

Influences of growth site on different wood properties in Spruce sap-/heartwood using CT-scanner measurements

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1 ABSTRACT

This investigation shows how different parameters affect liquid water absorption in Norway Spruce, which in its turn affects product life length and need of maintenance.

Logs from 20 trees, half of them suppressed and half of them dominant, were taken from two sites. One site had a good supply of free water (wet) and the other site was without free ground water (dry). The logs were approximately of the same breast height. The logs were sawn into boards and dried to 12% moisture content (MC) To evaluate absorption wood density and moisture content were measured by computed tomography (CT) scanning and image processing. The measurements were performed in room climate and CT scanned, after 1, 3, 7 and 14-15 days of liquid water absorption in end grain and during desorption for 6 days.

The most important findings in this investigation were:

- Large differences in water absorption were observed between heartwood and sapwood. The absorbed capillary water height (CWH) is higher in sapwood than in heartwood. The average CWH is about 4 times higher in the sapwood than in the heartwood after 24 hours of water absorption ($MC \geq 40\%$). After 14 days of water absorption the average CWH for sapwood was in the order of 3 times higher than for heartwood. There was a significant difference in heartwood/sapwood ratio between specimens from the “wet dominant” group and the other groups. Specimens from the “wet dominant” group showed the smallest difference in CWH between heartwood and sapwood.
- Specimens from the “wet dominant” and the “wet suppressed” group showed the lowest CWH in sapwood. There was a significant difference in CWH in sapwood between specimens from the “wet dominant” group and the “dry suppressed” group and the “dry dominant” group for 7 and 14-15 days absorption.
- Specimens from the “wet suppressed” group and the “dry suppressed” group had the lowest CWH in heartwood. There was a significant difference in CWH heartwood between trees from the “wet suppressed” group and the other groups for 7 and 14-15 days absorption
- There was no significant difference found in CWH between wood specimens standing with butt end or top end in water.
- Trees grown with poor access to water had a larger share of heartwood and grew more slowly than trees that grew with good supply of water.

2 INTRODUCTION

2.1 Background

Environmental considerations have made rules regarding chemical preservation of wood against fungi, have become tougher or even prohibitive. Therefore, using wood in building constructions put requirements on raw material and construction design for solutions that assure good durability. The durability for wood products not only depends on durability against microorganisms and finishing but also woods tendency to absorb capillary water [Sell 1982]. Wood absorbs water 1000 times faster by direct contact than by diffusion [Holbrow 1972]. Damages on constructions most commonly occur in the end grains on the products. Microorganisms, mainly fungi and bacteria, have different requirements on environment in order to live and propagate. Generally one could say that optimal moisture content for wood-rotting fungi is between 28-45% in the wood and optimal temperature is between 25-32 °C. Apart from durability, water absorption also affects dimensional change and strength.

Long ago, before the forestry became industrialized, wood for constructions was selected based on knowledge of the differences in quality and function between the trees. To know if the wood was suitable, parameters like crown size, bark, stem, site and branches etc. were considered in judging quality [Anon., 1985]. Pine heartwood is considered to be more durable than sapwood because it generally contains more extractives and absorbs less water. Spruce heartwood and sapwood are difficult to separate, and probably therefore their properties have seldom been investigated. It has been shown that in sound Spruce stems the amount of composition of extractives was dependent on radial position of the wood sample. The fatty acid concentration was higher in the sapwood and decreased towards the pith [Pensar 1967, Ekman 1980]. In this study trees have been selected to give big differences between parameters that can be expected to control the water distribution in the tree, such as the size of the crown, density, age and access to water. The use of CT

scanning permits mapping of water distribution during liquid end-grain absorption, which can be shown visually by image processing. Traditionally panels should be fitted with the butt end up. One of the objects of this study was to investigate if the fibre direction makes any differences in absorption between butt end down or butt end up. Another object was to measure how far from the end grain the water can be transported to cause damage. In the future the aim is to model parameters explaining the water absorption in Norway spruce (*Picea abies* (L.) Karst). The parameters should be measurable in the industrial chain from cutting the tree to the sawing operation on line and make it possible to separate appropriate raw material for products which requires low water absorption. The hypothesis is that differences in water absorption and desorption in the end grain cause differences in durability for building products, since micro-organisms in wood need a moisture content (MC) over fibre saturation point (FSP) to cause degradation. In other words, an increased product life and a decreased maintenance needs for Spruce products used outdoors above ground can be expected by choosing wood in a systematic way related to a number of characteristics that affect water absorption. In the future an X-ray Scanner could be used as a tool to control these parameters in the sawmill process [Grundberg, 1999].

3 MATERIALS AND METHODS

3.1 Materials

Twenty trees of Norway Spruce (*Picea abies* (L.) Karst.), half of them suppressed and half of them dominant, were taken from two sites. One site had a good supply of water, and one site was without free ground water. The spruces from the dry site were grown on a typical "sandy heath" 175 m above the sea level with an average age of 148 years. The dominant trees have an average diameter at breast height of 29 cm, and the suppressed trees an average of 18 cm. The spruce grown on "moist forest land", 250 m above sea level had an average age of 67 years. The dominant trees had an average diameter at breast height of 31 cm and the suppressed an average of 19 cm. Different characteristics for the four test groups, Table 1.

Table 1. Different characteristics for the four test groups

Test group	Age (year)	Growth rings width (mm)	Density (MC 12%) (kg/m ³)	Breast height diameter (cm)	Height (m)
Wet suppressed	67	1,48	407	19	18,3
Dry suppressed	137	0,63	484	18	14,3
Wet Dominant	66	2,56	378	31	21,8
Dry Dominant	158	0,96	440	29	22,2

Stem discs 5 cm thick were cut out 0.25 m and 5.25 m from the butt cut and stored in plastic bags and frozen until CT scanned. The trees were cut into 5 m logs. The logs were sawn through and through in north-south direction to 32 mm thick boards and dried to 12% MC. Test objects for absorption testing, 200 mm high were cut from 3 different heights (see Figure 1). In this investigation only test objects from the butt log end have been investigated.

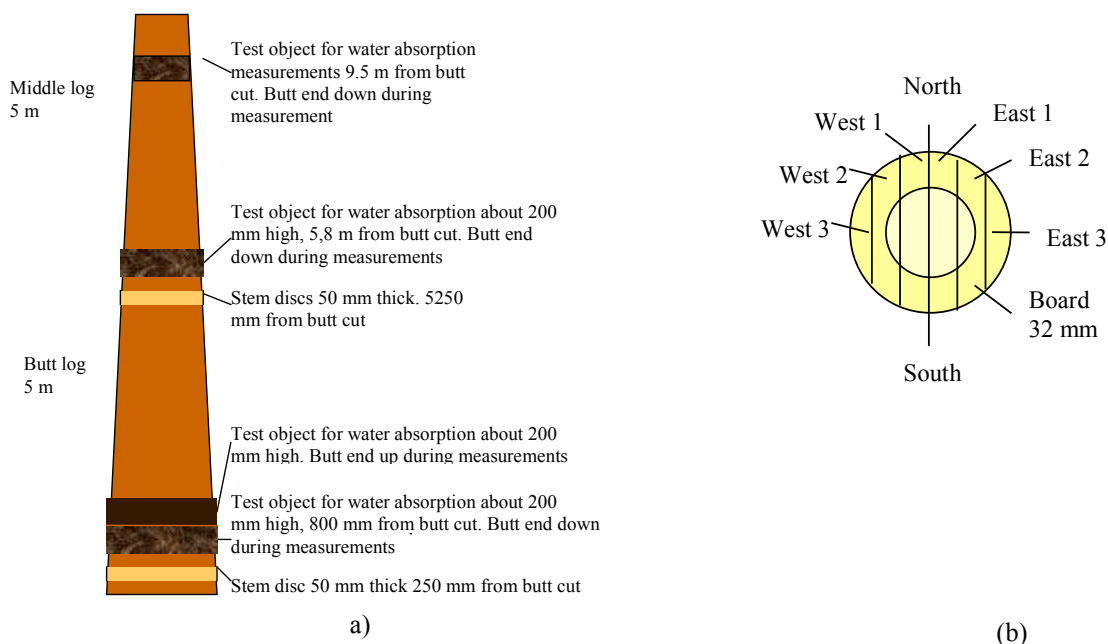


Figure 1. Sketches showing a) how the trees were divided and where the test object can be found in a stem. b) Sawing pattern.

The test objects were placed in a climate of standard conditioning RH 65% and temperature 22°C (corresponding approximately to MC 12%) for more than two months. The sawn flitches from the same height of the tree were assembled with a distance of 12 mm into one test object (see Figure 2).

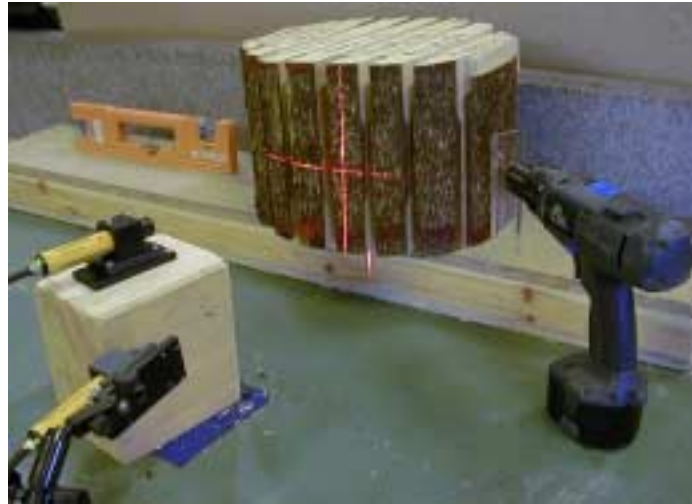


Figure 2. To ensure correct repositioning in the CT scanner, lasers were used to mark vertical reference points 100 mm from the end grain. A 3 mm diameter drill was used to make the holes.

3.2 Absorption and desorption of water

Test objects were placed in a basin on bars of stainless steel in 5 mm deep tap water for end grain absorption. The measurements were performed in room climate with the aid of a CT scanner after 1, 3, 7 and 14 days standing with butt end in water during absorption. The scan followed the grain in the middle of each board and was 10 mm wide. The test objects standing with the top end into the water were scanned after 15 days instead of 14 days, due to occupied CT scanner. Desorption was measured in room climate 23-25°C after 1, 3 and 5 days for the specimen with butt end down and 2, 4 and 6 days for the specimen with root part up. After absorption and desorption, the same test objects were oven dried at 103°C and CT scanned again to achieve dry reference images which were used in the image processing.

3.3 CT scanning

A CT-scanner method was chosen, as it is a powerful tool for non destructive measurement of density distribution and MC in wood. A CT scanner consists of an X-ray tube and a detector array which rotate around the object being examined. When the detectors have rotated around the object, a great number of X-ray absorption coefficients are calculated. The image is reconstructed with the help of mathematical algorithms, and the image created describes the density variations in the cross-section. The calculated X-ray linear absorption is normalized to the corresponding linear absorption coefficient for water, μ_{water} . This normalized value is referred to as the CT-number Eq. (1) [Herman, 1980].

$$\text{CT - number} = 1000 \times \frac{[\mu_x - \mu_{\text{water}}]}{\mu_{\text{water}}} \quad (1)$$

μ_x = absorption coefficient for the tested material

By giving each CT-number a certain grey scale value, an image can be evaluated showing the density variation within a slice of the object. A CT scanner, Siemens SOMATOM AR.T, at Luleå Technical University was used for measurements. The CT images have been obtained using the scan settings of 110 kV, 50 mA and scan width of 10 mm. For image reconstruction a standard Shepp-Logan algorithm was used. All images were stored as 512x512 pixel images.

3.4 Image processing of CT images

After CT scanning, raw data images were imported into a program called Scion Image for image processing. Moisture content measurements using a CT scanner is an indirect measurement method, as the CT-number couples to wood density. Two density measurements must be made to evaluate moisture content, one with unknown MC and one known reference MC level. Wood swells and shrinks during absorption and desorption, and therefore the images must be

geometrically transformed. An image processing program for geometric transform of images in such a way that the conditioned cross-section (after test) will appear to be identical to the immersed cross-section (before absorption) developed by Lindgren [1992] was used. Transformed images were then subtracted from the dry reference images to determine MC. The accuracy of the whole process of sampling two images, applying the algorithm and subtracting the images is size dependent. As an example in practice, an accuracy of $\pm 1,4\%$ below FSP and $\pm 4\%$ above FS in a 7×7 -pixel area (approx. 2×2 mm) can be expected [Lindgren 1992].

Thresholding of digital images was used to evaluate heartwood content and average (CWH) by reducing the grey scale image to two levels - white and black. When measuring CWH, a CT-number corresponding to $MC 40 \pm 1\%$ was chosen as threshold between “low” water uptake and “high” water uptake. The border between heartwood and sapwood (L_{s1} and L_{s2} in Figure 3) was measured in images after 14-15 days absorption. The same border was used for all images from the same test object. In a few test objects borders were difficult to define due to knots close to the surface or small differences in height between sap- and heartwood.

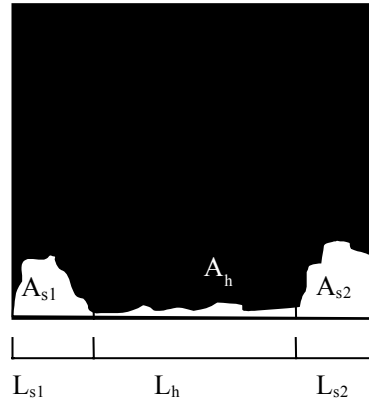


Figure 3. Threshold CT images showing average CWH ($MC \geq 40\%$) at end grain of spruce specimen. White areas correspond to wood that has absorbed water. Black corresponds to dry wood

3.5 Heartwood content

The heartwood content (C) was determined according to the areas (A) on the stem disc Eq. (2).

$$C = \frac{A_{\text{heartwood}}}{A_{\text{tot}}} \cdot 100 \quad (2)$$

3.6 Average capillary water height

The average CWH, (average altitude above the bottom end grain) was determined for sapwood (S_{average}), according to Eq. (3) and for heartwood (H), according to Eq. (4). The ratio, R between CWH in heartwood and sapwood was determined according to Eq. (5).

$$S_{\text{average}} = \frac{\left(\frac{A_{s1}}{L_{s1}} + \frac{A_{s2}}{L_{s2}} \right)}{2} \quad (3)$$

$$H = \frac{A_h}{L_h} \quad (4)$$

$$R = \frac{H}{S_{\text{average}}} \quad (5)$$

4 RESULTS AND DISCUSSION

4.1 Heartwood content

Figure 4 shows a cross-sectional CT images of stem discs in fresh state 250 mm from butt cut. Grey scale distribution shows variation in green density of the heartwood (dark grey) and the (white) sapwood. Heartwood was irregular close to the butt cut but became more concentric towards the top of the tree.

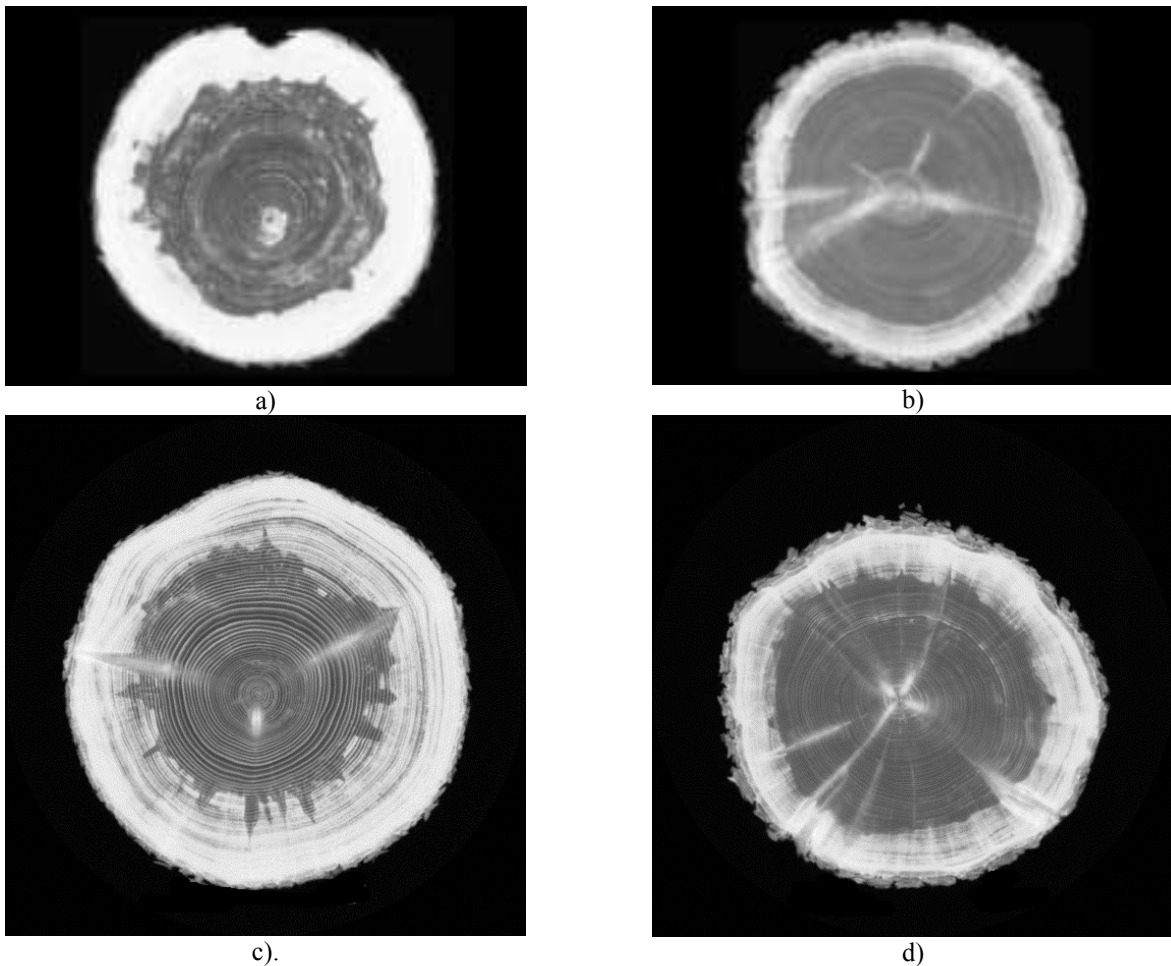


Figure 4. Cross-sectional CT images of stem disc in fresh state 250 mm from butt cut. Observe that the diameter varies between the stems. a) Suppressed spruce growing with good supply of water. $Area_{heartwood}/Area_{tot}=0.52$, $Diameter_{tot}=187$ mm, $Diameter_{heartwood}=128$ mm. Age 65 years. b) Suppressed spruce growing on dry site, $Area_{heartwood}/Area_{tot}=0.64$, $Diameter_{tot}=174$ mm, $Diameter_{heartwood}=145$ mm. Age 145 years. c) Dominant spruce growing with good supply of water. $Area_{heartwood}/Area_{tot}=0.42$, $Diameter_{tot}=246$ mm, $Diameter_{heartwood}=228$ mm. Age 65 years. d) Dominant spruce growing on dry site. $Area_{heartwood}/Area_{tot}=0.56$, $Diameter_{tot}=338$ mm, $Diameter_{heartwood}=226$ mm. Age 153 years.

Spruces that had been growing on a dry site had a significantly larger amount of heartwood than the trees from the wet site. The difference in heartwood content (group mean value), between dry site and wet site was evaluated with Students t-test (α -level of 0.05). The difference is shown in Figure 5. There was no significant difference in group mean value between heartwood content in butt log and middle log (α -level of 0.05).

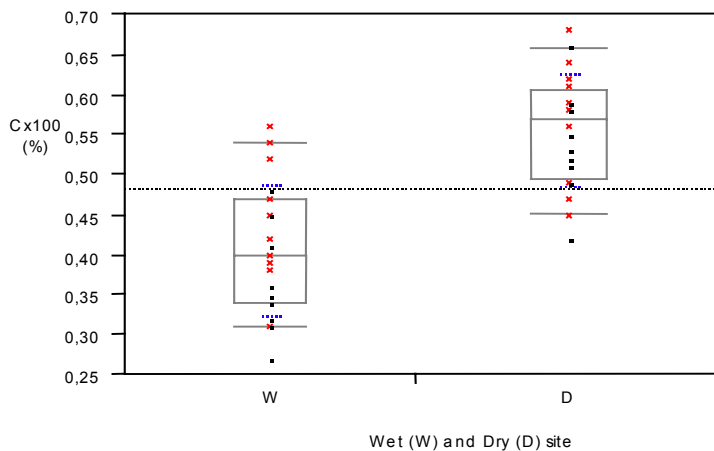


Figure 5. Heartwood contents in trees grouped by growth site, (wet site and dry site). The box plot shows the medium value and the spread from 39 observations (butt and middle log).

Even though there are few test objects (20 from the butt log and 19 from the middle log), the results showed a strong significant difference in heartwood content between sites. Trees from the dry site were more than twice as old as the other group even though they had approximately had the same diameter. Heartwood percentage often increases in direct proportion to the age of the tree for many wood species [Hillis 1987]. In a Swedish investigation from 1910 [Eneroth] the average heartwood content in spruce was 40 % when the trees were 70 years old and 58 % after 150 years. Those figures agree very well with the data in this investigation. In the same report one could see that the spread was very large. For example, after 120 years the average heartwood content was of 55 % with a maximum value of 78 % and minimum value of 30 %. After 130 years, spruce attained maximum heartwood content of 90 %.

4.2 Visual evaluation of butt log

A visual qualitative evaluation of the images shows differences but also similarities between the images (see Figure 6 Figure 7 and Figure 8). Variations in water absorption appear as different intensities in the grey scale where white areas indicate a high density due to absorption of water. Between heartwood and sapwood there is a clear boundary of water absorption after 14 days.

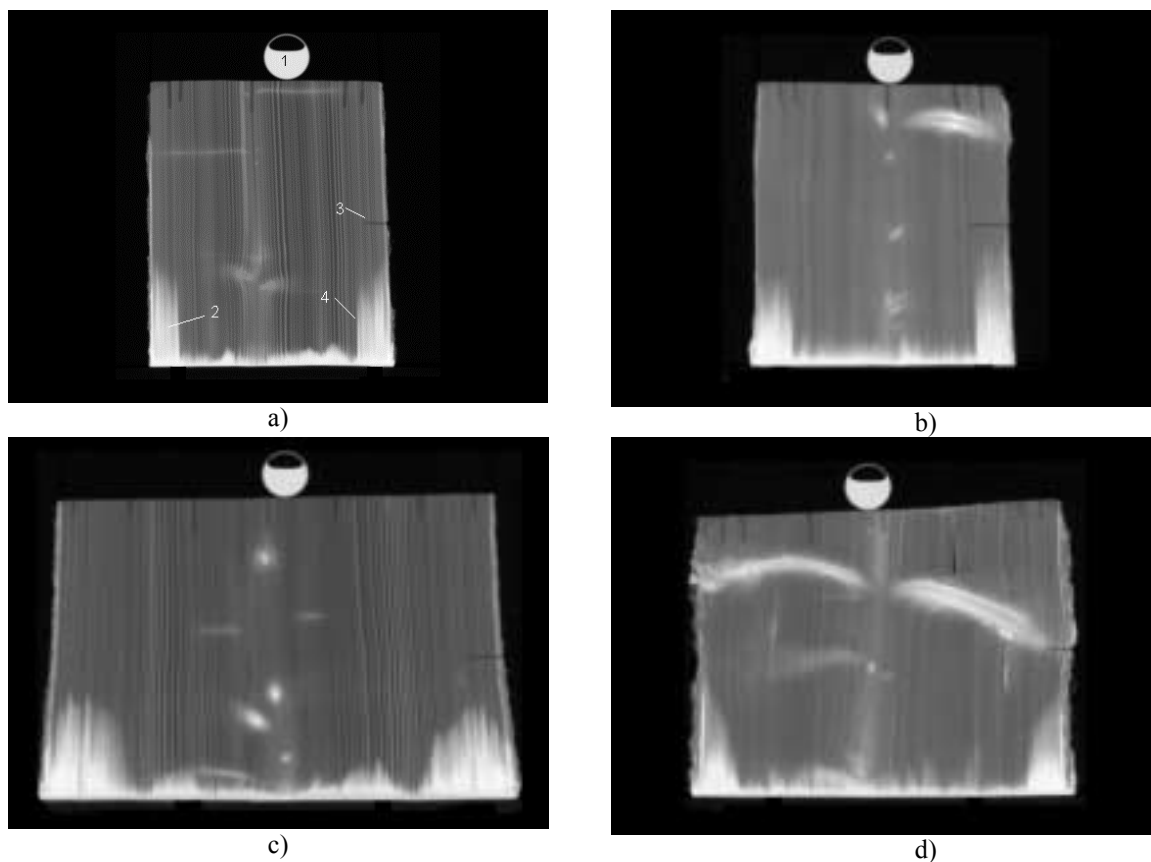


Figure 6. Vertical cross-section CT images showing absorption after 14 days in water. On top of the test objects is a jar with water as reference (1). The intensity is proportional to the amount of water. White areas indicate increased water content (2). Dark streaks on the right side of the images show a reference point, 100 mm from the bottom, on the north side of the stem (3). Between heartwood and sapwood there is a clear boundary of water absorption (4) Test objects that have grown a) suppressed with good supply of water (wet) b) suppressed without free ground water (dry) c) dominant with good supply of water d) dominant without free ground water.

No systematic difference in (CWH) could be seen between test objects when the top end or the butt end of the objects was immersed in water. In Figure 7 a) and b) one can see a large area (2) with increased moisture content ($MC \geq 40\%$) in heartwood. These two were the only test objects that behaved this way. Figure 7 c) and d) show a vertical white streak (3) in the wood and increased water around the pith (4). The white streak was dense compression wood in one annual ring vertical along that stem and did not extend east and west in the stem.

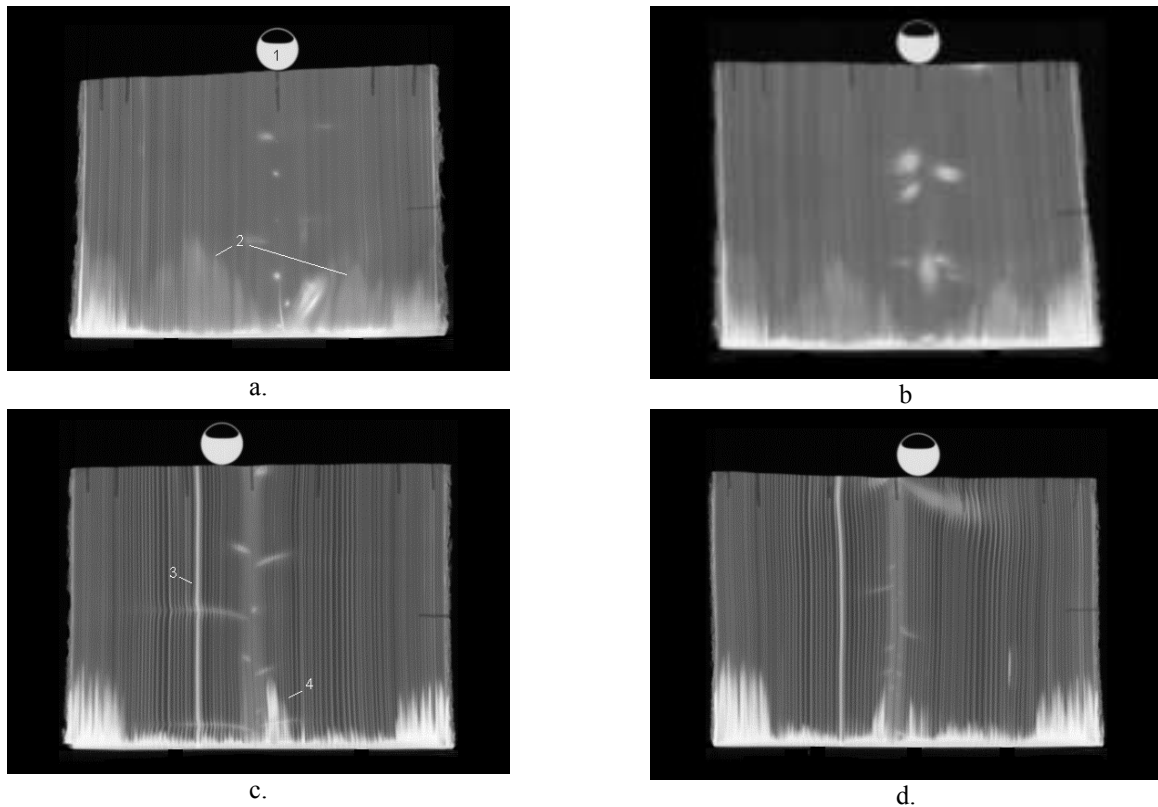


Figure 7. CT images showing capillary water height behavioural pattern after 14/15 days in water. (1) shows a reference jar containing water. Test objects in a) and c) stand with the butt end in water and in b) and d) with top end in water. (2) shows increased moisture content (MC still below 40%) in heartwood. (3) shows dense compression wood and (4) shows increased water around the pith caused by rot. Test objects a) dominant without free ground water, butt end down b) dominant without free ground water absorption 15 days, butt end up c) dominant good supply of water absorption 14 days, butt end down d) dominant good supply of water, absorption 15 days butt end up.

CWH behavioural patterns usually vary like a wave around the stem. In general it differs by a few millimetres between north and south. A rather extreme example is shown in Figure 8. The difference in this tree depends on a scar on the south side of the stem.

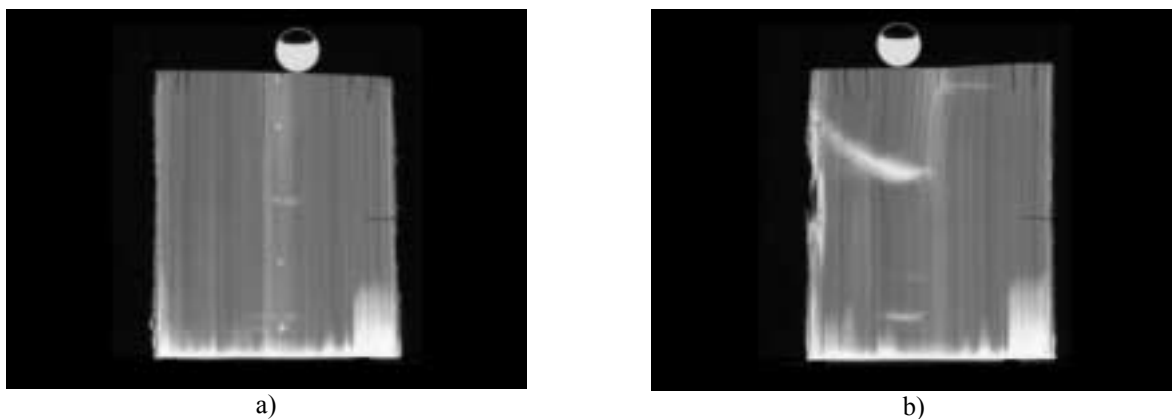


Figure 8. a) and b) show difference in capillary water height patterns between south and north side of the stem caused by a scar. The objects are suppressed, grown without free ground water (dry) a) butt end down, absorption 14 days b) butt end up, absorption 15 days.

4.3 Average capillary water height

The average CWH were measured on images from the middle board (with pith) in south-north direction when $MC \geq 40 \pm 1\%$. Specimens in Figure 7 a) and b) are not included in the test due to extreme deformation during drying in 103°C . A matched paired Student's t-test showed no significant difference in average CWH exists between test objects standing

with butt end down or butt end up in water. (α -level of 0.05). The difference in water uptake was greatest between heartwood and sapwood. In general, CWH in heartwood was about 1/3 of that in sapwood (MC \geq 40%), (see Table 2).

Table 2. Average ratio between CWH heartwood/sapwood (MC \geq 40%) 38 observations.

Time (days)	1 Day	3 Days	7 Days	14/15 Days
Heart-/Sapwood CWH	0.26 \pm 0.10	0.29 \pm 0.12	0.33 \pm 0.11	0.33 \pm 0.10

The ratio between CWH in heartwood and CWH in sapwood showed a significant difference between the specimens from the “wet dominant” group and the other groups, see Figure 9.

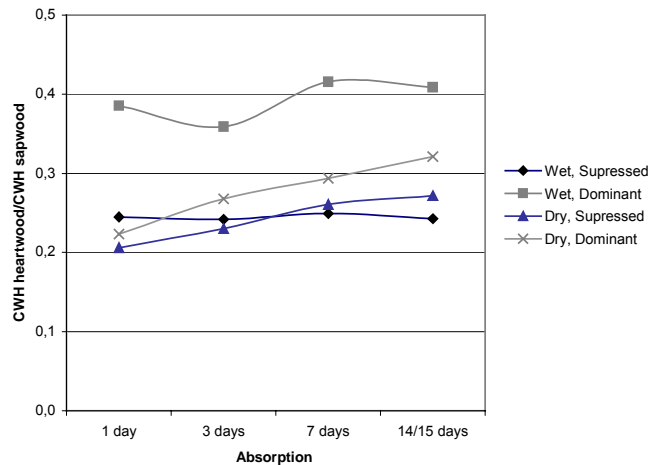


Figure 9. Ratio between average CWH heartwood and average CWH sapwood.

The average CWH in sapwood from absorption during 1 day to 15 days for the different test groups can be seen in Figure 10.

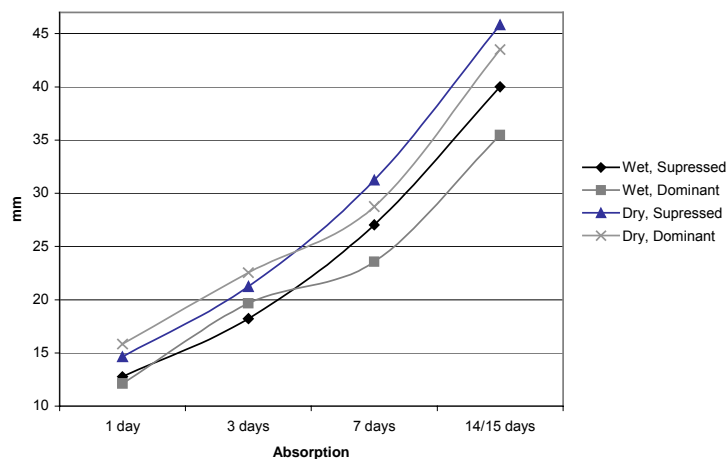


Figure 10. Average capillary water height in sapwood (MC \geq 40%) related to test groups.

The specimens from the “wet dominant” and the “wet suppressed” groups showed the lowest average CWH in sapwood. The difference between the groups increased with time. After one day absorption there was a significant difference between specimens from the “dry dominant” group and the “wet dominant” group (paired Student’s t-test, α -level of 0.05). There was a significant difference in CWH for sapwood, between the specimens from the “wet dominant” group and to specimens from both the “dry suppressed” group and the “dry dominant” group during absorption for 7 days and 14-15 days (paired Student’s t-test, α -level of 0.05).

The average CWH in heartwood after absorption for 1 day to 15 days related to test groups can be seen in Figure 11.

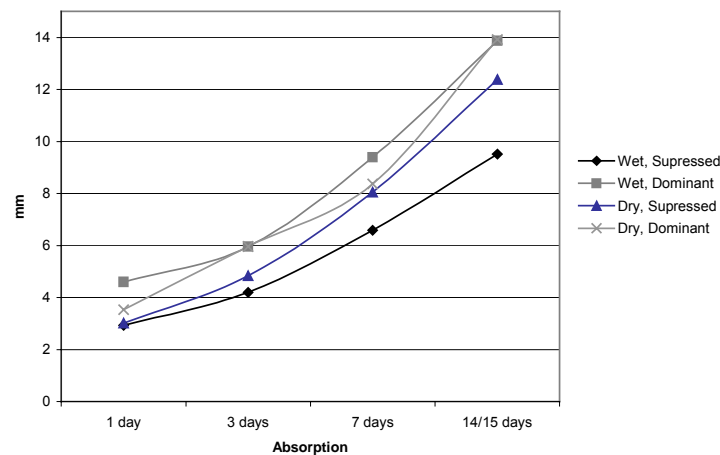


Figure 11. Average capillary water height in heartwood (MC ≥ 40%) related to test groups.

The specimens from the “wet suppressed” and the “dry suppressed” groups showed the lowest CWH in heartwood. The differences and the spread between the groups increased with time. There was a significant difference after 24 hours between the “wet dominant” group and to specimens from both “wet suppressed” and “dry suppressed” groups (paired Student’s t-test, α -level of 0.05). After 3 days there was a significant difference between specimens from the “wet suppressed” group and to specimens from both “dry dominant” and “wet dominant” groups (paired Student’s t-test, α -level of 0.05). A significant difference in CWH heartwood could be found between specimens from the “wet suppressed” and all other groups during absorption for 7 and 14-15 days (paired student’s t-test, α -level of 0.05). Average CWH for sapwood and heartwood can be found in Table 3.

Table 3 Average capillary water height (mm) in spruce when MC ≥ 40%, 38 observations.

Time	1 Day	3 Days	7 Days	14/15 Days
Sapwood	13.9 ± 3.4	21.0 ± 6.3	27.8 ± 6.3	41.47 ± 8.4
Heartwood	3.4 ± 1.3	5.6 ± 1.5	8.6 ± 1.7	13.3 ± 2.6

The figures can be compared to an investigation by Sell [1976]. Sell measured the CWH in spruce to 10 mm parallel with the fibres and 0.2 mm perpendicular to the fibres after 24 h. The heartwood and sapwood were not separated.

4.4 Desorption

Test objects were measured with a CT scanner, during desorption in room climate for 6 days. Before testing, the test objects had been standing in water for 14 days (with butt end down) and 15 days (with butt end up). After 5 days all test objects had reach MC < 40% in heartwood except specimens from the “wet dominant” group (see example Figure 12 b). Sapwood needed about two more days to reach MC < 40%.

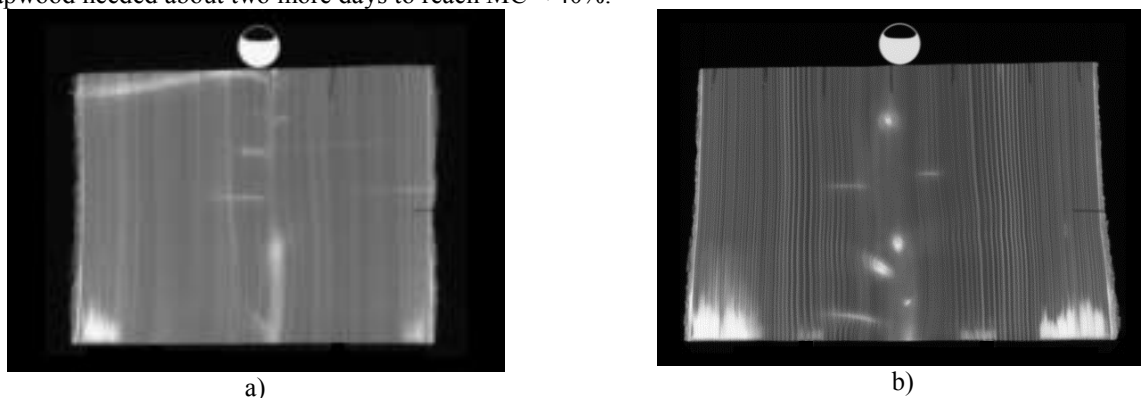


Figure 12. Desorption after 5 days in room climate. Heartwood reached MC < 40% faster than sapwood after absorption for 14/15 days. Sapwood dried unevenly between north and south side of the stem. The trees have been growing a) dominant in a dry site b) dominant in a wet site.

5 CONCLUSIONS

The most important findings in this investigation were:

- The largest difference in average CWH was between heartwood and sapwood ($MC \geq 40\%$). The average CWH was approximately 3 times as higher in sapwood than in heartwood.
- There was no significant difference in capillary water height (CWH) between test objects absorbing water with butt end down or up ($MC \geq 40\%$)
- The amount of heartwood depended on growth site. Trees that had grown in an area without free water (dry) were more than twice as old and have higher heartwood content than the ones from a moist forest land (wet) with a good supply of water.
- The differences and spread in CWH between the groups “wet dominant”, “wet suppressed”, “dry dominant” and “dry suppressed” increased with time.
- There was a significant difference in CWH for sapwood, between specimens from “wet dominant” group and specimens from both “dry suppressed” and “dry dominant” group during absorption for 7 days and 14-15 days.
- There was a significant difference in CWH for heartwood from group “wet suppressed” and to all other groups during absorption for 7 and 14-15 days.
- After 5 days in room climate all test objects were dry in heartwood except for the “wet dominant”. Sapwood still had wet areas and needed about two more days to dry.
- Test objects from the “wet dominant” group showed the lowest CWH in sapwood but dried slowly. It seems like a low CWH does not guarantee the fastest desorption. The quantity of water and the wood structure must be considered as well. The time for desorption probably affects possibility of wood to be attacked by fungi due to unfavourable environment. Therefore, the behaviour of desorption is an interesting area to investigate more in the future.
- CT scanning has earlier been proven to be a suitable technique for measurement of internal features in wood. This study shows that it is also possible to follow changes during absorption and desorption with good accuracy. In future work the middle log will be examined and compared to the butt log.
- Finding parameters that affect the water absorption is a complex problem. Many parameters can affect the absorption and interact with each other. Therefore, interesting parameters such resin content, age, density, diameter etc. will be evaluated with multivariate analysis in the future.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

- Anon.**, 1985: Var virket bättre förr? En orientering om traditionellt svenskt virkeskunnande 1985: 2 uppl Stockholm, Riksantikvarieämbetet, 75 s. (In Swedish)
- Eneroth O.**, 1922: "Vedens byggnad och egenskaper ", Ur: Handbok i Skogsteknologi Stockholm sid 24 (In Swedish)
- Ekman R.**, 1980: Wood extractives of Norway Spruce, A study of Nonvolatile Constituents and their Effects on *Fomes annosus*, Publications of the Institute of Wood Chemistry and Pulp and Paper Technology A 330, Åbo Akademi.
- Grundberg S.**, 1999: An X-ray Log Scanner- a tool for control the sawmill process, doctoral thesis, Luleå University of technology Skellefteå campus division of Wood Technology, rept nr 1999:37.
- Herman G.T.**, 1980: Image reconstruction from projections-the fundamentals of computerized tomography. New York: Academic Press.
- Hillis W.E.**, 1987: *Heartwood and Tree Exudates*. Berlin: Springer (Springer series in wood science). ISBN 3-540-17593-8.
- Holbrow G.L., Sherwood A. F., Dasgupta D., Gardiner D., Gibson M. C., Haines M. J.**,1972: Wood protection. Journal oil Col. Chem. Associ.55 s 35-51
- Lindgren O.**, 1992: Medical CT-Scanners for Non-Destructive Wood Density and Moisture Content Measurements, , Doctoral thesis, Luleå University of technology Skellefteå campus division of Wood Technology, rept nr 1992:111D.
- Pensar, G.**, 1967: Fördelning och sammansättning av extraktivämnen i ved, eterextrakt av vår och sommarvedsvävnad i gran. Acta Academiae Aboensis, Ser B Vol. 27 nr 5 Medd.nr. 211. (In Swedish)
- Sell J.**, 1976: Die Einwirkung äußerer Faktoren auf das Holtz: In: LIGNUM (Hrsg): Holzschutz und Oberflächenbehandlung, Bd.1, Holzschutz. Dokumentation Holz, TeilVII, Zürich, 3-6. (In German)
- Sell J.**, 1982:Untersucungen zur Optimerung des Oberflächenschutzes von Holzbauteilen, Teil 1: Bewitterungsversuche mit Fensterrahmen-Abschnitten. Holz Roh-Wekstoff 40:225-232. (In German)