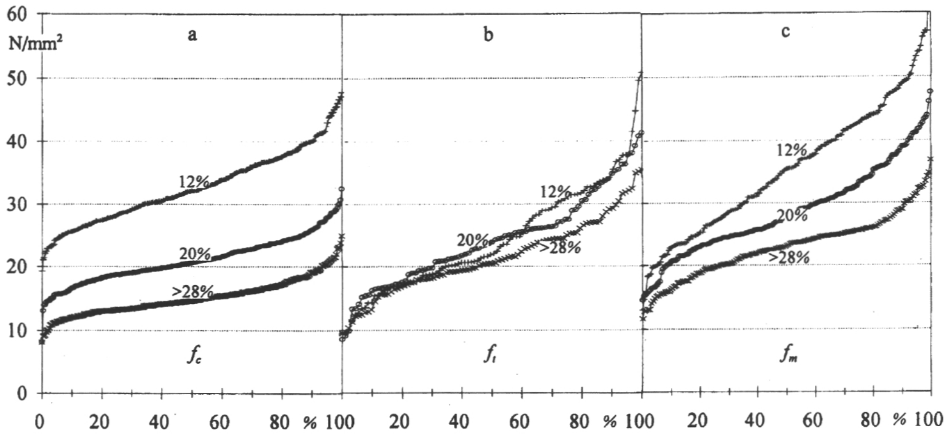


Fig. 10. Strength (N/mm^2) against percentile for matched samples of spruce (Picea abies) subjected to: a) compression, b) tension and c) bending at moisture content levels of 12 %, 20 % and more than 28%. (Hoffmeyer 1978, reproduced by Blass et al. 1995).

Hoffmeyer (1978) rearranged the results shown in Fig. 10 to illustrate the interrelationship between compression, tension and bending strength at equal moisture content levels (Fig 11.) Bending strength is generally higher than both compression and tension strength. This is partly explained statistically by the fact that the bending test subjects only a small amount of the individual specimens to high stresses.

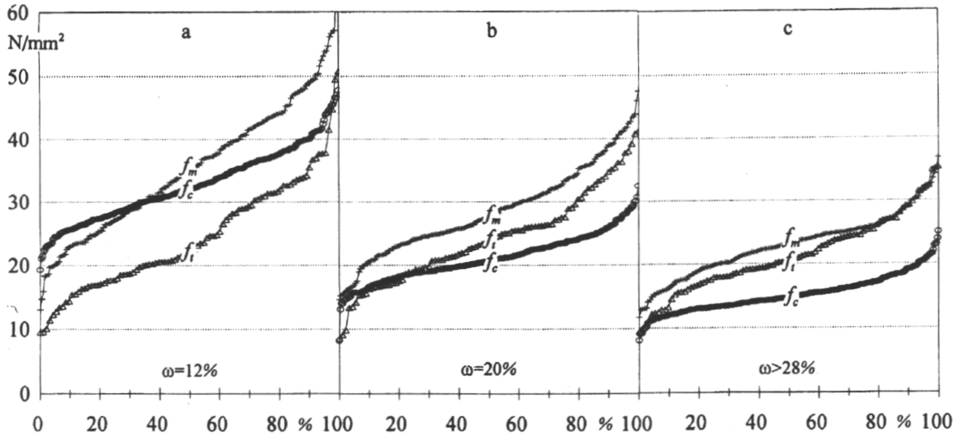


Fig. 11. Bending, compression and tension strength (N/mm^2) against percentile for matched samples of spruce (Picea abies) at moisture content levels of: a) 12 %, b) 20 % and c) more than 28% (Hoffmeyer 1978, reproduced by Blass et al. 1995).

Lindgren (1997) has reported that for Norway spruce and Scots pine, 30 % and 50 % of the variation in bending strength can be explained by the variation in knot size, respectively. Knots on the tension side of timber explain less than 30 % of the variation in bending strength, compared to all the knots measured in a cross-section. Approximately 40 % of the variation in bending strength can be explained by combining the two properties of knots and annual ring width. For Norway spruce and Scots pine, the modulus of elasticity alone can respectively explain more than 60 % and 70 % of the variation of bending strength. According to Nokelainen et al. (1989), the linear regression model based on knot area ratio (KAR) is the best method to determine the effects of knots on compression and tension strength. To consider the knot as a hole gave the best result in bending. The knots in Norway spruce have a smaller effect than the knots in Scots pine on the modulus of elasticity and strength in tension. Independently on tree species, a smaller knot has a greater effect on strength than its size would assume and a larger knot has a lower effect than its size would assume.

When drying temperature increases, the strength and modulus of elasticity of timber decrease nearly independently of moisture content (Siimes 1967). Ranta-Maunus (1999) concluded that drying at temperature of 110 °C decreased the bending strength of spruce by about 10% in comparison to seasoned timber. Thompson (1969) discovered that poles kiln dried at 66 °C had somewhat higher strength values than those dried at 83 °C but the differences were not deemed to be of any practical significance.

Because of the higher density, it might be expected that compression wood would also have higher strength than normal wood. However, compression wood is about equal in strength to normal wood. If material of similar density is compared, the relatively dense compression wood is inferior in most strength properties compared to normal wood (Ollinmaa 1959, Cockrell and Knudson 1973, Kärkkäinen and Raivonen 1977, Haygreen and Bowyer 1989).

Mechanical properties of wood change with changes in the environment. Changes in temperature, humidity, pH, chemical adsorption from the environment, UV radiation, fire or biological degradation can have significant effects on the strength of wood (Winandy and Rowell 1984). Bodig and Jayne (1982) reported that the chemical composition of wood has effects on mechanical properties. For example, tension strength decreases with increases in the amount of lignin (Zobel and van Buijtenen 1989). Hemicelluloses play key roles in the strength and stability of wood dried at high temperatures and of press-dried paper (Hillis 1984, Horn 1979).

Zhou and Smith (1991) did not observe that strength depended on the general slope of grain, when other wood characteristics were considered. However, Nokelainen et al. (1989) concluded that even a small slope of grain reduces compression strength. In addition, they found that the tension strength was greatly affected by slope of grain.

The effect of size of the specimen subjected to testing on the mechanical properties, especially in tension, has been explained by the weakest link theory (Blass et al. 1995). This theory states that when subjected to tension, a chain is as strong as its weakest link. In the case of compression and particularly in bending the use of this theory is debatable. For visually graded lumber, defect sizes increase with the size of the timber. This means that the material changes with size, which can mask a pure size effect. In particular, when the size effect is investigated in a mixture of grades, the effect of grading will have an influence on the size effect (Barrett and Lam 1992, Rouger et al. 1993, Blass et al. 1995, Ranta-Maunus 1999, Boren and Barnard 2000).

Round poles have a high strength and small strength variability, as they are processed conservatively. Therefore round poles wood fibres are not cut and consequently these continuous fibres guide stresses smoothly around knots (Mäkipuro 1981, Blass et al 1995). According to Nakai et al. (1994), the cross-sectional shape has an effect on the bending performance of Sugi (Cryptomeria japonica D. Don). From Table 2 it can be seen that the average modulus of elasticity in round timber was 1.14 times higher than that of square sawn timber. Similarly, the 5-percentile bending strength of round timber was 1.32 times higher than square sawn timber. According to Ranta-Maunus (1999) and Boren and Barnard (2000), manually debarked round wood has a higher bending and compression strength than machined round timber.

Table 2. The effect of cross-sectional shape on the bending performance of Sugi (Cryptomeria japonica D. Don). (Nakai et al 1994).

	Round timber	Partly sawn, edgewise	Partly sawn, flatwise	Square sawn
E_m (kN/mm^2)	1.14	1.20	1.03	1.00
f_m (N/mm^2)	1.14	1.18	1.08	1.00
$f_{m,\ 0.05}$ (N/mm^2)	1.32	1.21	1.13	1.00

Siimes (1967) concluded that Norway spruce has a somewhat higher strength but lower modulus of elasticity than Scots pine. According to the study of Covington and Fewell (1975), the modulus of elasticity of European redwood (pines) and whitewood (spruces) are similar when whitewood has about a 0.03 – 0.04 lower specific gravity than redwood. According to Nokelainen et al. (1989), at the same density, the Norway spruce has 10 to 20 % higher modulus of elasticity than Scots pine. In addition, density has a similar effect on strength in pine and spruce. However, Norway spruce has higher tension strength than Scots pine at a similar density.

1.6 EFFECTS OF TIMBER ORIGIN ON TIMBER PROPERTIES

Effects of timber origin on timber properties i.e. stand features and tree social status on chemical and physical properties and quality of trees, such as cellulose content, cell characteristics, density, ring width, knot quality and branchiness, is reported by many works (Wegelius 1939, Heikinheimo 1953, Hakkila 1966, Zopel et al. 1966, Hakkila and Uusvaara 1968, Uusvaara 1974, Hakkila 1979, Kellomäki and Tuimala 1981, Kärkkäinen and Uusvaara 1982, Kärkkäinen and Dumell 1983, Kärkkäinen 1984, Kärkkäinen et al. 1985, Uusvaara 1985, Pietilä 1989, Lämsä et al. 1990, Johansson 1992, Pape 1999). Generally, growing stand density has a positive effect on the density of wood and a negative effect on the width of knots. Accordingly, the site index, a measure of site fertility, has a negative effect on the density of wood and a positive effect on the width of knots. In dense forests, branches can not be pruned naturally so effectively. For example, Mäkinen (1999) concluded that the knot diameters of Scots pines are affected by stand properties and in particular crown base. Kärkkäinen and Uusvaara (1982) concluded that the growth rate affects numerous Scots pine timber quality factors regardless of the reason for growth variation. According to Lassila (1930) and Hakkila (1966), the weight of wood depends on forest types. For the Scots pine and Norway spruce average density decreases, when the fertility of site improves. Generally, density and its variation are affected by the location of sampling point, tree species, age of tree, growth rate, growth conditions and genotype (Hakkila 1966). Uusvaara (1974) reported that the average content of heartwood in plantation-grown Scots pine is only a half compared to stems of natural origin.

Jalava (1933b) concluded that forest site type has an effect on the mechanical properties of Scots pine, but in the same paper it is also concluded that specific gravity is dependent similarly on the forest site type than mechanical properties. Later, Jalava (1945) reported that the effect of forest site type on mechanical properties was negligent in his study, or, at least, the effect of forest site types is covered by other factors. Siimes and Liiri (1952) concluded that the effect of specific gravity on the Scots pine is somewhat linear so that heavy pine (0.601-0.650) can be two times stronger than light pinewood (0.301-0.350). Scots pine from North-Finland was usually equal or slightly better than Scots pine from South-Finland. Only bending strength was slightly lower for Scots pine from North-Finland than Scots pine from South-Finland. Uusvaara (1985) reported that according to visual strength grading, sawn timber from naturally grown Scots pine stands comprised more timber with a high strength class than sawn timber from plantation grown pine stands. However, the difference is not large, if the sawn goods from logs of the same quality are compared. Schaible and Gawn (1989) did not find any significant differences in strength between stands of Sitka spuce. Lindgren (1997) found that Norway spruce from Eastern Finland had somewhat better physical and mechanical properties than those of Southern Finland, but strong differences did not exist. In conclusion, when also taking into account the physical properties and characteristics of timber the origin of timber i.e. effects of stand features on the drying deformations and mechanical properties is negligent or at least weak (Johansson et al. 1992, Ranta-Maunus 1999, Boren and Barnard 2000).

1.7 TESTING MECHANICAL PROPERTIES OF TIMBER

1.7.1 CEN-strength classes and relationship between bending and compression strength

In Europe, several CEN standards relate to the determination of strength and modulus of elasticity of structural timber. These standards, EN 338 (1995), EN 384 (1995), EN 408 (1995) and EN 518 (1995), are generally applied to sawn timber. The summary of standards is presented here.

The requirements for European strength classes are summarised in Table 3 for poplar and conifer species (EN 338 standard 1995). Table 3 shows CEN-strength classes and their characteristic values for the modulus of elasticity in bending (E_m), compression strength parallel to grain ($f_{c,\,0}$), bending strength (f_m) and density at moisture content 12% (p_{12}). Allocation of a strength class can be achieved if the characteristic values E_m, f_m and p_{12} are defined for a population. Consequently the timber population may be assigned to a CEN strength class where the characteristic values are greater or equal.

Table 3 . CEN-strength classes and some of the characteristic values for poplar and conifer species according to the EN 338 standard (1995).

	C14	C16	C18	C22	C24	C27	C30	C35	C40
$f_{m,k}$ (N/mm^2)	14	16	18	22	24	27	30	35	40
$f_{c,0,k}$ (N/mm^2)	16	17	18	20	21	22	23	25	26
$E_{m,\,mean}$ (kN/mm^2)	7	8	9	10	11	12	12	13	14
$\rho_{12,k}$ (kg/m^3)	290	310	320	340	350	370	380	400	420

EN 384 (1995) standard presents a formula for the relationship between the characteristics bending and compression strength (Equation 1). In addition, it gives formulas for other mechanical properties but these are not studied in this research. Due to these relationships the population can be assigned to a specific strength class based on the characteristic values of bending strength, modulus of elasticity and density.

$$f_{c,\,0,\,k} = 5\,(f_{m,k})^{0{,}45} \qquad (1)$$

1.7.2 Determination of characteristic values

According to EN 384 standard (1995) the tested material should be divided into populations and then divided into samples. A sample is defined in the EN 384 (1995) standard as: a number of specimens of one cross-sectional size and from one population. 5-percentile values of the samples are determined by the following methods:

- For strength properties $f_{c,\,0}$ and f_m a non-parametric method is used, i.e. it is a test value for which 5 % of the values are lower. If this is not an actual test value, then interpolation between two adjacent values is permitted.
- For the modulus of elasticity (E), the mean value is a characteristic value.
- For density ρ_{12} the characteristics value is calculated from a normal distribution (Equation 2):

$$\rho_{12,\,05} = \text{Mean } \rho_{12} - 1.65 * \text{s.d} \qquad (2)$$

where s.d is standard deviation for the sample.

Characteristic values of the population for the E, $f_{c,\,0}$ and f_m are determined from Equations 3, 4 and 5 (EN 384 standard 1995):

$$E_{c,0,\,mean} \text{ or } E_{m,\,mean} = (\sum \text{mean } E_j * n_j) / \sum n_j \tag{3}$$

$$f_{c,\,0,\,k} \text{ or } f_{m,\,k} = (\sum f_{0.05,\,j} * n_j) / \sum n_j)) * k_s \tag{4}$$

$$p_{12,\,k} = (\sum p_{12,\,0.05,\,j} * n_j) / \sum n_j \tag{5}$$

where

- j = index of the sample j = 1, 2, 3...
- n_j = the number of specimens in sample j
- k_s = adjustment factor for $f_{c,\,0}$ and f_m. The value of the adjustment factor k_s for $f_{c,\,0}$ and f_m is dependent on the number of samples and the number of specimens in the smallest sample.

The characteristic value of strength for a population in a grade, f_k , is calculated by Equation 6:

$$f_k = f_{05} k_s k_v \tag{6}$$

where f_{05} is the weighted mean of the sample 5-percentile values, k_s is a factor relative to the number of samples and their size, and $k_v = 1$ for visual grading.

Standard EN 384 (1995) specifies how adjustments for the moisture content at 12% shall be made: modulus of elasticity by 2% (Equation 7) and compression strength are adjusted by 3% (Equation 8) for every percentage point difference in moisture content. Density is decreased by 0.5% for every percentage point difference in moisture content (Equation 9). This assumes that both the mass and volume are measured at the test moisture content.

$$E_{12} = E_u * (1 - 0.02 * (12 - u)) \tag{7}$$

$$f_{c,\,0,\,12} = f_{c,\,0,\,u} * (1 - 0.03 * (12 - u)) \tag{8}$$

$$p_{12} = p_u * (1 + 0.005 * (12 - u)) \tag{9}$$

where u = moisture content at the moment of the test.

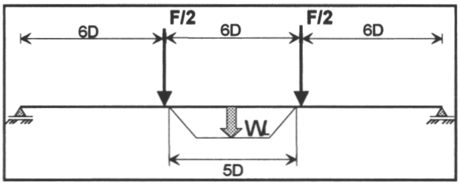
EN 384 standard (1995) states that 5-percentile of bending strength shall be adjusted to 150 mm depth by dividing by k_h (Equation 10):

$$k_h = (150 / h)^{0.2} \tag{10}$$

where h = depth of specimen.

1.7.3 Bending and compression test

Fig. 12 shows methods to measure global and local modulus of elasticity. The accuracy in the determination of modulus of elasticity depends on material characteristics as knots. Global modulus of elasticity is less sensitive to the effect of large knots but can be especially recommended for cylindrical poles (Ranta-Maunus 1999).



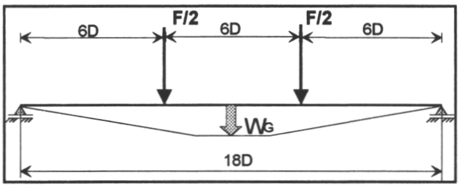


Figure 12. Schematic of bending test. Left: local modulus of elasticity, right: global modulus of elasticity determination.

According to the EN 408 (1995), the bending test shall be performed in the following way: The four point bending test is to be used to determine the modulus of elasticity (E_m) and the bending strength (f_m). In principle, the span shall be 18 times the diameter and the distance between two symmetrical loads should be 6 times the diameter. Local deflection between loads shall be measured for determination of E_m. Average diameter is used for the calculation of E_m. For strength determination the minimum diameter close to the failure location is used for calculation of the bending stress.

The test piece shall have a minimum length of 19 times the diameter of the round timber. Where this is not possible, the length of the timber shall be reported. The test piece shall be symmetrically loaded at two points over a span of 15 to 21 times the minimum diameter of the round timber. The loading heads shall be placed at the third points of the span as shown in Fig 12.

Load shall be applied at a constant rate. The rate of movement of the loading heads shall be not greater than 0.003 h mm/s, where h is height of specimen. The loading rate is adjusted so that the maximum load is reached within 300 ±120 seconds in the case of determining bending strength. The loading equipment used shall be capable of measuring the load to an accuracy of 1 % of the load applied to the test piece, for loads less than 10 % of the maximum applied load, and with an accuracy of 0.1 % of the maximum applied load.

Deformations shall be determined with accuracy of 1 % or, for deformations less than 2 mm, with an accuracy of 0.02 mm. The rotation of the test piece during the test shall be considered and taken into account. The diameters in the direction of the load, d_v, and perpendicular to the load, d_h, are measured at the mid-span.

The local modulus of elasticity in bending E_m (Fig. 12, left) is given by the Equation 11

$$E_m = \frac{a_1 l_1^2 (F_2 - F_1)}{16I(w_{L2} - w_{L1})} \tag{11}$$

where

- a_1 = distance between a loading position and the nearest support in a bending test (mm)
- l_1 = gauge length for the determination of modulus of elasticity (mm)
- I = second moment of area (mm^4)
- $F_2 - F_1$ = an increment of the load F (N) on the straight-line portion of the load deformation curve, in newtons. Note: F_1 and F_2 should respectively be taken as 10 % and 50 % of the maximum load.
- $w_{L2} - w_{L1}$ = the increment of local deflection (mm) corresponding to $F_2 - F_1$, having been measured at the centre of a central gauge length of about five times the diameter of the round timber.

Equation 12 shows second moment of area (I) for round (left) and square (right) form.

$$I = \frac{\pi \bar{d}^4}{64} \qquad\qquad I = \frac{h\bar{d}^3}{12} \tag{12}$$

The bending strength (f_m) is given by the Equation 13.

$$f_m = \frac{a_1 F_{max}}{2W} \tag{13}$$

where

- a_1 = distance between the loading position and the nearest support in the bending test (mm)
- d_v = diameter in the direction of the load (mm)
- d_h = diameter perpendicular to the load (mm)
- F_{max} = maximum load (N)
- W = section modulus (mm^3)

Equation 14 shows section modulus (W) for round (left) and square (right) form:

$$W = \frac{\pi \bar{d}^3}{32} \qquad\qquad W = \frac{hd^2}{6} \tag{14}$$

The strength shall be calculated to an accuracy of 0.1 N/mm^2.

In the test of compression parallel to the grain (EN 408 standard 1995) the test piece shall be of full cross section, and shall have a length of six times the diameter of the round timber. The end surfaces shall be accurately prepared to ensure that they are plane and parallel to one other and perpendicular to the axis of the piece. The test piece shall be loaded concentrically and load shall be applied at constant rate. The rate of movement of the loading head shall not be greater than 0.00005 l mm/s, where l is length of specimen. Maximum load should be reached within (300$\pm$120) s and time to failure of each test piece shall be recorded and its average reported. Any single piece diverging for more than 120 seconds from the target of 300 s shall be reported.

The modulus of elasticity in compression is given by Equation 15

$$E_{c,0} = \frac{l_1(F_2 - F_1)}{A(w_2 - w_1)} \tag{15}$$

The compressive strength is given by Equation 16

$$f_{c,0} = \frac{F_{\max}}{A} \tag{16}$$

where
- A = cross-sectional area (mm^2)
- F_{max} = maximum load (N)
- l_1 = gauge length for the determination of modulus of elasticity (mm)
- w = deformation (mm)

The diameters in two perpendicular directions, d_1 and d_2, are measured at or close to the fracture.

1.8 STRENGTH GRADING OF TIMBER

Due to the large variations in the mechanical properties of wood, between species, within species and even within a specimen, different strength grades exist for structural timber. Since the use of structural timber is based on its characteristic values, i.e. the lower 5-percentile of the population, the high strength of the majority of the pieces cannot be utilized unless the timber is graded (Fig 13). Traditionally, strength grading is carried out by visual assessment, taking into account the strength reducing factors that can be identified. These are primarily the knots and annual ring width. Since the grading decision depends on the judgement of the grader it can never be totally objective. In addition, important strength determining characteristics, such as density, cannot be assessed satisfactorily (Blass et al. 1995). However, strength grading machines have been developed. These are currently only used for sawn timber and no strength grading rules have been developed for round structural timber (Ranta-Maunus 1999)

In principle, every visible timber property or feature is suitable for strength grading provided that there exists a relationship between property and strength and modulus of elasticity. Examples of these factors are: slope of grain, annual ring width, knots, wane, distortions and decay caused by micro-organism. Visual strength grading is therefore defined as classifying timber according to its strength, based on statistical relationships between visible features and the load-carrying capacity (Blass et al. 1995).

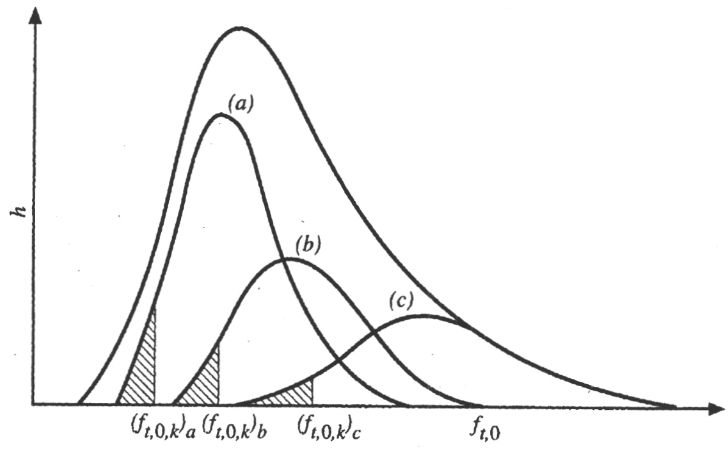


Fig. 13. Scheme of tensile strength distribution of structural timber assigned to three grades a, b, c. (Diebold and Glos 1994).

Based on experiences with sawn timber, there are some disadvantages in visual grading for example the relationship between the measured parameters and the strength of a piece of timber is relatively weak. Correlation coefficient with knots is only about 0.5, and with ring width 0.4 (Blass et al. 1994). Extensive research is necessary to determine the visual grading parameters that will enable the wood industry to classify small diameter round wood (Ranta-Maunus 1999).

During the last 10 years, grading systems for sawn timber have been developed and improved in order to increase the yield with respect to strength. A reasonable relationship has been found between modulus of elasticity, some visual features (knots, growth ring data) and bending strength. Both visual and machine strength grading are established in the wood industry, and the trend is now towards machine strength grading (Ranta-Maunus 1999).

Traditionally, conifers, such as pine and spruce, are strength graded visually with the same criteria. If density is considered, Scots pine and Norway spruce is graded separately (Lipitsäinen 1994 a, 1994b). In conjunction with the European Union (EU) project titled Small Diameter Round Timber for Construction (EU - Fair Programme CT95-0091) the strength grading system was created for round timber in accordance with EN standards, and given the characteristics values for these classes. A synopsis of visual grading parameters for machine round Scots pine and Norway spruce for grades A and B are given in Table 4. (Ranta-Maunus 1999).

Table 4. Strength grading parameters of machine round pine and spruce for grades A and B (Ranta-Maunus 1999).

Visual grading parameter	Grade A	Grade B
Knot sum per diameter ks/d [%]	75	100
Max knot per diameter mk/d [%]	25	30
Ring width r [mm]	3	5

1.9 HYPOTHESES AND AIMS OF STUDY

The primary hypothesis of the study is that twisting and mechanical properties of pith enclosed Scots pine and Norway spruce timber are mainly affected by physical properties and wood characteristics, such as age i.e. number of annual rings, ring width, density, moisture content, knots, defects, form and size of the specimen. The origin of timber, i.e. the stand properties and tree social status is only a background factor thus affecting mainly wood characteristics, knots and physical properties of wood. This primary hypotheses comprised following items which were based on author's synthesis from related theoretical background of wood properties and features and previous studies. These were studied by actual measurements on wood characteristics, mechanical and physical properties and statistical methods.

1. Origin of timber i.e. stand properties affect knot properties of timber.
2. When keeping round shape instead of rectangular in wood processing, the knot angle, the angle between specimens surface and the knot, is optimum, so that the knot area is minimised on the specimen surface. Therefore, round timber contains on average less visible knots than sawn timber.
3. For round timber, the change in knot quality from dead measured over bark to sound measured after wood processing is dependent on knot diameter over bark, the change of diameter of timber, longitudinal position in the stem and the rate of growth i.e. ring width.
4. Origin of timber i.e. stand properties have no significant effects on the twisting and mechanical properties of timber, when wood characteristics and physical properties are considered.
5. In seasoning and conventional drying cracking takes place in pith enclosed timber, especially in round timber, because the surface of round timber dries and shrink while the proportionally large inner part is still moist.
6. Twisting takes place in pith enclosed timber. In round timber, in particular, other drying deformations are not detrimental, because round timber does not have any opposite sides, where the opposite stresses could develop and cause crook or bow. But because of the large extent of juvenile wood, the age and moisture content of small diameter pith enclosed timber have great effect on the twisting.
7. In bending, due to the round form the mechanical properties of round timber should be better than those of rectangular timber. A volume, which is subjected to the highest stress, is smaller in round form than rectangular. Therefore, the probability that in the tension zone of round timber the weak point in the highest stress zone is lower.
8. Because of the unprocessed wood fibers, manually debarked round timber should have better mechanical properties than machine processed round timber.
9. The pith enclosed timber does not have any negative size effect on bending strength. A high proportion of juvenile wood in smaller sections suggest that

the strength of pith enclosed timber should increase with growing diameter / height i.e. age, which is the opposite of the EN384 size adjustment rule for sawn timber. The other mechanical properties should increase with growing diameter and age.

10. Due to the juvenile age of the wood, age has a positive effect on the mechanical properties of the timber.
11. Moisture content has a negative effect on the mechanical properties of timber.
12. The effect of knots on mechanical properties is dependent on the size of timber.
13. The mechanical properties of pine and spruce timber are considered similar, providing the specimens have similar physical properties, except density. At similar density, spruce is stronger than pine.
14. The same visual strength grading parameters and EN strength classes can be used for pith enclosed round pine and spruce.

The primary aim of the study is to find out factors affecting mechanical properties and twisting of pith enclosed round and sawn Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) timber produced from small-size thinning wood. Effects of age i.e. number of annual rings, knots, defects, physical properties, form and size of the specimen, wood processing, origin of timber and tree species are studied. In addition, factors affecting knot properties of pith enclosed round and sawn timber produced from small-sized thinning wood are studied. Characteristics of timbers from thinnings are discussed in order to determine the possible obstacles and benefits to utilise pith enclosed timber from thinning in constructions.

The study was performed in conjunction with the EU-Project Small Diameter Round Timber for Construction (FAIR CT95-0091). The testing of mechanical properties were performed in order to determine the characteristic strength and modulus of elasticity of small diameter round timber in accordance with EN standards. Therefore, special attention is given to the applicability of EN standards for tested round timber. Issues to be studied and discussed include adjustment factors, strength classes and grading established in the EU-project for Scots pine and Norway spruce. The purpose is to initiate and produce scientific information for a process to develop international standards for strength grading of small diameter round timber for structural use.

2. MATERIAL AND METHODS

2.1 DETERMINATION OF PHYSICAL PROPERTIES, WOOD CHARACTERISTICS AND TWISTING

A general description of the material used and its flow from the forest to the testings is presented in Table 7. Due to the fact that the material was collected in conjunction with the EU-Project Small Diameter Round Timber for Construction (FAIR CT95-0091), the studied material consisted mainly of round, full-size Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) specimens, hereinafter mentioned as pine and spruce, respectively. However, tested material gave a possibility to compare round and sawn specimens. Round form timber containing pith is optimum for the study of age effects i.e. the number of annual rings effects on properties of full-size timber, this is because age can be determined nearly unambiguously in this type of timber. Fig 14. shows the age determination method used in different models for different forms of timber.

The material was sampled according to the origin of logs and wood processing method (Table 7). The following information is presented for samples: origin of timber i.e. stand number and properties, the applied wood processing and drying methods and date. In addition, the locations of bending and compression specimens in the timber, butt or top, are presented. Test logs were harvested from six stands located in Eastern and Southern Finland during the years 1996-1998. All logs were butt logs and the lengths were approximately four meters. Test logs were randomly selected from each stand with the following criteria: 1) only the butt logs of the trees were harvested and 2) logs had to appear relatively straight without any detrimental surface defects. Both small-knot and large-knot trees were harvested. In addition, from the stand numbers 1, 3 and 5, trees were randomly selected for different processing methods. After harvesting, test logs were processed i.e. converted by debarking, machine rounding or sawing to timber. Then the processed logs i.e. timber was either seasoned or kiln dried and finally conditioned in climate chambers. From each piece of timber one bending and compression specimen were taken. The bending and compression specimens were separated by cutting before strength testing. The presumed failure points in the bending and compression specimens were predicted on the basis of knots (Fig. 15.). Properties of material were characterised by the following phases of measurements:

1. Measurement before bark removal

- Logs were numbered and the bending direction was determined and marked, considering the crookness. The sharpest crook point was placed randomly as either the tension or compression zone of the test log.
- Failure point presumed for each log was marked for both bending and compression parts.
- The bending and compression parts of the logs were measured from at least

two and one closest whorls at the presumed breaking point, respectively (Fig. 15).

- From each whorl the width and location of knots were determined (Fig. 16). The quality and location of the thickest knot was determined and the circumference of timber was measured. The knots located closer than 15 cm from the whorl were measured.

After these measurements, the test logs were processed i.e. converted by debarking, machine rounding or sawing to timber.

2. Measurements after processing

- The butt and top end parallel twisting lines of the test logs were marked from pith to surface (Fig. 17). Twisting was measured on timber from the stands 1, 2, 3 and 5.
- Timber from the stands 1, 2, 3 and 5 was weighed for the estimation of mean moisture content.

Following these measurements, timber from stands 1, 2, 3 and 5 were stacked and seasoned in the open air for three months. Timber from stands 4 (pine specimens 226-275) and 6 (spruce specimens 176-225) were kiln dried. The applied kiln drying formulas are shown in Tables 5 and 6.

Table 5. Drying formula for pine specimens 226…275, f_4, with a diameter of 125 mm and target moisture content of 12%. T = dry bulb temperature, WBD = wet bulb depression, RH = relative humidity.

Time	T (°C)	WBD (°C)	RH (%)
0	20	17	75
2	70	47	30
20	70	47	30
27	70	60	62
44	70	60	62
48	70	55	48
335	70	55	48
340	70	63	72
430	70	63	72
432	70	66	83
440	70	66	83

Table 6. Drying formulas for spruce specimens 176…225, f_6, with a diameter of 125 mm and target moisture content of 12%. T = dry bulb temperature, WBD = wet bulb depression, RH = relative humidity.

Time	T (°C)	WBD (°C)	RH (%)
0	5	2	72
10	70	25	25
20	70	25	25
22	70	6	75
36	70	6	75
40	70	25	25
192	70	25	25
196	70	2	91

3. Measurement after seasoning / kiln drying

- Cracking of the timber was recorded.
- The same whorls as used in measurement 1 were measured again in a similar manner.
- Timber from the stands 1, 2, 3 and 5 was weighed for the estimation of mean moisture content.

After seasoning / kiln drying, timber was conditioned for at least two weeks under different humilities and at a constant temperature of 22°C in chambers of VTT Building technology laboratories in Otaniemi, Finland.

4. Measurements after conditioning

- Crook was measured at interval of 50 to 250 cm from the butt end of the specimen according to bending direction, convex (+) or concave (-).
- Cracking of specimens was recorded.
- Cross grain was measured at one meter interval, where the highest value was measured.
- Twisting was measured in timber from stands 1, 2, 3 and 5 with an electric angle meter.
- Then specimens were cut to bending and compression parts. Simultaneously was sawn two about 3 centimetre thick disks for the determination of density, moisture content and gradient in the timber from stands 1, 2, 3 and 5.
- Finally, bending and compression tests were performed (chapter 2.3). From bending and compression specimens were sawn about 3 centimetre thick disks close to failure points. Then density and moisture content of the bending and compression parts were determined by weighing and water immersion. The density was adjusted at a moisture content of 12% with Equation 9. Age was also determined.

Cracking was recorded according to grading: 1= no cracking, 2 = very small cracks (<1 mm), 3 = small cracks (1…4 mm) and 4 = big cracks (>4 mm).

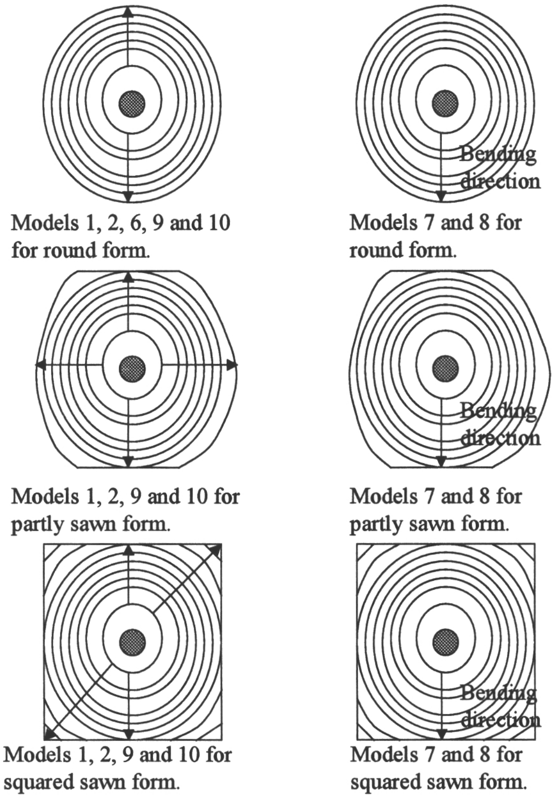


Fig. 14. Age used in different models for different forms of timber. Age used was calculated as a mean value of ages along the directions of arrows close to pith to surface of timber.

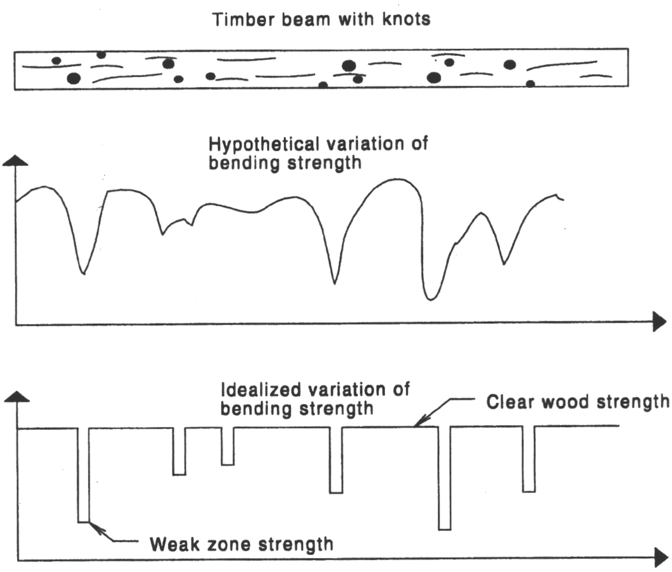


Fig 15. Lengthwise variation of bending strength in timber beams according to Riberholt et al. (1979) and Isaksson (1999).

The diameter of the knots was measured around the circumference of the log i.e. at right angles to the longitudinal direction of the specimen (Fig.16).

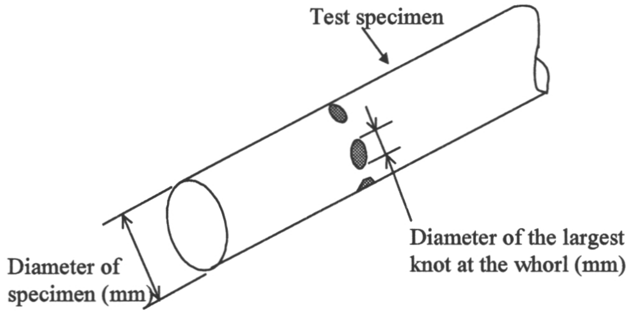


Fig. 16. Method used to measure knot diameter.

The principle to measure twisting (°/m) was the same for all specimens. On the test logs, parallel twisting lines were marked from pith to surface (Fig. 17). Notation b (mm/m) indicates the deviation on timber surface caused by the twisting of round timber. It can be calculated from Equation 17:

$$b = \frac{\pi d T}{360} \tag{17}$$

where

- b = deviation on timber surface (mm/m)
- d = diameter of specimen (mm)
- T = twisting (°/m)

Test specimens twisted both right hand side and left hand side. Absolute values of twisting were used in analyses since absolute values give a correct figure for the value of twisting causing problems in wood processing and utilisation.

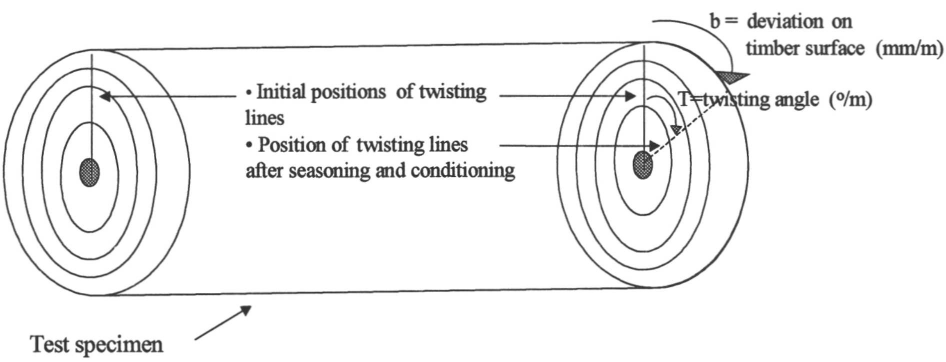


Fig. 17. Method used to measure twisting of timber.

Table 7. Description of the test log samples.

Stand code	Location, species and numbers of test logs	Processing method	Drying method and date	Bending specimen was taken from	Compression specimen was taken from	Forest site type	Age of stand (a)	Mean length of trees (m)	Timber volume (m^3/ha)
f_1	Vihti, Pine, 1…25	Manually debarked	Seasoning 1.5 –31.8.96	Base of the log	Top of the log	VT	30	12	150
f_1	Vihti, Pine, 26…100	Machine processed, not calibrated	Seasoning 1.5 –31.8.96	Base of the log	Top of the log	VT	30	12	150
*f_1	Vihti, Pine, 101…125	Two opposite faces partly sawn and the rest manually debarked, depth 100 mm	Seasoning 1.5 –31.8.96	Base of the log	Top of the log	VT	30	12	150
**f_2	Vihti, Pine, 126…150	Two opposite faces partly sawn and the rest manually debarked, depth 100 mm	Seasoning 1.5 –31.8.96	Base of the log	Top of the log	MT	75	21	220
f_1	Vihti, pine, 151…175	Squared sawn, 100 mm * 100 mm	Seasoning 1.5 –31.8.96	Base of the log	Top of the log	VT	30	12	150
f_3	Jokioinen, Pine, 176…200	Machine processed, not calibrated	Seasoning 1.5 –31.8.96	Base of the log	Top of the log	MT	24	10	141
*f_3	Jokioinen, Pine, 201…225	Two opposite faces partly sawn and the rest manually debarked, depth 100 mm	Seasoning 1.5 –31.8.96	Base of the log	Top of the log	MT	24	10	141
f_4	Suonenjoki, Pine, 226…275	Machine processed, calibrated to uniform diameter of 125 mm	Kiln drying 1.8 –31.8.98	Top of the log	Base of the log	VT	32	11	130
f_5	Vihti, spruce, 1…150	Machine processed, not calibrated	Seasoning 1.5 –31.8.96	Base of the log	Top of the log	MT	55	15	194
f_5	Vihti, spruce, 151…175	Squared sawn, 100 mm * 100 mm	Seasoning 1.5 –31.8.96	Base of the log	Top of the log	MT	55	15	194
f_6	Joensuu, spruce, 176…225	Machine processed, calibrated to uniform diameter of 125 mm	Kiln drying 1.10-31.10.98	Top of the log	Base of the log	OMT	45	15	280

*edgewise direction in bending test i.e. manually debarked surface on tension zone
** flatwise direction in bending test i.e. sawn surface on tension zone

2.2 KILN DRYING EXPERIMENT

Seasoning in the outdoors is an uncertain method of timber drying since it is totally dependent on the weather. In this study, a separate pine sample was kiln dried in order to test the applicability of a drying formula developed by VTT for round wood. The drying material, 156 round pines of 3 meter length machined to uniform diameter of 100 mm, was obtained from a Finnish round wood supplier, O-WOOD Ltd. and dried in the kiln of Pori Forestry college in Kullaa, Western Finland. The aim of this study was to obtain preliminary information on cracking and drying deformations of round timber during kiln drying. The drying formula was selected in order to produce round pine timber with few small cracks required for high quality wooden products. The drying formula used is presented in Table 8.

Table 8. Drying formula in special kiln drying experiment for round timber of pine. T = dry bulb temperature, dT = wet bulb temperature, RH= relative humidity.

Time, h	T, °C	dT, °C	RH, %
0	ambient	ambient	ambient
10	70	25	25
20	70	25	25
30	70	10	62
42	70	10	62
48	70	15	47
110	70	15	47
116	70	3	87
128	70	3	87
Target moisture content for Scots pine 15%			

Twisting was measured according to Fig. 15. After drying, the crook was measured at the same point as prior to and after machine rounding. Distribution of moisture content from seven pieces and dry-weight density from two pieces were also measured. The investigation attempted to examine the share of compression wood and normal wood at the point of maximum crook in the specimens. Gross grain was measured at one meter interval in the specimens, where it appeared the worst. In addition, the cracking was recorded.

2.3 METHODS FOR THE MEASUREMENT OF MECHANICAL PROPERTIES

In this paper the following mechanical properties were studied: 1) Modulus of elasticity in bending (E_m); 2) bending strength (f_m); 3) modulus of elasticity in compression parallel to grain ($E_{c,0}$) and 4) compression strength parallel to grain ($f_{c,0}$). Testing and calculation of mechanical properties was performed in the VTT Building technology laboratories of Otaniemi, Finland. The test procedures were based as closely as practical to the EN standards, which are intended for the testing of sawn timber. Some deviations from the standard had to be adopted because of the round form and, in some cases, variable diameter of the timber. In addition, second moment of area and section modulus for partly sawn timber was determined individually for each specimen either using equations for round or square form (Equations 12 and 14) depending on actual form of specimen. These were not assumed to significantly influence the applicability of the results. The differences in the conditions for testings the modulus of elasticity and strength compared to the EN standards were as follows:

- The moisture content of the specimens was higher than the reference condition of 12%. A moisture adjustment, according to the EN 384 (1995) standard, should be carried out at the 5-percentile or the mean value to the reference moisture content when the mean moisture content of the sample is in the range of 10% to 18%. In some cases the moisture content of the sample, mean or 5-percentile, was more than 18%.
- Individual diameters of tested specimens deviated from the 150 mm reference diameter for bending.
- In the bending test the span should be $l = 18$ d and in the compression test $l = 6$ d, where d is the mean cross-sectional diameter. As the diameter of some specimens varied and the form of some specimens was conical neither the span nor length were exactly similar, as prescribed in the EN standards. When the diameter of the timber was constant along the length, the span was 18 times the diameter. When the actual diameter was not processed with a constant diameter, the span corresponding to the top diameter of the sample was taken from the Table 9.

Table 9. The span used corresponding to the top diameter of the sample in bending, when the actual diameter of the timber was not processed to a constant diameter.

Top diameter range, mm	Nominal diameter, mm	Span, mm
75 to 99	75	1500
100 to 124	100	1950
125 to 149	125	2400
150 to 174	150	2850
175 to 199	175	3300
200 to 224	200	3750
225 to 249	225	4200
250 to 275	250	4650

Shaped wooden blocks of length not greater than the diameter of the round timber were inserted between the piece and the loading heads or supports to minimise local indentation. The blocks under loading heads had different heights to take into account the possible tapering of the specimen. In the testing procedure, the loading forces were equally maintained. The set up for the bending test is shown in Fig.

18.

The compression test was carried out in accordance with EN standards. A schematic layout for the compression test procedure is shown in Fig 18. Deformations for the determination of $E_{c,\,0}$ were measured using two LVDTs placed at either side of the specimen on a centroidal plane. Two gauges were used in order to measure the centroidal movement in case of uneven load take up or minor buckling. For the determination of compression strength, load was increased until it started to decrease after failure.

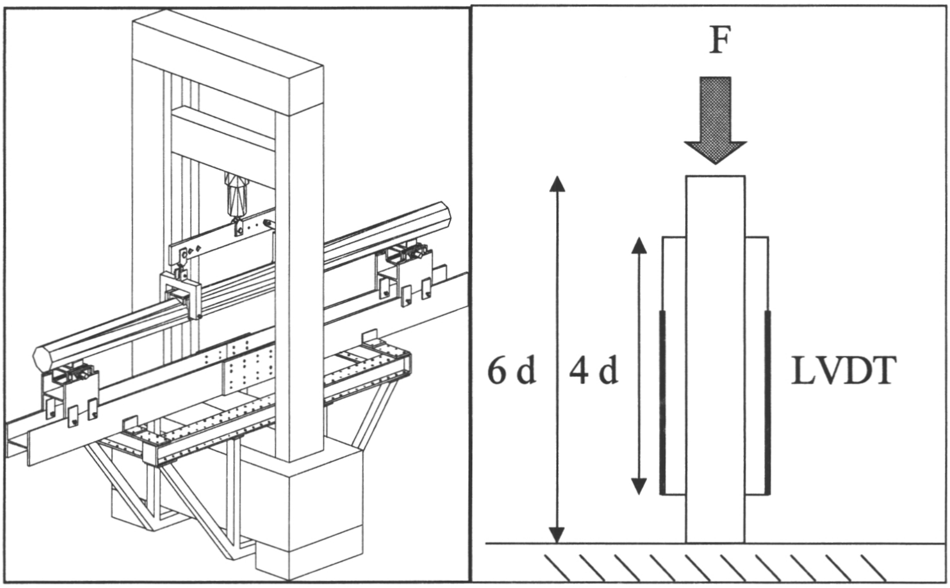


Fig 18. Set up for the bending test (left) and schematic details of compression test (right). (Ranta-Maunus 1999).

2.4 VERIFICATION OF THE APPLICABILITY OF EN STANDARDS, AND VISUAL GRADING OF GRADES A AND B

International standardisation harmonises production and gives possibilities for long term planning for both producers and customers. Therefore standardisation is an important measure to increase of utilisation of product.

The standard EN 384 standard (1995) lists adjustment factors for modulus of elasticity in compression ($E_{c,0}$) and in bending (E_m) and for compression strength ($f_{c,0}$) and bending strength (f_m) with regard to moisture content and size, assuming no other information is available.

The applicability of EN 384 standard (1995) for machine round pine and spruce timber was studied by comparing the prescription of EN standards to the results of this study. Table 4 presents established common visual strength grading parameters and limits for small diameter machine round pine and spruce (Ranta-Maunus 1999). In this paper, the established strength grading parameters and criteria were applied to tested materials in accordance with EN standards in order to determine the characteristic values and strength classes of the material. If the results of this study show evidence to revise prescriptions of EN standards, the results of the revised method are also shown. To validate these factors and to study the significance of the various features for strength and modulus of elasticity of round timber, they were analysed by the multiple regression analysis. $E_{c,0}$, E_m, $f_{c,0}$ and f_m were used as dependent variables.

2.5 ESTABLISHING RELATIONSHIPS BETWEEN MODULUS OF ELASTICITY AND BENDING STRENGTH

Machine grading will become possible for small diameter round wood when its use as a load bearing material increases and enterprises exists who are willing to invest for higher production yields. Usually in machine grading, the modulus of elasticity is measured and bending strength is determined on the basis of the known relationship with modulus of elasticity (Ranta-Maunus 1999). The relationship between modulus of elasticity and bending strength was established for machine processed round pine and spruce by simple regression analysis.

2.6 STATISTICAL METHODS

The primary hypothesis of the study was that twisting and mechanical properties are mainly affected by physical properties and wood characteristics. The origin of timber i.e. stand properties is only as a background factor i.e. it affects the mainly wood characteristics and physical properties of wood. The most convenient method to study the hypothesis of the study is a multiple regression analysis. Wood characteristics and physical properties can be used as independent variables, and the significance of background variables, such as the origin of timber, can also be tested.

At first, standard deviation (s.d.), standard error of the mean (s.e.), covariance (s_{xy}) and mean ($\bar{x}$) were calculated respectively by Equations 18, 19, 20 and 21.

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

$$s.e. = \frac{s.d.}{\sqrt{n}} \tag{19}$$

$$s_{xy} = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{n-1} \tag{20}$$

$$\bar{x} = \frac{\sum x_i}{n} \tag{21}$$

Because the regression model should not contain independent variables, which are strongly correlated to each other (Bowerman et al. 1990), a correlation analysis was also performed for the material. The coefficient of correlation is defined by Equation 22:

$$r = \frac{s_{xy}}{s.d._x \, s.d._y} \tag{22}$$

In general, the form of the regression equation is

$$y = B_o + \sum \; B_i \, x_i \tag{23}$$

where y is the dependent variable, x_i are the independent variables, B_o is the constant of the model and B_i are the multipliers of the independent variables x_i. The regression analysis supposed that the dependent variable is normally distributed and the dependent variable corresponding to different values of independent variable have equal variances. In some cases, it was observed that a logarithm i.e. transformation of the dependent variable improved the homoscedasticity of the model (Bowerman et al. 1990). When predicting values by the logarithmic (lg) model, the factor Q (Equation 24) was added to the constant B_o:

$$Q = 0.5*(s^2*\ln(10)) \tag{24}$$

where s = standard error of the logarithmic model (Mäkelä and Salminen 1991). This reduces bias due to logarithmic transformation.

If the independent variables comprise qualitative (nonnumeric) variables, they can be used as dummy variables in regression model. Dummy variable has only two values: 0 and 1. If specimen has a particular qualitative feature, it can be demonstrated by value 1, and if not by value 0 (Bowerman et al. 1990).

The material also contained dependent variables, which only had values of 0 or 1.

According to Cox (1970) and Hosmer and Lemeshow (1989), when this kind of dichotomous variable is set as a dependent variable there are two primary reasons for choosing the logistic regression. These are: (1) from a mathematical point of view, it is an extremely flexible and easily used method and (2) it leads itself to a biologically meaningful interpretation. According to Hosmer and Lemeshow (1989), for the logistic regression the risk level 0.2 in Wald test can be acceptable.

The specific form of the logistic regression model follows the form of Equation 25 (Hosmer and Lemeshow 1989):

$$\pi(x) = \frac{e^{\beta_0+\beta_1 x}}{1+e^{\beta_0+\beta_1 x}} \tag{25}$$

In summary, in a regression analysis when the outcome variable is dichotomous (Hosmer and Lemeshow 1989):

1. The conditional mean of the regression equation must be formulated to be bounded between 0 and 1. The logistic regression model, $\pi(x)$ given in equation (25) satisfies this constraint.
2. The binomial, not the normal, distribution describes the distribution of errors and will be the statistical distribution upon which the analysis is based.
3. The principles that guide an analysis using linear regression will also guide the logistic regression.

All models were constructed as follows: The relationships between the studied properties and other variables were investigated at first by tabulating the mean values and standard deviations, performing correlation analysis and making observations by figures. After that numerous models comprising different variables, their transformations and interactions were constructed and tested. The selection of models was based on the multiple coefficients of determination of the model, as well as standard errors, form of residuals and their normal probability plots. In addition, the selection of individual variable to the model was based on its t-value and significance and correlations with other variables.

In a conjunction with logistic regression, a lowess fit line is used to present the relationship between dependent and independent variables. The lowess fit line uses an iterative locally weighed least-squares method to fit a curve to a set of points (SPSS® Base 7.5 for Windows® User's guide 1997).

3. EFFECTS OF WOOD PROCESSING ON KNOTS

3.1 EFFECTS OF WOOD PROCESSING ON KNOT AREA RATIO

From the material presented in Table 7 knot related properties were measured over bark (ob) i.e. prior to wood processing, and under bark (ub) i.e. after wood processing. The ΔKAR is a change of knot area ratio (%). A positive change of knot area ratio indicates a growth of knot area ratio. Here is analysed separately for pine and spruce how knot area ratio changes when a log with bark is machine rounded or at least partly sawn. The objective of the analysis is shown that after wood processing knot area ratio is smaller in round timber than in sawn timber and study how knot area ratio change with wood processing. Knot area ratio is an important feature in structural timber since it is widely used as a strength grading criteria for timber. The sample Pine 1-25, f_1, manually debarked specimens, was left out of the analysis since the change in knot properties and timber size was negligent.

It is shown in Table 10 and Fig. 19, how the reduction in circumference in relation to the circumference of over bark (X_1), the share of sawn circumference from total circumference after wood processing (X_2) and origin of timber affect the knot area ratio of pine and spruce. The knot area ratio of pine and spruce increases with the reducing circumference of timber both in machine rounding and sawing, when timbers from the same stand were compared. On average, the change of knot area ratio of pine and spruce increased more in sawing than in machine rounding, when timbers from the same stand were compared. Pine timbers from stand f_2 had lower knot area ratio than other pines. Spruce timbers from stand f_6 had higher knot area ratio and change of knot area ratio than other spruce timbers. The variables used were calculated as follows:

- The change of knot sum ΔKAR (%) is:

$$\Delta KAR = KAR_{ub} - KAR_{ob} = ks/c_{ub} - ks/c_{ob} \quad (26)$$

- The reduction in circumference in relation to circumference over bark X_1 (%) is:

$$X_1 = 100 * (c_{ob} - c_{ub}) / c_{ob} \quad (27)$$

- The share of sawn circumference from total circumference after wood processing X_2 (%) is:

$$X_2 = 100 * s\,c_{ub} / c_{ub} \quad (28)$$

where

- c = circumference (mm).
- c_{ob} = circumference over bark (mm).
- c_{ub} = circumference under bark (mm).
- ΔKAR = a change of knot area ratio (%).
- $KAR_{ob} = ks/c_{ob}$ = knot sum per circumference over bark (%) i.e. prior to wood processing.
- $KAR_{ub} = ks/c_{ub}$ = knot sum per circumference under bark i.e. after wood processing (%).
- s = length of sawn circumference (mm).
- $s\ c_{ub}$ = length of sawn circumference after wood processing (mm).
- X_1 = reduction in circumference in relation to circumference over bark (%).
- X_2 = share of sawn circumference from the total circumference after wood processing (%).

Table 10. Means and standard deviation of knot area ratio (KAR), reduction in circumference in relation to circumference over bark (X_1) and share of sawn circumference from the total circumference after wood processing (X_2) by sample.

Sample, number of specimens	ΔKAR (%) $\bar{x}$ / s.d.	KAR_{ob} (%) $\bar{x}$ / s.d.	KAR_{ub} (%) x / s.d.	X_1 (%) $\bar{x}$ / s.d.	X_2 (%) $\bar{x}$ / s.d.
Pine 26-100, f_1, n = 132	4.0 / 3.6	18.8 / 6.9	22.6 / 7.7	16.6 / 5.6	0 / 0
Pine 101-125, f_1, n = 46	3.6 / 3.2	15.3 / 6.4	18.7 / 7.1	14.8 / 3.8	51.8 / 6.8
Pine 126-150, f_2, n = 43	4.7 / 3.0	4.9 / 4.3	9.0 / 5.8	16.8 / 3.3	53.4 / 4.6
Pine 151-175, f_1, n = 46	12.7 / 6.4	16.8 / 5.7	29.2 / 8.4	33.7 / 9.8	99.6 / 1.3
Pine 176-200, f_3, n = 40	1.7 / 2.9	26.0 / 7.3	27.7 / 6.6	9.7 / 2.9	0 / 0
Pine 201-225, f_3, n = 50	5.8 / 5.4	24.4 / 6.4	30.2 / 6.1	10.8 / 2.1	41.8 / 8.2
Pine 226–275, f_5, n = 97	3.7 / 2.4	8.6 / 4.7	12.3 / 5.4	27.5 / 7.9	0 / 0
Pine round, n = 269	**3.6 / 3.2**	**16.2 / 8.8**	**19.9 / 8.9**	**19.6 / 8.9**	**0 / 0**
Pine sawn, n = 185	**6.7 / 5.9**	**15.7 / 9.0**	**21.8 / 11.0**	**18.8 / 10.3**	**61.8 / 23.2**
Spruce 1-150, f_5, n = 227	2.4 / 3.2	10.1 / 3.9	12.5 / 4.7	19.5 / 5.6	0 / 0
Spruce 151 – 175, f_5, n= 50	3.9 / 3.0	9.5 / 3.0	13.3 / 4.3	23.3 / 5.7	100 / 0
Spruce 176-225, f_6, n = 56	7.4 / 4.4	12.5 / 3.8	19.9 / 5.8	29.0 / 5.0	0 / 0
Spruce round, n = 283	**3.4 / 4.0**	**10.6 / 4.0**	**13.9 / 5.8**	**21.4 / 6.6**	**0 / 0**
Spruce sawn, n = 50	**3.9 / 3.0**	**9.5 / 3.0**	**13.3 / 4.3**	**23.3 / 5.7**	**100 / 0**

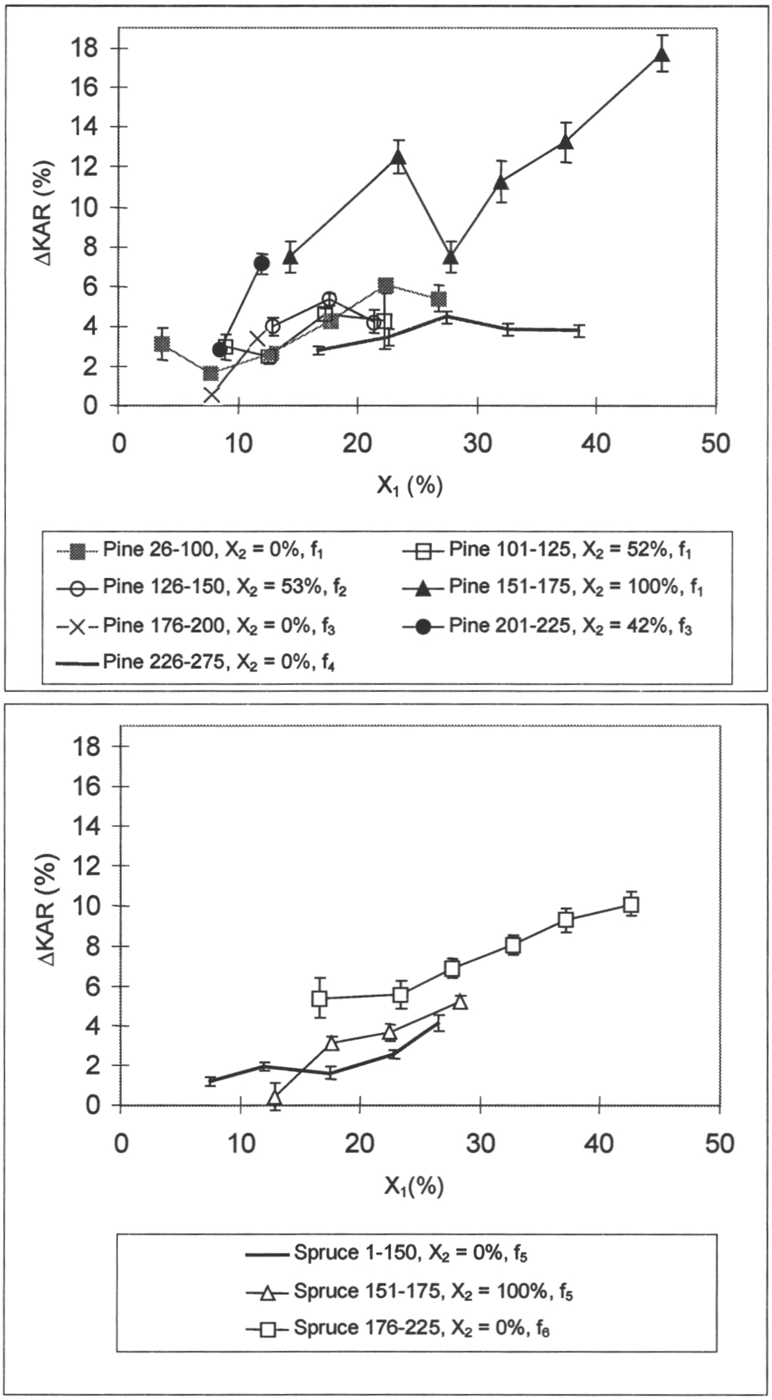


Fig. 19. Means and standard errors of a change of knot area ratio (ΔKAR) by reduction in circumference in relation to circumference over bark (X_1), for pine (above) and spruce (below). The share of sawn circumference from the total circumference after wood processing (X_2), and origin of timber (f_i) are also presented.

The regression models were constructed separately for pine (Model 1) and spruce (Model 2). The origin of timber has effects on change of knot area ratio both in pine and spruce material. The reduction in circumference in relation to the circumference of over bark (X_1) and the share of sawn circumference from total circumference after wood processing (X_2) have both positive effect on the change of knot area ratio (ΔKAR). For spruce, the interaction between the reduction in circumference in relation to the circumference of over bark (X_1) and the share of sawn circumference from total circumference after wood processing (X_2) was found.

Model 1 for pine:

$$\lg(\Delta KAR+10) = 1.021+0.002403 f_{1\ \mathrm{and}\ 3} X_1+0.003963X_1+ 0.001104X_2 \quad (1)$$

When factor Q (Equation 24) is added to the constant the model 1 is as follows after transformations:

$$\Delta KAR = (10^{1.034 + 0.002403 f_{1\ \mathrm{and}\ 3} X_1 + 0.003963 * X_1 + 0.001104 X_2}) - 10$$

where $f_{1\ \mathrm{and}\ 3} = 1$ for stand numbers 1 and 3, with others as 0.

For Model 1, the F-value was 76.3 (n = 453), the multiple coefficient of determination (adjusted R^2) was 0.33 and the standard error (s) 0.1056. All multipliers in Model 1 were significant and the basic statistical assumptions behind the regression Model 1 were met (Tables 11 and 12, Fig. 20). The residuals show three outlayers, which had no effect on analysis. Residuals follow expected cumulative probability.

Table 11. Multipliers, t- values, significance levels and 95% confidence intervals for multipliers in Model 1 for pine.

				95% Confidence interval for B	
Variable	B	t-value	Sig.	Lower Bound	Upper Bound
Constant	1.021	89.0	.000	0.988	1.043
$f_{1\ \mathrm{and}\ 3} X_1$	0.002403	4.5	.000	0.001	0.003
X_1	0.003963	7.2	.000	0.003	0.005
X_2	0.001104	6.5	.000	0.00077	0.001435

Table 12. Correlation coefficients between the variables in Model 1 for pine.

	$F_{1\ \mathrm{and}\ 3} X_1$	X_1	X_2
$f_{1\ \mathrm{and}\ 3} X_1$	1.0		
X_1	-0.22	1.00	
X_2	-0.44	-0.10	1.00

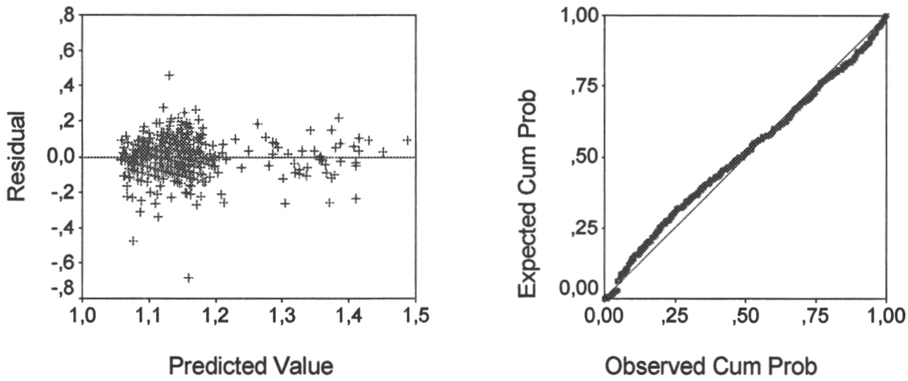


Fig 20. Residuals and their normal probability plot of Model 1 for pine.

Model 2 for spruce:

$$\lg(\Delta KAR+10) = 0.974+0.09482f_6+0.005405X_1+0.0000155X_1X_2 \qquad (2)$$

When factor Q (Equation 24) is added to the constant the Model 2 is as follows after transformations

$$\Delta KAR = 10^{0.988+0.09482f_6+0.005405X_1+0.0000155X_1X_2} - 10$$

where $f_6 = 1$ for stand number 6, with others as 0.

For Model 2, the F-value was 37.0 ($n = 332$), the multiple coefficient of determination (adjusted R^2) was 0.25 and the standard error (s) was 0.1087. All multipliers in Model 2 were significant and the basic statistical assumptions behind the regression Model 2 were met (Tables 13 and 14, Fig. 21). The residuals show one outlayer, which had no effect on analysis. Residuals follow expected cumulative probability.

Table 13. Multipliers, t- values, significance levels and 95% confidence intervals for multipliers in Model 2 for spruce.

				95% Confidence interval for B	
Variable	B	t-value	Sig.	Lower Bound	Upper Bound
Constant	0.974	42.9	.000	0.929	1.019
f_6	0.09482	4.9	.000	0.056	0.133
X_1	0.005405	4.8	.000	0.003	0.008
$X_1 X_2$	0.0000155	2.1	.038	0.0000083	0.0000230

Table 14. Correlation coefficients between the variables in Model 2 for spruce.

	F_6	X_1	X_2
f_6	1.0		
X_1	-0.56	1.00	
X_1X_2	-0.33	-0.33	1.00

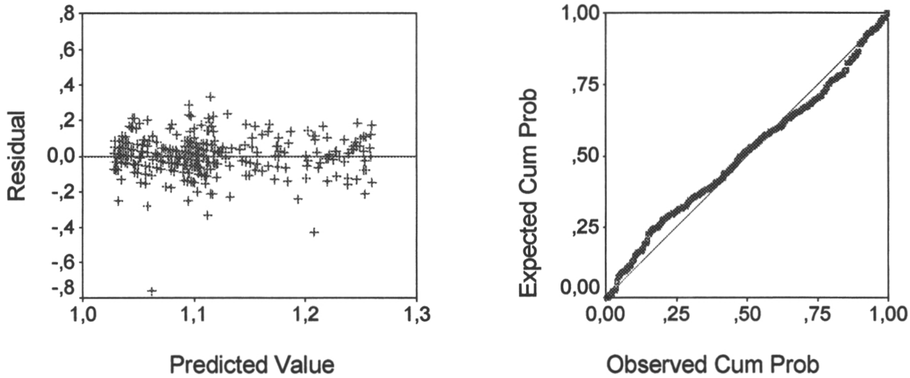


Fig 21. Residuals and their normal probability plot of Model 2 for spruce.

The respective results for pine and spruce by models 1 and 2 are illustrated in Tables 15 and 16 showing that sawing results higher increase in knot area ratio than machine rounding. The increase in knot area ratio in sawing has practical significance for pine, in particular. In addition, knot area ratio increased with a reduction in circumference. Origin of timber had also effect on the knot area ratio and change of knot area ratio (fig. 19).

Table 15. The effect of machine rounding and sawing on the change of knot area ratio of pine and spruce by models 1 and 2, respectively.

c_{ob} (mm)	c_{ub} (mm)	s (mm)	ΔKAR (%) for pine	ΔKAR (%) for spruce	Form
500	400	0	4.5	2.5	Round
500	400	200	6.5		Partly sawn
500	400	400	8.7	3.4	Squared sawn

Table 16. The effect of degree of wood processing on the respective knot area ratio of round pine and spruce by models 1 and 2.

c_{ob} (mm)	c_{ub} (mm)	s (mm)	ΔKAR (%) for pine	ΔKAR (%) for spruce	Form
500	450	0	2.5	1.0	Round
500	400	0	4.5	2.5	Round
500	350	0	6.8	4.1	Round

3.2 EFFECTS OF DEGREE OF WOOD PROCESSING ON THE QUALITY OF THE THICKEST KNOT

The change in the thickest knot quality from dead over bark to sound after wood processing was studied by a logistic regression for separately machine round pine samples 26-100, 176-200, 226-275 and for machine round spruce samples 1-150 and 176-225. The pine material comprised 248 dead knots over bark of which 78 were sound after wood processing. The spruce material comprised 192 dead knots over bark of which 50 were sound after wood processing. Table 17 shows basic information on the properties of the thickest knots, which were dead over bark. From Table 17 and the trend lines in Fig. 22 for pine and spruce it could be concluded that the knots which regularly changed to sound were larger over bark than the knots which remained dead. The diameter of the thickest knot over bark in relation to circumference over bark (X_3), was defined as follows:

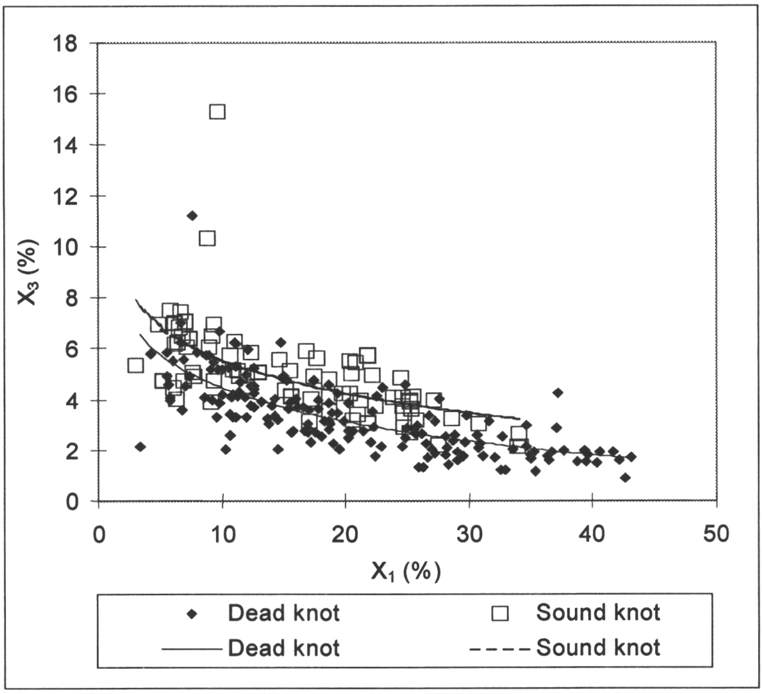
$$X_3 = 100 * mk_{ob} / c_{ob} \quad (29)$$

where

- mk_{ob} = diameter of the thickest knot over bark (mm).
- c_{ob} = circumference over bark (mm).
- X_3 = the diameter of the thickest knot over bark in relation to circumference over bark (%).

Table 17. Distribution of the quality of the thickest knots in pine and spruce whorls after machine rounding, and their means and standard deviations before (mk_{ob}) and after wood processing (mk_{ub}) and reduction in circumference in relation to circumference over bark (X_1).

	Quality after wood processing		mk_{ob} (mm) $\bar{x}$ / s.d.	mk_{ub} (mm) $\bar{x}$ / s.d.	X_1 (%) $\bar{x}$ / s.d.
Pine	Dead knot	n=170	15.9 / 5.5	16.4 / 5.6	20.2 / 10.1
	Sound knot	n=78	20.9 / 6.2	21.1 / 6.1	16.2 / 8.2
Spruce	Dead knot	n=142	10.8 / 3.6	9.9 / 3.3	16.8 / 6.8
	Sound knot	n=50	13.1 / 3.6	13.7 / 4.6	21.2 / 8.4



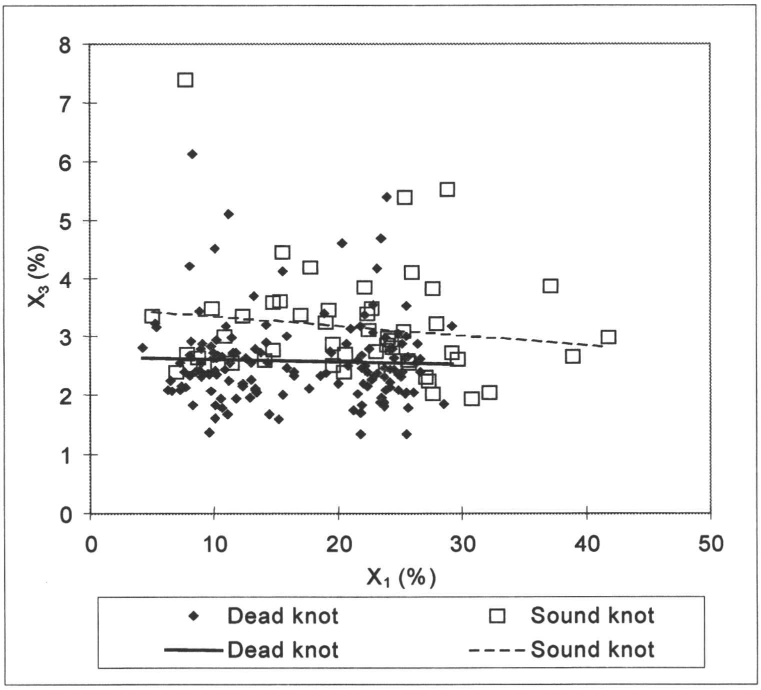


Fig. 22. The change of knot quality from dead knot over bark to sound after wood processing for round pine (above) and spruce (below) as a function of reduction in circumference in relation to circumference over bark (X_1) and diameter of the thickest dead knot over bark in relation to circumference over bark (X_3). The trend lines are presented, as well.

The respective Models 3 and 4 for machine round pine and spruce indicated that the change in the knot quality from dead knot to sound can be predicted at a certain level of accuracy as a function of the reduction in circumference in relation to circumference over bark (X_1) and the diameter of the thickest knot over bark in relation to circumference over bark (X_3) both for pine and spruce. In addition, it was found that for pine the origin of the timber and the circumference of over bark affects the probability that the knot quality changes from dead to sound within the radial distance studied. For spruce, it was found that the location of the whorl, butt or top end of the base log, and the age of the timber and ring width affect this probability.

Model 3 for pine is shown below. The –2 log likelihood of Model 3 was 239.6 and the significance 0.0000. All multipliers in Model 3 were significant and the basic statistical assumptions were met (Tables 18 and 19). Model 3 predicted the change in knot quality from dead to sound correctly in 51% of cases, when actual change was observed (Table 20). In addition, Model 3 correctly predicted 90% of cases, when an actual change was not observed. In total, the predictions were correct for 78% of the cases. Lowess fit lines for the probabilities predicted by Model 3 followed the real values, which means that model 3 worked correctly for the tested material (Fig 23).

$$\pi = \frac{e^{-5.5046-0.0026c_{ob}+0.9825f_1+8.3216\lg(x_1 \lg x_3)}}{1+e^{-5.5046-0.0026c_{ob}+0.9825f_1+8.3216\lg(x_1 \lg x_3)}} \qquad (3)$$

where the new variables are

- π = probability (0…1) of changing knot quality from dead to sound.
- c_{ob} = circumference over bark (mm).
- e = 2.71828
- f_1 = 1 for stand number 1, other = 0.
- lg (X_1 * lg X_3) = logarithm from reduction in circumference in relation to circumference over bark multiplied by logarithm from diameter of the thickest knot over bark in relation to circumference over bark.

Table 18. Multipliers, Wald – values, significance levels and Exp (B) in Model 3.

Variable	B	Wald	Sig.	Exp (B)
Constant	-5.5046	13.2	.000	
c_{ob}	-0.0026	2.2	.143	0.997
f_1	0.9825	8.7	.003	2.671
lg (X_1 * lg X_3)	8.3216	26.9	.000	4111.8

Table 19. Correlation coefficients between the variables in Model 3.

	c_{ob}	f_1	lg (X_1* lg X_3)
c_{ob}	1.00		
f_1	-0.27	1.00	
lg (X_1* lg X_3)	0.30	-0.04	1.00

Table 20. Results of the logistic regression Model 3 for the tested material.

	Predicted		
Observed	Dead	Sound	Percent correct
Dead	153	17	90.0
Sound	38	40	51.3
		Overall	77.8

Model 4 for spruce is shown below. The –2 log likelihood of Model 4 was 160.6 and significance 0.0000. All multipliers in Model 4 were significant and the basic statistical assumptions were met (Tables 21 and 22). Model 4 predicted the change in knot quality from dead to sound correctly in 58% of the cases, when an actual change was observed (Table 23). In addition, Model 4 correctly predicted 95% of the cases, when actual change was not observed. The predictions were correct in 85% of the total cases. Lowess fit lines for the probabilities predicted by model 4 follow the scatter plots of real values, which means that model 4 worked correctly in tested material (Fig 24).

$$\pi = \frac{e^{-2.6524-0.1018a+5.4327\lg(x_1 \lg x_3)+1.03d_1+0.7054r}}{1+e^{-2.6524-0.1018a+5.4327\lg(x_1 \lg x_3)+1.03d_1+0.7054r}} \tag{4}$$

The new variable is:

- d_1 = 1, if the location of the thickest knot was at the top end (3…4 height meters higher than the stump) of the base log and d_1 = 0 if the location of the thickest knot was at the butt end (0…1 meters from the stump) of the base log.

Table 21. Multipliers, Wald – values, significance levels and Exp (B) in Model 4.

Variable	B	Wald	Sig.	Exp (B)
Constant	-2.6524	1.2	0.273	
a	-0.1018	4.8	0.029	0.903
d_1	1.0291	6.4	0.012	2.800
lg (X_1 * lg X_3)	5.4327	10.7	.001	228.8
r	0.7054	2.4	0.125	2.024

Table 22. Correlation coefficients between the variables used in Model 4.

	a	d_1	lg (X_1* lg X_3)
a	1.00		
d_1	0.13	1.00	
lg (X_1* lg X_3)	0.33	0.07	1.00
r	0.52	0.03	0.23

Table 23. Results of the logistic regression Model 4 for the tested material.

	Predicted		
Observed	Dead	Sound	Percent correct
Dead	135	7	95.1
Sound	21	29	58.0
		Overall	85.4

Figs. 25 and 26 illustrate how the respective probabilities predicted by Models 3 and 4 for round pine and spruce, depended on wood processing and wood characteristics. Results for pine indicated that independent of knot size, the dead knots over bark changed with a high probability, over 70 %, to sound in the vicinity of the wood surface, at a distance of 15 mm from surface. For spruce similar phenomena could be seen, however, ring width had a significant effect on this probability. The effect of ring width was very steep; when the ring width changed from 1 mm to 2 mm the probability increased by more than 60 %. The small knots (< 10 mm), however, did not change to sound close to the surface. In addition, for spruce the location of the knot has an effect on the probability. The knots close to the butt of spruce remained dead with a greater probability than the knots located higher in the stem.

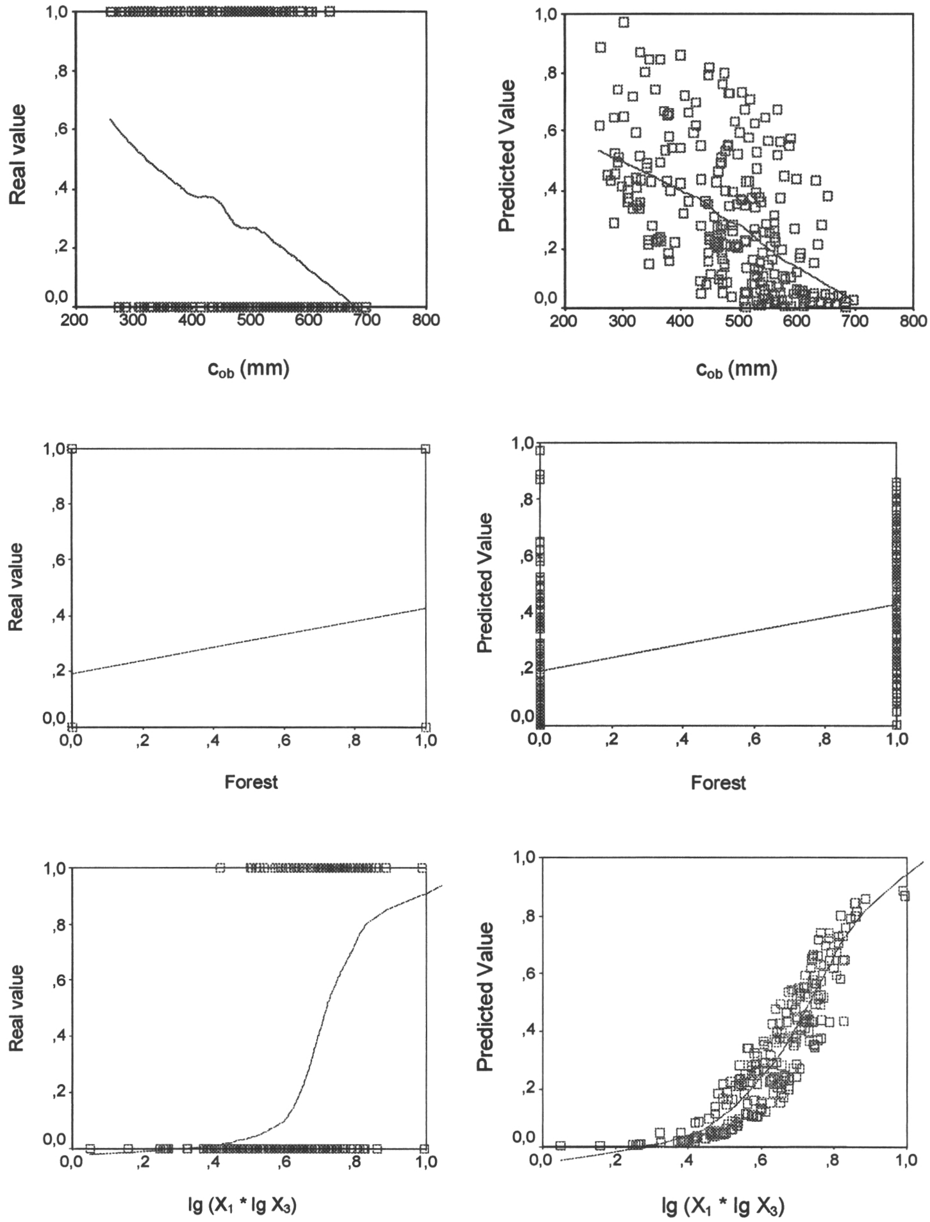


Fig 23. Lowess fit lines applied to the real values (left) and probabilities predicted by Model 3 for pine (right).

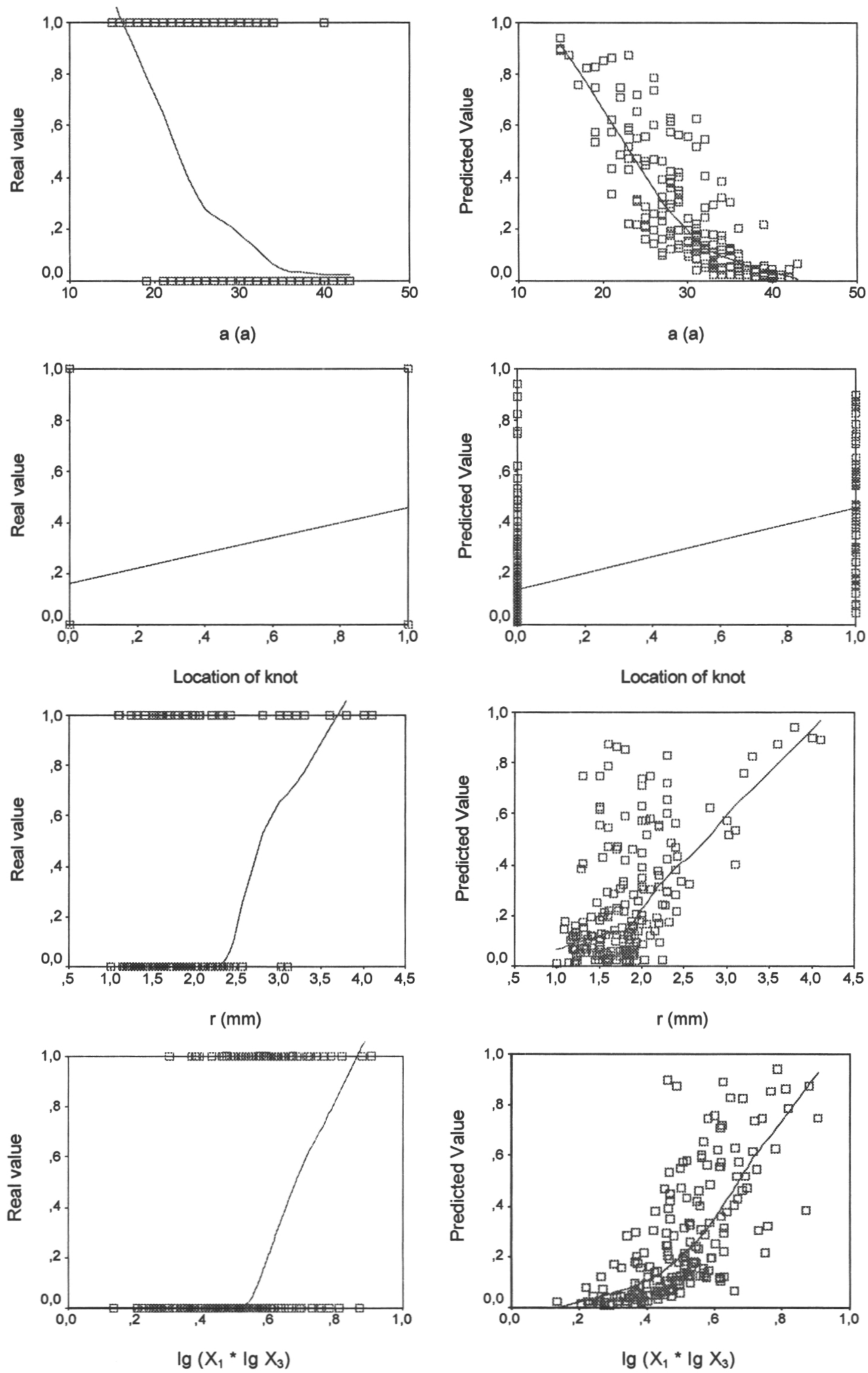


Fig 24. Lowess fit lines applied to the real values (left) and probabilities predicted by Model 4 for spruce (right).

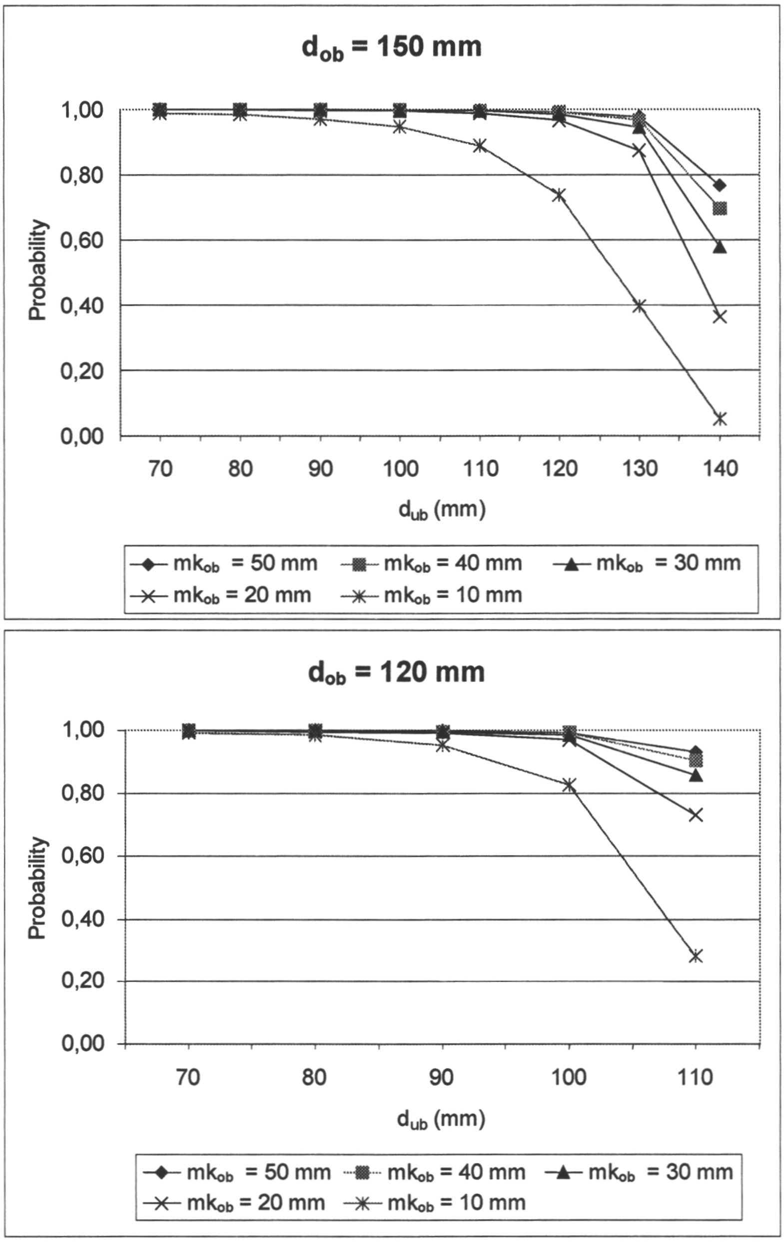


Fig. 25. Predicted probabilities for knots to change from dead over bark to sound by Model 3 for round pine in diameters 150 mm (above) and 120 mm (below) as functions of diameter after wood processing and diameter of the thickest knot.

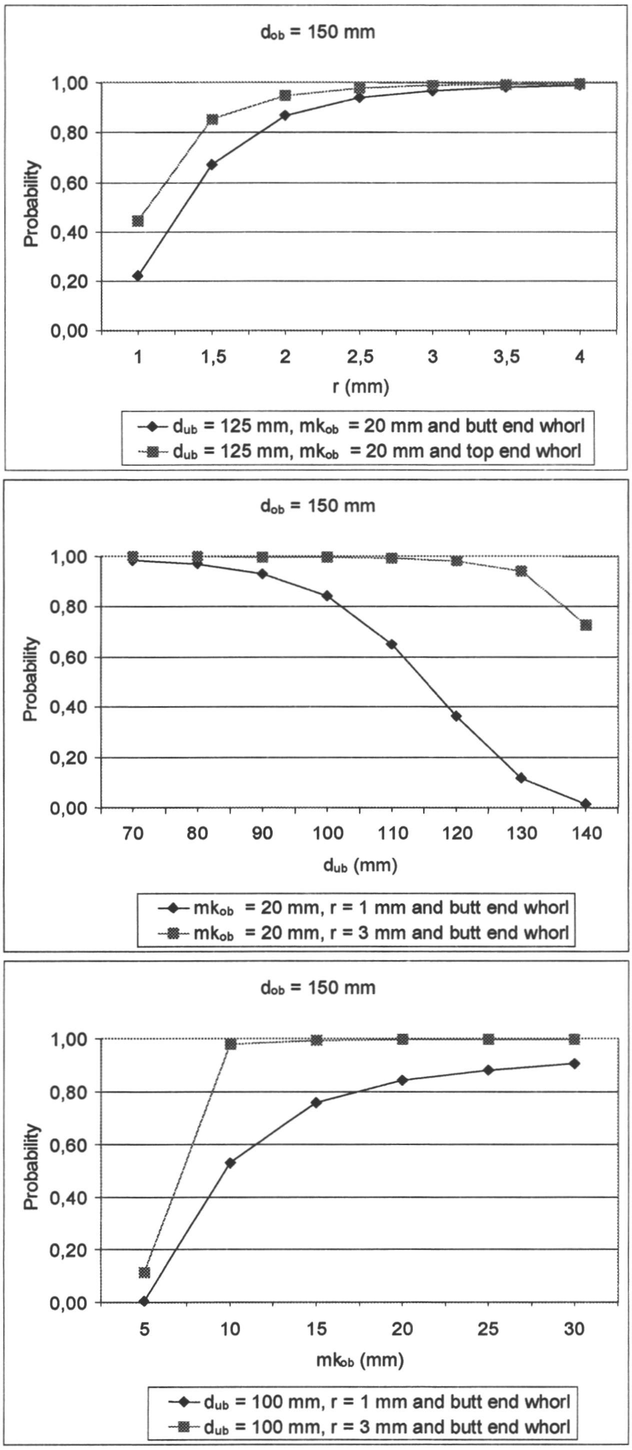


Fig. 26. The predicted probabilities of knots to change from dead over bark to sound by Model 4 for round spruce with a diameter of 150 mm over bark as functions of ring width and location of the whorl (above), diameter after wood processing (middle) and diameter of the thickest knot over bark (below).

4. DRYING DEFORMATIONS

4.1 TWISTING OF PINE AND SPRUCE

Table 24 shows the absolute twisting, moisture content and age of the samples presented in Table 7. The twisting is measured from a green state to showed moisture content. Absolute mean values and standard deviations of twisting of pine and spruce appear to be quite equal considering that there were some deviations in the mean age and moisture content between species. The age used in this chapter is measured from the top end of the timber as presented in Fig. 14. The density, diameter and ring width was also measured from the top end of the timber.

Correlation analysis was performed between twisting and other variables separately for pine and spruce (Table 25). For both tree species, negative correlations were found between age and diameter and positive between cross grain. For pine, twisting and moisture content had a small negative correlation. For spruce, negative correlation was obvious between twisting and moisture content.

Fig. 27 shows scatter-plots for twisting versus age, diameter, gross grain, moisture content, density and ring width separately for pine and spruce. The linear trend lines are also presented to clarify effect of single variable. With increasing age, diameter, moisture content and density the twisting decreased somewhat similarly for both tree species. The greater the cross grain the higher the equivalent twisting was for both tree species. The direction of the effect of ring width was different in pine and spruce materials. This might be due to the fact that the ring width range was narrower in spruce than in pine material. For pine, twisting increased with increasing ring width unlike for spruce.

Table 24. Means and standard deviations of twisting, moisture content and age of the samples presented in Table 7.

Sample	Twisting, (^{0}/m) $\bar{x}$ / s.d.	Moisture content, (%) $\bar{x}$ / s.d.	Age, (year) $\bar{x}$ / s.d.
Pine 1-50, f_1	1.9 / 1.2	20.1 / 1.2	18 / 4
Pine 51-100, f_1	2.1 / 1.6	14.3 / 0.4	16 / 4
Pine 101-125, f_1	1.4 / 1.2	18.4 / 0.7	16 / 5
Pine 126-150, f_2	1.1 / 1.0	18.6 / 1.4	31 / 6
Pine 151-175, f_1	1.7 / 0.9	20.2 / 0.5	14 / 2
Pine 176-200, f_3	1.2 / 0.8	19.3 / 0.4	13 / 1
Pine 201-225, f_3	1.4 / 0.9	18.6 / 0.4	12 / 2
Pine total	**1.6 / 1.2**	**18.2 / 2.3**	**17 / 6**
Spruce 1-100, f_5	1.6 / 1.4	14.9 / 0.6	25 / 5
Spruce 101-150, f_5	0.8 / 0.8	19.1 / 0.8	28 /6
Spruce 151-175, f_5	0.8 / 0.7	20.6 / 0.4	25 / 4
Spruce total	**1.3 / 1.2**	**17.0 / 2.5**	**26 / 5**

Table 25. Correlation coefficient between twisting and age (a), diameter (d), cross grain (G), density (ρ_{12}), ring width and moisture content (u) for pine and spruce separately.

	a	d	G	ρ_{12}	r	u
T (pine)	-0.17	-0.27	0.49	-0.09	0.11	-0.11
T (spruce)	-0.31	-0.39	0.32	-0.10	-0.08	-0.36

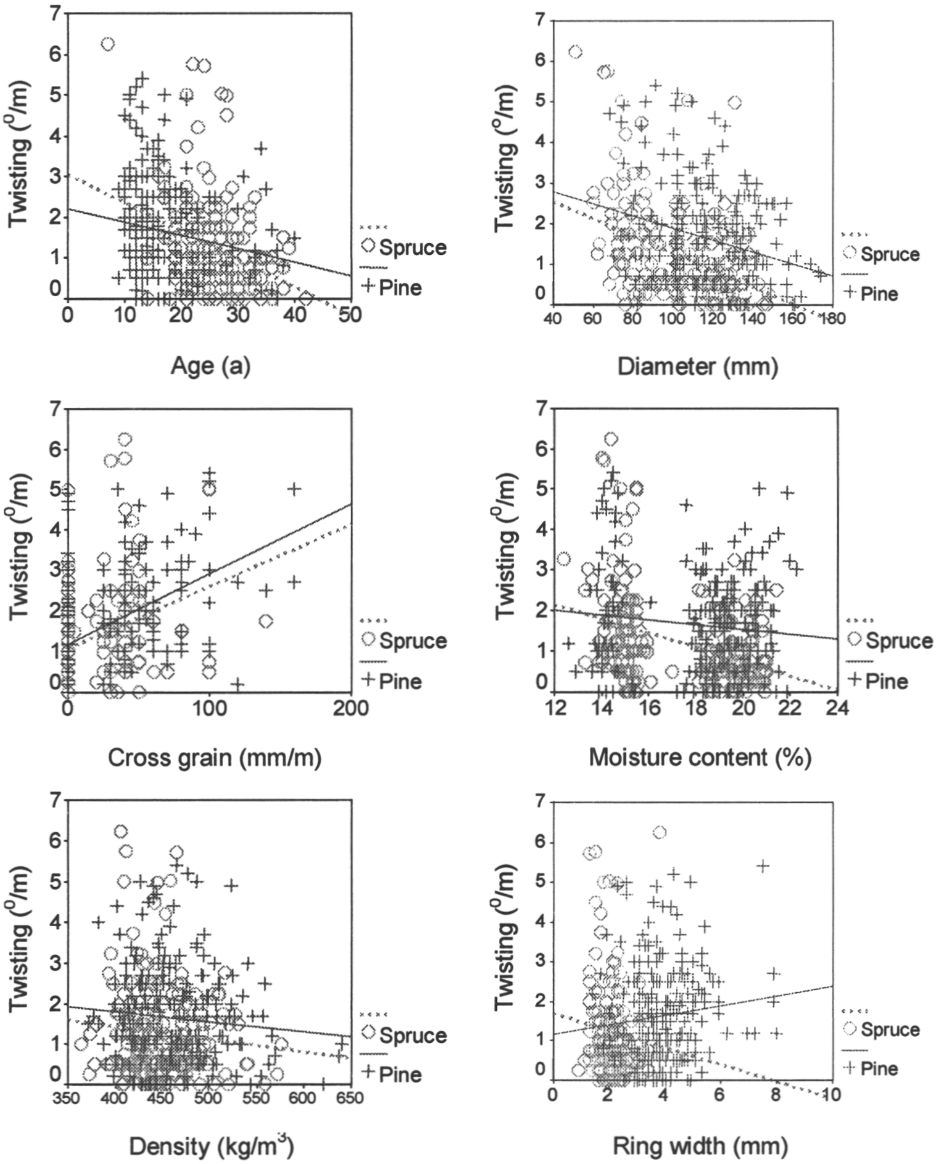


Fig. 27. Twisting versus age, diameter, cross grain, moisture content, density and ring width for pine and spruce specimens. The linear trend lines are presented, as well.

Fig. 28 shows means and standard errors for twisting by age classes, and the mean moisture content and origin of the samples. Moisture content is relatively constant with regards to the age distribution. Twisting for the older specimen compared to younger was smaller both for pine and spruce. In addition, the moisture content had a remarkable effect on twisting i.e. the lower the moisture content the greater the twisting was. The effect of moisture content decreased with increasing age.

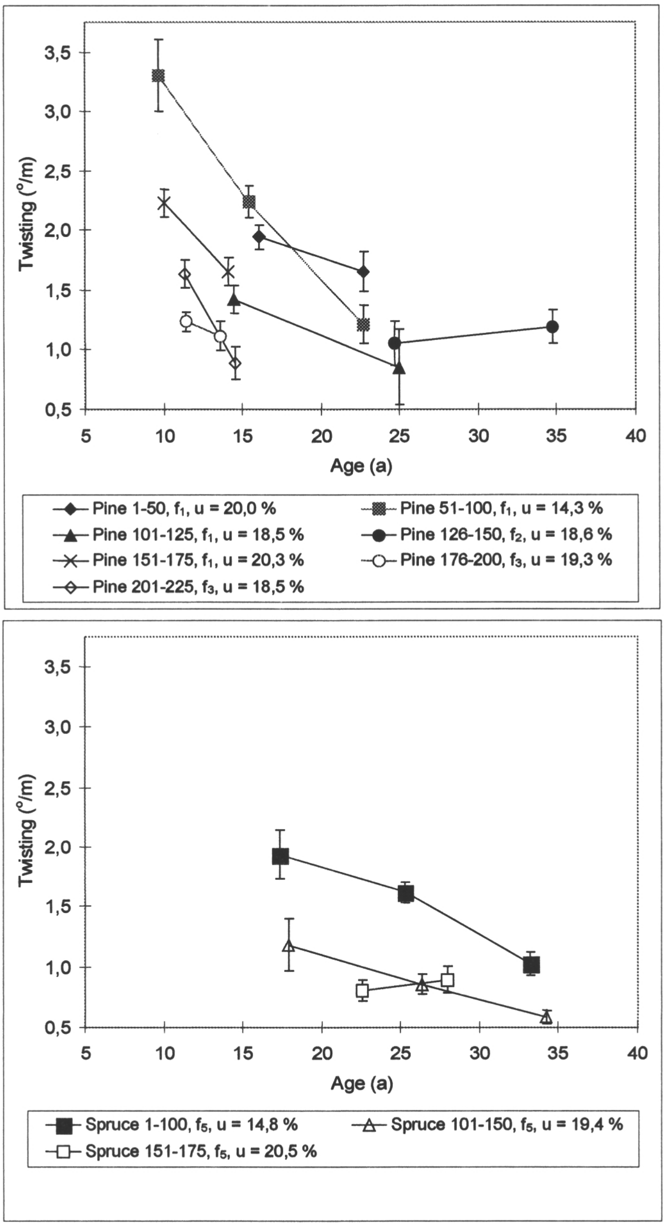


Fig. 28. Mean and standard errors for twisting by species, samples and age classes. The mean moisture content and origin of the samples are presented, as well.

Regression models for twisting were constructed separately for pine and spruce. Form, processing method, origin and ring width of the specimen did not have a statistically significant effect on twisting. For pine it was found that age, gross grain, moisture content and density had statistically significant effects on twisting (Model 5). For spruce, interactions were found between age, cross grain and moisture content (Model 6). The diameter of the specimen had a negative effect on the twisting of pine and spruce, however, the better indicator of juvenility of wood was found to be age.

Model 5 for pine:

$$\lg (T+1) = 0.926 - 0.226 \lg a + 0.116 \lg (G+1) + 0.000774 \rho_{12} - 0.576 \lg u \qquad (5)$$

When factor Q (Equation 24) is added to the constant the Model 5 is as follows after transformation:

$$T = 10^{\,0.962 - 0.226 \lg a + 0.116 \lg (G+1) + 0.000774 \rho_{12} - 0.576 \lg u} - 1$$

where age (a) and density (ρ_{12}) were measured from the top end of the specimens.

The F-value of Model 5 was 18.7 (n = 205), the multiple coefficient of determination for the model (adjusted R^2) 0.26 and the standard error (s) 0.1766. All multipliers were significant and the basic statistical assumptions were met (Tables 26 and 27, Fig. 29). The residuals have relatively equal variances and they follow expected cumulative probability.

Table 26. Multipliers, t- values, significance levels and 95% confidence intervals for multipliers in Model 5 for pine.

				95% Confidence interval for B	
Variable	B	t-value	Sig.	Lower Bound	Upper Bound
Constant	0.926	3.3	.001	0.370	1.482
lg a	-0.226	-2.2	.026	-0.424	-0.027
lg u	-0.576	-2.8	.001	-0.984	-0.169
ρ_{12}	0.000774	2.3	.025	0.000099	0.001449
lg (G+1)	0.116	7.8	.000	0.087	0.145

Table 27. Correlation coefficients between the variables in Model 5 for pine.

	lg a	lg (g+1)	ρ_{12}	lg u
lg a	1.00			
lg (G+1)	0.13	1.00		
ρ_{12}	-0.47	0.17	1.00	
lg u	0.04	-0.16	-0.15	1.00

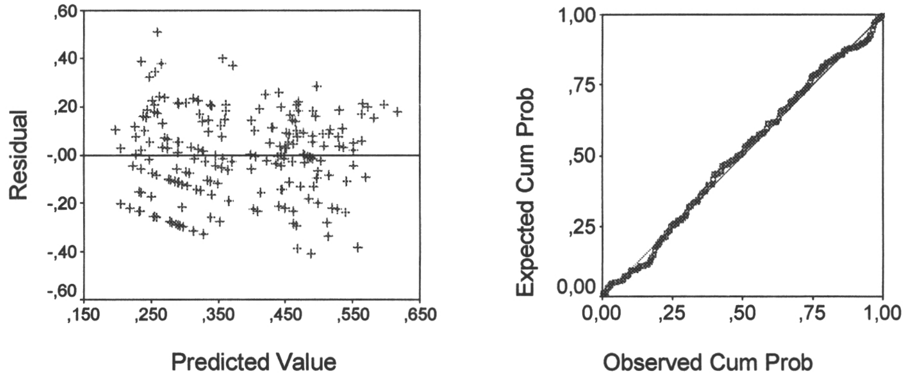


Fig. 29. Residuals and their normal probability plot of Model 5 for pine.

Model 6 for spruce:

$$\lg (T + 1) = 0.253 + 0.007604 * (G+1) * (28 - u) / a \qquad (6)$$

When factor Q (Equation 24) is added to the constant the model 6 is as follows after transformations:

$$T = 10^{\,0.29 + 0.007604 \,*\, (G+1) \,*\, (28 - u) / a} - 1$$

where age (a) were measured from the top of the specimens.

The F-value of Model 6 was 43.2 (n = 171), the multiple coefficient of determination for the model (adjusted R^2) 0.20 and the standard error (s) 0.1785. All multipliers in Model 6 were significant and the basic statistical assumptions were met (Tables 28 and 29, Fig. 30). The residuals have relatively equal variances considering only a few residual points in greater predicted values. Residuals follow expected cumulative probability with minor deviations.

Table 28. Multipliers, t- values, significance levels and 95% confidence interval for multipliers in Model 6 for spruce.

				95% Confidence interval for B	
Variable	B	t-value	Sig.	Lower Bound	Upper Bound
Constant	0.253	16.3	.000	0.222	0.284
(G+1)*(28–u) / a	0.007604	6.6	.000	0.005	0.010

Table 29. Correlation coefficients between the variables in Model 6 for spruce.

	a	G	u
a	1.00		
G	-0.08	1.00	
u	0.19	0.16	1.00

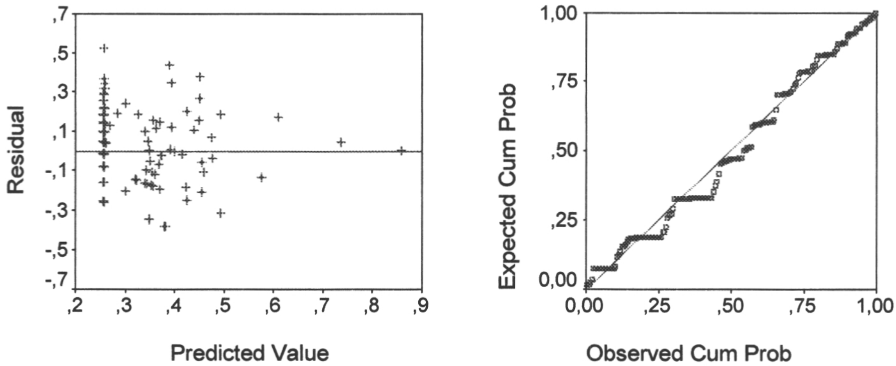


Fig. 30. Residuals and their normal probability plot for Model 6 for spruce.

The effects of age, density, gross grain and moisture content on the respective twisting of pine and spruce by Models 5 and 6 are presented in Figs. 31, 32, 33 and 34. The younger the age the greater the twisting was found to be. Due to the interaction between age and moisture content in Model 4 for spruce, the effect of moisture content was greater for young spruce specimens compared to older specimens. Both for pine and spruce, twisting was concluded to be about 1.5 greater with a moisture content level of 12% compared to twisting when the moisture content was at a level of 18%. The material did not comprise specimens at moisture content level 12%, thus the results of moisture content had to be extrapolated. However, the result in Table 24 and Fig. 27 and 28 supported this conclusion. Cross grain had a significant positive effect on twisting. For pine the positive effect of density on twisting could be also be observed. The rise in density increases twisting of pine.

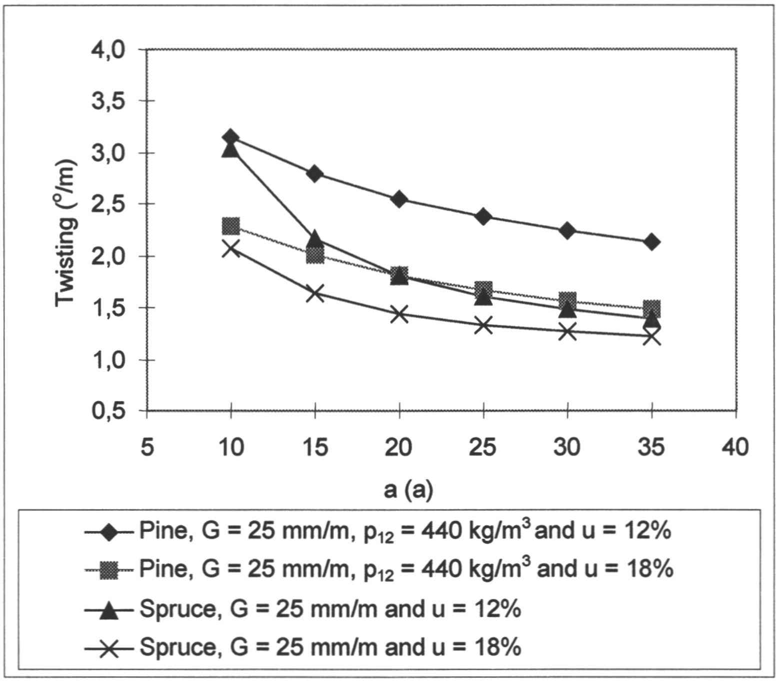


Fig. 31. The effects of age and moisture content on twisting of pine and spruce by Models 5 and 6, respectively.

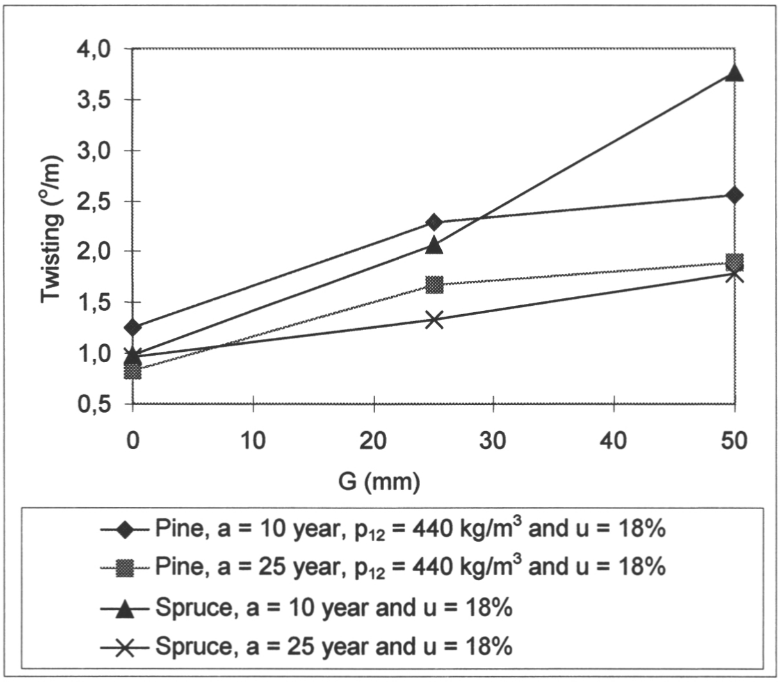


Fig. 32. The effects of age and cross grain on twisting of pine and spruce by Models 5 and 6, respectively.

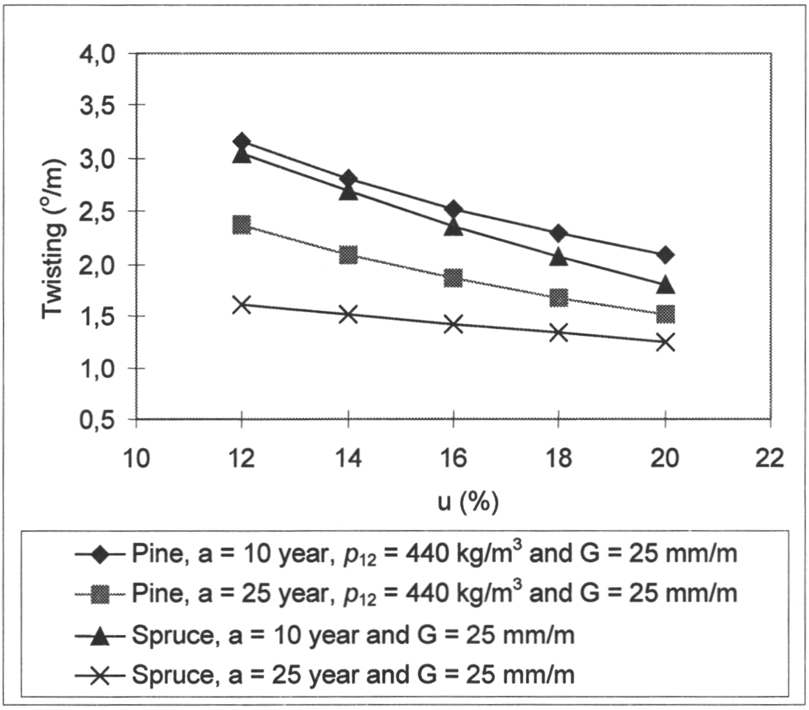


Fig. 33. The effects of age and moisture content on twisting of pine and spruce by Models 5 and 6, respectively.

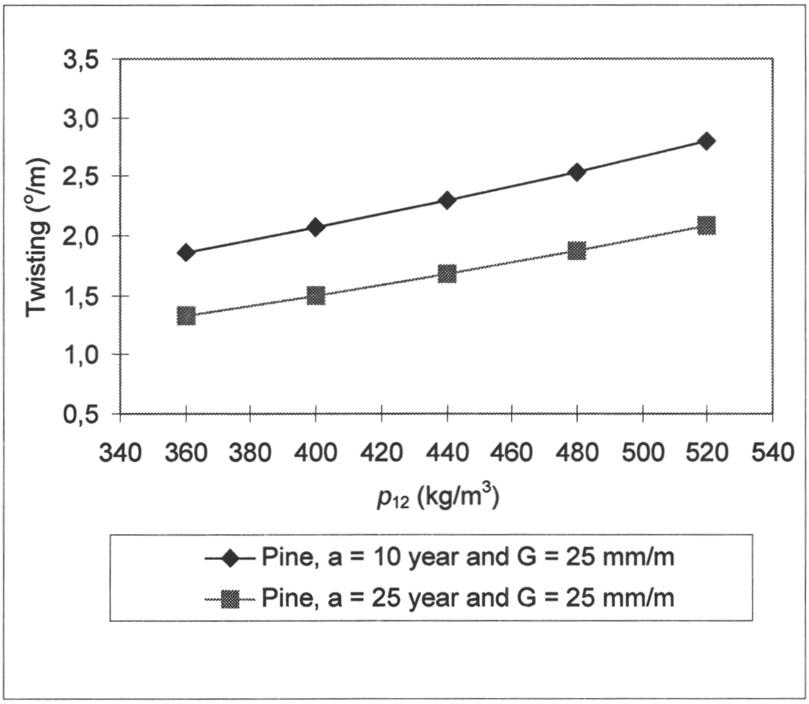


Fig. 34. The effects of age and density on twisting of pine by Models 5.

4.2 KILN DRYING EXPERIMENT

A separate pine sample was kiln dried in order to test the applicability of a drying formula (Table 8) developed by VTT for round wood. The aim of this study was to obtain preliminary information on cracking and drying deformations of round timber during kiln drying. The drying formula was selected in order to produce round pine timber with few small cracks required for high quality wooden products.

Totally uncracked or specimens with only small cracks comprised only 8.8 % of the test material. Distribution of cracking is presented below:

- no cracking = 4.0 %
- very small cracks (<1 mm) = 1.6 %
- small cracks (1…4 mm) = 3.2 %
- big cracks (>4 mm) = 91.3 %

Means and standard deviations of the properties of material studied are presented in Table 30. The moisture gradient was quite large ($u_{gradient}$ = 5.6%), which was a possible reason for big cracking. The crook was about the same after drying ($C_{after\ drying}$ = 2 mm) than before drying ($C_{machine\ rounded}$ = 2 mm). The mean twisting (2.9) of specimens was large, as well as the standard deviation (2.2). The results elaborated the hypothesis that twisting takes place in round timber and other drying deformations are insignificant. However, there are difficulties for drying round timber by conventional methods if timber with small cracks is required.

Table 30. Means and standard deviations of the properties of specimens in the special kiln drying experiment.

Variable	$\bar{x}$	s.d.
u_{mean} (%)	13.9	1.5
$u_{surface}$ (%)	11.6	1.2
$u_{gradient}$ (%)	5.6	1.7
G (mm/m)	22	23
ρ_0 (kg/m^3)	435	37
$\rho_{0\ compression\ side}$ (kg/m^3)	439	41
$\rho_{0\ neutral\ side}$ (kg/m^3)	431	37
C_{ob} (mm)	10	9
$C_{machine\ rounded}$ (mm)	2	3
$C_{after\ drying}$ (mm)	2	2
T (°/m)	2.9	2.2

5. DENSITY AND MECHANICAL PROPERTIES IN BENDING AND COMPRESSION PARALLEL TO GRAIN

5.1 OVERVIEW

Density and mechanical properties of pine and spruce are analysed together, since in strength grading same criteria (Lipitsäinen 1994b) and strength classes (EN standard 338) are applied for them. In addition, the combined material gave a possibility to study statistically the between species differences in density, mechanical properties and factors affecting these properties when wood characteristics and physical properties were similar. Cumulative frequencies of the most important wood characteristics, physical and mechanical properties of the material are illustrated in Appendices 1 and 2.

Correlation analysis was first performed for test results at the test moisture content separately for pine and spruce bending and compression materials (Tables 31, 32, 33 and 34). Correlations between mechanical properties and other wood properties are similar in pine and spruce material both in bending and compression. In general, however, spruce had lower correlations between mechanical properties and other wood properties. Knot related properties and ring width had clear negative correlations with mechanical properties in pine and spruce material. Bending and compression strength had a moderate negative correlation with moisture content, whereas the modulus of elasticity did not have any correlation. Age and density had high positive correlation with the mechanical properties in pine and spruce material, particularly in compression. The size of timber (d or h), and tree species had weak correlations with mechanical properties both in pine and spruce material. Age, knot related properties and ring width all correlated strongly with each other both in pine and spruce material.

Mean values and standard deviations of the samples in Table 7 are given in Table 35. As a whole, the material is comprehensive covering a large range of variation in the wood characteristics, mechanical and physical properties. An average, spruce had better mechanical properties than pine both in bending and compression. Spruce had also lower density and fewer knots than pine. An average, pine material is 5 to 7 years younger than spruce material, although mean diameters of spruce material are smaller than pine material.

Table 31. Correlation matrix for pine bending material.

	E_m	f_m	a	h	ks	KAR	mk	ρ_{12}	r	t
f_m	0.68	1.00								
a	0.52	0.53	1.00							
h	0.05	-0.11	0.40	1.00						
ks	-0.52	-0.64	-0.46	0.29	1.00					
KAR	-0.54	-0.59	-0.61	-0.04	0.91	1.00				
mk	-0.46	-0.62	-0.37	0.34	0.84	0.71	1.00			
ρ_{12}	0.53	0.57	0.50	-0.12	-0.50	-0.51	-0.42	1.00		
r	-0.61	-0.70	-0.75	0.08	0.66	0.63	0.62	-0.58	1.00	
t	-0.11	-0.27	-0.01	0.30	0.32	0.26	0.33	-0.20	0.10	1.00
u	-0.17	-0.44	-0.19	-0.07	0.19	0.16	0.25	0.01	0.19	0.21

Table 32. Correlation matrix for spruce bending material.

	E_m	f_m	a	h	ks	KAR	mk	ρ_{12}	r	t
f_m	0.61	1.00								
a	0.31	0.58	1.00							
h	-0.08	-0.27	0.04	1.00						
ks	-0.28	-0.56	-0.57	0.35	1.00					
KAR	-0.22	-0.45	-0.58	0.06	0.94	1.00				
mk	-0.30	-0.55	-0.52	0.36	0.78	0.69	1.00			
ρ_{12}	0.45	0.67	0.73	-0.18	-0.56	-0.50	-0.53	1.00		
r	-0.32	-0.64	-0.84	0.39	0.67	0.56	0.63	-0.72	1.00	
t	0.08	0.35	0.43	-0.07	-0.35	-0.29	-0.26	0.36	-0.40	1.00
u	-0.12	-0.36	0.14	0.06	0.06	-0.02	0.02	-0.03	-0.10	-0.21

Table 33. Correlation matrix for pine compression material.

	$E_{c,0}$	$f_{c,0}$	a	d	ks	KAR	mk	ρ_{12}	r
$f_{c,0}$	0.84	1.00							
a	0.74	0.71	1.00						
d	0.27	0.28	0.50	1.00					
ks	-0.75	-0.78	-0.62	-0.03	1.00				
KAR	-0.75	-0.80	-0.74	-0.39	0.90	1.00			
mk	-0.65	-0.69	-0.49	0.06	0.86	0.74	1.00		
ρ_{12}	0.71	0.60	0.63	0.22	-0.50	-0.51	-0.46	1.00	
r	-0.65	-0.63	-0.71	-0.24	0.65	0.65	0.56	-0.55	1.00
u	-0.50	-0.80	-0.38	-0.15	0.58	0.55	0.56	-0.24	0.40

Table 34. Correlation matrix for spruce compression material.

	$E_{c,0}$	$f_{c,0}$	a	d	ks	KAR	mk	ρ_{12}	r
$f_{c,0}$	0.81	1.00							
a	0.68	0.53	1.00						
d	-0.33	-0.21	0.17	1.00					
ks	-0.70	-0.58	-0.48	0.33	1.00				
KAR	-0.55	-0.45	-0.58	-0.14	0.85	1.00			
mk	-0.52	-0.48	-0.30	0.32	0.74	0.59	1.00		
ρ_{12}	0.83	0.71	0.65	-0.22	-0.52	-0.41	-0.34	1.00	
r	-0.81	-0.65	-0.72	0.54	0.62	0.40	0.47	-0.69	1.00
u	-0.01	-0.46	0.20	0.03	0.00	-0.10	0.13	0.43	-0.05

Table 35. Means and standard deviations of the properties measured for the tested bending and compression materials by samples (see Table 7).

Bending material

$\bar{x}$ / s.d.

	Pine, f_1 1-25	Pine, f_1 26-100	Pine, f_1 101-125	Pine, f_2 126-150	Pine, f_1 151-175	Pine, f_3 176-200	Pine, f_3 201-225	Pine, f_4 226-275	**Pine Total**	Spruce, f_5 1-150	Spruce, f_5 151-175	Spruce, f_6 176-226	**Spruce total**
f_m (N/mm^2)	48.4 / 7.8	46.7/ 10.6	45.5 / 6.1	56.5 / 6.2	28.6 / 5.9	44.6 / 5.5	42.2 / 4.5	59.4/ 10.4	**47.7/ 11.8**	64.5 / 9.3	45.1 / 4.9	45.5 / 9.8	**58.1/ 12.7**
E_m (kN/mm^2)	10.5 / 1.8	11.1 / 3.0	12.2 / 3.1	13.6 / 1.4	6.8 / 2.9	9.8 /1.5	10.6 / 1.3	11.3 / 1.7	**10.9 / 2.8**	12.5 / 2.6	11.3 / 2.1	10.7 / 1.8	**12.0 / 2.5**
a (year)	19 / 3	20 / 4	25 / 8	24 / 5	10 / 3	16 / 1	17 /1	22 / 6	**20 / 6**	31 / 6	18 / 7	14 / 5	**27 / 8**
h (mm)	124 / 12	136 / 25	155 / 16	155 / 12	100 / 0	96 / 10	133 / 6	124 / 3	**126 / 25**	109 / 23	100 / 0	125 / 1	**110 / 19**
ks_{ub} (mm)	84 / 28	84 / 30	75 / 32	33 / 22	107 / 37	72 / 18	113 / 17	63 /14	**78 / 33**	36 / 13	54 / 21	77 / 27	**47 / 25**
KAR (%)	22 / 7	20 / 7	15 / 6	7 / 4	27 / 9	24 / 5	27 / 4	16 / 4	**19.4 / 8.1**	11 / 4	14 / 5	20 / 7	**13.1 / 6.0**
ρ_{12} (kg/m^3)	465 / 53	459 / 33	461 / 43	555 / 40	420 / 29	473 / 16	453 / 39	485 / 39	**470 / 48**	466 / 38	426 / 29	340 / 36	**434 / 63**
r (mm)	3.2 / 0.6	3.6 / 0.7	3.2 / 0.7	2.4 / 0.8	5.1 / 1.0	3.2 / 0.8	3.9 / 0.3	3.0 / 0.7	**3.4 / 0.9**	1.7 / 0.4	2.3 / 0.4	4.0 / 0.9	**2.3 / 1.0**
u (%)	20.7 / 0.6	15.3 / 2.7	17.0 / 0.7	19.1 / 0.5	20.3 / 0.6	18.7 / 0.4	19.0 / 0.5	13.3 / 1.7	**17.0 / 3.0**	15.6 / 2.6	20.7 / 0.3	15.5 / 1.5	**16.2 / 2.7**

Compression material

$\bar{x}$ / s.d.

	Pine, f_1 1-25	Pine, f_1 26-100	Pine, f_1 101-125	Pine, f_2 126-150	Pine, f_1 151-175	Pine, f_3 176-200	Pine, f_3 201-225	Pine, f_4 226-275	**Pine Total**	Spruce, f_5 1-150	Spruce, f_5 151-175	Spruce, f_6 176-226	**Spruce total**
$f_{c,0}$ (N/mm^2)	19.8 / 2.5	23.8 / 3.8	21.2 / 2.9	28.7 / 3.4	16.1 / 1.7	17.8 / 1.8	18.8 / 1.4	37.3 / 4.6	**24.4 / 7.7**	30.1 / 4.2	22.9 / 2.2	20.7 / 2.6	**27.2 / 5.5**
$E_{c,0}$(kN/mm^2)	8.6 / 1.4	8.7 / 1.5	7.9 / 1.3	11.6 / 1.7	6.3 / 1.1	8.0 / 1.3	6.8 / 0.7	11.5 / 0.8	**8.9 / 2.3**	12.5 / 1.6	10.9 / 1.3	5.3 / 1.2	**10.7 / 3.3**
a (year)	16 / 3	18 / 4	16 / 5	31 / 6	13 / 2	13 / 1	12 / 2	26 / 6	**19 / 7**	26 / 6	25 / 4	16 / 3	**24 / 6**
d (mm)	105 / 11	125 / 26	143 / 16	150 / 12	100 / 0	88 / 8	124 / 7	126 / 1	**118 / 20**	101 / 24	100 / 0	124 / 1	**105 / 21**
ks_{ub} (mm)	104 / 30	100 / 31	98 / 29	52 / 31	132 / 26	87 / 19	130 / 24	33 / 15	**88 / 42**	42 / 14	53 / 13	83 / 28	**52 / 24**
KAR (%)	32 / 10	26 / 8	22 / 6	11 / 6	33 / 7	32 / 6	33 / 6	8 / 4	**23.4/ 11.5**	14 / 5	13 / 3	21 / 7	**15.6 / 6.4**
ρ_{12} (kg/m^3)	462 / 41	452 / 31	449 / 36	533 / 49	423 / 30	474 / 29	449 / 35	506 / 43	**469 / 48**	453 / 38	438 / 35	347 / 21	**428 / 55**
r (mm)	3.9 / 1.1	3.9 / 1.1	3.8 / 0.9	2.8 / 0.8	5.0 / 0.6	3.7 / 1.1	4.5 / 0.4	2.5 / 0.5	**3.7 / 1.2**	1.9 / 0.4	2.6 / 0.4	3.7 / 0.7	**2.4 / 0.9**
u (%)	19.9 / 0.5	15.4 / 2.4	18.0 / 0.5	18.3 / 0.4	20.3 / 0.6	18.6 / 0.6	17.9 / 0.3	10.8 / 0.3	**16.4 / 3.4**	15.7 / 2.3	20.6 / 0.4	15.6 / 1.6	**16.3 / 2.5**

5.2 DENSITY OF PINE AND SPRUCE

In Fig. 35 scatter plots of density versus ring width, and the fitted second power polynomial regression curves as a function of ring width are presented for pine and spruce. When the ring width was greater than 5 mm the density did not show any further decrease. At a ring width of 3 mm the mean density was 480 kg/m^3 for pine and 394 kg/m^3 for spruce i.e. the difference in level of density was 86 kg/m^3. At a ring width of 5 mm the mean density was 431 kg/m^3 for pine and 329 kg/m^3 for spruce for i.e. the difference between species was 102 kg/m^3. At similar ring width, the density of Scots pine is higher than that of Norway spruce. The smaller the ring width the smaller the difference.

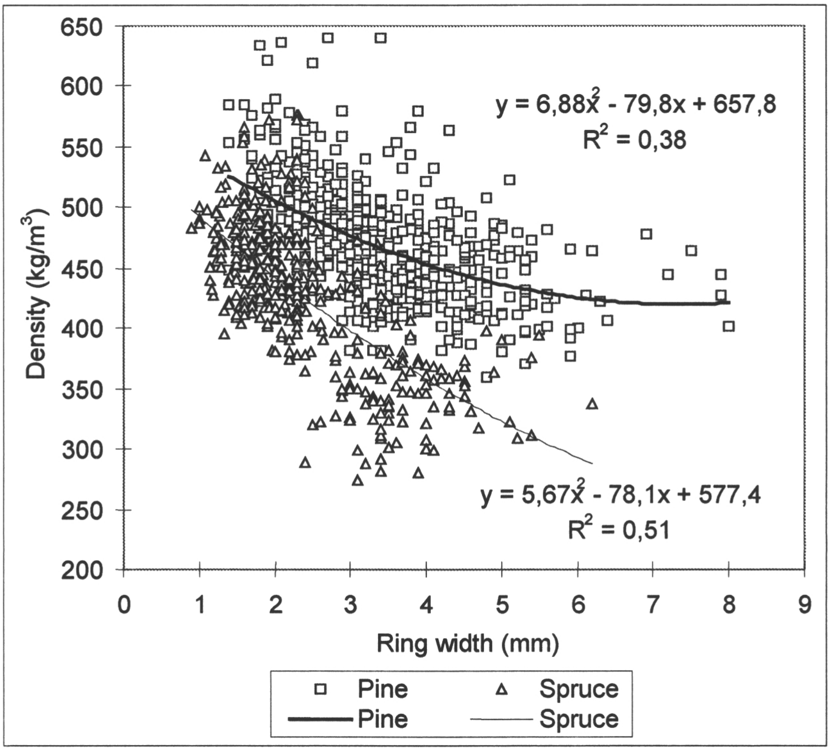


Fig. 35. The relationships between density and ring width for pine and spruce.

5.3 MODULUS OF ELASTICITY AND STRENGTH OF TIMBER PROCESSED BY DIFFERENT METHODS

Tested materials were categorised according to tree species and manufacturing process. The modulus of elasticity, strength and moisture content values obtained in bending and compression tests are summarised in Table 36. The mean values and standard deviations are given for different processing methods and species. The mean bending strength was high for tested materials, except for square sawn pine. Mean modulus of elasticity and compression strengths were generally considerably lower than expected on the basis of bending strength.

Table 36. Means and standard deviations of mechanical properties by different processing at the test moisture content for pine and spruce.

Sample	Bending			Compression		
	f_m (N/mm^2)	E_m (N/mm^2)	u (%)	$f_{c,0}$ (N/mm^2)	$E_{c,0}$ (N/mm^2)	u (%)
Pine		$\bar{x}$ / s.d.			$\bar{x}$ / s.d.	
Round, manually debarked (n=25)	48.4 / 7.8	10.5 / 1.8	20.7 / 0.6	19.8 / 2.5	8.6 / 1.4	19.9 / 0.5
Round, machine processed (n=150)	50.6 / 1.6	10.9 / 2.5	15.2 / 2.8	27.3 / 8.3	9.5 / 2.1	14.4 / 3.3
Partly sawn (n=50)*	43.9 / 5.5	11.4 / 2.5	18.0 / 1.2	20.0 / 2.5	7.3 / 1.1	18.0 / 0.4
Partly sawn (n=25)**	56.5 / 6.2	13.6 / 1.4	19.1 / 0.5	28.7 / 3.4	11.6 / 1.7	18.3 / 0.4
Partly sawn together (n=75)	48.1 / 8.3	12.2 / 2.4	18.4 / 1.1	22.9 / 5.0	8.8 / 2.4	18.1 / 0.5
Square sawn (n=25)	28.6 / 5.9	6.8 / 2.9	20.3 / 0.6	16.1 / 1.7	6.3 / 1.1	20.3 / 0.6
Spruce						
Round, machine processed (n=200)	59.8 / 12.5	12.1 / 2.6	15.6 / 2.3	27.8 / 5.6	10.7 / 3.4	15.7 / 2.1
Square sawn (n=25)	45.1 / 1.9	11.3 / 2.1	20.7 / 0.3	22.9 / 2.2	10.9 / 1.3	20.6 / 0.4

*edgewise direction in bending test i.e. manually debarked surface is on the tension zone
** flatwise direction in bending test i.e. sawn surface is on the tension zone

5.4 REGRESSION MODELS FOR MECHANICAL PROPERTIES

Correlation analysis was first performed for all test results at the moisture content during the test separately for bending and compression materials (Tables 37 and 38). Knot related properties and ring width had clear negative correlations with mechanical properties. Bending and compression strength had a moderate negative correlation with moisture content, whereas the modulus of elasticity did not have any correlation. Age has a clear positive correlation with the mechanical properties. Density had only a moderate positive correlation with the mechanical properties. The size of timber (d or h), and tree species had weak correlations with mechanical properties. Age, knot related properties and ring width all correlated strongly with each other.

Table 37. Correlation matrix for all bending material.

	E_m	f_m	a	h	ks	KAR	mk	ρ_{12}	r	S	t
E_m	1.00										
f_m	0.66	1.00									
a	0.44	0.63	1.00								
h	-0.06	-0.28	0.03	1.00							
ks	-0.47	-0.68	-0.60	0.41	1.00						
KAR	-0.46	-0.60	-0.64	0.13	0.93	1.00					
mk	-0.44	-0.66	-0.55	0.45	0.86	0.76	1.00				
ρ_{12}	0.38	0.43	0.38	-0.03	-0.28	-0.30	-0.23	1.00			
r	-0.50	-0.73	-0.84	0.33	0.73	0.67	0.71	-0.37	1.00		
S	0.21	0.39	0.48	-0.33	-0.46	-0.40	-0.48	-0.31	-0.51	1.00	
t	-0.08	-0.09	0.09	0.22	0.17	0.15	0.19	0.07	-0.01	-0.13	1.00
u	-0.17	-0.42	-0.09	0.02	0.19	0.14	0.21	0.04	0.13	-0.14	0.09

Table 38. Correlation matrix for all compression material.

	$E_{c,0}$	$f_{c,0}$	a	d	ks	KAR	mk	ρ_{12}	r	S
$E_{c,0}$	1.00									
$f_{c,0}$	0.79	1.00								
a	0.72	0.66	1.00							
d	-0.15	0.02	0.22	1.00						
ks	-0.70	-0.73	-0.63	0.22	1.00					
KAR	-0.65	-0.72	-0.72	-0.15	0.91	1.00				
mk	-0.60	-0.64	-0.63	0.26	0.87	0.76	1.00			
ρ_{12}	0.57	0.50	0.43	0.11	-0.23	-0.24	-0.16	1.00		
r	-0.72	-0.64	-0.75	0.18	0.72	0.66	0.63	-0.29	1.00	
S	0.31	0.20	0.34	-0.31	-0.45	-0.38	-0.45	-0.37	-0.51	1.00
u	-0.25	-0.67	-0.17	-0.07	0.39	0.36	0.41	-0.10	0.23	-0.03

Figs. 36 and 37 show the mean and standard errors for the tested mechanical properties of pine and spruce by age class. Origin of timber and mean moisture content of the samples are presented, as well. Within presented samples, the moisture content is relatively constant along the age distribution. Figs. 36 and 37 clearly show that the mechanical properties of pith enclosed pine and spruce timber grow with increasing age, for both pine and spruce. In addition, moisture content had a positive effect on mechanical properties i.e. the lower the moisture content was the greater the modulus of elasticity and strength, both in bending and compression.

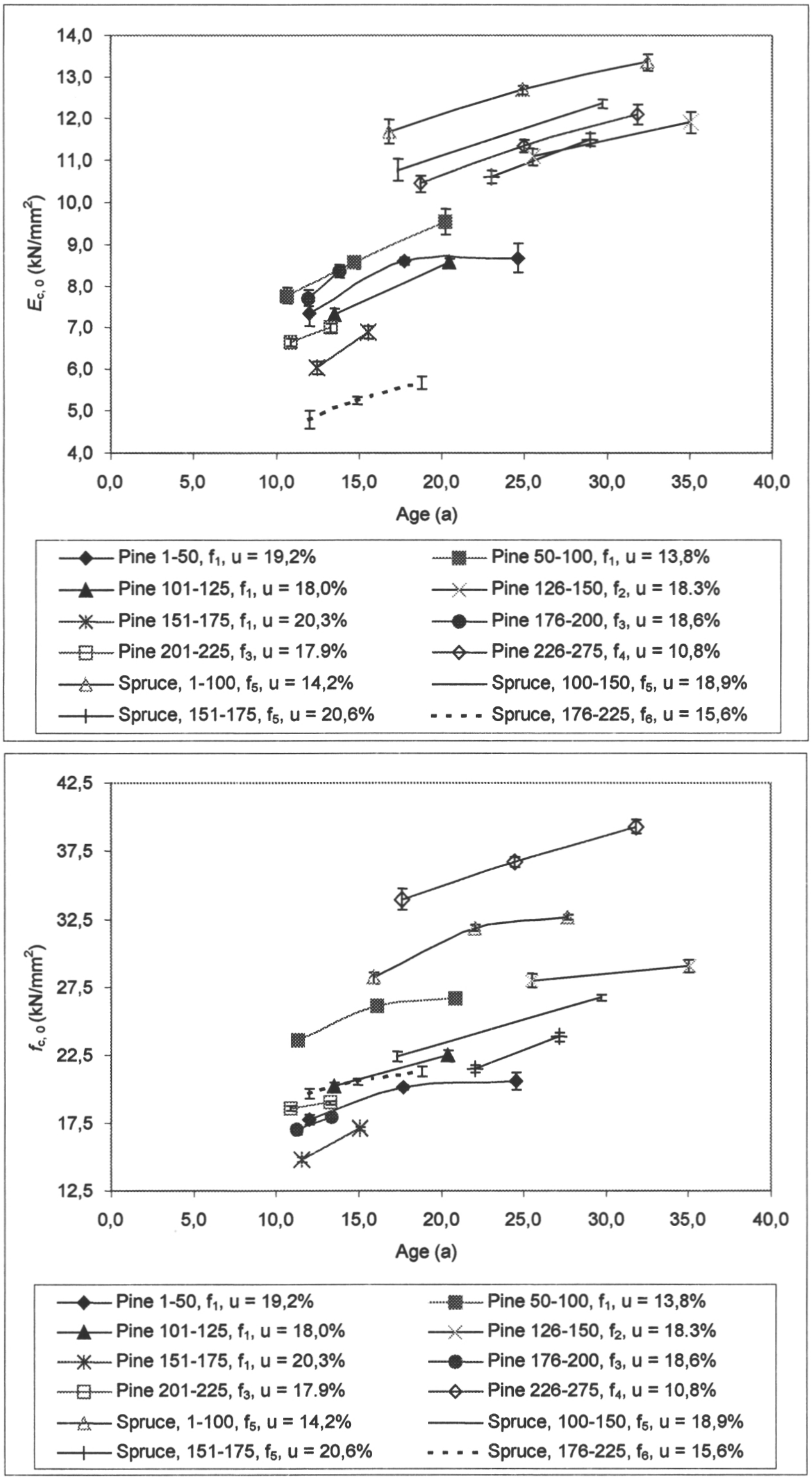


Fig. 36. Mean and standard error values for the modulus of elasticity ($E_{c,0}$) and strength ($f_{c,0}$) in compression for pine and spruce by sample and age class.

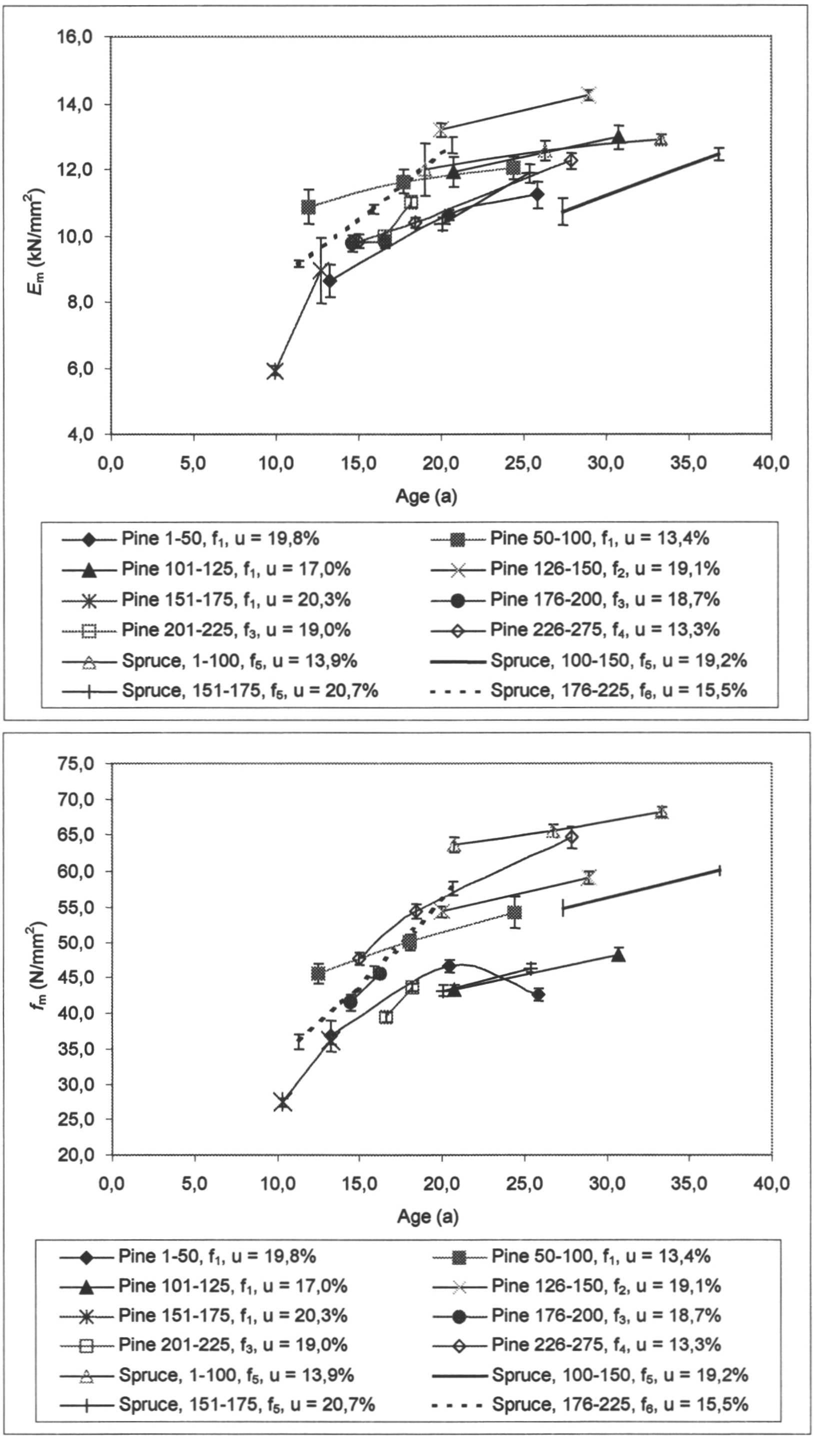


Fig. 37. Mean and standard error values for the modulus of elasticity (E_m) and strength (f_m) in bending for pine and spruce by sample and age class.

Figs. 38 and 39 show the modulus of elasticity and strength in bending and compression versus ring width and density. The linear trend lines are presented to clarify effect of ring width and density. Modulus of elasticity and strength are at test moisture content. Pine and spruce had a somewhat similar strength at similar ring width but there appeared some between-species differences in modulus of elasticity, both in bending and compression. At similar density, spruce seemed to be stronger and stiffer than pine, both in bending and compression.

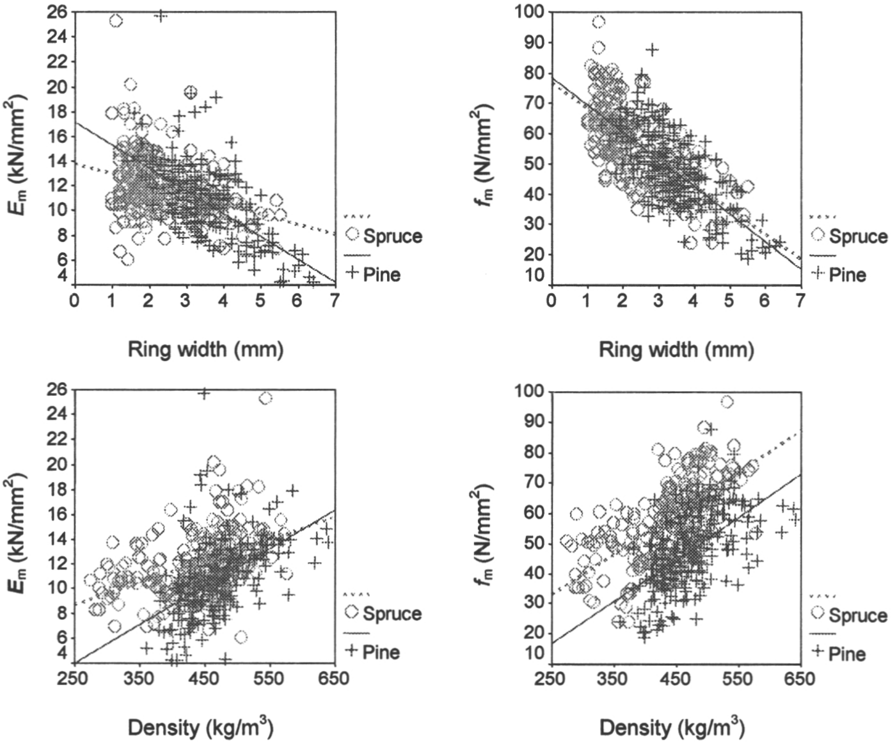


Fig. 38. Modulus of elasticity (E_m) and strength (f_m) in bending versus ring width and density. The linear trend lines are presented, as well. Modulus of elasticity and strength are at the test moisture content.

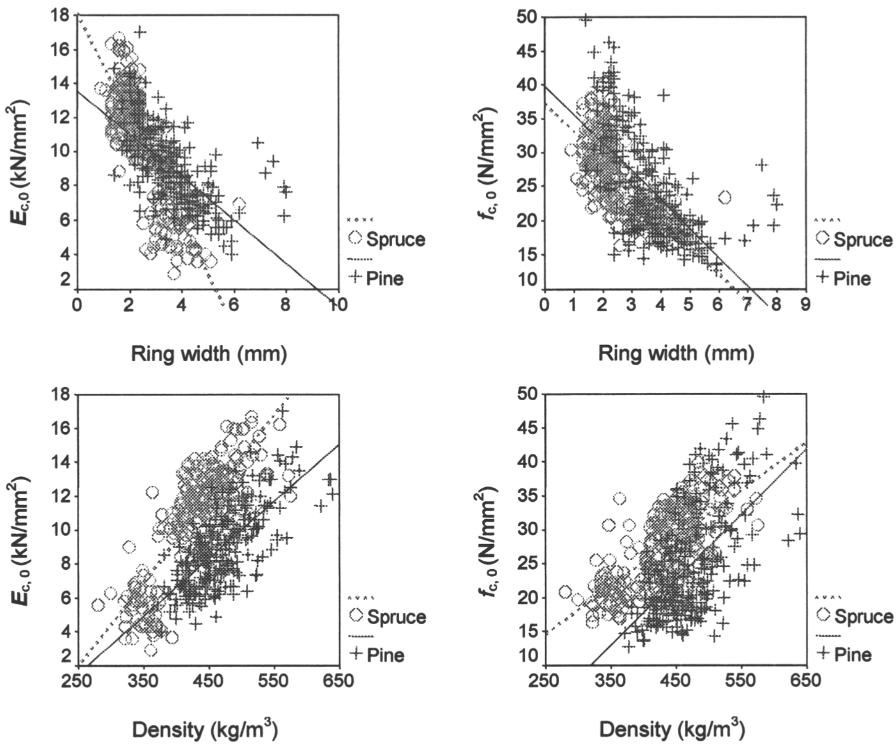


Fig. 39. Modulus of elasticity ($E_{c,\,0}$) and strength ($f_{c,\,0}$) in compression versus ring width and density. The linear trend lines are presented, as well. Modulus of elasticity and strength are at the test moisture content.

Fig. 40 shows the modulus of elasticity and strength in bending and compression versus knot area ratio (KAR). The linear trend lines are presented to clarify effect of knot area ratio. Modulus of elasticity and strength are at the test moisture content. On average, pine and spruce had a similar modulus of elasticity and strength at similar knot area ratio. However, there appeared some between-species differences in modulus of elasticity in bending and compression.

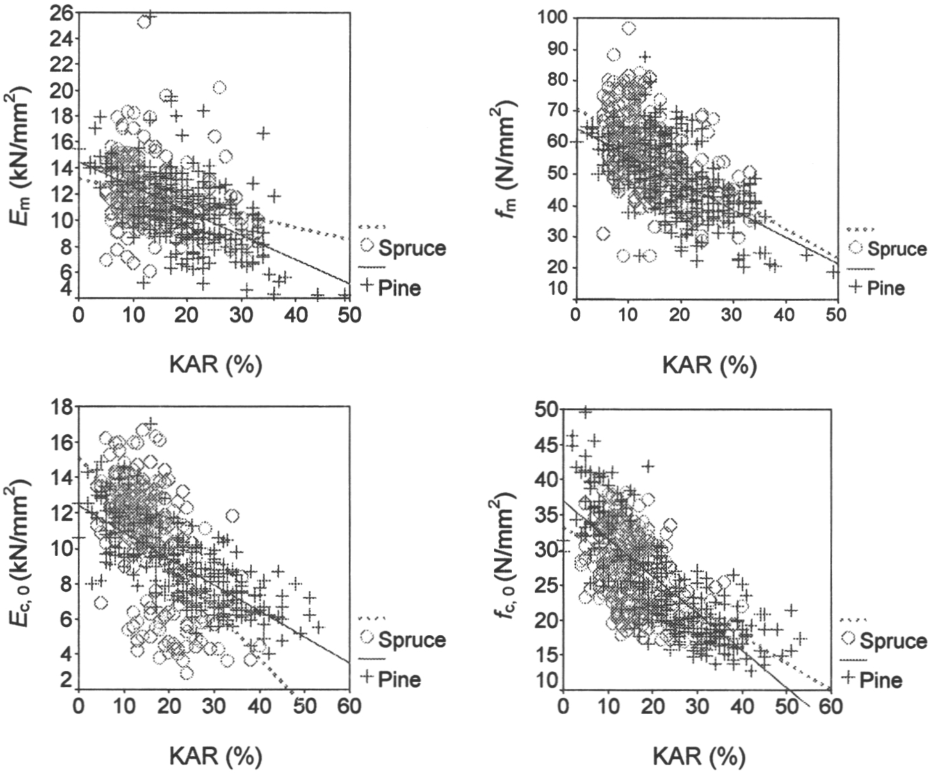


Fig. 40. Modulus of elasticity and strength in bending and compression versus knot area ratio (KAR). The linear trend lines are presented, as well. Modulus of elasticity and strength are at the test moisture content.

In all cases, the interaction of moisture content and age was an interesting phenomenon in the statistical analysis of mechanical properties. Figs 41. and 42 show these interactions with the studied mechanical properties. In addition, modulus of elasticity and strength versus height/diameter is presented. The linear trend lines are also presented to clarify effect of variables. Although moisture content and age did not correlate strongly (Tables 31, 32, 33 and 34), manipulating moisture content with various transformations of age improved the relationship of moisture content with mechanical properties, especially with regards to compression. On average, pine and spruce had similar mechanical properties at similar age and moisture content. The height of timber had slightly negative effect in bending. The diameter of pine timber had positive effect on modulus of elasticity and strength in compression. On contrast, the diameter of spruce timber had negative effect on modulus of elasticity and strength in compression.

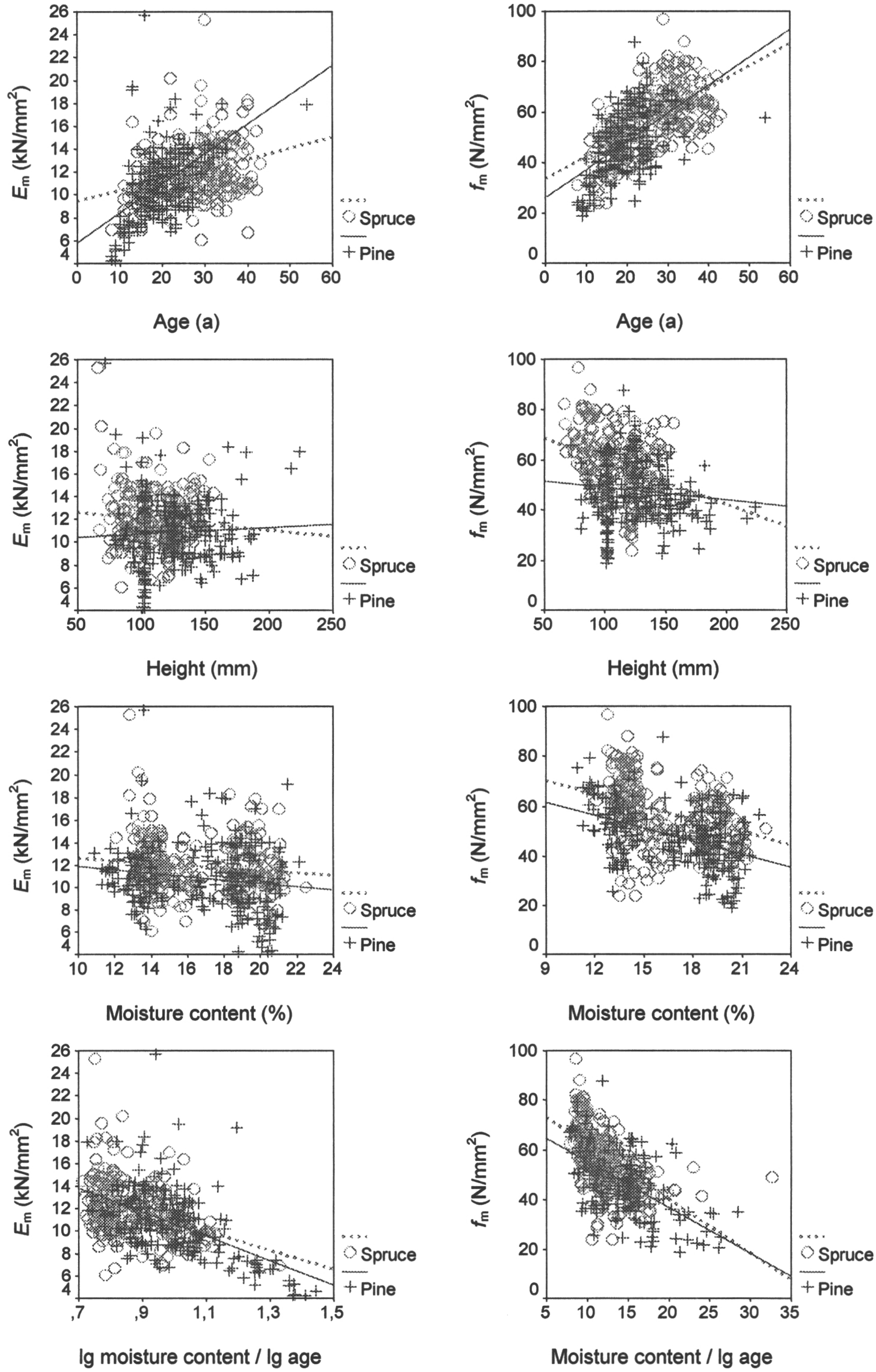


Fig. 41. Modulus of elasticity (E_m) and strength (f_m) in bending versus age, height, moisture content and age divided by moisture content. The linear trend lines are presented, as well.

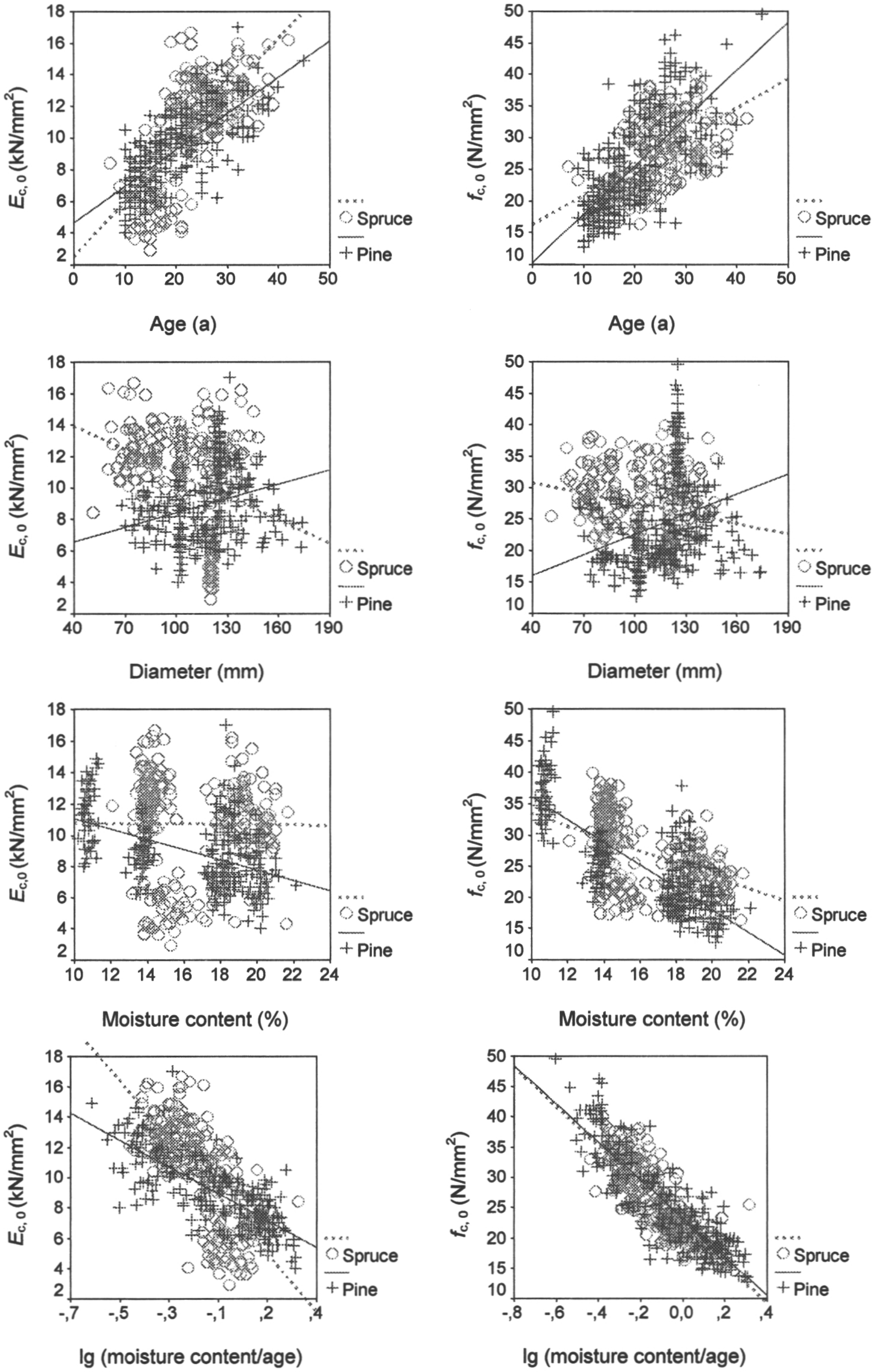


Fig. 42. Modulus of elasticity ($E_{c,0}$) and strength ($f_{c,0}$) in compression versus age, diameter, moisture content and age divided by moisture content. The linear trend lines are presented, as well.

Multiple regression models 7, 8, 9 and 10 for $E_{c,0}$, E_m, $f_{c,0}$ and f_m, respectively, are shown below for pine and spruce. Pine and spruce differed from each other in every case; at a similar density spruce was stronger and stiffer than pine. Result indicated that, in bending, the variable sawn surface in compression and tension zone had a negative effect on strength. In bending, manually debarked pine was the strongest sample. Furthermore, in bending machine processing interacted with knots, a wood surface with knots increased the negative effect of machine processing. In compression, differences were found between the origin of timber.

Model 7 for E_m is:

$$E_m = 12.26 - 0.061\mathrm{KAR_m} + 0.01219\rho_{12} + 0.00132\rho_{12}\mathrm{S} - 0.114\mathrm{t} - 5.88\lg \mathrm{u} / \lg \mathrm{a}$$

The new variables used are:

- $\mathrm{KAR_m}$ (%) = knot sum of machine processed surface per total circumference (manually debarked pine: $\mathrm{KAR_m} = 0$).
- lg u / lg a = logarithm from moisture content (%) per logarithm from age (a).
- S = tree species (pine = 0, spruce = 1).

The F-value of Model 7 is 50.4 (n = 465), the multiple coefficient of determination (adjusted R^2) was 0.35 and standard error (s) 2.23. All multipliers were significant and the basic statistical assumptions were met (Tables 39 and 40 and Fig. 43). The residuals have relatively equal variances and they follow expected cumulative probability. The residuals show two outlayers, which had no effect on analysis.

Table 39. Multipliers, t- values, significance levels and 95% confidence intervals for multipliers in Model 7.

				95% Confidence interval for B	
Variable	B	t-value	Sig.	Lower Bound	Upper Bound
Constant	12.26	7.6	.000	9.07	15.45
$\mathrm{KAR_m}$	-0.061	-4.0	.000	-0.091	-0.031
lg u/ lg a	-5.88	-5.9	.000	-7.83	-3.94
ρ_{12}	0.01219	5.9	.000	0.00816	0.01621
$\rho_{12}\mathrm{S}$	0.00132	2,3	.025	0.000169	0.02463
t	-0.114	-3.3	.001	-0.182	-0.045

Table 40. Correlation coefficients between the variables in Model 7.

	KAR_m	lg u/ lg a	ρ_{12}	$\rho_{12}S$	T
KAR_m	1.00				
lg u/ lg a	-0.26	1.00			
ρ_{12}	0.24	0.37	1.00		
$\rho_{12}S$	0.12	0.52	0.40	1.00	
t	0.22	0.02	0.04	0.12	1.00

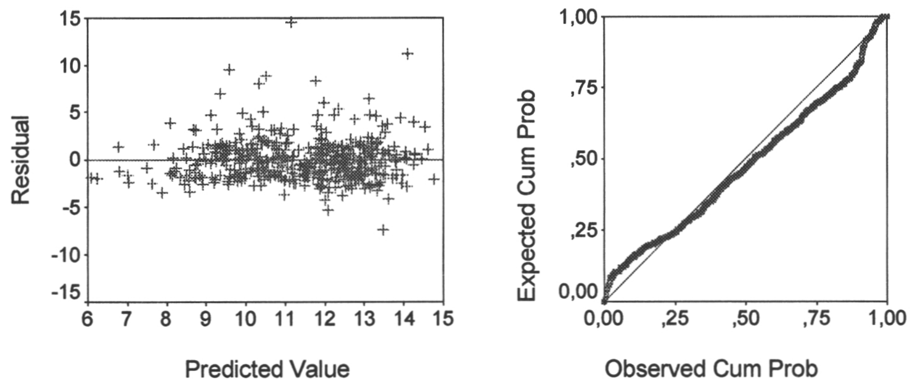


Fig. 43. Residuals and their normal probability plot for Model 7.

Model 8 for f_m :

$$\lg f_m = 1.835 - 0.000874h - 0.00262KAR_m + 0.0004686\rho_{12} + 0.0000519\rho_{12}S - 0.032r - 0.06238ss - 0.008378u/\lg a$$

When factor Q (Equation 24) is added to the constant and the transformations are made, the form of Model 8 is:

$$f_m = 10^{1.840 - 0.000874h - 0.00262KAR_m + 0.0004686\rho_{12} + 0.0000519\rho_{12}S - 0.032r - 0.06238ss - 0.008378u/\lg a}$$

The new variables used are:

- u/lg a = moisture content (%) per logarithm from age (a).
- ss = sawn surface in compression and tension zone (round ss = 0, sawn ss = 1).

The F-value of model 8 is 159.5 (n = 467), the multiple coefficient of determination for the model 2 (adjusted R^2) was 0.70 and standard error (s) was 0.0651. All multipliers were significant and the basic statistical assumptions were met (Table 41 and 42 and Fig. 44). The residuals have relatively equal variances and they follow expected cumulative probability. The residuals show two outlayers, which had no effect on analysis.

Table 41. Multipliers, t- values, significance levels and 95% confidence interval for multipliers in Model 8.

				95% Confidence interval for B	
Variable	B	t-value	Sig.	Lower Bound	Upper Bound
Constant	1.835	39.3	.000	1.744	1.927
h	-0.000874	-5.7	.000	-0.00117	-0.00057
KAR_m	-0.00262	-5.6	.000	-0.04	-0.02
ρ_{12}	0.0004686	7.2	.000	0.00034	0.000597
$\rho_{12}S$	0.0000519	2.6	.010	0.000013	0.000091
r	-0.032	-6.6	.000	-0.042	-0.023
ss	-0.06238	-5.6	.000	-0.084	-0.040
u/lg a	-0.008378	-7.0	.000	-0.011	-0.006

Table 42. Correlation coefficients between the variables in Model 8.

	h	KAR_m	ρ_{12}	$\rho_{12}S$	r	ss	u/lg a
h	1.00						
KAR_m	0.26	1.00					
ρ_{12}	-0.03	0.11	1.00				
$\rho_{12}S$	0.14	-0.03	0.50	1.00			
r	-0.32	-0.43	0.43	0.54	1.00		
ss	0.28	0.06	-0.22	-0.07	-0.06	1.00	
u/lg a	0.10	0.04	0.16	0.13	-0.27	-0.55	1.00

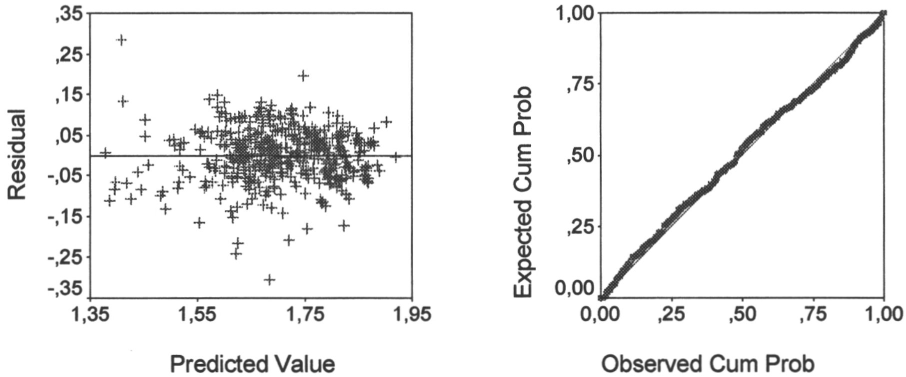


Fig 44. Residuals and their normal probability plot for Model 8.

Model 9 for $E_{c,0}$:

$E_{c,0} = 4.09 - 3.33f_6 - 0.06336KAR + 0.0159\rho_{12} + 0.0047\rho_{12}S - 2.2\lg r - 2.27\lg (u/a)$

The new variable used was:

- $f_6 = 1$ for stand number 6 (spruce), others 0.

The F-value of Model 9 is 417.7 (n = 480), the multiple coefficient of determination (adjusted R^2) was 0.84 and the standard error (s) was 1.17. All multipliers were significant and the basic statistical assumptions were met (Tables 43 and 44 and Fig. 45). The residuals have relatively equal variances and they follow expected cumulative probability. The residuals show one outlayer, which had no effect on analysis.

Table 43. Multipliers, t- values, significance levels and 95% confidence interval for multipliers in Model 9.

				95% Confidence interval for B	
Variable	B	t-value	Sig.	Lower Bound	Upper Bound
Constant	4.09	4.9	.000	2.46	5.73
f_6	-3.33	-14.0	.000	-3.80	-2.86
KAR	-0.06336	-7.5	.000	-0.080	-0.047
ρ_{12}	0.0159	10.9	.000	0.013	0.019
$\rho_{12}S$	0.0047	12.2	.000	0.004	0.005
lg r	-2.2	-3.5	.000	-3.45	-0.95
lg (u/a)	-2.27	-4.2	.000	-3.34	-1.20

Table 44. Correlation coefficients between the variables in Model 9.

	f_6	KAR	ρ_{12}	$\rho_{12}S$	lg r	lg (u/a)
f_6	1.00					
KAR	0.07	1.00				
ρ_{12}	0.52	0.02	1.00			
$\rho_{12}S$	-0.20	0.14	0.33	1.00		
lg r	-0.27	-0.05	0.15	0.63	1.00	
lg (u/a)	0.15	-0.57	0.20	-0.19	-0.49	1.00

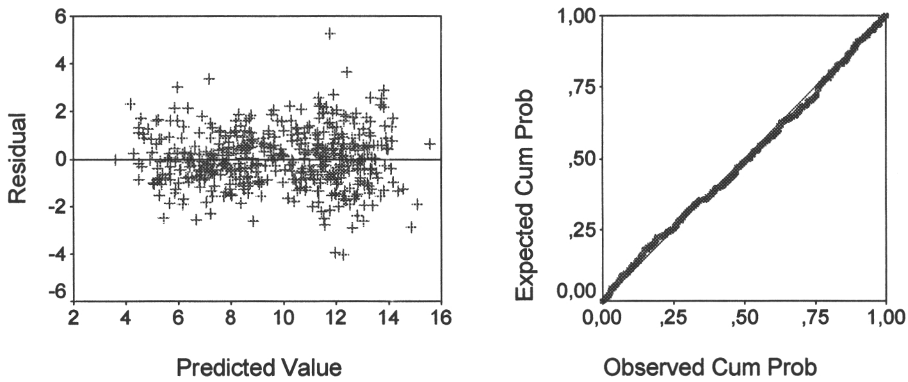


Fig. 45. Residuals and their normal probability plot for Model 9.

Model 10 for $f_{c,\,0}$:

$$f_{c,\,0} = 18.35 - 0.05127d - 4.58f_4 - 0.0898KAR + 0.02676\rho_{12} + 0.00226\rho_{12}S - 21.13lg(u/a)$$

The new variable used was:

- $f_4 = 1$ for stand number 4 (pine), others 0

The F-value of Model 10 is 374.8 ($n = 480$), the multiple coefficient of determination (adjusted R^2) was 0.83 and the standard error (s) was 2.93. All multipliers in Model 10 were significant and the basic statistical assumptions were met (Table 45 and 46 and Fig. 46). The residuals have relatively equal variances and they follow expected cumulative probability.

Table 45. Multipliers, t- values, significance levels and 95% confidence interval for multipliers in Model 10.

				95% Confidence interval for B	
Variable	B	t-value	Sig.	Lower Bound	Upper Bound
Constant	18.35	9.5	.000	14.6	22.1
d	-0.05127	-7.0	.000	-0.066	-0.037
f_4	-4.58	7.0	.000	3.30	5.86
KAR	-0.0898	-4.2	.000	-0.132	-0.048
ρ_{12}	0.02676	8.9	.000	0.021	0.033
$\rho_{12}S$	0.00226	2.2	.032	0.000199	0.004311
-lg (u / a)	21.13	-15.0	.000	-23.9	-18.4

Table 46. Correlation coefficients between the variables in Model 10.

	d	f_4	KAR	ρ_{12}	$\rho_{12}S$
d	1.00				
f_4	0.22	1.00			
KAR	0.12	0.17	1.00		
ρ_{12}	0.23	0.12	0.03	1.00	
$\rho_{12}S$	0.50	0.60	0.29	0.43	1.00
lg (u / a)	0.33	0.49	-0.47	0.41	0.49

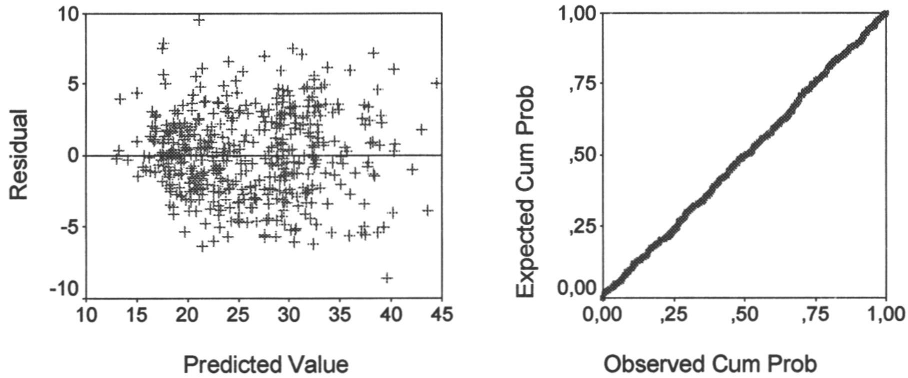


Fig. 46. Residuals and their normal probability plot for Model 10.

6. APPLICATION OF RESULTS OF DENSITY AND MECHANICAL PROPERTIES AND THEIR COMPARISON TO EN 384 STANDARD

In this chapter particular emphasis is given to the illustration and discussion of the effects of the components used in Models 7, 8, 9 and 10 on the mechanical properties of machine round pith enclosed timber. The effects are illustrated for grades A and B (Table 4), so that their grading parameters are kept constant when possible. However, because age i.e. number of annual rings, density, ring width and size of timber were dependent upon each other, the effects are illustrated in accordance with these relationships. This method is assumed to give a better illustration of the effects of the components of Models 7, 8, 9 and 10 and their interactions in the nature have on the mechanical properties of wood. The effects of the components of Models 7, 8, 9 and 10 on mechanical properties are compared to the EN 384 standard (1995) when possible. In all cases, density was calculated with the models presented in Fig. 35 for pine and spruce.

Tables 47, 48 and 49 show the effects of specimen form, wood processing method and tree species on mechanical properties by Models 7, 8, 9 and 10, when the same log is processed from manually debarked round timber to square sawn timber. The size of pith-enclosed timber, diameter and height depends on the wood processing method applied. Therefore, the size of timber is the smallest for square sawn timber. Virtually pine and spruce had different densities at similar ring width (Fig. 35). Models 7, 8, 9 and 10, however, show that ring width has an equivalent effect on the mechanical properties of pine and spruce. Therefore, the effects of form, processing method and tree species are presented for pine and spruce at the same ring width but at different density. In bending, the form of tension zone and machine processing had negative effects on strength. Manually debarked pine differed from machined in bending, because manual debarking does not break outer wood fibers especially in the vicinity of knots. Therefore, machine processing interacted with knot area ratio (KAR), i.e. a high knot sum increased the negative effect of machine processing. In bending, the modulus of elasticity and strength were 5 to 15 % higher for round timber compared to sawn timber. In compression, any effects of form or wood processing method were not found.

Figs. 47 and 48 show the effect of density on the mechanical properties in bending and compression for machine round pine and spruce at a diameter of 125 mm, knot area ratio 23.9% and at moisture contents of 12% and 18%. Age ranged from 8 to 48 years and ring width from 6 to 1 mm, in reverse order. Along this interval of ring width, density ranged from 420 to 580 kg/m^3 and from 310 to 500 kg/m^3 for pine and spruce, respectively.

Figs. 49 and 50 show the effect of ring width on modulus of elasticity and strength in bending and compression for machine round pine and spruce at diameter of 125 mm, knot area ratio of 23.9% and at moisture contents of 12% and 18%. Along this interval of ring width, density ranged from 580 to 420 kg/m^3 for pine and from 500 to 310 kg/m^3 for spruce. Age ranged from 48 to 8 years.

Figs. 51 and 52 show the effect of age on modulus of elasticity and strength in bending and compression for machine round pine and spruce at a diameter of 125 mm, knot area ratio of 23.9% and at moisture contents of 12% and 18%. Ring width ranged from 6 to 1 mm. Along this interval of ring width, density ranged from 580 to 420 kg/m^3 for pine and from 500 to 310 kg/m^3 for spruce.

At a similar density, spruce is stronger and stiffer than pine in bending and compression. The mechanical properties increased almost linearly with increasing density. At similar ring width and age pine had about 2.5 N/mm^2 higher bending strength and about 2.0 N/mm^2 higher compression strength than spruce. The modulus of elasticity of pine was about 0.5 kN/mm^2 higher than that of spruce in bending at similar ring width and age. The modulus of elasticities of pine and spruce were rather similar in compression at similar ring width and age. The effect of moisture content was independent of density. The relationship between ring width and mechanical properties was similar to that observed between ring width and density (Fig. 35). Mechanical properties increased rapidly with increasing age upto 20 years. After that, growth of the mechanical properties slowed with increasing age. Mechanical properties were about double at the age of 30 year compared to timber at the age of 10 years.

Table 47. Effects of wood processing method, form of specimen and tree species on modulus of elasticity in bending (r = 3 mm and u =18%) by Model 7.

a (a)	h (mm)	Total c (mm)	ks_m (mm)	KAR_m (%)	t (mm/m)	Pine E_m ρ_{12}=480 kg/m^3	Spruce E_m ρ_{12}=390 kg/m^3	Wood processing method
20	150	471	0	0	5	11.9		Manually debarked
20	150	393	30	7.6	2,5	11.7		* Partly sawn and manually debarked
16	125	393	60	15.3	0	11.0	10.4	Machine round
12	100	393	30	7.6	2,5	10.4		** Partly sawn and manually debarked
12	100	400	60	15.0	0	10.3	9.7	Square sawn

*edgewise direction in bending test i.e. manually debarked surface on tension zone
** flatwise direction in bending test i.e. sawn surface on tension zone

Table 48. The effect of processing method, form of specimen and tree species on the bending strength (r=3 mm and u=18%) by model 8.

a (a)	h (mm)	Total c (mm)	Total ks (mm)	KAR_m (%)	Pine f_m ρ_{12}=480 kg/m^3	Spruce f_m ρ_{12}=390 kg/m^3	Wood processing method
20	150	471	60	0	52.1		Manually debarked
20	150	393	60	7.6	49.8		* Partly sawn and manually debarked
16	125	393	60	15.3	48.9	46.4	Machine round
12	100	393	60	7.6	45.0		** Partly sawn and manually debarked
12	100	400	60	15.0	43.0	40.9	Square sawn

*edgewise direction in bending test i.e. manually debarked surface on tension zone
** flatwise direction in bending test i.e. sawn surface on tension zone

Table 49. Effect of tree species on modulus of elasticity and strength in compression by Models 9 and 10. The age used was 16 years, diameter 125 mm, circumference 393 mm and knot area ratio 15.3%. The densities used were 480 and 390 kg/m^3 for pine and spruce, respectively.

	$E_{c,0}$	$f_{c,0}$
Pine	9.6	22.2
Spruce	10.0	20.7

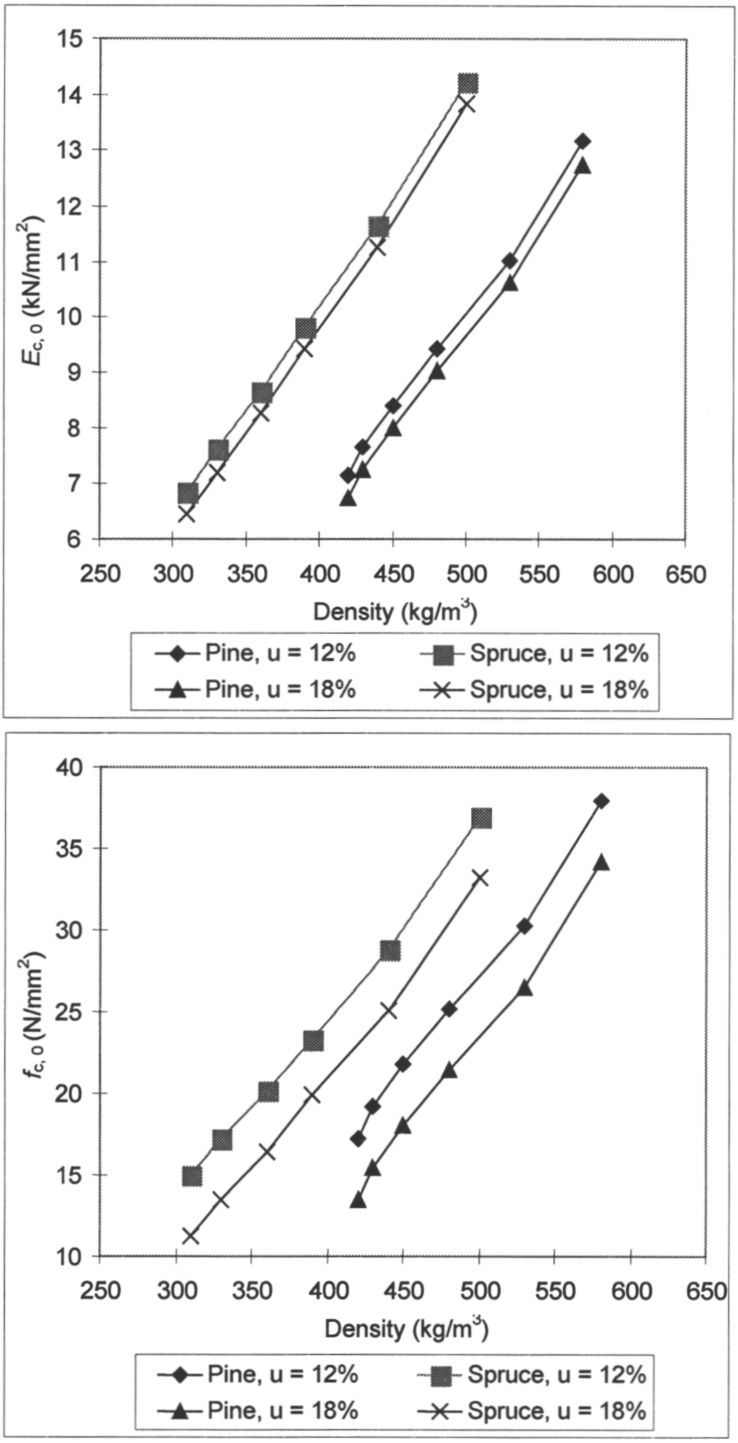
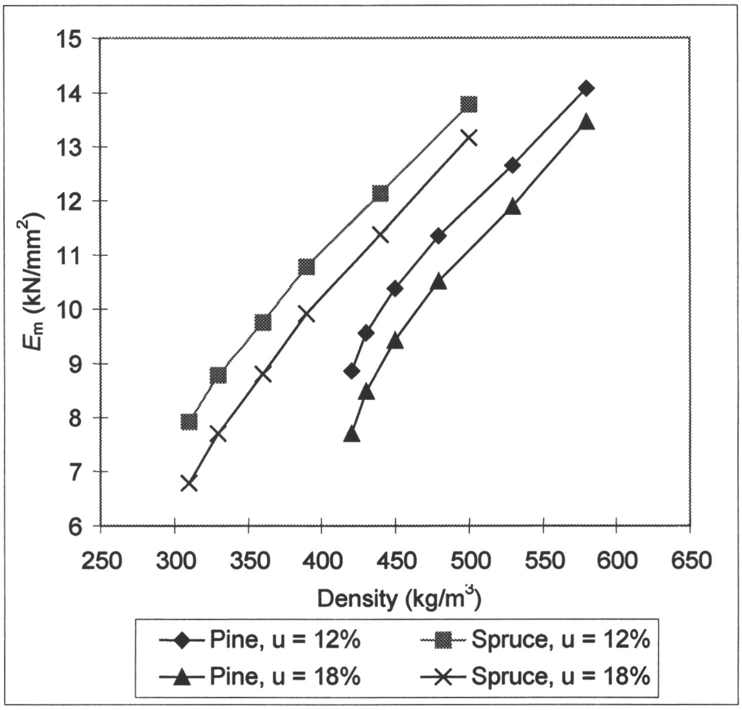


Fig. 47. Effect of density on the modulus of elasticity (above) and strength (below) in compression for machine round pine and spruce at the diameter of 125 mm, knot area ratio of 23.9% and moisture contents of 12% and 18%. Age ranged from 8 to 48 years, whilst ring width ranged from 6 to 1 mm, along this interval of age.



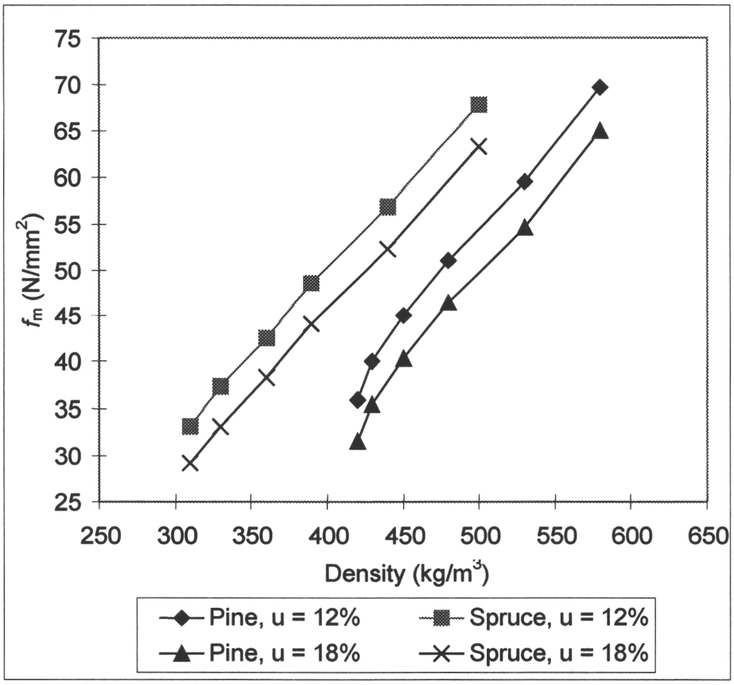
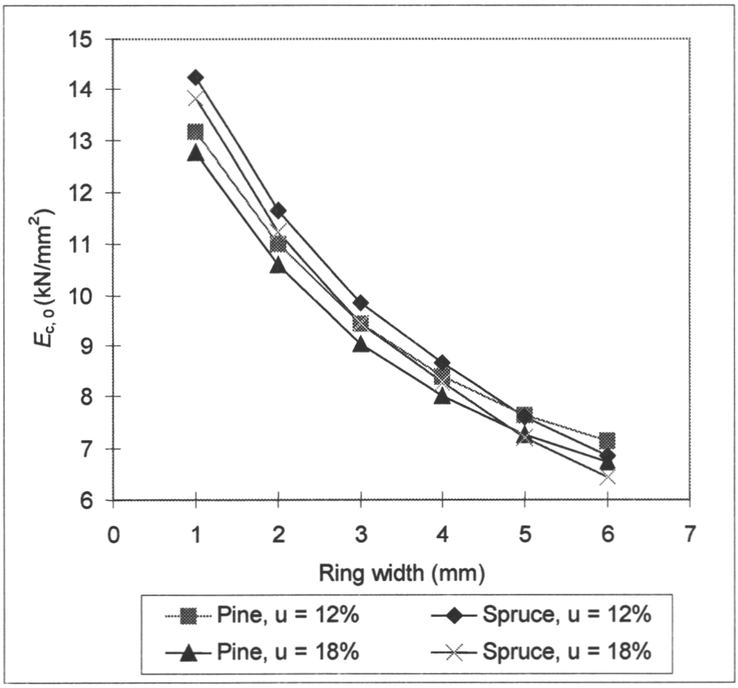


Fig. 48. Effect of density on the modulus of elasticity (above) and strength (below) in bending for machine round pine and spruce at the diameter of 125 mm, knot area ratio of 23.9% and moisture contents of 12% and 18%. Age ranged from 8 to 48 years whilst ring width ranged from 6 to 1 mm, along this interval of age.



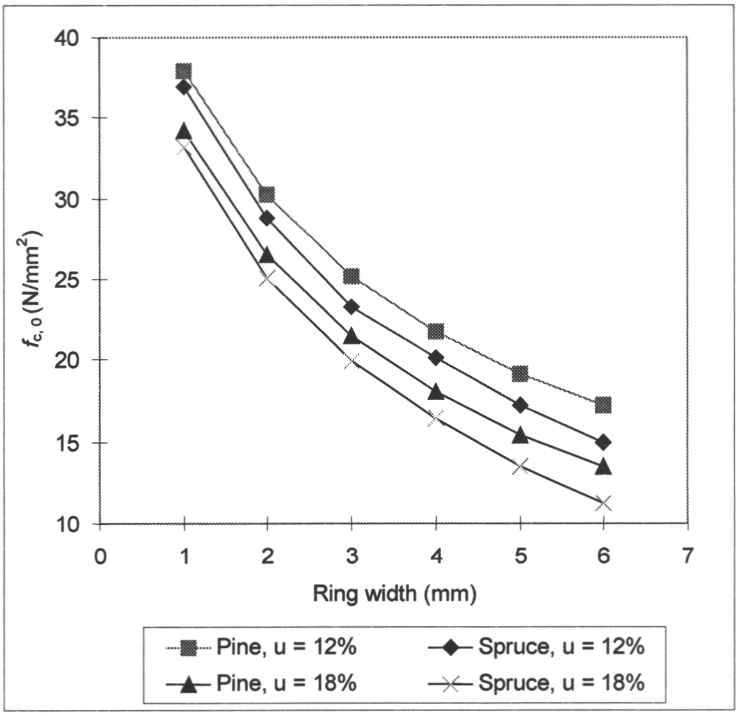
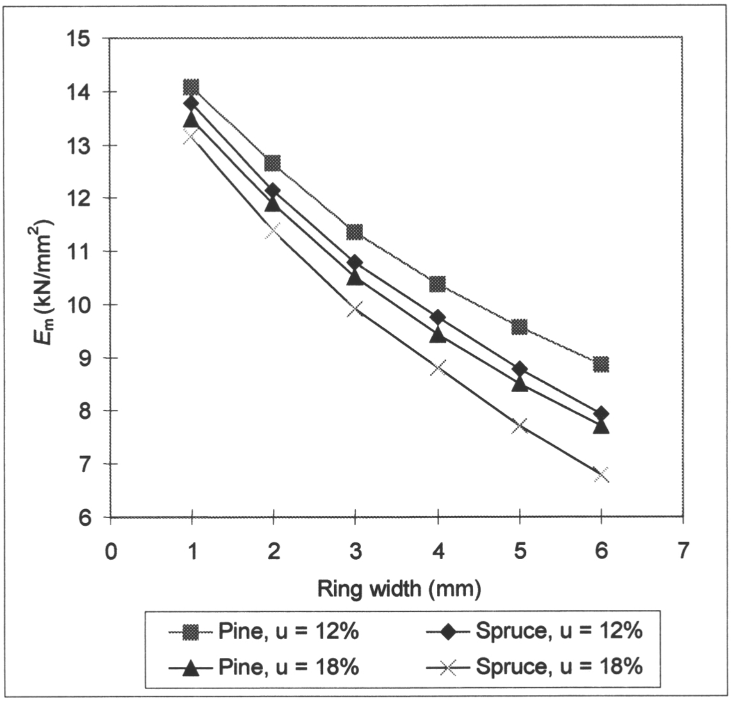


Fig. 49. Effect of ring width on the modulus of elasticity (above) and strength (below) in compression for machine round pine and spruce at the diameter of 125 mm, knot area ratio of 23.9% and moisture contents of 12% and 18%. Density ranged from 580 to 420 kg/m^3 for pine and from 500 to 310 kg/m^3 for spruce, whilst age ranged from 48 to 8 years.



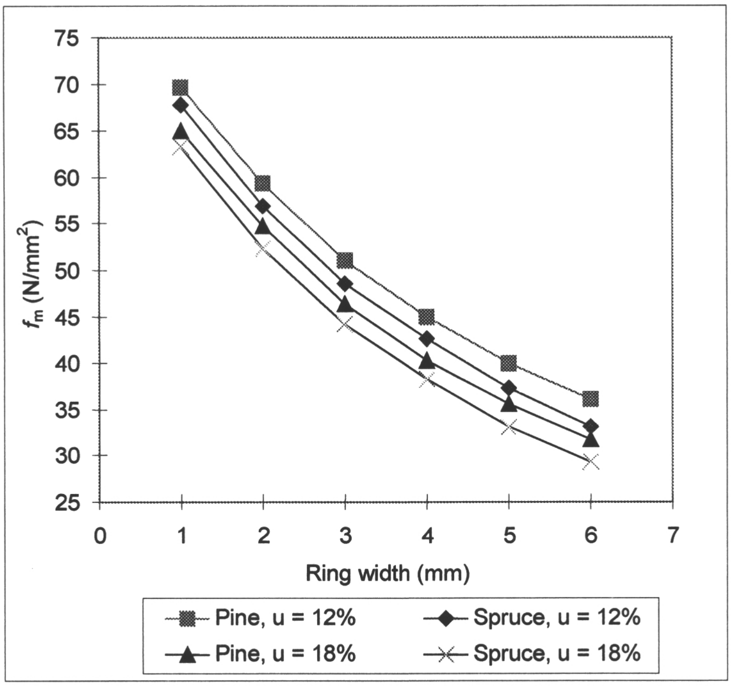


Fig. 50. Effect of ring width on the modulus of elasticity (above) and strength (below) in bending for machine round pine and spruce at the diameter of 125 mm, knot area ratio of 23.9% and moisture contents of 12% and 18%. Density ranged from 580 to 420 kg/m^3 for pine and from 500 to 310 kg/m^3 for spruce, whilst age ranged from 48 to 8 years.

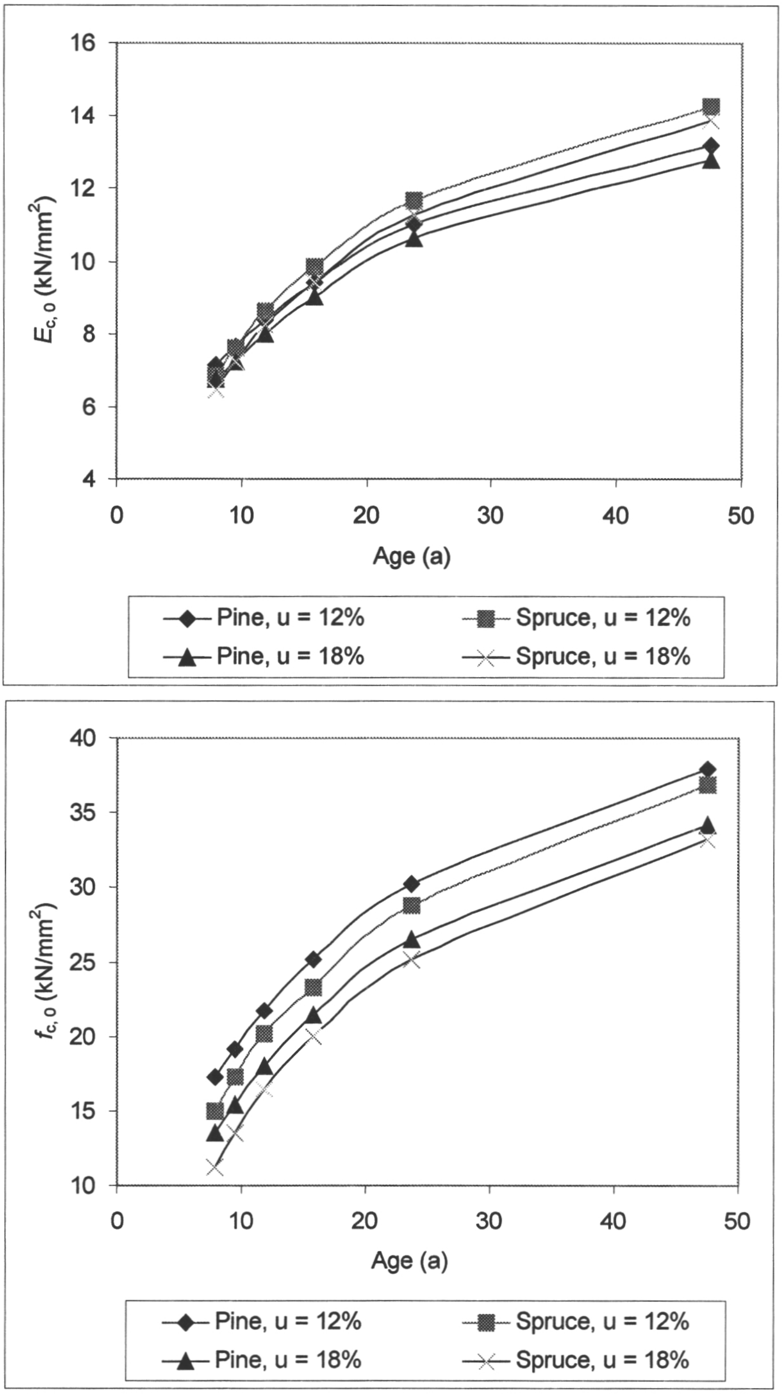
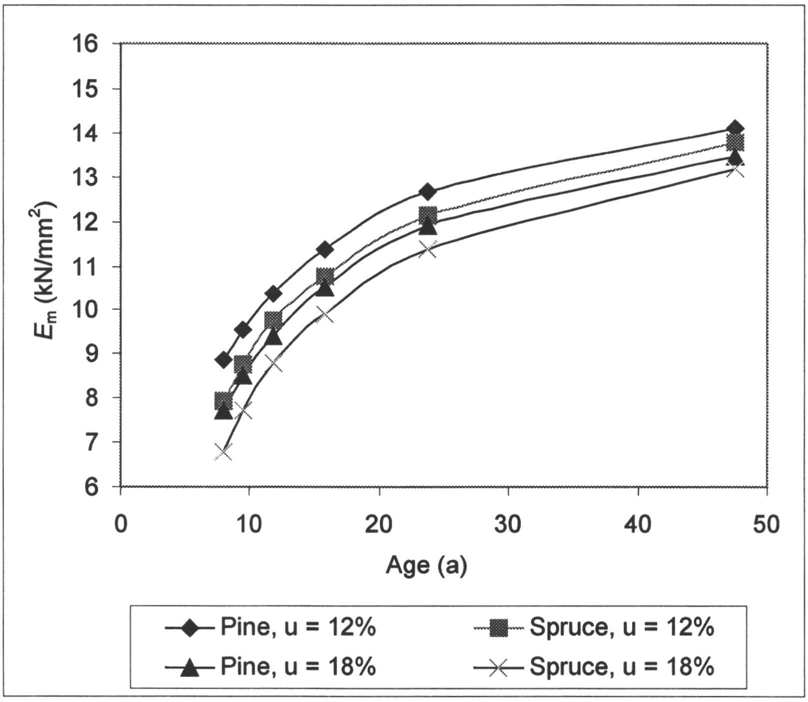


Fig. 51. Effect of age on the modulus of elasticity (above) and strength (below) in compression for machine round pine and spruce at the diameter of 125 mm, knot area ratio of 23.9% and moisture contents of 12% and 18%. Ring width ranged from 6 to 1 mm. Density ranged from 580 to 420 kg/m^3 for pine and from 500 to 310 kg/m^3 for spruce, along this interval of ring width.



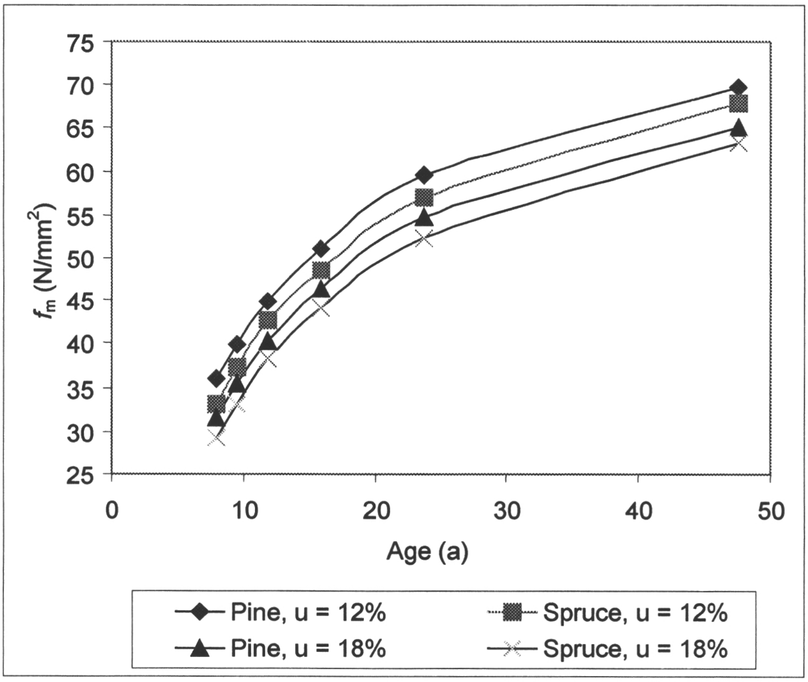


Fig. 52. Effect of age on the modulus of elasticity (above) and strength (below) in bending for machine round pine and spruce at the diameter of 125 mm, knot area ratio of 23.9% and moisture contents of 12% and 18%. Ring width ranged from 6 to 1 mm. Density ranged from 580 to 420 kg/m^3 for pine and from 500 to 310 kg/m^3 for spruce, along this interval of ring width.

Figs. 53 and 54 show the effect of knot sum on the modulus of elasticity and strength in compression and bending for machine round pine and spruce at the ring widths 3 mm and 5 mm and at the moisture contents of 12% and 18 %. Densities used in the calculations were 480 and 430 kg/m^3 for pine, and 390 and 330 kg/m^3 for spruce. The diameter used was 125 mm and knot area ratio ranged from 0 to 30.6%. Bending strength decreased 10 N/mm^2 and compression strength 3 N/mm^2 with an increase in knot sum from 0 to 125 mm. The negative effect of knot sum had a similar trend on the modulus of elasticity in bending and compression. The decrease was about 2 kN/mm^2, when the knot sum increased from 0 to 125 mm.

Tree age and ring width determines the size of timber (i.e. diameter, height or circumference). In addition, according to statistical analysis, age and moisture content had an interaction. The interactions between age, ring width and size of timber are presented in Figs. 55, 56, 57 and 58 for machine round pine and spruce for grade A and B criteria (see Table 4). For grade A timber, age ranged from 8 to 20 years and for grade B timber, age ranged from 5 to 12 years when for both grades, the respective size of timber i.e. diameter or height, ranged from 75 to 150 mm. Densities used in the calculations for grade A and B were 480 and 430 kg/m^3 for pine and 390 and 330 kg/m^3 for spruce. For modulus of elasticity in bending (E_m) and compression ($E_{c,\ o}$) and compression strength ($f_{c,\ 0}$), age had a clear positive effect. However, this effect diminished after the age of 20 years. The effect of age was connected to the size of timber. Fig. 56 illustrates both the positive and negative effect of age on bending strength (f_m) in contrast to Fig. 52, where the height of timber was constant. In Fig. 58, the EN 384 standard (1995) size adjustment calculated with Equation 10 is also presented for bending strength. The size adjustment is calculated from a height of 75 mm to the reference height of 150 mm with the value given by Model 8 at a height of 75 mm (dashed line). Model 8 for bending strength appears to show a negative size effect on first inspection, but however the Model 8 takes into account age and ring width, as well. Therefore it gives both negative and positive size effects for the given values. The EN 384 standard (1995) gave a clear negative size effect. For other mechanical properties, Models 7, 9 and 10 give clear positive size effects.

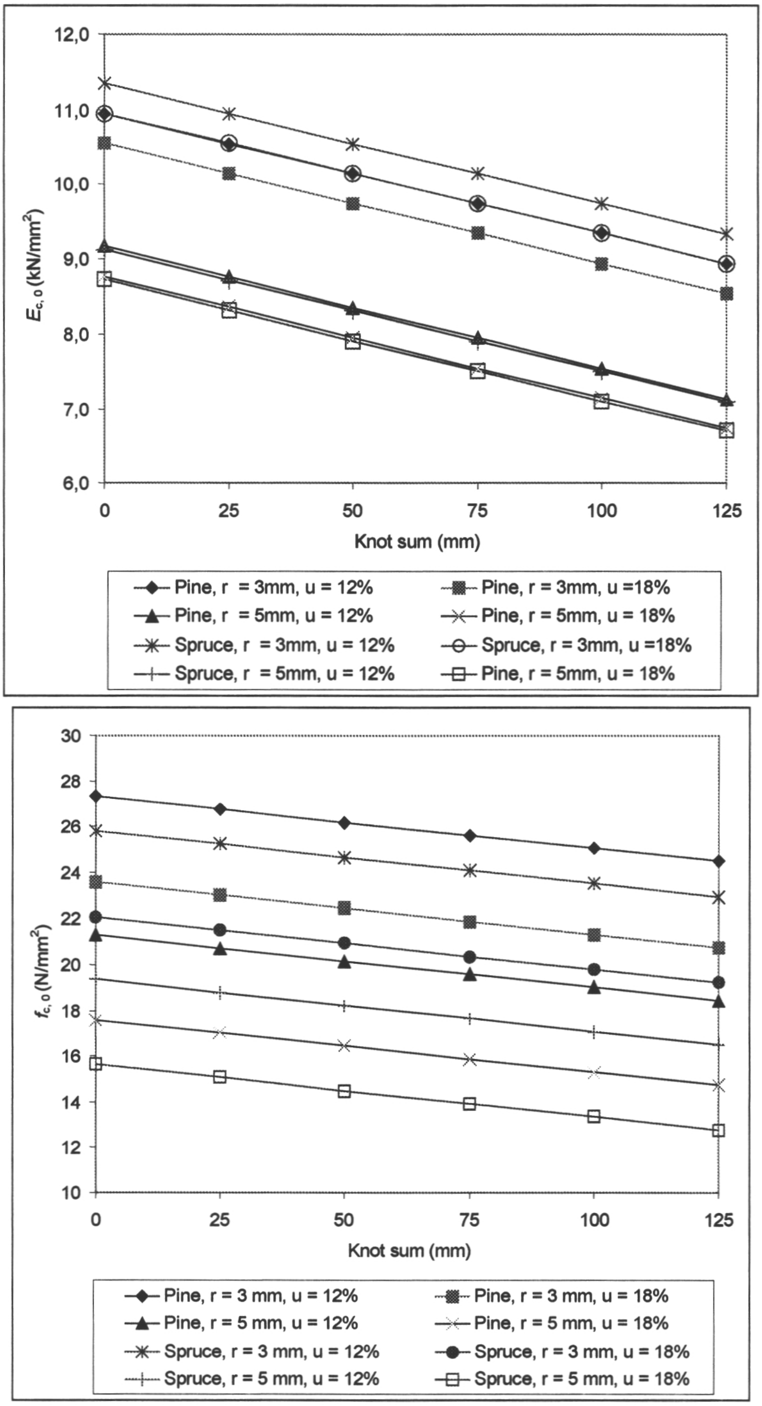


Fig. 53. Effect of knot sum on the modulus of elasticity (above) and strength (below) in compression for machine round pine and spruce at the ring width of 3 mm and 5 mm and at the moisture contents of 12% and 18 %. Densities used in the calculations were 480 and 430 kg/m^3 for pine and 390 and 330 kg/m^3 for spruce. The diameter was 125 mm and knot area ratio ranged from 0 to 30.6%.

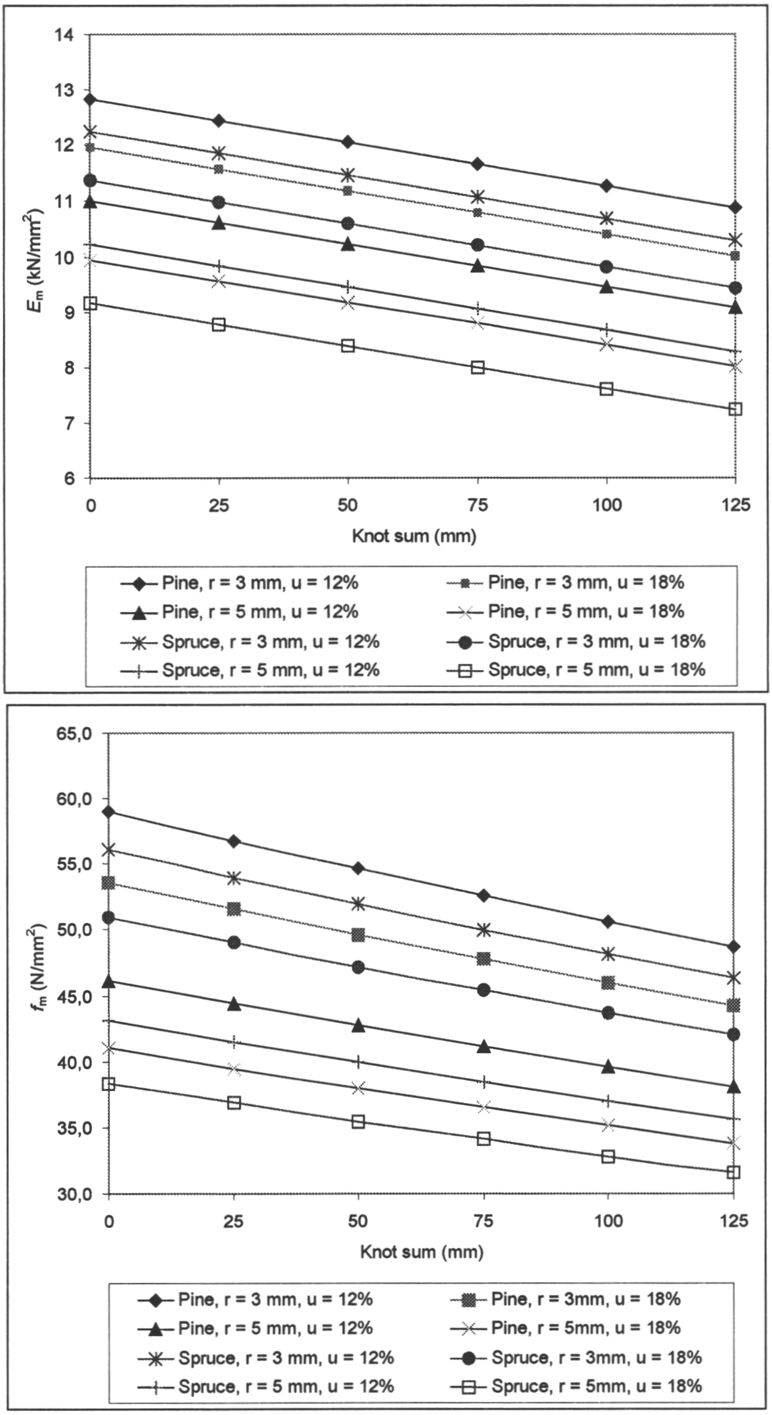


Fig. 54. Effect of knot sum on the modulus of elasticity (above) and strength (below) in bending for machine round pine and spruce at the ring width of 3 mm and 5 mm and at the moisture contents of 12% and 18 %. Densities used in the calculations were 480 and 430 kg/m^3 for pine and 390 and 330 kg/m^3 for spruce. The diameter was 125 mm and knot area ratio ranged from 0 to 30.6%.

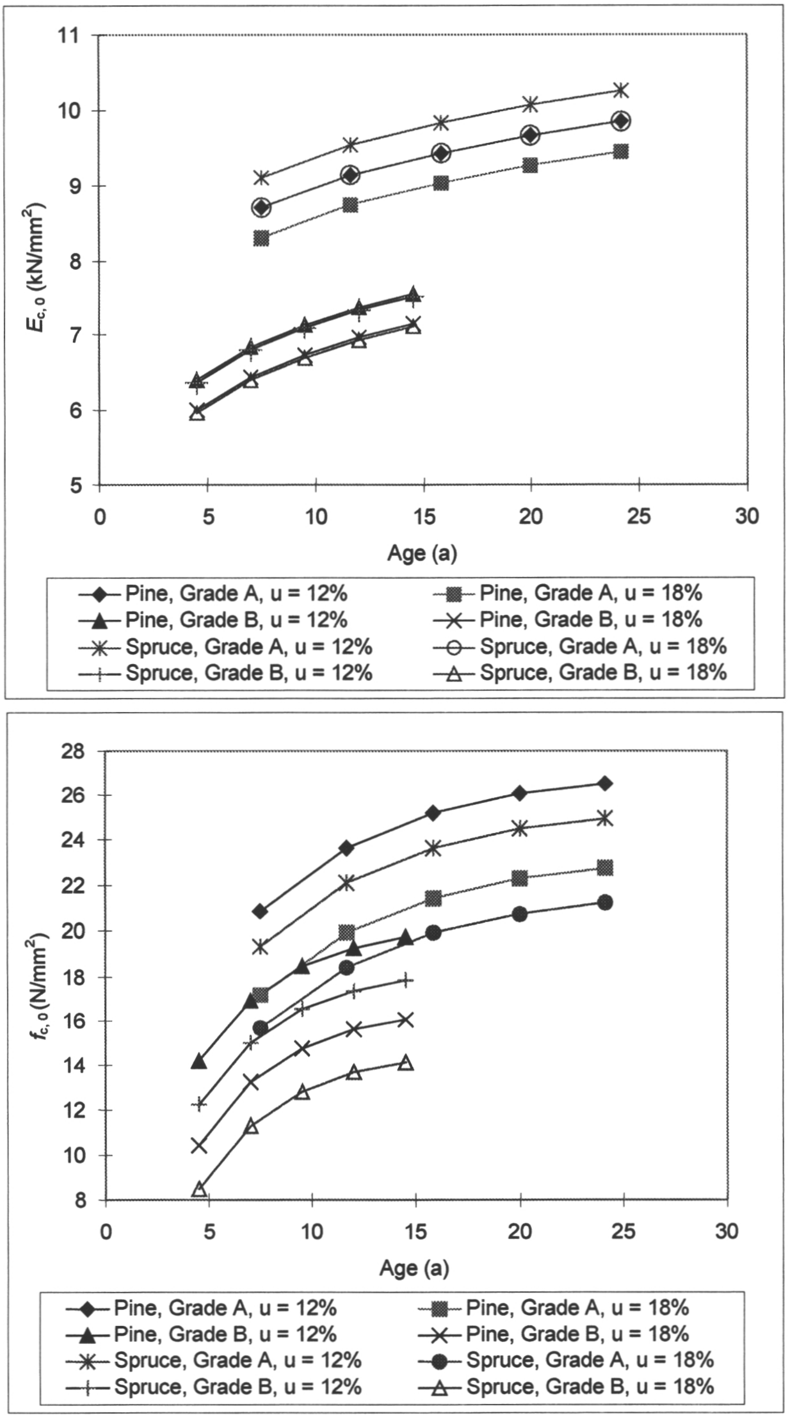
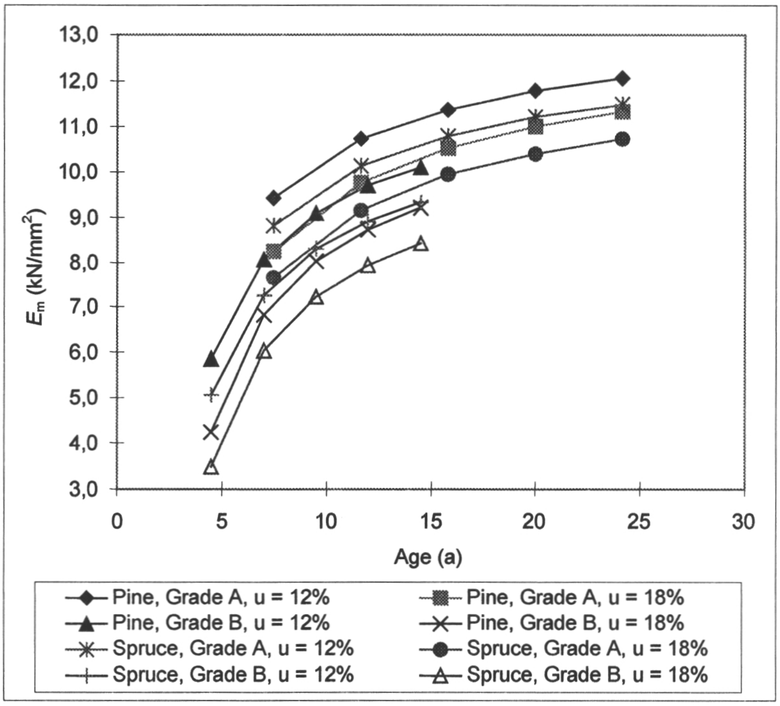


Fig. 55. Effect of age at Grade A and B criteria on the modulus of elasticity (above) and strength (below) in compression for machine round pine and spruce. Diameter ranged from 75 to 150 mm. Densities used for grade A and B were 480 and 430 kg/m^3 for pine, and 390 and 330 kg/m^3 for spruce.



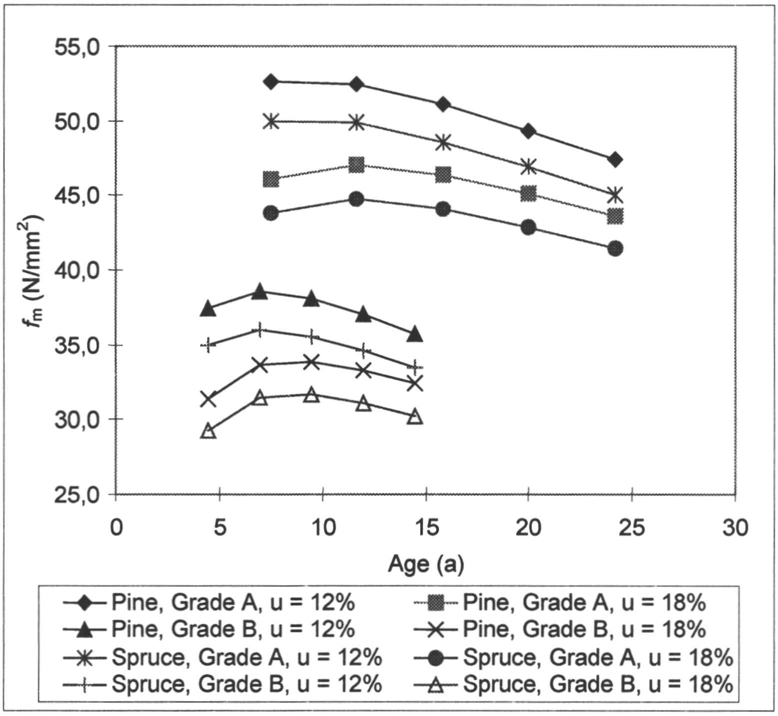


Fig. 56. Effect of age at grade A and B criteria on the modulus of elasticity (above) and strength (below) in bending for machine round pine and spruce. Height ranged from 75 to 150 mm. Densities used for grade A and B were 480 and 430 kg/m^3 for pine, and 390 and 330 kg/m^3 for spruce.

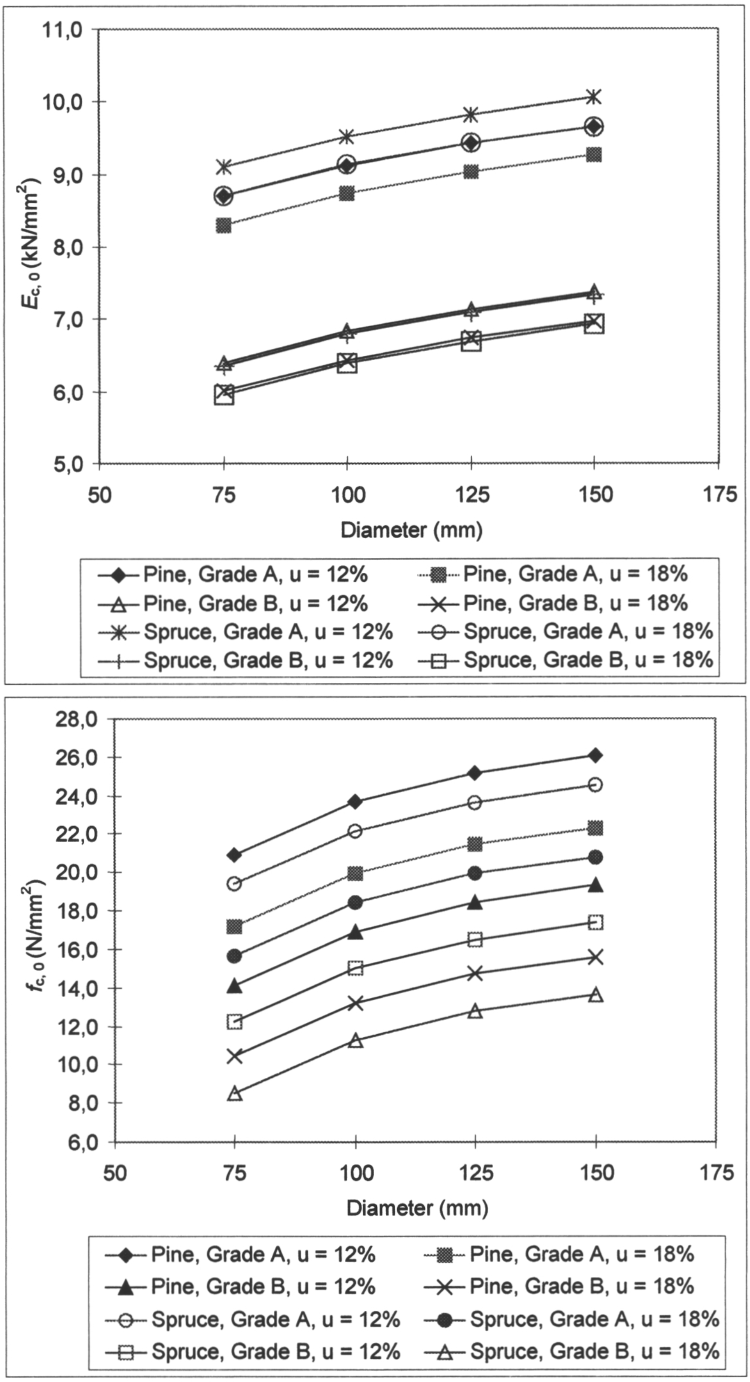


Fig. 57. Effect of diameter on the modulus of elasticity (above) and strength (below) in compression at grade A and B criteria for machine round pine and spruce. Densities used for grades A and B were 480 and 430 kg/m^3 for pine and 390 and 330 kg/m^3 for spruce. For grade A timber, the age ranged from 8 to 20 years and for grade B timber from 5 to 12 year.

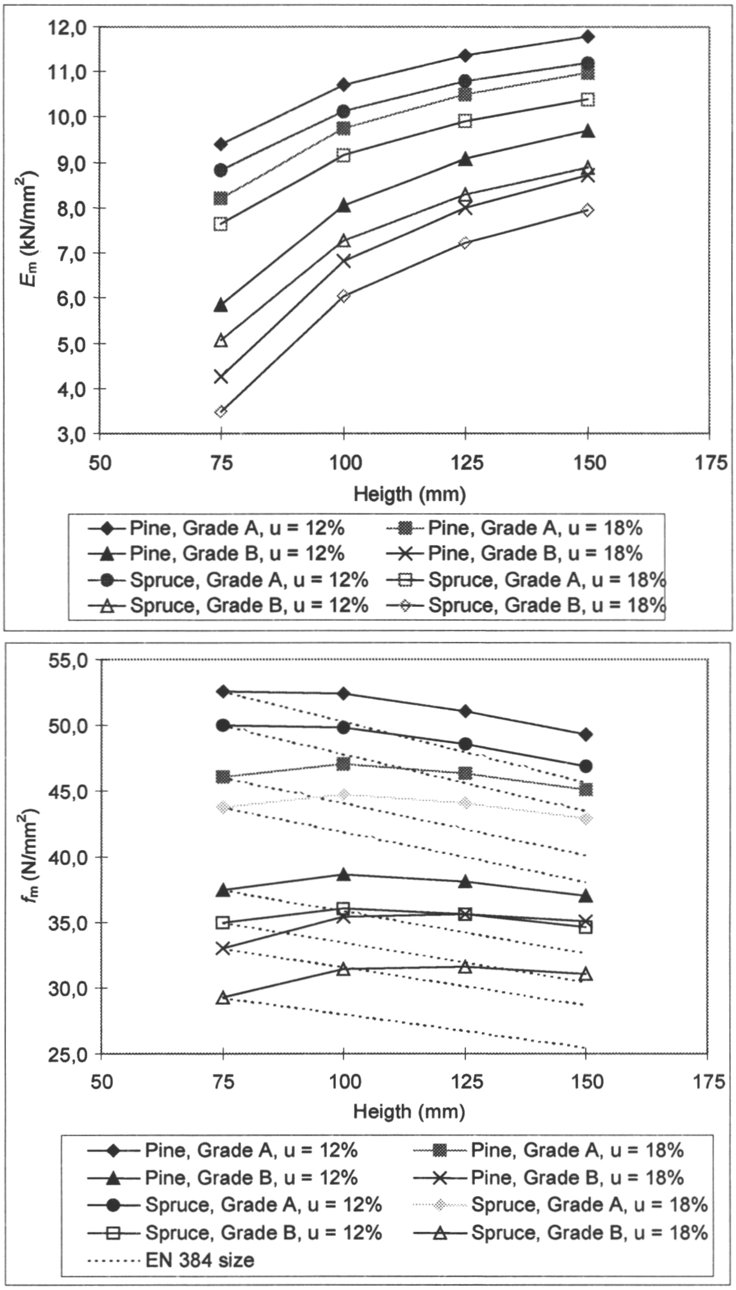


Fig. 58. Effect of diameter on the modulus of elasticity (above) and strength (below) in bending at grade A and B criteria for machine round pine and spruce by Model 8. The EN 384 standard (1995) size adjustment is presented for bending strength from a height of 75 mm to the reference height of 150 mm with the value given by Model 8 at a height of 75 mm (dashed line). Densities used for grades A and B were 480 and 430 kg/m^3 for pine, and 390 and 330 kg/m^3 for spruce. For grade A timber, age ranged from 8 to 20 years and for grade B timber 5 to 12 years.

Moisture content has a clear negative effect on mechanical properties (Tables 50 and 51). Densities used for grades A and B were 480 and 430 kg/m^3 for pine, and 390 and 330 kg/m^3 for spruce as shown in Tables 50 and 51. The younger specimens were, the stronger the effect of moisture, in particular for grade B timber. The greatest change due to moisture content was observed for the modulus of elasticity in bending (E_m) and compression strength ($f_{c,0}$) for grade B timber at the of diameter 75 mm and age of 5 years. These properties changed by about 7% when moisture content changed by 1%. That is two to three times higher change than for the same grade at the diameter of 150 mm and age of 12 years. For other mechanical properties similar but weaker trends could be seen. The interaction of age and moisture content for grades A and B was notable as regards modulus of elasticity and strength in bending and compression strength. However, for the modulus of elasticity in compression, this interaction seemed to be practically negligent.

The effect of moisture content in Models 7, 8 9 and 10 is presented and compared to the EN 384 standard (1995) moisture content adjustment in Figs. 59 and 60. The EN 384 standard (1995) adjustments should be applied to 5-percentile values of the sample. This was reason why the comparison was made for strength grades A and B (Table 4). Constant diameter 125 mm were used for grades A and B whilst age used were 10 and 16 years, respectively. Again, the densities used for grades A and B were 480 and 430 kg/m^3 for pine and 390 and 330 kg/m^3 for spruce. Moisture content had a remarkable effect on the bending strength although the EN 384 standard (1995) did not give any adjustment for this condition. Model 10 for compression strength showed a similar adjustment to the EN 384 standard (1995) for grade A. For grade B, however, the EN 384 standard (1995) adjustment was one unit lower than with Model 10. For the modulus of elasticity, Models 7 and 9 gave significantly lower adjustments for grade A than the EN 384 standard (1995), but the adjustment was somewhat similar for grade B in bending. For the modulus of elasticity in compression, Model 9 gave also significantly lower adjustment for grade B than EN 384 standard (1995).

Table 50. Relative difference (%) in modulus of elasticity and strength in bending between moisture content levels of 12 to 18% for diameters 75 and 150 mm of machine round pine and spruce for grade A and B timber by Models 7 and 8. Densities used for grades A and B are 480 and 430 kg/m^3 for pine and 390 kg/m^3 and 330 kg/m^3 for spruce.

	f_m (N/mm^2) Grade A limits h = 75 mm a = 8 year	f_m (N/mm^2) Grade A limits h = 150 mm a = 20 year	f_m (N/mm^2) Grade B limits h = 75 mm a = 5 year	f_m (N/mm^2) Grade B limits h = 150 mm a = 12 year	E_m (kN/mm^2) Grade A limits h = 75 mm a = 8 year	E_m (kN/mm^2) Grade A limits h = 150 mm a = 20 year	E_m (kN/mm^2) Grade B limits h = 75 mm a = 5 year	E_m (kN/mm^2) Grade B limits h = 150 mm a = 12 year
Pine								
u = 12%	50.4	47.2	35.5	35.1	8.9	11.3	5.2	9.1
u = 18%	44.1	43.2	29.7	31.5	7.7	10.5	3.6	8.1
Difference (%)	14.3	9.3	19.5	11.4	15.6	7.6	44.4	12.3
Difference (%/%)	2.4	1.5	3.3	1.9	2.6	1.3	7.4	2.1
Spruce								
u = 12%	50	46.9	35.0	34.6	8.8	11.2	5.1	8.9
u = 18%	43.8	42.9	29.3	31.1	7.6	10.4	3.5	7.9
Difference (%)	14.2	9.3	19.5	11.3	15.8	7.7	45.7	12.7
Difference (%/%)	2.4	1.6	3.2	1.9	2.6	1.3	7.6	2.1

Table 51. Relative difference (%) in strength and modulus of elasticity in compression between moisture content levels of 12 to 18% for the diameters 75 and 150 mm of pine and spruce for grade A and B timber by Models 9 and 10. Densities used for grades A and B are 480 and 430 kg/m^3 for pine and 390 and 330 kg/m^3 for spruce.

	$f_{c,0}$ (N/mm^2) Grade A limits h = 75 mm a = 8 year	$f_{c,0}$ (N/mm^2) Grade A limits h = 150 mm a = 20 year	$f_{c,0}$ (N/mm^2) Grade B limits h = 75 mm a = 5 year	$f_{c,0}$ (N/mm^2) Grade B limits h = 150 mm a = 12 year	$E_{c,0}$ (kN/mm^2) Grade A limits h = 75 mm a = 8 year	$E_{c,0}$ (kN/mm^2) Grade A limits h = 150 mm a = 20 year	$E_{c,0}$ (kN/mm^2) Grade B limits h = 75 mm a = 5 year	$E_{c,0}$ (kN/mm^2) Grade B limits h = 150 mm a = 12 year
Pine								
u = 12%	19.8	25.0	12.8	18.0	8.1	9.0	5.6	6.6
u = 18%	16.1	21.3	9.1	14.2	7.7	8.6	5.2	6.2
Difference (%)	23.0	17.4	40.7	26.8	5.2	4.7	7.7	6.5
Difference (%/%)	3.8	2.9	6.8	4.5	0.9	0.8	1.3	1.1
Spruce								
u = 12%	19.4	24.8	12.2	17.4	9.1	10.1	6.4	7.3
u = 18%	15.6	20.8	8.5	13.7	8.7	9.7	6	6.9
Difference (%)	24.4	19.2	43.5	27.0	4.6	4.1	6.7	5.8
Difference (%/%)	4.1	3.2	7.3	4.5	0.8	0.7	1.1	1.0

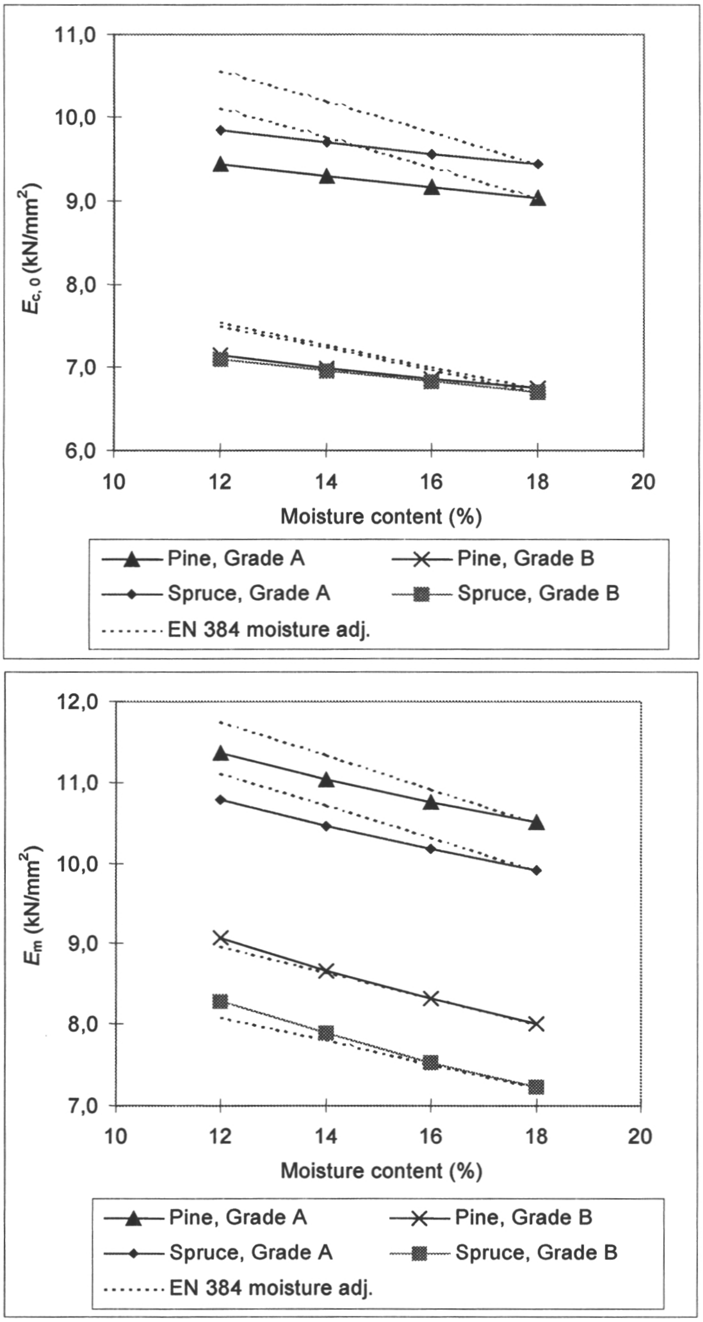
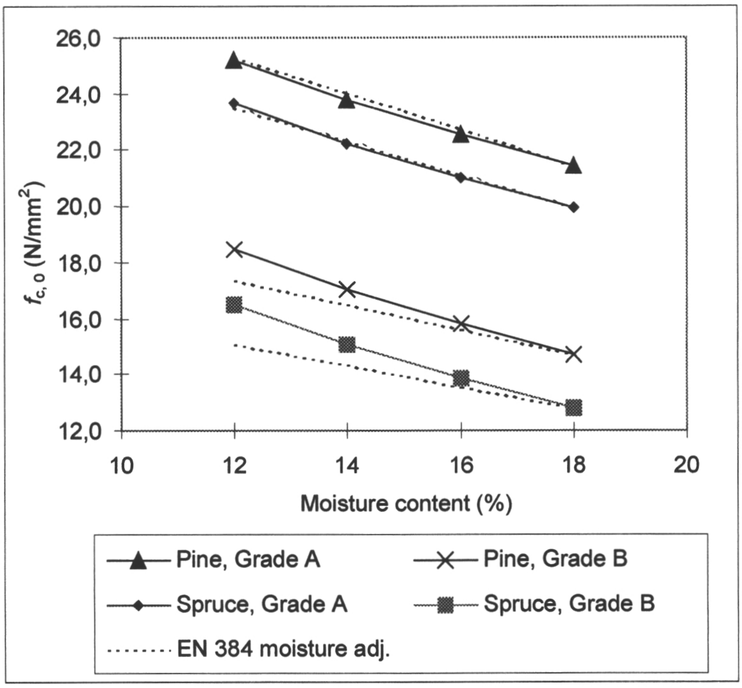


Fig. 59. Effect of moisture content on the modulus of elasticities in compression (above) and bending (below) by models 7 and 9 in comparison to the moisture content adjustment according to EN 384 standard (dash line) at grade A and B timber for machine round pine and spruce. Densities used for grades A and B were 480 and 430 kg/m^3 for pine, and 390 and 330 kg/m^3 for spruce. Constant diameter 125 mm were used for grades A and B whilst age used were 10 and 16 years, respectively.



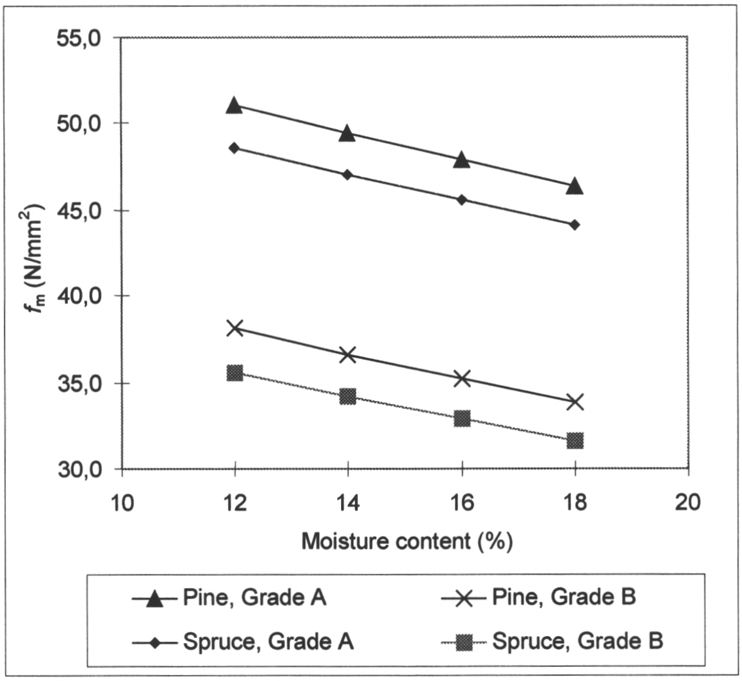


Fig. 60. Effect of moisture content on the compression (above) and bending (below) strength by Models 8 and 10 in comparison to the moisture content adjustment according to the EN 384 standard (1995) for grades A and B timber for machine round pine. Densities used for grades A and B are 480 and 430 kg/m^3 for pine and 390 and 330 kg/m^3 for spruce. Constant diameter 125 mm were used for grades A and B whilst age used were 10 and 16 years, respectively.

Scatter-plots for modulus of elasticity and strength in compression and bending versus age for machine round pine and spruce are presented in Figs. 61 and 62. The modulus of elasticity and strength were adjusted to correspond the moisture content of 12% by Equations 7 and 8 in accordance to the EN 384 standard (1995). The positive effect of age on the compression decreased after the age of 20 to 30 years for spruce whilst for pine the positive effect increased somewhat linearly from 10 to 35 years. The positive effect of age on the modulus of elasticity in bending increased somewhat linearly from 10 to 35 years both for pine and spruce. At first, the bending strength increased with increasing age up to age of 25 to 30 years, but then it began to decrease, in particular in spruce material.

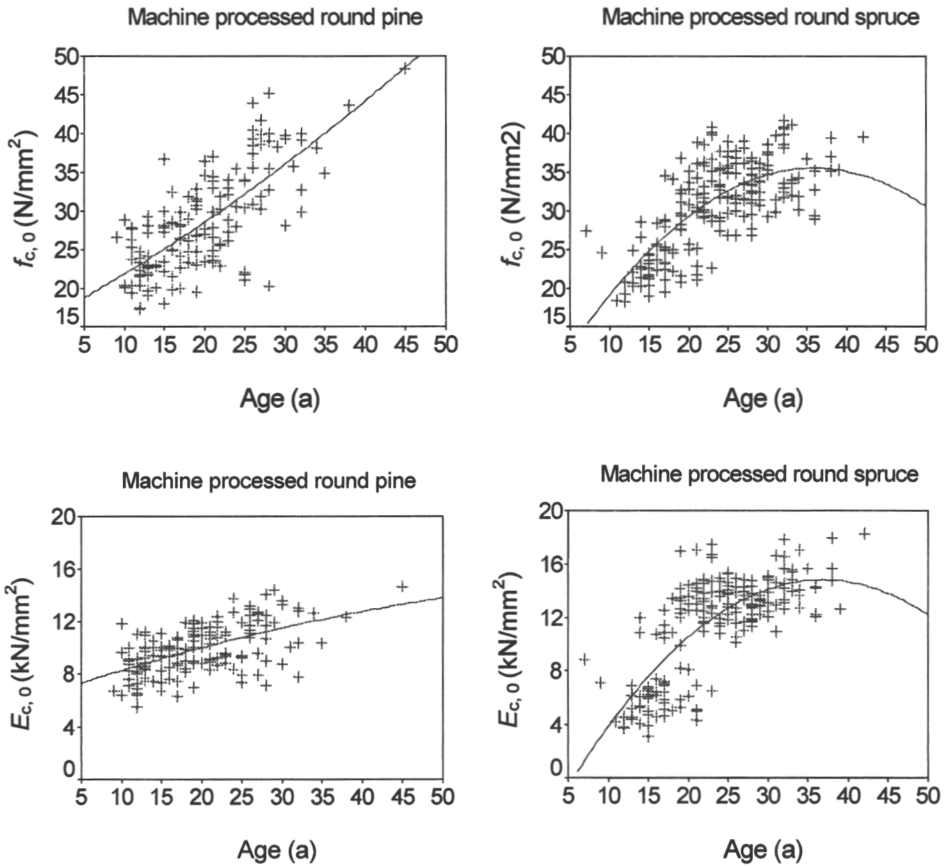


Fig. 61. Scatter-plots for modulus of elasticity and strength in compression versus age for machine round pine and spruce. The modulus of elasticity and strength are adjusted to correspond with the moisture content of 12% by Equations 7 and 8 in accordance to the EN 384 standard (1995). The fitted second power trend line is presented, as well.

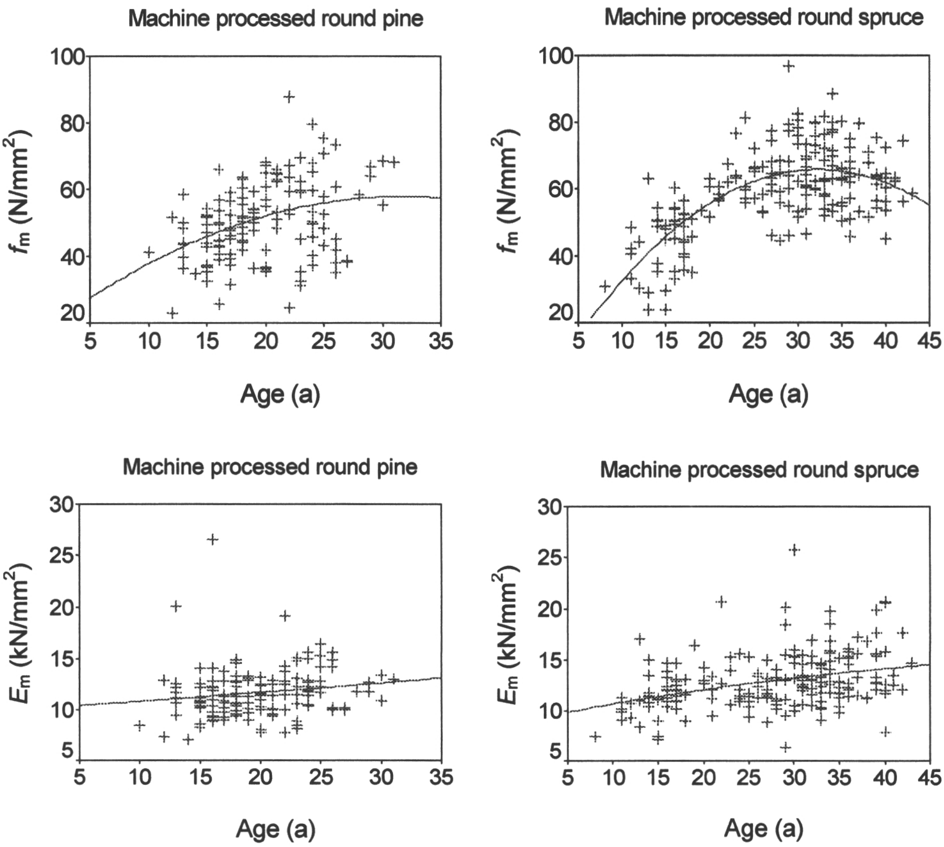


Fig. 62. Scatter-plots for modulus of elasticity and strength in bending for machine round pine and spruce. The modulus of elasticity are adjusted to correspond to the moisture content of 12% by Equation 7 in accordance with the EN 384 standard (1995). The fitted second power trend line is presented, as well.

Fig. 63 shows the relationship of characteristics compression strength ($f_{c,o,k}$) and bending strength ($f_{m,k}$) by Equation 1 according to the EN 384 standard (1995) for grade A and B timber (Table 4). Fig. 64 shows the relationship of characteristics compression strength ($f_{c,o,k}$) and bending strength ($f_{m,k}$) by Equation 1 according to EN 384 standard (1995), and relationships between predictions by Model 10 for compression strength and Model 8 for bending strength at a moisture content of 12%. In Models 8 and 10 the following densities were used for grade A and B timber: 480 and 430 kg/m^3 for the pine and 390 and 330 kg/m^3 for the spruce, respectively. Equation 1 (EN 384 standard 1995) gave a higher ratio between compression and bending strength than was obtained for grades A and B with the tested values and predictions of Model 10 for compression strength and Model 8 for bending strength. Therefore, if only density, modulus of elasticity and strength in bending are used for assigning pith enclosed round timber to a CEN strength class, the result could be too high strength class. Therefore, compression strength must also be tested, when assigning small diameter pith enclosed round timber to a strength class.

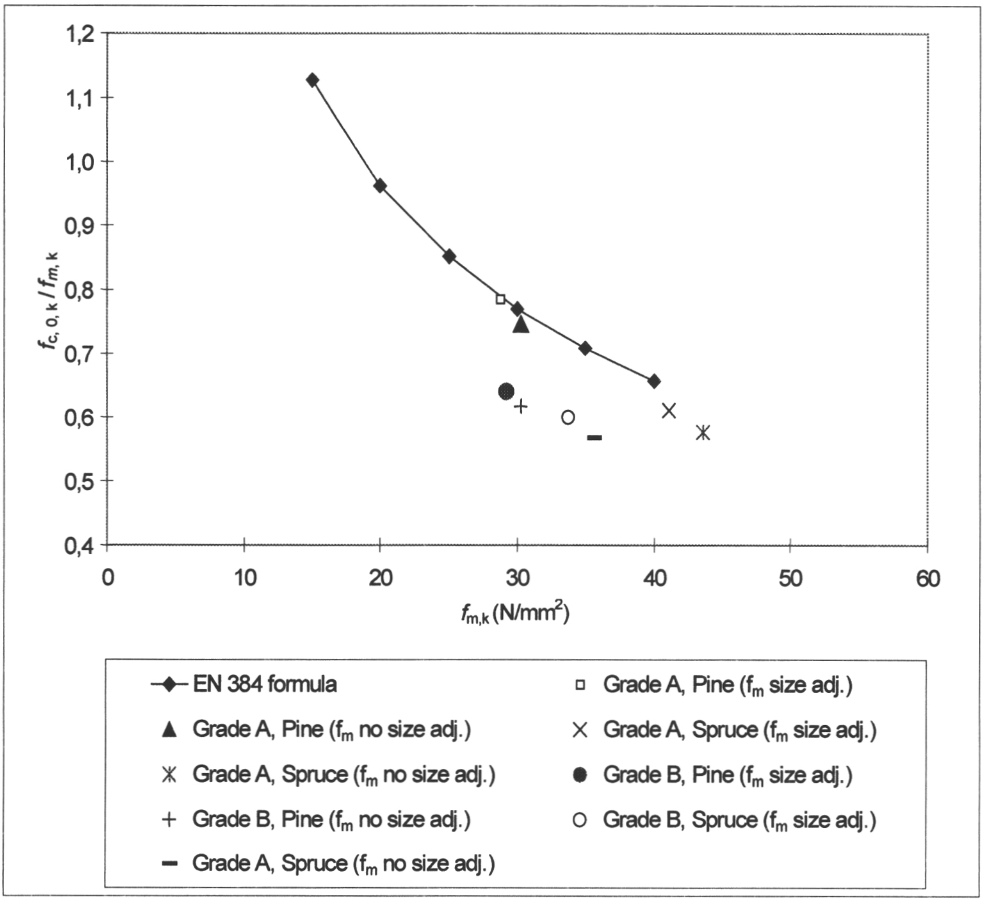


Fig. 63. The relationship of characteristics compression strength ($f_{c,\ o,\ k}$) and bending strength ($f_{m,\ k}$) according to Equation 1 (EN 384 standard 1995) for grade A and B timber (Table 4).

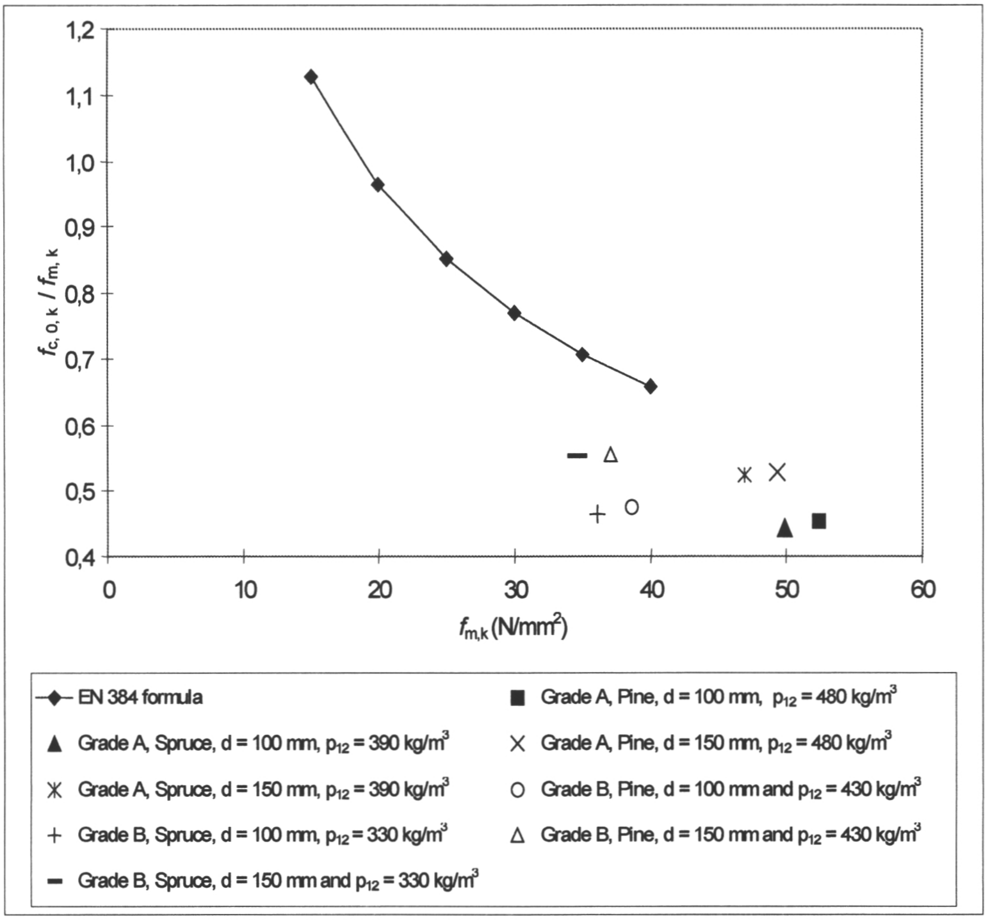


Fig. 64. The relationship of characteristics compression strength ($f_{c,\ o,\ k}$) and bending strength ($f_{m,\ k}$) according to Equation 1 (EN 384 standard 1995), and the relationships between predictions by Model 10 for compression strength and Model 8 for bending strength at a moisture content of 12%.

7. CHARACTERISTIC VALUES AND GRADING

7.1 CHARACTERISTIC VALUES FOR MECHANICAL PROPERTIES OF THE ENTIRE MATERIAL

Tables 50 and 51 showed that the moisture adjustment is dependent on the age of timber for the material used in this study. Bending strength should also be adjusted, unlike prescribed in the EN 384 standard (1995). Bending strength of round timber is, however, so high compared to compression strength and modulus of elasticity that this does not cause too low a strength class (Fig. 61 and 62). Fig. 56 shows that round pith enclosed timber has both a minor positive and minor negative size effect in bending depending on the characteristics of timber. Therefore, it is recommended that size adjustment stated in the EN 384 standard (1995) should not be used for the bending strength.

Table 52 shows characteristics of tested material sampled by tree species and processing methods. Mechanical properties are adjusted to correspond to moisture content of 12 % in accordance with the EN 384 standard (1995). Size adjustment for bending strength is used, as well. Lower 5-percentile values for strength were determined by the ranking method and for density by normal distribution. The values obtained were adjusted to correspond to a moisture content of 12% in accordance with the EN 384 standard (1995): compression strength was adjusted by 3% and modulus of elasticity by 2% for every percentage point difference in moisture content (Equations 7 and 8). Size adjustment was also made for bending strength by Equation 10.

When size adjustments were taken into account, bending strengths lower 5-percentile ranged from 17.8 to 41.6 N/mm^2. For compression strength and modulus of elasticity in bending and compression, lower 5-percentile ranged from 16.2 to 28.0 N/mm^2 and from 7.4 to 15.6 kN/mm^2, respectively. Square sawn timber had considerably lower values than others. Bending strength suggests that the strength grade C30 is possible to achieve for unsorted round timber. Considering also compression strength, density and modulus of elasticity C18 can only be achieved for unsorted round timber.

Table 52. Characteristics of tested material sampled by tree species and processing methods. Mechanical properties are adjusted to correspond to a moisture content of 12 % in accordance with the EN 384 standard (1995). Size adjustment for bending strength is used, as well.

Species and sample	n	h_{mean} (mm)	ρ_{mean} (kg/m ^{3})	ρ_{05} (kg/m^3)	$f_{m,mean}$ (N/mm^2)	$f_{m,05}$ / $f_{m,05\ size\ adj.}$ (N/mm^2)	$E_{m,mean}$ (kN/mm^2)	d_{mean} (mm)	ρ_{mean} (kg/m^3)	ρ_{05} (kg/m^3)	$f_{c,mean}$ (N/mm^2)	$f_{c,05}$ (N/mm^2)	$E_{c,0,mean}$ (kN/mm^2)
Pine		**Bending**						**Compression**					
Round, manually Debarked	25	124	465	378	48,4	38.0 / 36.6	12.2	109	462	394	24.5	18.5	9.9
Round, machine processed	150	124	470	413	50.6	34.8 / 33.5	11.6	119	474	404	28.6	19.1	9.9
*Partly sawn and manually debarked in tension zone	50	153	457	389	43.9	36.1 / 36.2	12.8	12.1	449	391	23.6	20.0	8.2
**Partly sawn in tension zo-ne and manually debarked	25	102	555	489	56.5	44.9 / 41.6	15.6	131	533	453	34.2	28.0	13.1
Partly sawn , total	75	136	488	387	48.1	37.0 / 36.3	13.7	125	477	384	27.1	20.3	9.8
Square sawn	25	102	420	373	28.6	19.2 / 17.8	7.9	102	423	374	20.1	16.2	7.4
Spruce		**Bending**						**Compression**					
Round, machine Processed	200	111	434	325	59.8	35.4 / 32.8	12.9	105	426	332	30.7	20.8	11.5
Square sawn	25	102	426	378	45.1	35.9 / 33.2	13.2	102	438	381	28.9	25.0	12.8

*edgewise direction in bending test i.e. manually debarked surface on tension zone
** flatwise direction in bending test i.e. sawn surface on tension zone

7.2 APPLICABILITY OF VISUAL GRADING RULES FOR GRADE A AND B FOR ROUND TIMBER

In this chapter visual grading rules are applied which were established in the EU-project Small Diameter Round Timber for Construction (EU – Fair Programme CT95-0091) for machine round pine and spruce (Ranta-Maunus 1999). The grading rules are presented in Table 4. The purpose is to study, how the selected grading parameters correlate with the mechanical properties of the tested machine round pine and spruce material and what was the yield of timber in each strength class.

Correlation analysis was performed between mechanical properties at a moisture content of 12% adjusted in accordance with the EN 384 standard (1995) and possible visual grading parameters of machine round pine and spruce in bending and compression (Tables 53, 54, 55 and 56). Ring width had a clear negative correlation with mechanical properties. Knot sum (ks) and the diameter of the thickest knot (mk) also had high correlations with mechanical properties in bending and compression. Knot sum and the diameter of the thickest knot correlated strongly with ring width. Therefore it would be sensible to use knot sum and the diameter of the thickest knot as a grading parameter in relation to diameter of timber (ks/d and mk/d), because they correlated less with ring width, except for compression of pine. In addition, it was stated previously in the study that the effect of knots on mechanical properties is dependent on the size of timber. Therefore, establishing grading criteria between relationships of the diameter of knot and timber would give more reliable results.

The applicability of visual grading criteria for ring width was studied by the relationship between ring width and density. In Fig. 35 scatter plots of density versus ring width, and fitted second power polynomial regression curves as a function of ring width are shown for pine and spruce. Ring widths of 3 mm and 5 mm are sensible criteria for grade A and B, respectively.

Fig. 65 shows the scatter-plots of mechanical properties adjusted to correspond to a moisture content of 12%, Equations 7 and 8, versus knot sum and diameter of the thickest knot in relation to diameter of timber, ks/d and mk/d, respectively. The linear trend lines are presented to clarify effect of variables. The negative effect of knot sum and the thickest knot in relation to diameter on mechanical properties is obvious. The thickest knot of spruce had positive effect on the modulus of elasticity and strength in bending, however. Generally, strength grading rules, however, give criteria for the largest knot, because a large knot is an indicator of possible top defect, which is not allowed in structural timber.

Table 53. Correlations coefficients between the characteristics of machine processed round pine for bending material. Modulus of elasticity in bending (E_m) is adjusted to correspond to a moisture content of 12% (Equation 7).

	E_m	f_m	G	d	ks	ks/d	mk	mk/d	p_{12}	r	t
f_m	0.54	1.00									
G	-0.13	-0.13	1.00								
h	-0.16	-0.16	0.11	1.00							
ks	-0.38	-0.58	0.13	0.42	1.00						
ks/d	-0.32	-0.54	0.04	-0.19	0.80	1.00					
mk	-0.37	-0.54	0.09	0.49	0.83	0.58	1.00				
mk/d	-0.31	-0.51	0.00	-0.20	0.60	0.81	0.73	1.00			
p_{12}	0.33	0.47	-0.05	-0.08	-0.37	-0.34	-0.33	-0.31	1.00		
r	-0.37	-0.52	0.10	0.28	0.56	0.45	0.55	0.42	-0.47	1.00	
t	-0.28	-0.57	0.18	0.16	0.54	0.49	0.49	0.42	-0.35	0.44	1.00
u	0.04	-0.47	-0.02	0.06	0.23	0.25	0.23	0.24	0.05	0.11	0.28

Table 54. Correlations coefficients between the characteristics of machine processed pine for compression material. Modulus of elasticity ($E_{c,0}$) and ($f_{c,0}$) strength in compression are adjusted to correspond to a moisture content of 12% (Equation 7 and 8).

	$E_{c,0}$	$f_{c,0}$	D	G	ks	ks/d	mk	mk/d	p_{12}	r
$f_{c,0}$	0.74	1.00								
d	0.20	0.23	1.00							
G	-0.10	0.02	0.05	1.00						
ks	-0.54	-0.75	0.17	0.06	1.00					
ks/d	-0.62	-0.83	-0.32	0.02	0.87	1.00				
mk	-0.47	-0.63	0.30	0.07	0.90	0.70	1.00			
mk/d	-0.61	-0.77	-0.28	0.03	0.80	0.90	0.82	1.00		
p_{12}	0.66	0.62	0.10	-0.08	-0.48	-0.49	-0.48	-0.53	1.00	
r	-0.49	-0.58	-0.19	0.08	0.57	0.65	0.49	0.61	-0.49	1.00
u	-0.34	-0.77	-0.10	-0.05	0.68	0.69	0.58	0.64	-0.28	0.35

Table 55. Correlations coefficients between characteristics of machine processed round spruce for bending material. Modulus of elasticity in bending (E_m) is adjusted to corresponds to a moisture content of 12% (Equation 7).

	E_m	f_m	G	h	ks	ks/d	mk	mk/d	p_{12}	r	t
f_m	0.57	1.00									
G	-0.06	-0.15	1.00								
h	-0.05	-0.35	0.09	1.00							
ks	-0.26	-0.58	0.15	0.38	1.00						
ks/d	-0.22	-0.48	0.13	0.08	0.94	1.00					
mk	-0.31	-0.57	0.21	0.40	0.78	0.69	1.00				
mk/d	0.09	0.29	0.00	-0.32	-0.16	-0.01	0.12	1.00			
p_{12}	0.44	0.71	-0.12	-0.19	-0.57	0.41	-0.55	0.41	1.00		
r	-0.34	-0.69	0.14	0.40	0.70	0.59	0.66	-0.45	-0.73	1.00	
t	0.05	0.23	0.01	-0.15	-0.36	-0.32	-0.26	0.30	0.39	-0.44	1.00
u	0.13	-0.20	0.08	0.19	0.00	-0.05	-0.04	-0.11	-0.01	-0.14	0.06

Table 56. Correlations coefficients between the characteristics of machine processed spruce for compression material. Modulus of elasticity ($E_{c,0}$) and ($f_{c,0}$) strength in compression are adjusted to correspond to a moisture content of 12% (Equation 7 and 8).

	$E_{c,0}$	$f_{c,0}$	d	G	ks	ks/d	mk	mk/d	p_{12}	r
$f_{c,0}$	0.89	1.00								
d	-0.31	-0.22	1.00							
G	-0.15	-0.14	0.07	1.00						
ks	-0.71	-0.65	0.34	0.18	1.00					
ks/d	-0.56	-0.56	-0.14	0.16	0.86	1.00				
mk	-0.52	-0.50	0.33	0.17	0.75	0.62	1.00			
mk/d	-0.29	-0.34	-0.30	0.10	0.51	0.71	0.78	1.00		
p_{12}	0.84	0.82	-0.23	-0.10	-0.54	-0.41	-0.36	-0.17	1.00	
r	-0.83	-0.75	0.46	0.15	0.64	0.43	0.49	0.18	-0.71	1.00
u	0.10	-0.12	0.07	0.05	-0.01	-0.03	0.11	0.08	0.02	-0.13

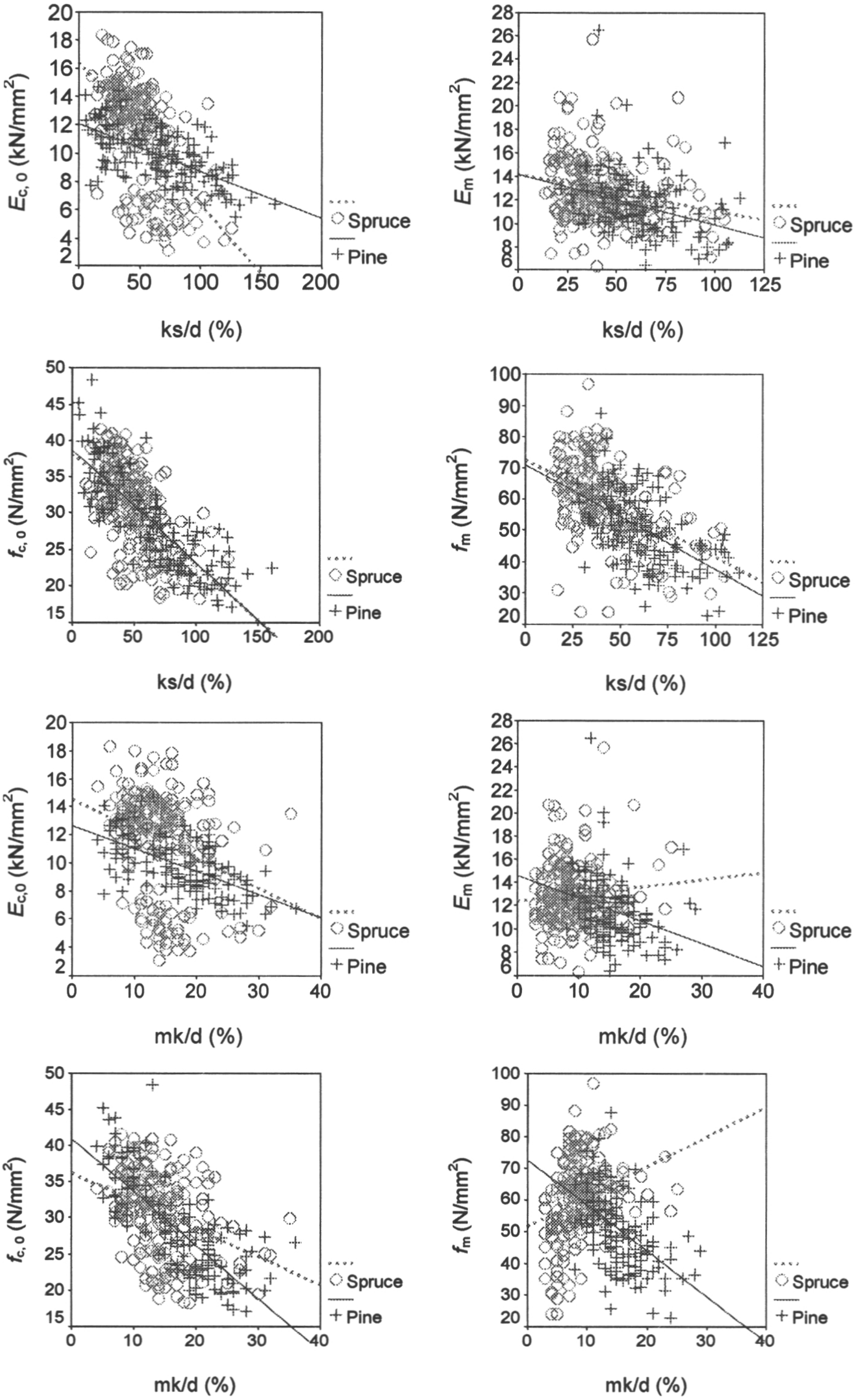


Fig 65. Mechanical properties adjusted to correspond to a moisture content of 12% (Equation 7 and 8) versus knot sum and diameter of the thickest knot in relation to diameter, ks/d and mk/d, respectively. The linear trend lines are presented, as well.

Ring width, knot sum and diameter of the thickest knot in relation to the round timber's diameter are applicable parameters for visual strength grading parameters for machine processed round pine and spruce, similar results were observed by Ranta-Maunus (1999).

7.3 DETERMINATION OF STRENGTH CLASSES OF MACHINE ROUND PINE AND SPRUCE MEETING THE REQUIREMENTS OF GRADE A AND B TIMBER

Normally, grading criteria are decided at first and then is analyzed what strength class they yield. In here, grading criteria specified in the EU project Small Diameter Round Timber for Construction (EU – Fair Programme CT95-0091) were applied to the tested machine processed round pine and spruce (Table 4). Results are summarised in Tables 57 and 58 by the number of specimens meeting grading criteria and the mechanical characteristics of the sample. EN 384 standard (1995) was applied in analyses.

The pine material comprised of 150 machine processed specimens for bending and compression of which 52 bending specimens and 47 compression specimens met the grade A criteria, and 127 bending specimens and 119 compression specimens met grade B criteria.

The spruce material comprised of 200 machine processed specimens for bending and compression of which 142 bending specimens and 149 compression specimens met the grade A criteria. The spruce material meeting grade A was divided into three samples according to the moisture content of specimens. In total, 186 bending specimens and 188 compression specimens met grade B criteria. The spruce material meeting grade B was divided into 4 sample according to the moisture content of specimens.

Table 57. 5-percentile values of graded machine round timber by species and sample for bending adjusted to correspond to the moisture content of 12 % in accordance with EN 384 standard (1995). Size adjustment for bending strength is presented, as well.

Species, sample and grade	n	Mean d (mm)	Mean u (%)	Mean ρ_{12} (kg/m^3)	ρ_{05} (kg/m^3)	$f_{m,05}$ / $f_{m,05\ size\ adj.}$ (N/mm^2)	$E_{m,mean}$ (kN/mm^2)
pine A	52	117	14.7	489	434	38.3 / 36.4	12.5
pine B	127	127	15.2	474	417	35.2 / 34.0	11.8
spruce 1 A	47	100	13.5	462	395	45.0 / 41.5	12.9
spruce 2 A	48	117	14.6	460	367	52.5 / 50.0	12.8
spruce 3 A	47	115	19.2	467	411	46.2 / 43.8	14.1
spruce 1 B	46	103	13.4	455	375	35.7 / 33.1	13.4
spruce 2 B	46	107	14.2	449	361	33.7 / 31.5	12.5
spruce 3 B	47	128	15.7	382	249	34.3 / 33.2	12.2
spruce 4 B	47	115	19.3	463	396	46.2 / 43.8	14.1

Table 58. 5-percentile values of graded machine round timber by species and sample for compression adjusted to correspond to the moisture content of 12 % in accordance with EN 384 standard (1995).

Species, sample and grade	n	Mean d (mm)	Mean u (%)	Mean ρ_{12} (kg/m^3)	ρ_{05} (kg/m^3)	$f_{c,05}$ (N/mm^2)	$E_{c,0,mean}$ (kN/mm^2)
pine A	47	124	11.1	507	435	28.6	11.3
pine B	119	123	13.8	477	405	21.8	10.3
spruce 1 A	49	100	13.8	447	381	28.2	12.8
spruce 2 A	50	101	14.6	458	390	29.6	13.5
spruce 3 A	50	109	18.7	443	364	25.1	13.3
spruce 1 B	47	99	13.8	443	370	21.5	12.2
spruce 2 B	47	106	14.3	433	343	21.2	12.2
spruce 3 B	47	117	15.7	395	286	20.3	9.2
spruce 4 B	47	107	19.1	443	361	22.1	13.2

The equivalence between the visual grades and strength classes is shown in Tables 59 and 60. EN 338 and EN 384 standard (1995) were applied in analyses. The mean values of grading parameters, ring width, knot sum and diameter of the thickest knot in relation to the diameter of timber, were quite close to each other for grade A and B timber for both tree species. The characteristic values and strength classes were therefore close to each other, as well. It attempted to use only the specimens in grade B, which were rejected by grade A criteria but approved by grade B criteria. As a consequence, enough specimens were not left for analysis of characteristic values in accordance with the EN standards. Considering the characteristic values of modulus of elasticity in bending ($E_{m,mean}$), compression strength ($f_{c,k}$) bending strength ($f_{m,k \text{ size adj.}}$) and mean density ($\rho_k$), the following conclusions were obvious for the equivalence between visual grades and strength classes:

- grade A for pine = C27.
- grade B for pine = C18.
- grade A for spruce = C30.
- grade B for spruce = C22.

If size adjustment is not taken into account, grade A for pine also belongs to the C30 strength class. Recommended equivalence between visual grades and strength classes are then as follows:

- grade A for pine and spruce = C30.
- grade B for pine and spruce = C18.

Table 59 . Characteristic values of the graded populations, their CEN strength class and mean values of physical properties in bending. Bold property limit the grade and sample to strength class.

Species	Grade	k_s	$f_{m,k}$ / $f_{m,k\ size\ adj.}$ (N/mm^2)	$E_{m,mean}$ (kN/mm^2)	ρ_k (kg/m^3)	**Strength class**	Mean a (year)	Mean ks/d (%)	Mean mk/d (%)	Mean r (mm)	Mean t (mm/m)
Pine	A	0.79	30.3 / **28.8**	12.5	434	**C27**	22	51	13	2.7	1
Pine	B	0.86	30.3 / 29.2	**11.8**	417	**C24**	21	57	15	3.2	2
Spruce	A	0.91	43.6 / 41.1	13.3	**390**	**C30**	32	33	9	1.8	4
Spruce	B	0.95	35.6 / 33.7	13.1	**345**	**C22**	28	40	9	2.2	4

Table 60. Characteristic values of the graded populations, their CEN strength classes and mean values of physical properties in compression. Bold property limit the grade and sample to strength class.

Species	Grade	k_s	$E_{c,0,mean}$ (kN/mm^2)	$f_{c,k}$ (N/mm^2)	ρ_k (kg/m^3)	**Strength class**	Mean a (year)	Mean ks/d (%)	Mean mk/d (%)	Mean r (mm)
Pine	A	0.79	**11.3**	22.6	435	**C24**	27	27	9	2.3
Pine	B	0.86	**10.3**	18.7	405	**C18**	21	54	15	3.1
Spruce	A	0.91	13.2	25.1	**378**	**C27**	26	42	13	1.9
Spruce	B	0.95	11.7	20.2	**340**	**C22**	24	48	14	2.3

7.4 DETERMINATION OF THE CORRELATION COEFFICIENT BETWEEN BENDING STRENGTH AND MODULUS OF ELASTICITY FOR ROUND TIMBER

Fig. 66 shows relationships between bending strength (f_m) and modulus of elasticity (E_m) for all tested machine processed round pine and spruce. The corresponding relationships are also shown between bending strength (f_m) and modulus of elasticity (E_m) for samples calibrated machine round pine 226 - 275 and spruce 176 - 225 (see Table 7). Correlation coefficients were low, 0.38 and 0.40 for machine round pine and spruce, respectively. The correlation were higher, 0.50 and 0.62, when only calibrated machine round pine and spruce were considered.

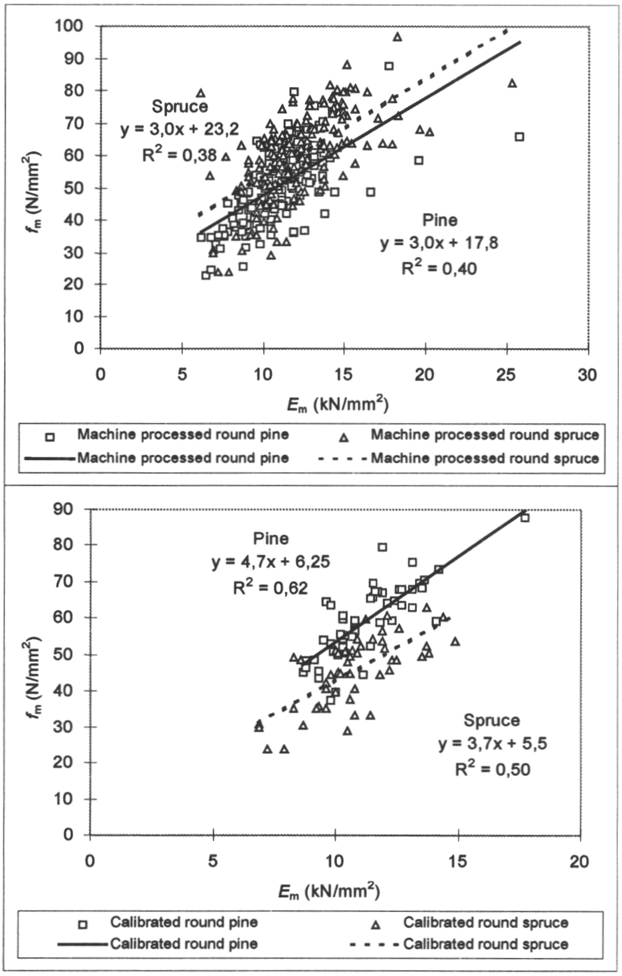


Fig. 66. The relationships between bending strength (f_m) and modulus of elasticity (E_m) for all tested machine processed round pine and spruce (above). The corresponding relationships are also shown between bending strength (f_m) and modulus of elasticity (E_m) for the samples calibrated machine round pine 226 - 275 and spruce 176 - 225 (below, see also Table 7).

8. DISCUSSION

8.1 SOURCES OF ERROR, VALIDITY AND GENERALISATION

The following properties were measured and determined by either devices or other objective methods: age, density, moisture content, mechanical properties, ring width, size of timber and twisting. In addition, the following were subjectively determined with the help of devices: gross grain, knots and tapering. Possible sources of errors in measurements are as follows:

- Knot properties i.e. diameter of knot and knot sum, and dimensions of timber were measured manually by meter tape in every phase of the study. Random measurement errors could have occurred, since borderlines of knots were determined subjectively. In addition, some errors could be made, when recording the results of measurements. The measurement accuracy was 1 mm.
- The quality of the thickest knots was determined subjectively. It was assumed that borderline cases deviated randomly either as dead or sound knots. Again, more significant errors could have been made, during the recording of results.
- Twisting was measured with electric angle meter. A significant error could have occurred, when parallel twisting lines at the butt and top end of the specimens were drawn. This, however, was rechecked with the angle meter after the drawing of lines. Again, more significant errors could have been done, during the recording of results. The measurement accuracy was 0.1 degree.
- Age i.e. the number annual rings and ring width was determined from disks by scanning and use of the Windendro computer program. This program automatically determined these properties. The measurer ensured the result by observing the screen of the computer and when needed, changing it. Information obtained was recorded automatically. Because judgements were dependent on scanning results, measurer and computer program, some random errors could have been made.
- Moisture content was measured by oven drying, which is a simple and exact method. Again, some errors could be made, during the recording of results. The measurement accuracy was 0.1 percent.
- Density was measured by an immersion method, which is a simple and relatively exact method. Again, some errors could be made, during the recording of results.
- The bending and compression test procedure for the modulus of elasticity and strength was made in accordance with EN standards with the following differences:
  - In the bending test the span should be l = 18 d and in the compression test l = 6 d, where d is the mean cross-sectional diameter. Because the diameter of some specimens varied and the form of some specimens was conical neither the span nor length were exactly similar, as prescribed in the EN standards.

When the diameter of the timber was constant along the length, the span was 18 times the diameter. When the actual diameter was not processed to a constant diameter, the span corresponding to the top diameter of the sample was taken from Table 8.
   - These differences had no significant influence on the results, since they were not shown to be significant in statistical analysis.
- The testing procedure took into account the minor rotation of the test piece during the bending test and minor buckling in the compression test.
- Testing of mechanical properties was performed in the VTT Building technology laboratories of Otaniemi, Finland, which have certified testing machines. Testing data was recorded manually in the bending test and automatically in the compression test. Therefore, for the bending test in particular, some errors could be made, during the recording of results. The measurement accuracy was 1 % both in deformation and loads.

Bending and compression test material for testing the modulus of elasticity and strength deviated to those prescribed in EN standards as follows:
- The moisture content of the specimens was higher than the reference condition of 12%. Moisture adjustment, according to the EN 384 (1995) standard, should be carried out at the 5-percentile or the mean value to the reference moisture content when the mean moisture content of the sample is in the range of 10% to 18%. In some cases the moisture content of the sample, mean or 5-percentile, was more than 18%.
- Individual diameters of tested specimens deviated from the 150 mm reference diameter for bending.

These differences in testing of mechanical properties were included on purpose in order to study the effects of moisture content and diameter of specimen on the mechanical properties. These differences are not assumed to cause any significant errors in study results.

The measurements involve always a risk of systematic errors. A systematic error cause problems, since its alter reality and comparison of results to other studies are difficult, in particular. In this study, measurements were partly done with certified devices, which reduces possible risks of systematic errors.

Multiple regression models 1, 2, 5, 6 and 7 had relatively low multiple coefficient of determination and Models 8, 9 and 10 had high multiple coefficient of determination. However, all variables were statistically significant and effects of single variables in models 1, 2, 5, 6, 8, 9 and 10 had similar trends than in tested material (figs. 19, 26, 27, 28, 31, 32, 33, 34, 36, 37, 38, 39, 40, 41, 42, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57 and 58). In addition, studied specimens were full-size, but some properties, like age, density, moisture content and ring width were determined only one or two places of specimens. These properties can have a relatively large variation within specimen and therefore add variability. This might be one reason for the relatively low multiple coefficient of determination of multiple regression models 1, 2, 5, 6 and 7.

Logistic regression Models 3 and 4 had high significance and all variables were statistically significant and effects of single variables in models had similar trends than in tested material (figs. 22, 23, 24 and 25). However, the prediction in change of knot quality from dead to sound did not successfully as well as the prediction of knots remained dead, both in pine and spruce. The reason might be that the quantity of knots changed to sound was smaller than knots remained dead. However, the quantity of knots changed to sound were enough for logistic regression analysis in both cases (Table 17).

Effect of origin of timber was found in Models 1, 2, 3, 9 and 10. Effect of origin is difficult to characterise, since its involve various factors, like soil fertility, stand density, tree social status and history. Effects of these factors cannot be determined in this study.

The studied material included a large variation in wood characteristics, physical and mechanical properties of Scots pine and Norway spruce from thinnings, although the material comprised of only four pine and two spruce stands, from Southern Finland. The variations within the stand and tree species and between the stands were great, as well. However, according to Figs. 19, 27, 35, 38, 39, 40, 41 and 42, the range of age, diameter/height, density, knot area ratio, moisture content and ring width of pine and spruce are all rather similar. Although according to Tables 10, 17, 24 and 35, the mean values and standard deviations of the wood characteristics and physical properties of the samples presented in Table 7 were not equal. The applied statistical method, regression analysis, supposes that the dependent variable is normally distributed and the dependent variables corresponding to different values of independent variable have similar variances (Bowerman and O'Connell 1990). The performed regression models met these requirements moderately.

The study comprised of sections of basic and applied research. In the applied part, the effects of various properties including mechanical properties are presented at moisture content levels of 12% and 18%. Because the studied material actually comprised of only a few specimens at a moisture content of 12% and age level as low as 5 years, some results with regards the effects of moisture content and age are based on minor extrapolations. However, this is not believed to significantly affect the validity of the conclusion presented considering the given level of generalisation in this study.

The applied wood processing methods did not have equally random distribution considering the origin of timber and tree species. This was, from the point of view of economics and time consumption, the most reasonable method to perform the study. If the wood characteristics and the physical properties of the material are considered, the wood processing methods were somewhat randomly distributed with regards the material. Growth conditions have a straight effect on wood characteristics and physical properties. These properties determined greatly the studied properties: knottiness, drying deformations and mechanical properties of timber.

Consequently it is believed that the results of the study are not significantly affected by the interaction of the wood processing method, tree species and origin of timber. Therefore results of the statistical analysis of the study are valid. However, there is a risk, that possible differences between samples could be induced not by processing method but due to different growth conditions. However, the results of the statistical analysis concerning wood processing are described only specimens where the same wood processing method was applied. The other conclusions drawn in this study are not significantly affected by the possible statistical interaction between the origin of timber and wood processing methods.

In general, the factors found in this study affecting knots, twisting and mechanical properties can be generalised for pith enclosed pine and spruce timber produced from butt logs up to four meters stem height originated from forest site types MT and VT in Southern Finland where age of obtained timber ranges from 5 to 50 years and diameter ranges from 50 mm to 180 mm. This concerns machine round pith enclosed timber, in the first hand. However, the degree of the effects has to be conservatively generalised.

8.2 COMPARISON OF THE RESULTS TO PREVIOUS STUDIES

8.2.1 Knots

The origin of wood affects the amount of knots in timber (Heikinheimo 1953, Kellomäki and Tuimala 1981, Uusvaara 1985 and Mäkinen 1999). The diameter of branches increases proportionally slower than the diameter of the stem (von Wedel et al. 1968). These results are in agreement with this study's observation that knot area ratio i.e. knot sum per circumference, of pith enclosed pine and spruce timber increases with the reducing circumference of timber. This result is also in consistent with hypothesis of the study. Pietilä (1989), however, reported that Scots pine have a clear, approximately linear, positive correlation between diameter of inner knot and visible knot. According to Ager (1972), the sum of branch diameters of pine and spruce depend on the diameter of the stem at breast height (1.3 m).

According to this study, radial distance from the surface where the dead knot over bark changes to sound is dependent on the knot diameter over bark and the original size of timber both for pine and spruce. From the trend lines in Fig. 20 for pine and spruce it could be concluded that the knots regularly changed to sound were larger over bark than the knots remained dead after wood processing. This is due to the fact that the larger the knot diameter is the longer the branch has been alive i.e. sound. This result is in consistent with hypothesis of the study. Johansson (1992) found that for Norway spruce the height of the first living branch and the thickest branch diameter have a correlation (0.61) agreeing with a similar trend found in this study. Mäkinen and Colin (1999) concluded that for Scots pine that the probability of the branch being alive is connected to its age, tree age, tree height in relation to breast height diameter and its relative diameter within the branch whorl. In this study, dead knots over bark changed with a high probability, more than 70 %, to the sound knots to the very close, about 15 mm, from the wood surface. Thinning wood is young and small-sized; therefore the knots dead over bark have, in general, been dead for only a few years, resulting in only a narrow radial dead knot zone close to the surface of the stem.

According to this study, for spruce the faster the growth and higher the location of knots in the stem the closer to the bark the dead knot changed to sound. The origin of wood affected the radial position when the dead knot over bark change to the sound, Mäkinen et al. (2000) concluded similarly. This result is also in consistent with hypothesis of the study. The high growth rate is also a result of vigorous crown i.e. living branches. The branches close to the base of the stem have worse living conditions than the branches higher in the stem. Therefore, branches close to the base die earlier with a higher probability than the branches upper in the stem.

8.2.2 Drying deformations

In this study it was found that age i.e. number of annual rings of wood has a great effect on the twisting of pith-enclosed pine and spruce. This result is in consistent with hypothesis of the study. Perstorper (1994) concluded that the ratio of grain angle to pith distance is the best parameter for the prediction of twisting. Krempl (1970), Danborg (1994a) and Ormarsson (1995) showed that the twisting of boards is dependent on their radial location in a log. The closer the location is to the pith the more severe is the twisting. In this study, an interaction was found between moisture content and age for spruce, in particular. A possible reason for this is that juvenile wood contains more lignin and hemicelluloses than mature wood. A low or reduced hemicelluloses content has been associated with the high dimensional stability of timber (Hillis 1984). In addition, chemical composition i.e. the extractives, and physical organisation of skeletal cell wall affect water-vapour sorption by wood (Wangaard and Granados 1967). The effect of moisture content is in consistent with hypothesis of the study, but unexpected phenomena was interaction between age and moisture content.

Twisting of pith enclosed timber could cause problems for prefabricated components, which have to be assembled and are exposed variations in humidity. For example, twisting of pith enclosed pine and spruce, was about 1.5 °/m at the moisture content of 18% and age of 20 years. If the diameter and length of round timber are 125 mm and 3 meters, respectively, the deviation on the timber surface caused by twisting is 5 mm (Equation 17). Depending on the structure, the effect is negligent or a detrimental fault. In round timber, in particular, other drying deformations were not detrimental, because a piece of round timber does not have opposite sides, where the opposites stresses could consequently develop and cause crook or bow. Warping of a board is caused by differences in longitudinal shrinkage in different parts of the board (Kollman and Côte 1968, Skaar 1988).

8.2.3 Density and mechanical properties

Pape (1999) achieved a similar relationship between ring width and density for Norway spruce (Picea abies) as reported in this study. In addition, Hakkila (1996) achieved a similar difference in densities between pine and spruce at the same ring width as this study. At similar ring width, the density of Scots pine is higher than that of Norway spruce. The smaller the ring width the smaller the difference.

Mechanical properties are determined greatly by visual characteristics and physical properties of wood, Blass et al. (1995) concluded similarly. This result is also in consistent with hypothesis of the study. Differences between stands, however, were found in this study for compression: spruce stand number 6 differed negatively from other stands for the modulus of elasticity in compression and pine stand number 4 differed negatively from other stands for the compression strength. However, these stands did not differ from other stands in terms of bending. Therefore, the differences were probably induced by inner defects of timber, such as the presence of inner knots and reaction wood, which were not measured directly in this study.

Round timber has high strength with little strength variability, because the timber is processed conservatively. Therefore, wood fibres of round timber are not cut and the continuous fibres guide stress smoothly around knots (Mäkipuro 1981, Blass et al. 1995, Ranta-Maunus 1999, Boren and Barnard 2000). For bending, mechanical wood processing had negative effects on modulus of elasticity and strength. This is due to the fact that processing breaks outer wood fibers, especially close to knots increasing these effects. The plane (sawn) surface in tension stress had a negative effect on bending strength compared to the round form in this study. These results are in consistent with hypothesis of the study. In bending, a round specimen has a smaller volume under stress than a rectangular specimen in bending. Therefore, the probability that round timber has a weak point in the high stress zone is relatively lower than for rectangular timber. According to Nakai et al (1994), the cross sectional form of timber has an effect on the bending performance of Sugi (Cryptomeria japonica D. Don). The average modulus of elasticity in round timber was 1.14 higher than square sawn timber. Similarly, the 5 th percentile bending strength of round timber was 1.32 times higher than square sawn timber. According to this study, modulus of elasticity and strength in bending are 5 to 15 % higher for round timber than for sawn timber. Ranta-Maunus et al. (1998) compared the bending strength and modulus of elasticity of round spruce (N=200) to those of sawn Norway spruce timber 42x145 mm (N=600). For testing and analysis, EN 338, EN 384, EN 408 and EN 518 standards were applied. Cumulative distributions of bending strength, modulus of elasticity and density obtained in the study are presented in Fig. 67. Density distributions were similar to this study except the lower 30% of round timber had a clearly lower density than sawn timber, with lower 5-percentiles of the distributions being 306 and 376 kg/m^3, respectively. However, the modulus of elasticity was fairly similar in the study. Bending strength of round timber was higher, lower 5th percentiles being 35.4 and 27.7 N/mm^2. If the low density material of round timber is disregarded so that the density distributions of sawn and round timber are similar, then the 5-percentile value of bending strength for round spruce is double the value of sawn spruce.

In this study no clear size effect on bending strength for pith enclosed timber was observed. This result is in consistent with hypothesis of the study. A high proportion of juvenile wood in smaller sections suggests that the strength of pith enclosed timber should increase with increasing diameter or height i.e. age, which is opposite to the EN 384 standard (1995) size adjustment for sawn timber. According to this study, the pith enclosed slow-grown pine and spruce have a small negative size effect and a rapid grown pine and spruce have a small positive size effect. For every growth rate, the position where the size effect turns from positive to negative is different. The effect of size on mechanical properties, especially in tension, have been explained by the weakest link theory (Blass et al. 1995). This theory states that when subjected to tension, a chain is as strong as its weakest link. In the case of compression and bending the use of this theory is debatable. For visually graded lumber, defect size increases with size of the timber. This means that the material changes with the size, which can mask a pure size effect. In particular, when the size effect is investigated in a mixture of grades, the effect of grading has an influence on the size effect (Barrett and Lam 1992, Rouger et al. 1993, Blass et al. 1995, Ranta-Maunus 1999, Boren and Barnard 2000). In conclusion, the size adjustment of EN 384 standard (1995) for bending strength should not be used for pith enclosed timber.

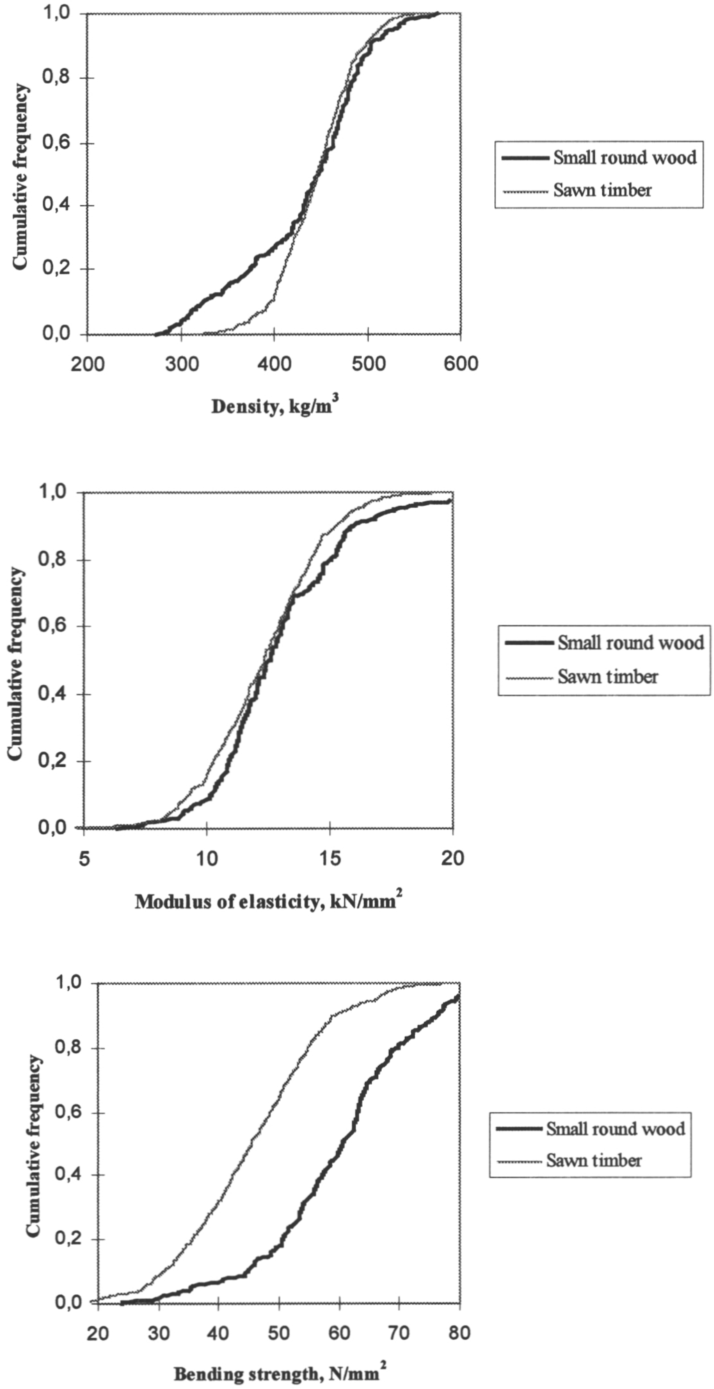


Fig. 67. Comparison of density, modulus of elasticity and bending strength of round and sawn unsorted spruce timber (Ranta-Maunus et al. 1998).

In this study, at the similar density, spruce was stronger than pine. This result is in consistent with hypothesis of the study. Lipitsäinen (1994a) stated similarly. This was due to the fact that pine contains more extractives than spruce (Hakkila 1968, Kärkkäinen 1981). In this study, at similar ring width, the pine was somewhat stronger and stiffer than spruce. The relationship between ring width and mechanical properties was similar to the relationship between ring width and density (Fig. 35). Although ring width and density have a clear relationship, ring width still effects mechanical properties. For example, Kärkkäinen and Hakala (1983) and Kärkkäinen and Dumell (1983) showed that the strength of spruce is greater in slow grown trees when compared to fast grown trees, even if density is considered.

Mechanical properties improved rapidly with an increase in age up to 20 years. This result is in consistent with hypothesis of the study. After that, the mechanical properties increased more slowly with the increasing age. The mechanical properties were about double at age of 30 years compared to age of 10 years. Bendtsen and Senft (1986) comprehensively studied the relationships between age, mechanical and anatomical properties of plantation-grown eastern cottonwood and Loblolly pine. The form of relationships between mechanical properties and age were similar to those found in this study (see Figs. 8, 36 and 37). Average mechanical properties of juvenile wood ranged from 47% to 63% for mature pinewood and from 62% to79% in cottonwood. The age of demarcation between juvenile wood and mature wood varied by species and property, ranging from 13 to 20 years. Leban and Haines (1999) showed that the modulus of elasticity of hybrid larch could be predicted by age, rings per centimetre and density of the specimens. They also concluded that prediction is possible without density. Nakai et al. (1994) concluded that the modulus of elasticity in 50 to 60 year old Sugi (Cryptomeria japonica D. Don) is 1.4 to 1.6 times higher than that obtained in 20 year old thinning Sugi.

Previous studies (Hoffmeyer 1978, Madsen 1975, Madsen et al. 1980) showed that the effect of moisture content on bending strength is low or even negligible at the 5-percentile level. The explanation was that defects of wood have a greater effect on strength at the 5-percentile level than at higher strength levels. Therefore, the negative effects of moisture content do not show at 5-percentile level. In this study, strength at 5-percentile level was high, which resulted in greater effects of moisture content on the mechanical properties. In addition, it was previously shown that the higher the density or strength the greater the effect of moisture on mechanical properties (Siimes 1967, Kollman and Côte 1968, Hoffmeyer 1978, Madsen 1975, Madsen et al. 1980). High density indicates a high volumetric percentage of cell wall in wood, where the moisture can penetrate and weaken cell wall structure. The statistical analysis of this study showed, however, an interaction between age and moisture with density considered. The effect of moisture content on mechanical properties is in consistent with hypothesis of the study, but unexpected phenomena was interaction between age and moisture content. In juvenile wood, the microfibril angle is greater than in the mature wood. Zobel and van Buijtenen (1989) reported that the chemical composition of wood has an influence on mechanical properties, for example tension strength decreases with increases in the amount of lignin. Juveline wood comprises more hemicellulose and lignin than mature wood. Olesen (1977) showed a rapid increase in tracheid diameter with increasing ring number from pith in Norway spruce. The tangential tracheid diameter was about 15 μm around the pith and increased rapidly to about 30 μm in ring no. 10. In conclusion, there are a greater number of tracheids and gaps per cross-sectional area close to the pith than in outer rings. In addition, there are more tracheids per unit and tracheids comprise more lignin and hemicellulose and have greater microfibril angle in juvenile wood than mature wood. The different chemical composition and cell structure are possible explanations for the greater effect of moisture content on twisting and mechanical properties in juvenile wood than mature wood with a similar density.

An interaction was observed in this study between knots and timber size i.e. the relative amount of knots in timber size has an influence on the modulus of elasticity and strength in bending and compression. This result is in consistent with hypothesis of the study. This fact is commonly used as a visual strength grading criteria (Lipitsäinen 1994a, 1994b, Blass et al.1995). In bending, the knots located in the tension zone had no particular effect on bending strength and modulus of elasticity, Isaksson (1999) concluded similarly. Furthermore, in bending machine processing interacted with knots, a wood surface with knots increased the negative effect of machine processing, because it breaks outer wood fibers especially in the vicinity of knots.

The results of this study elaborate on the strength grading rules (Lipitsäinen 1994a, 1994b) that when strength grading is established by density, pine and spruce should be graded with different rules. This result is in consistent with hypothesis of the study. However, grading according to knots and ring width is possible on the basis of the same rules for pine and spruce and origin of timber should also be taken into account in visual grading.

The relationship of characteristics of compression strength $f_{c,\,o,\,k}$ and bending strength $f_{m,\,k}$ achieved in this study is lower than given in EN 384 standard (1995). On average, the moisture adjustment of the EN 384 standard (1995) is rather similar for the modulus of elasticity and compression strength as that achieved in this study. However, for compression strength and modulus of elasticity the moisture adjustment for fast-grown pith enclosed timber should be double compared to that in the EN 384 standard (1995).

In this study, the correlation coefficient between bending strength (f_m) and modulus of elasticity (E_m) were low, with 0.38 to 0.40 for round timber. In general, the correlation coefficient between bending strength (f_m) and modulus of elasticity (E_m) have been for sawn timber from 0.6 to 0.8 (Blas et al. 1995).

However, stronger correlations were found when considering only calibrated machine round specimens, with 0.50 to 0.62. Ross et al. (1997) concluded that the modulus of elasticity of a log correlates well with the average modulus of elasticity of lumber obtained from the same particular log. In addition, this relationship exists between the modulus of elasticity of individual lumber specimens of the same log. Ross et al. (2000) observed a close relationship between non-destructive evaluation of small-diameter Ponderosa pine logs and the quality of veneer obtained from those logs. Ridoutt et al. (2000) found a close relationship between non-destructive evaluation of radiata pine logs and the yield of structural timber from the same logs. In conclusion, the sawing of small-size thinning wood yield timber with a high probability of poor mechanical properties compared to traditional large-dimensional wood from final cuttings.

In the EU- project Small Diameter Round Timber for Construction (EU – Fair Programme CT95-0091), it was concluded that a common visual strength grading system should be established for small diameter round pine and spruce based on knot- related properties and ring width (Ranta-Maunus 1999). The selected grading parameters (Table 4) seemed to be convenient for yielding two separate CEN strength classes in this study (chapter 4.4).

9. CONCLUSIONS AND RECOMMENDATIONS

The conclusions drawn from this study can be summarised as follows as regards to knots:

1. The origin of wood affects the amount of knots of timber. Knot area ratio (KAR) of pith enclosed pine and spruce timber increases with the reducing circumference of timber, both in machine rounding and sawing.
2. After wood processing, round timber contains on average less visible knots than sawn timber. When keeping the round shape in wood processing instead of rectangular, the knot angle i.e. the angle between the timber surface and the knot, is optimum, minimising the knot area on the timber surface.
3. The radial distance from the surface of timber to the point where the dead knot changes to the sound is dependent on the relationship between knot diameter over bark and the original size of timber, both for pine and spruce. In addition, for spruce, the faster the diameter growth and the higher the location of knot in the stem is, the closer to bark the knot change to sound.
4. The origin of wood affects the distance of where the dead knot over bark changes to the sound for pine and spruce.
5. The probability of dead knots over bark changing to sound in very close to the wood surface (15 mm) is high, more than 70 % for pine and spruce.

The conclusions drawn from this study can be summarised as follows concerning drying deformations:

6. Twisting is great in pith-enclosed pine and spruce, about 1.5 °/m at moisture content of 18% and age of 20 years.
7. Age has a great the great negative effect on twisting in pith-enclosed pine and spruce specimens younger than 20 years. For older specimens, the effect of age diminishes with increasing age.
8. An interaction was found between moisture content and age for spruce, in particular. The younger the age is the higher the effect of moisture on twisting.
9. Effects of timber origin and form of the specimen are negligible with regards to twisting when timber with similar wood characteristics and physical properties is considered.
10. Twisting of pith enclosed timber could cause problems for prefabricated components, which have to be subsequently assembled and are exposed to humidity variations.
11. In round timber, drying deformations other than twisting are not detrimental.
12. In seasoning and conventional drying cracking takes place in pith enclosed timber, especially in round timber, because the surface of timber dries and shrinks while the proportionally larger inner part of round timber remains moist.

The conclusions drawn from this study can be summarised as follows with regards to physical and mechanical properties and strength classes:

13. At similar ring width, the density of pine was about 90 kg/m^3 higher than that of spruce, when considering wood from thinnings.
14. The origin of timber considered in this study did not have any remarkable effects on mechanical properties in bending, when visible wood characteristics and physical properties were considered.
15. The origin of timber considered in this study did have a significant effect on mechanical properties in compression, although visible wood characteristics and physical properties were considered.
16. For bending, mechanical wood processing has negative effects on modulus of elasticity and strength. This is due to the fact that processing breaks outer wood fibers, especially close to knots increasing these effects.
17. Plane (sawn) surface in tension stress zones has a negative effect on bending strength compared to round form. A round specimen has a smaller volume under stress than a rectangular specimen in bending. Therefore, the probability that round timber has a weak point in the zone of high stress is relatively low.
18. The form of the specimen does not have any significant effect on the modulus of elasticity in bending.
19. At similar density, spruce is stronger and stiffer than pine both in bending and compression, when wood from thinnings are considered.
20. The mechanical properties of pine and spruce increase almost linearly with increasing density.
21. At similar age and ring width, pine has about 2.5 N/mm^2 higher bending

strength than spruce, and about 2.0 N/mm^2 higher compression strength than spruce. Respectively, modulus of elasticity of pine is about 0.5 kN/mm^2 higher than that of spruce in bending, but at the same level in compression at the similar ring width and age. In general, modulus of elasticity and strength of pine and spruce timber can be considered similar, providing the specimens have the same physical properties and wood characteristics, other than density.

22. The relationship between ring width and mechanical properties follows the same pattern as that of ring width and density (Fig. 35).
23. Mechanical properties grow rapidly with increasing age upto 20 years and slower after that. Mechanical properties are the about double at the age of 30 years compared to the age of 10 years.
24. Bending strength decreases by 10 N/mm^2 and compression strength by 3 N/mm^2 while knot sum increases from 0 to 125 mm. The negative effect of knot sum is similar on the modulus of elasticity in bending and compression, about 2 kN/mm^2, when knot sum increases from 0 to 125 mm.
25. In bending, knots located in the tension zone have no particular effects on bending strength and modulus of elasticity.
26. There is an interaction between knots and timber size i.e. the relative amount of knots in timber has an influence on the modulus of elasticity and strength in bending and compression. Accordingly, different limits of absolute knot size are not necessarily needed for different sizes of timber, if the size of knots is compared to timber size.
27. The mechanical properties of sawn timber suffer due to the higher knot area ratio compared to round timber.
28. Moisture content affects modulus of elasticity and strength in bending and compression. The lower the age the higher the effect of moisture contents. On average, however, the effect is similar than as given by the EN 384 standard (1995). Unlike prescribed in this standard, bending strength should also be adjusted by moisture content.
29. Pith enclosed timber does not have any clear size effect with regards to bending strength. A high proportion of juvenile wood in smaller sections suggests that the strength of pith enclosed timber should increase with growing diameter or height i.e. age. This is opposite to the EN 384 standard (1995) size adjustment for sawn timber. According to this study, the pith enclosed slow-grown pine and spruce have a small negative size effect and rapid-grown pine and spruce have a small positive size effect. For every growth rate, the radial position, where the size effects turn from positive to negative is different.
30. For mechanical properties other than bending strength the size effect is clearly positive for pith-enclosed pine and spuce.
31. The relationship between compression strength and bending strength is lower for pith enclosed timber than as given by the EN 384 standard (1995). Therefore, judgements concerning strength class of pith enclosed timber cannot be established on the basis of the bending test only; the compression test should also be performed.
32. Density and mechanical properties of pith enclosed pine and spruce timber

produced from thinning wood are high enough for load bearing structures.

33. The strength class of C18 is only achieved with unsorted pith enclosed round pine and spruce timber.
34. Grades A and B (Table 4) defined for machine round timber in the EU-project Small Diameter Round Timber for Construction (EU – FAIR programme CT95-0091) are equivalent with the CEN-strength classes as follows:
    - grade A for pine and spruce = C30
    - grade B for pine and spruce = C18
35. Grades A and B and the respective CEN strength classes can be applied to manually debarked round pine and spruce, as well.
36. The correlation coefficient between strength and modulus of elasticity in bending for calibrated round timber were high enough for applications in machine strength grading. However, if tapered round timber is used, machine strength grading is not recommendable.
37. If sawing small-sized thinning wood there is a high probability that the timber produces will have poor mechanical properties compared to traditional large-dimensioned wood taken from final cuttings.

In general, hypotheses and results of the study were consistent with each other's. Surprising phenomena were the strong interaction effects of age and moisture content on twisting and mechanical properties. There were also found both minor positive and negative size effects for bending strength. It was initially assumed that there exists no size effects in pith enclosed timber. In addition, there was found that origin of timber has effect on modulus of elasticity and strength in compression, although it was initially assumed that the origin of timber should not have any effect on the mechanical properties when physical properties and characteristics of wood are considered.

More testing is needed to yield independent data to verify the degree of effects of factors of physical and mechanical properties for small-sized thinning wood found in this study. The external properties of log affecting inner knot characteristics in small-sized pine and spruce, such as knot sum and quality of knots was found in this study. Therefore it would be useful study, whether these relationships could be used for the determination of sawing or peeling sets in the wood industry. For example, Lemiux et al. (2000) developed a simulation model for the sawing and grading of black spruce timber according to knots measured on the log's surface. Effects of origin of timber should be studied more comprehensively, as well. The stabilisation methods to prevent drying deformations of timber are now an even more interesting subject to study and develop than was traditionally thought. Round form has better strength and modulus of elasticity in bending compared to rectangular form. Therefore it would be beneficial to develop a structural system, where round small-size timber can be used as load bearing material. Finally, mechanical properties of tested timber, in particular grade A and B round timber met the requirements of the EN standards for structural timber i.e. properly dried and graded round thinning wood can be used in load bearing structures.

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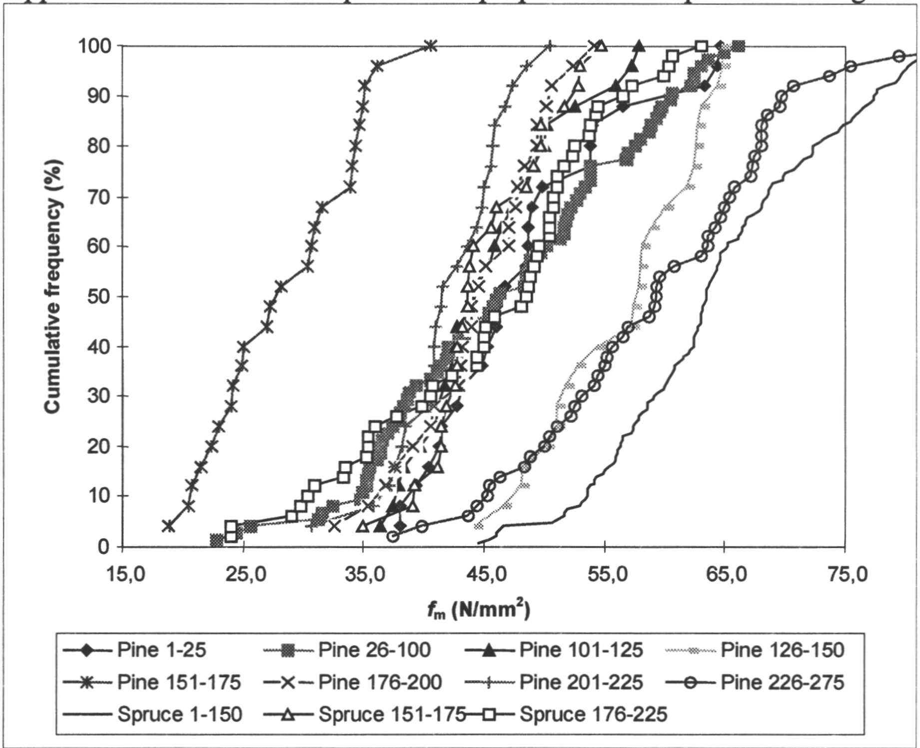
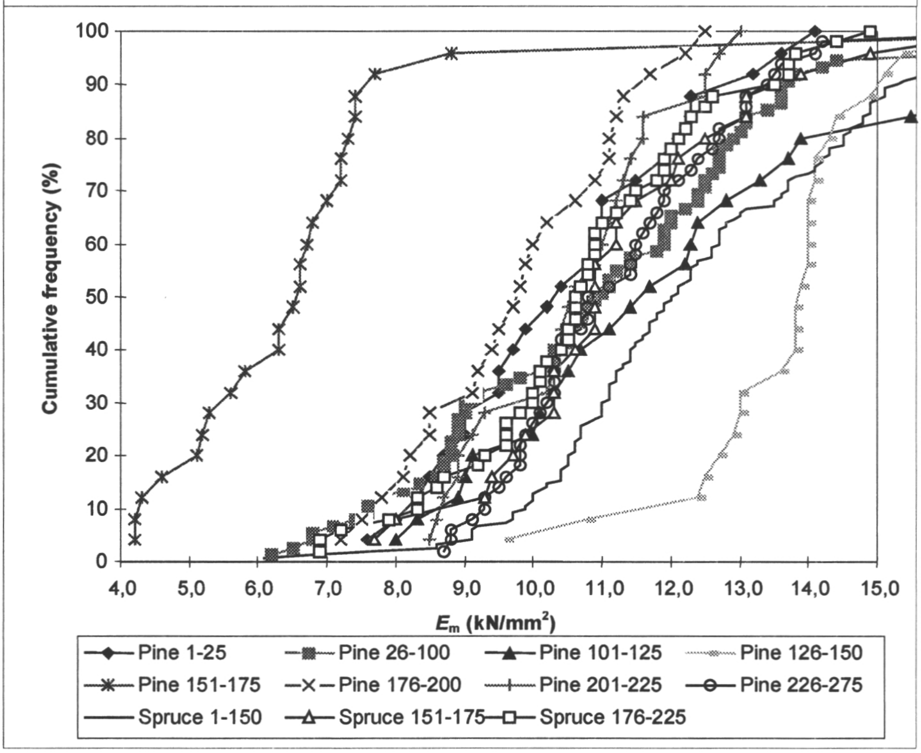
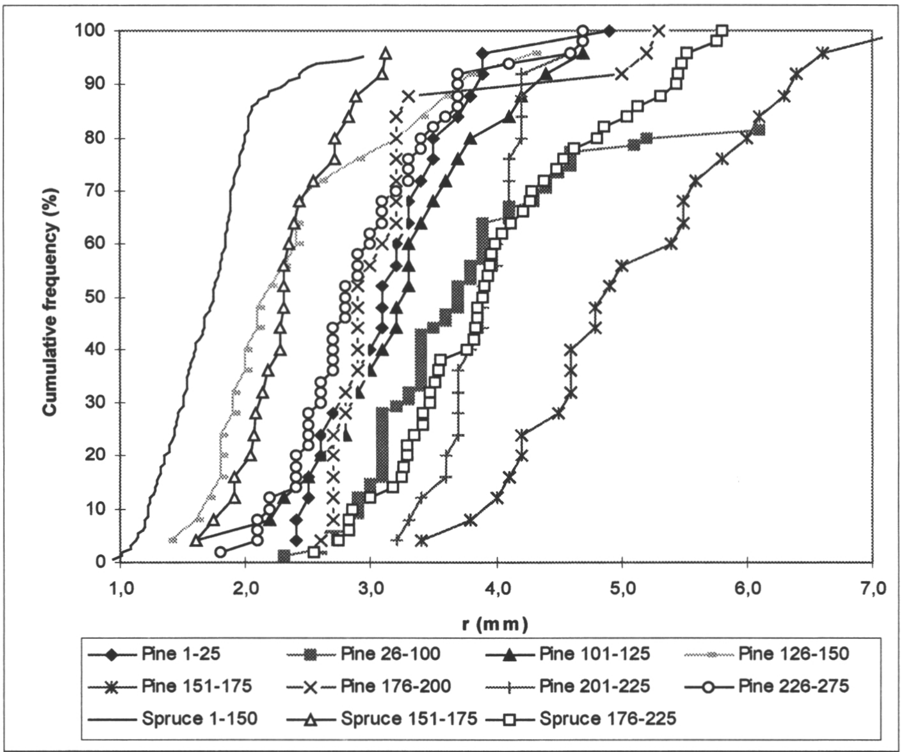
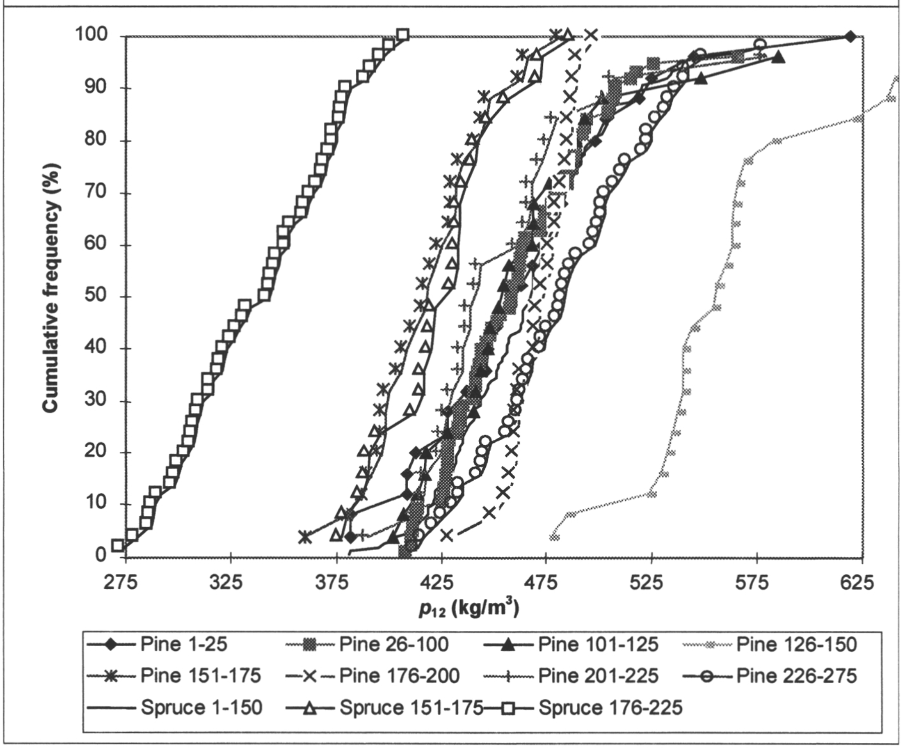
Appendix 1. Cumulative frequencies of properties of samples in bending test.



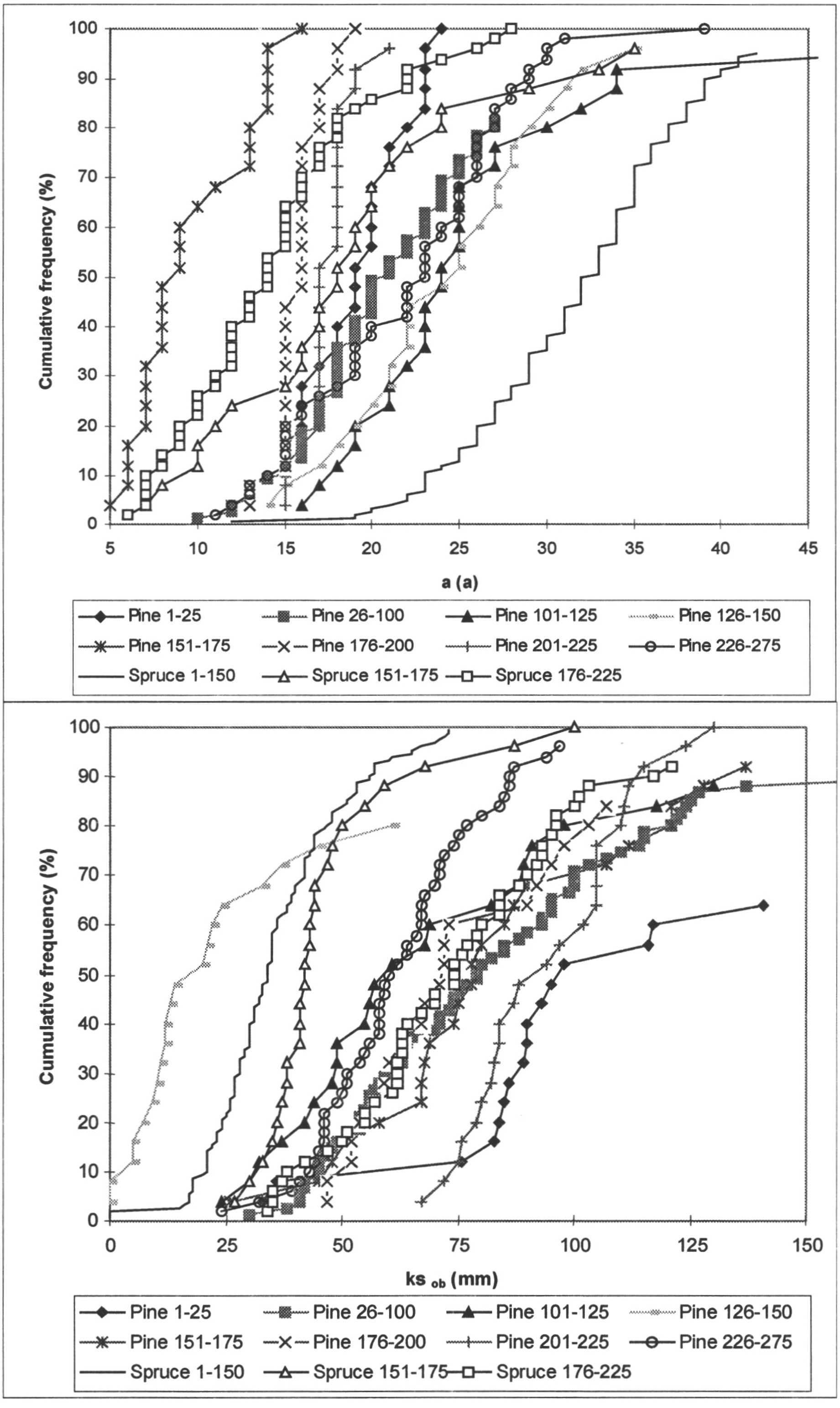


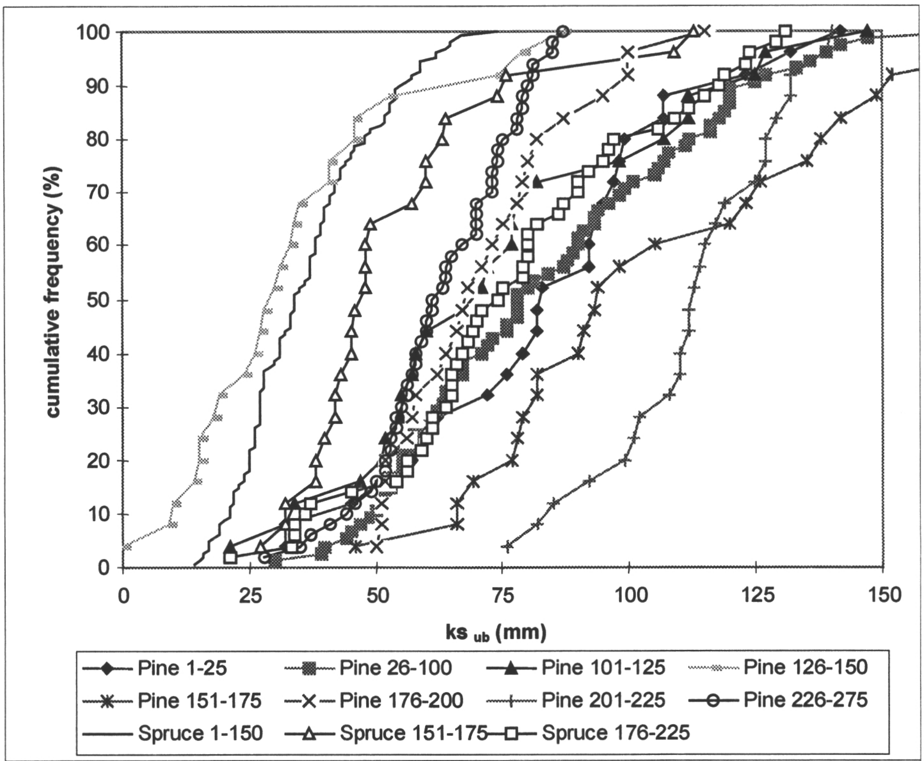


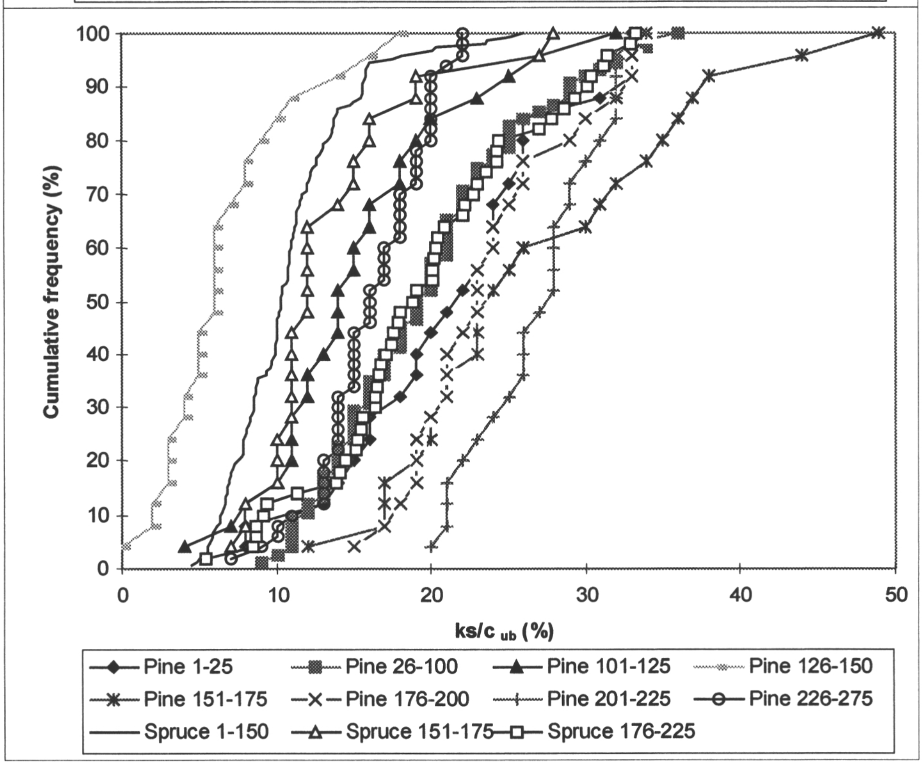
Cumulative frequency (%)
r (mm)
Pine 1-25
Pine 26-100
Pine 101-125
Pine 126-150
Pine 151-175
Pine 176-200
Pine 201-225
Pine 226-275
Spruce 1-150
Spruce 151-175
Spruce 176-225

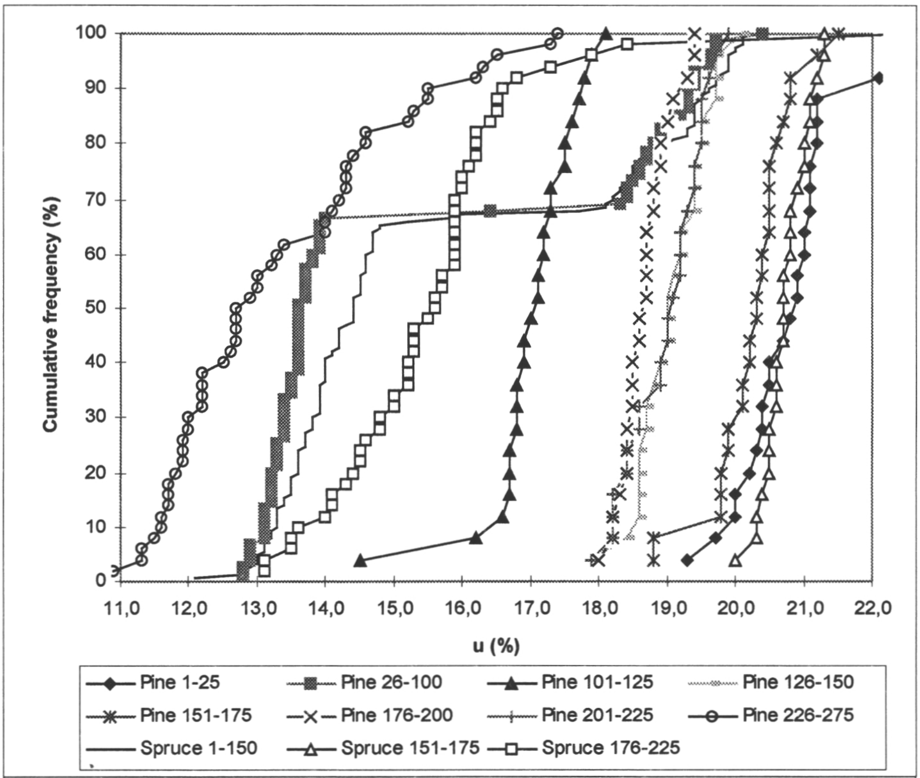


Cumulative frequency (%)
p_{12} (kg/m³)
Pine 1-25
Pine 26-100
Pine 101-125
Pine 126-150
Pine 151-175
Pine 176-200
Pine 201-225
Pine 226-275
Spruce 1-150
Spruce 151-175
Spruce 176-225

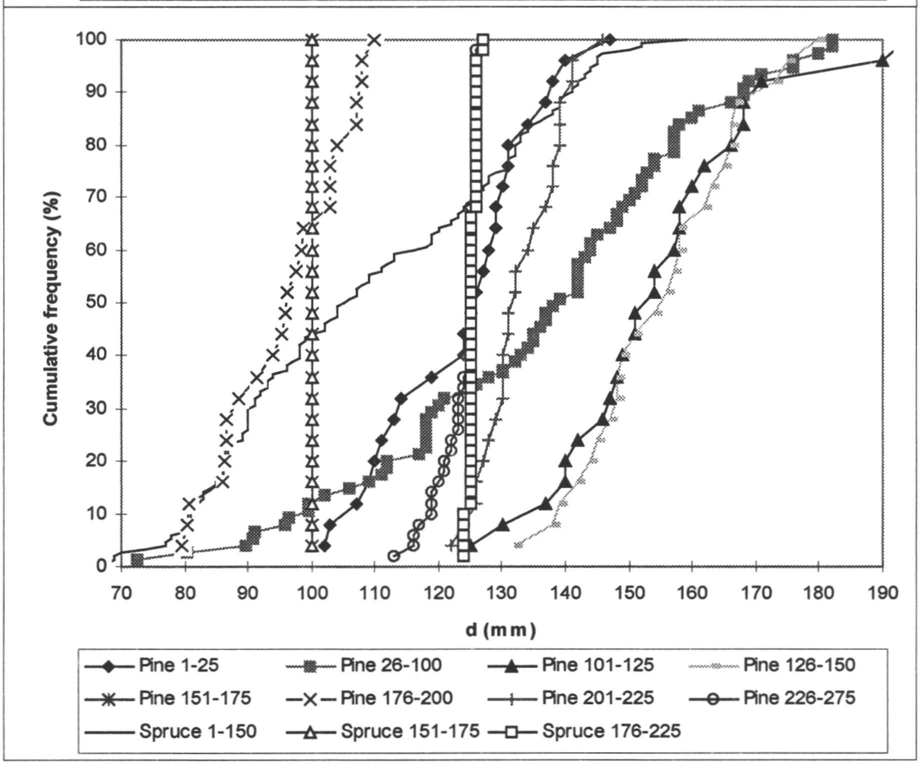

100
90
80
70
60
50
40
30
20
10
0
Cumulative frequency (%)
5
10
15
20
25
30
35
40
45
a (a)
Pine 1-25
Pine 26-100
Pine 101-125
Pine 126-150
Pine 151-175
Pine 176-200
Pine 201-225
Pine 226-275
Spruce 1-150
Spruce 151-175
Spruce 176-225
0
25
50
75
100
125
150
ks ob (mm)


cumulative frequency (%)
ks ub (mm)
Pine 1-25
Pine 26-100
Pine 101-125
Pine 126-150
Pine 151-175
Pine 176-200
Pine 201-225
Pine 226-275
Spruce 1-150
Spruce 151-175
Spruce 176-225


Cumulative frequency (%)
ks/c ub (%)
Pine 1-25
Pine 26-100
Pine 101-125
Pine 126-150
Pine 151-175
Pine 176-200
Pine 201-225
Pine 226-275
Spruce 1-150
Spruce 151-175
Spruce 176-225

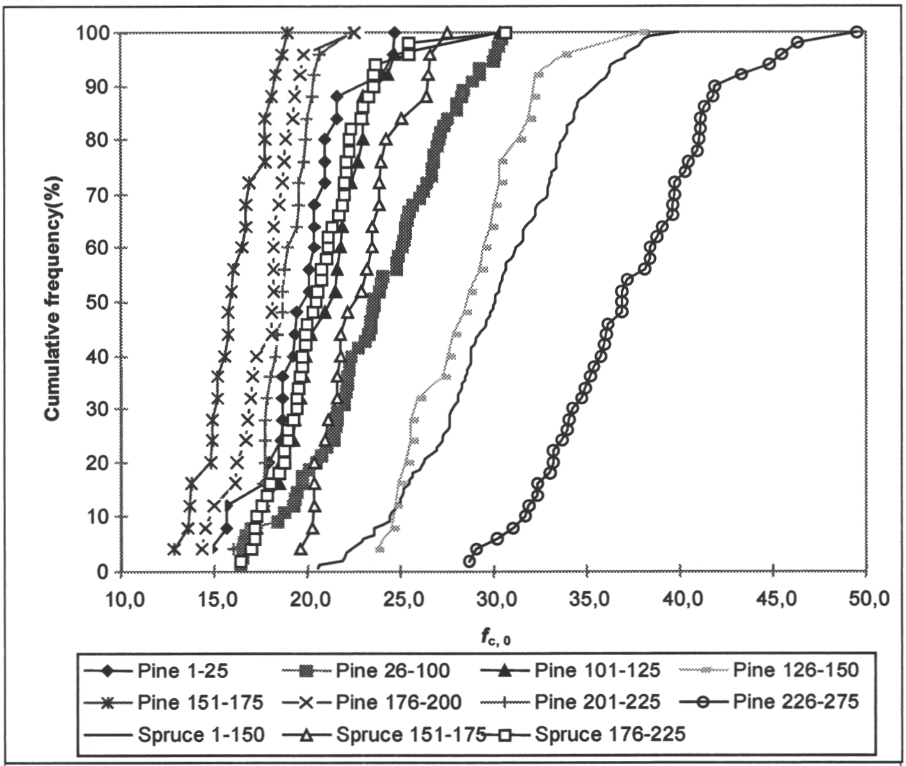


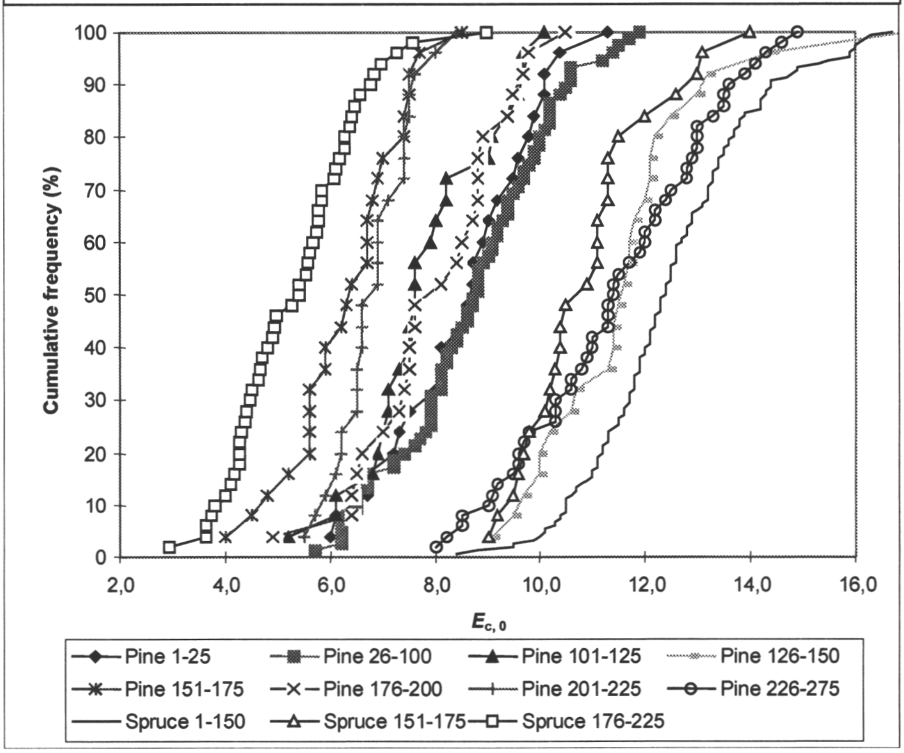
Cumulative frequency (%)
u (%)
Pine 1-25
Pine 26-100
Pine 101-125
Pine 126-150
Pine 151-175
Pine 176-200
Pine 201-225
Pine 226-275
Spruce 1-150
Spruce 151-175
Spruce 176-225

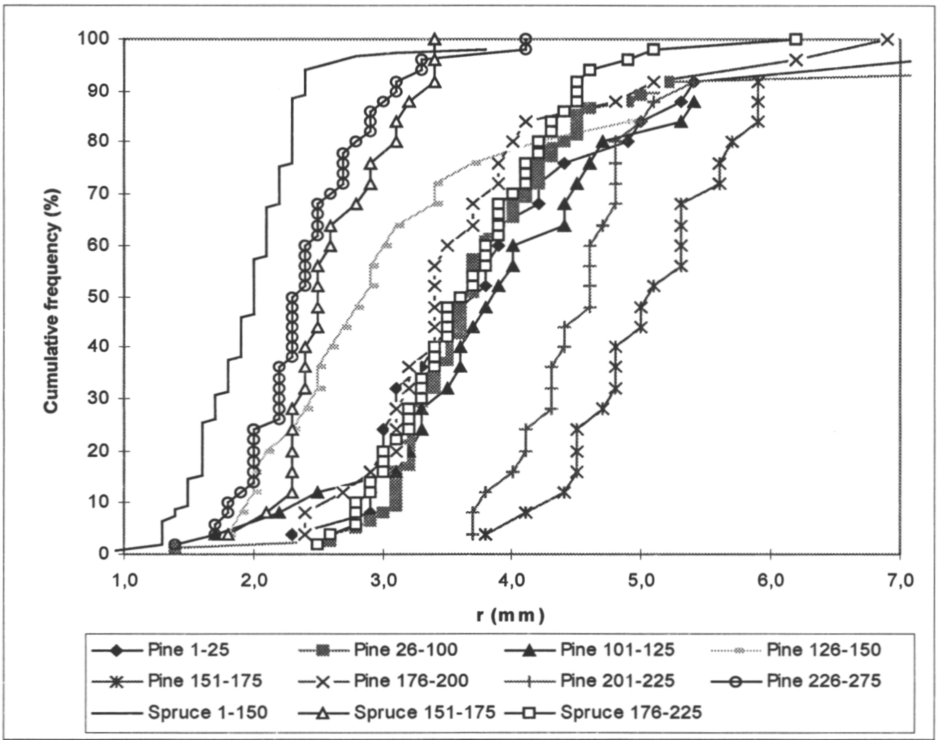


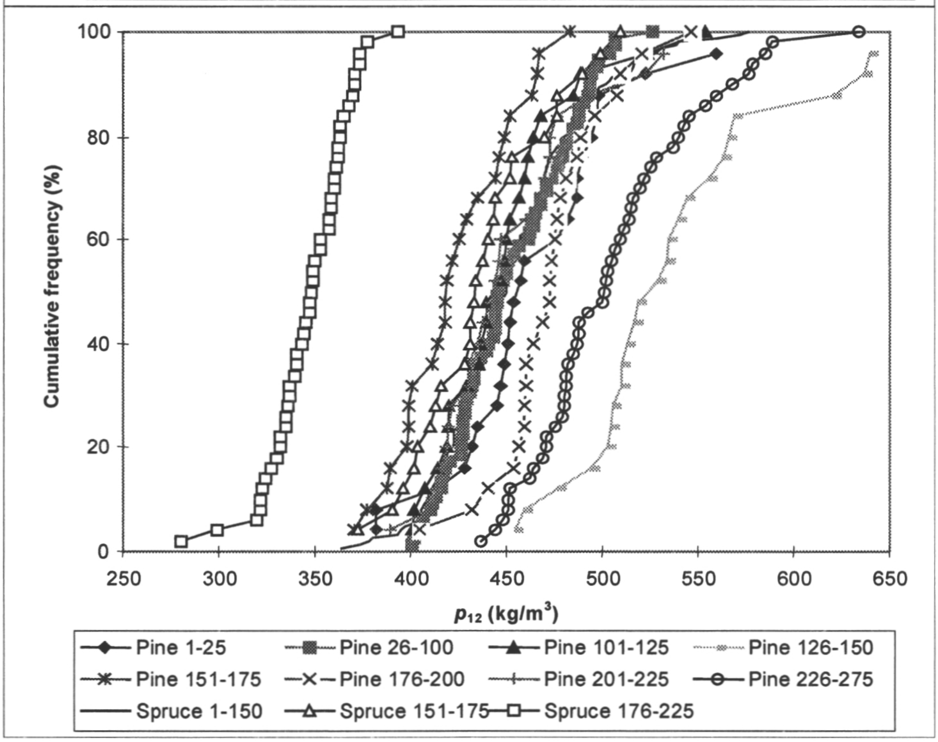
Cumulative frequency (%)
d (mm)
Pine 1-25
Pine 26-100
Pine 101-125
Pine 126-150
Pine 151-175
Pine 176-200
Pine 201-225
Pine 226-275
Spruce 1-150
Spruce 151-175
Spruce 176-225

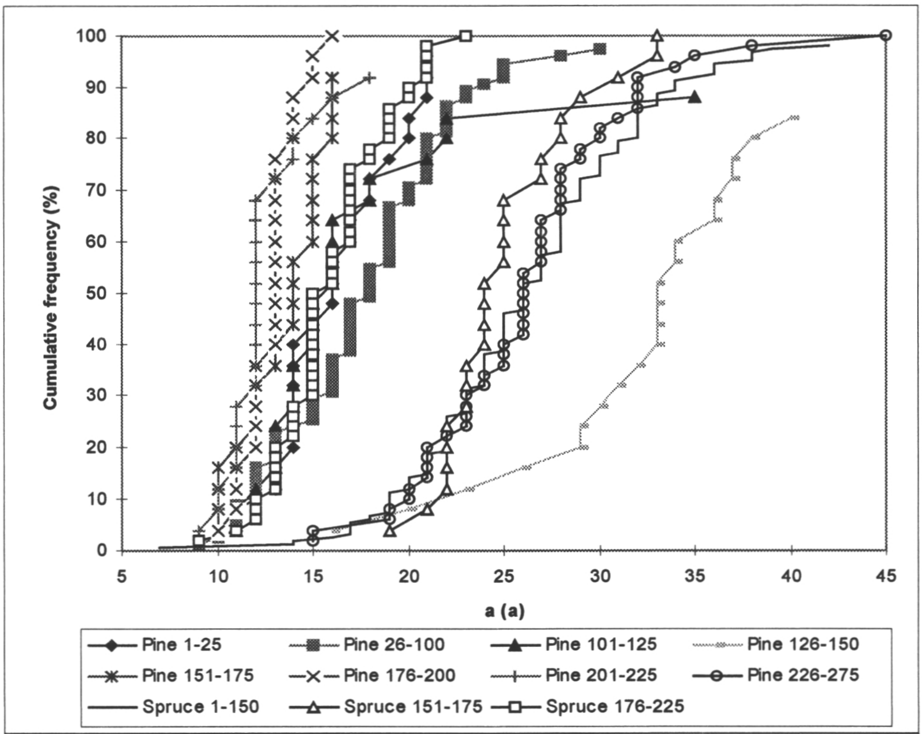
Appendix 2. Cumulative frequencies of the properties of samples in compression test.

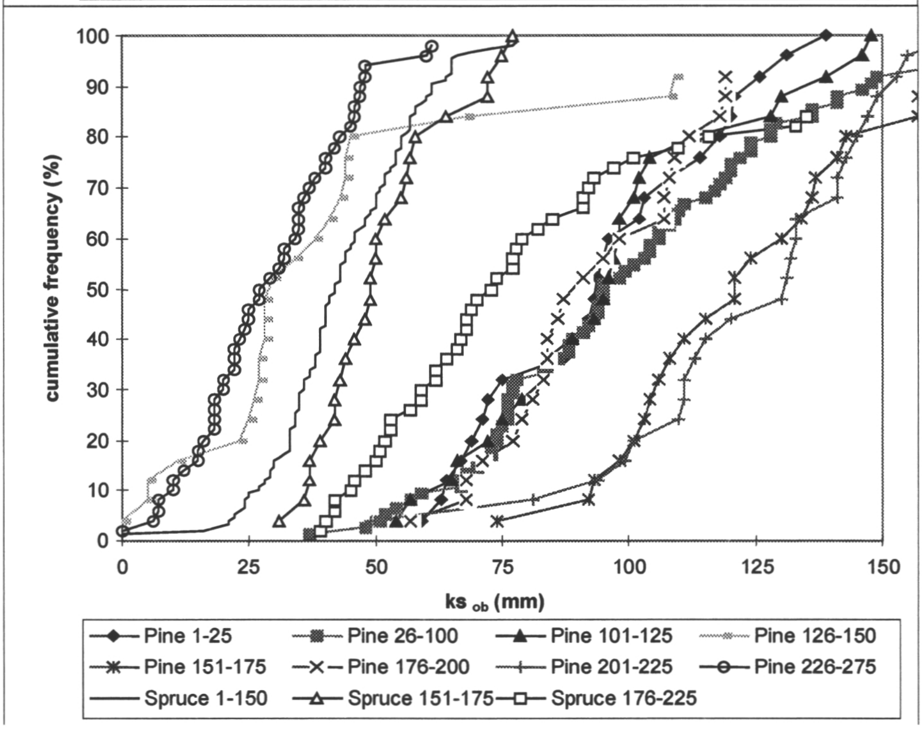


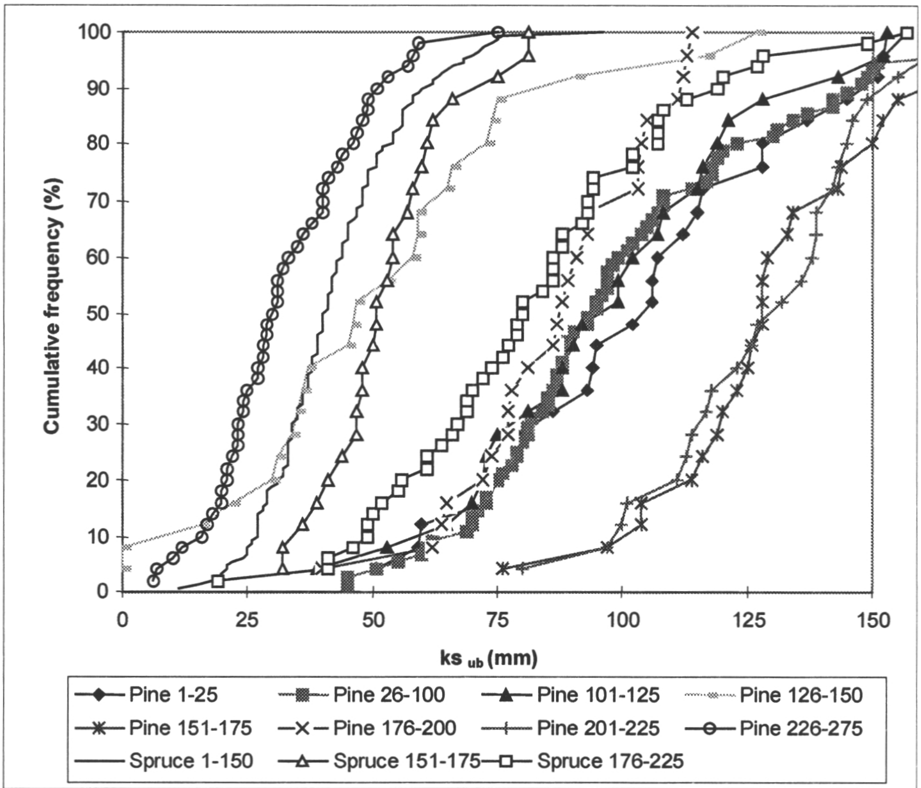



Cumulative frequency (%)
r (mm)
Pine 1-25
Pine 26-100
Pine 101-125
Pine 126-150
Pine 151-175
Pine 176-200
Pine 201-225
Pine 226-275
Spruce 1-150
Spruce 151-175
Spruce 176-225

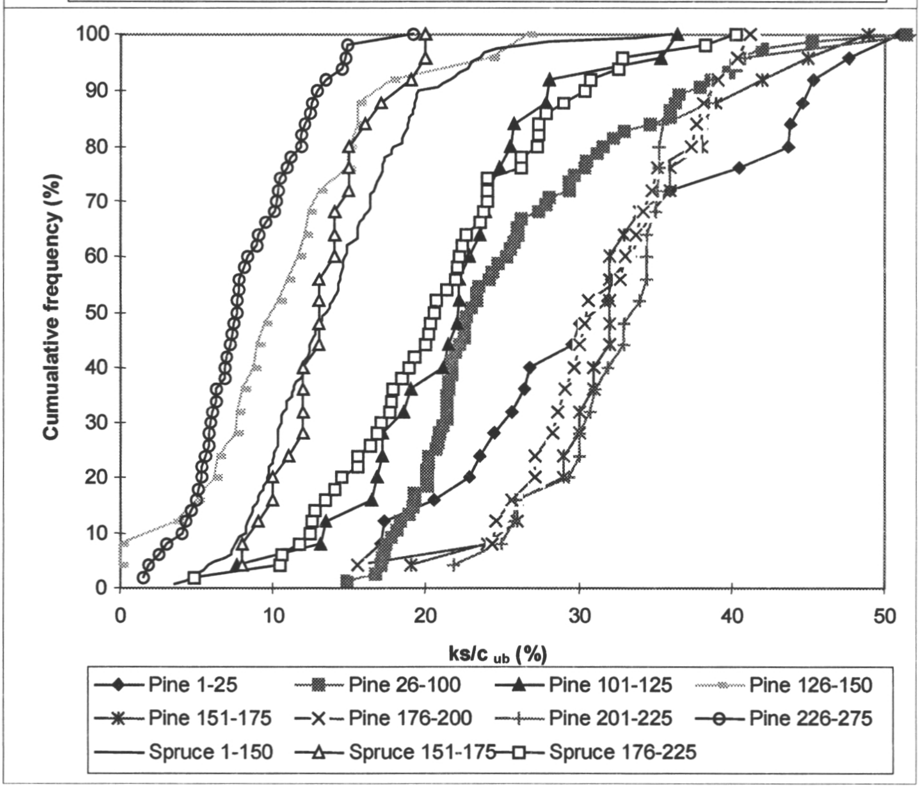

Cumulative frequency (%)
ρ_{12} (kg/m^3)
Pine 1-25
Pine 26-100
Pine 101-125
Pine 126-150
Pine 151-175
Pine 176-200
Pine 201-225
Pine 226-275
Spruce 1-150
Spruce 151-175
Spruce 176-225


Cumulative frequency (%)
a (a)
Pine 1-25
Pine 26-100
Pine 101-125
Pine 126-150
Pine 151-175
Pine 176-200
Pine 201-225
Pine 226-275
Spruce 1-150
Spruce 151-175
Spruce 176-225


cumulative frequency (%)
ks ob (mm)
Pine 1-25
Pine 26-100
Pine 101-125
Pine 126-150
Pine 151-175
Pine 176-200
Pine 201-225
Pine 226-275
Spruce 1-150
Spruce 151-175
Spruce 176-225



Cumulative frequency (%)
ks ub (mm)
Pine 1-25
Pine 26-100
Pine 101-125
Pine 126-150
Pine 151-175
Pine 176-200
Pine 201-225
Pine 226-275
Spruce 1-150
Spruce 151-175
Spruce 176-225



Cumualative frequency (%)
ks/c ub (%)
Pine 1-25
Pine 26-100
Pine 101-125
Pine 126-150
Pine 151-175
Pine 176-200
Pine 201-225
Pine 226-275
Spruce 1-150
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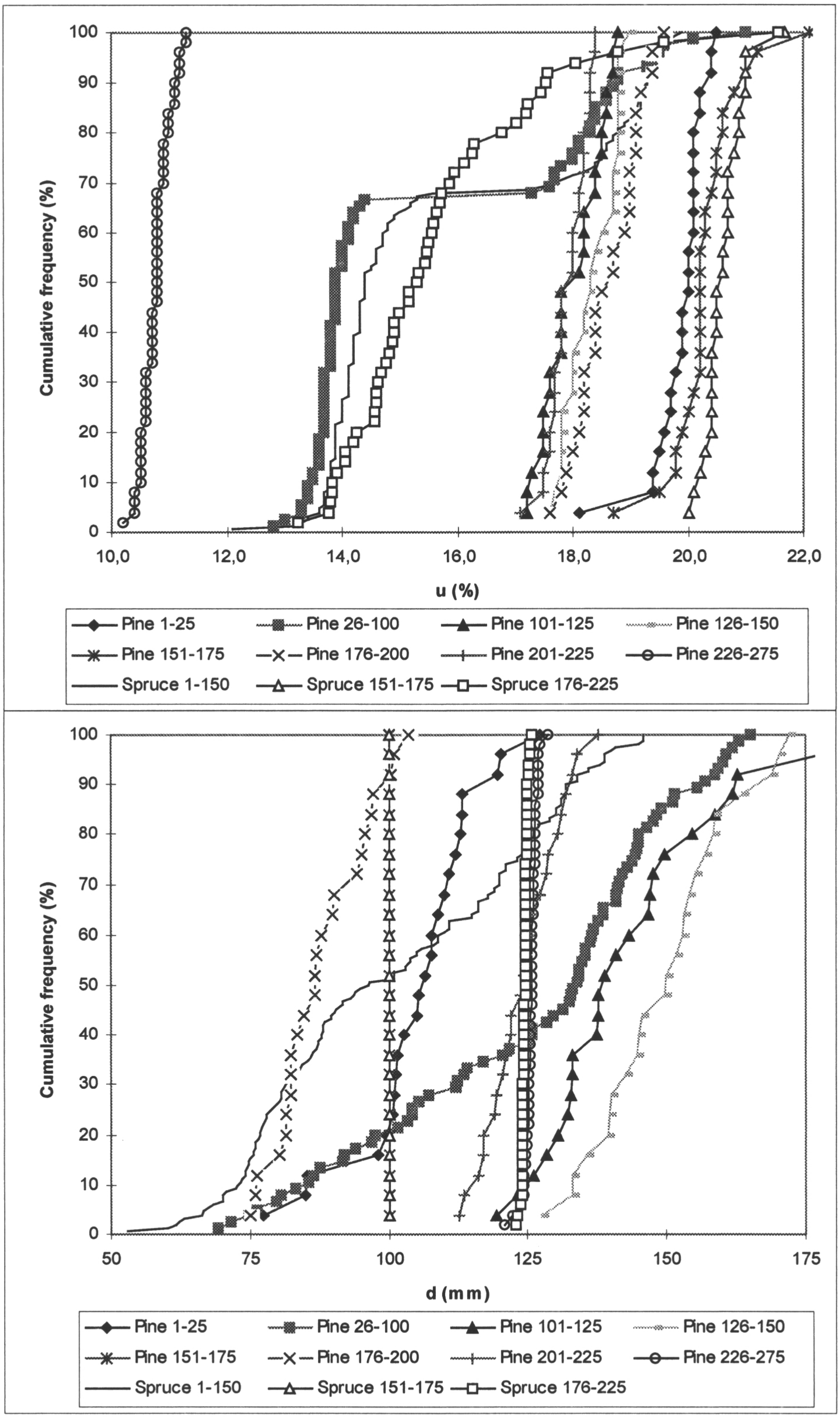
Cumulative frequency (%)
u (%)
Pine 1-25
Pine 26-100
Pine 101-125
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Pine 151-175
Pine 176-200
Pine 201-225
Pine 226-275
Spruce 1-150
Spruce 151-175
Spruce 176-225
Cumulative frequency (%)
d (mm)
Pine 1-25
Pine 26-100
Pine 101-125
Pine 126-150
Pine 151-175
Pine 176-200
Pine 201-225
Pine 226-275
Spruce 1-150
Spruce 151-175
Spruce 176-225

The photos in front cover:

Top left:
Thinning stands of Scots pine are the most abundant resource of small-sized timber in Finland.
A stand of natural origin in Northern Ostrobothnia, age 40 years.
Photo: Erkki Verkasalo

Top right:
Heavy loading equipment used for testing mechanical properties of round and sawn timber.
Photo: VTT Building and Transport, Espoo

Down left:
Typical manifestation of knottiness in small-diameter Scots pine.
Photo: Tapio Wall

Down right:
Twisting behaviour of round timber is of importance for the mechanical connections in timber structures.
Photo: Henrik Heräjärvi

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