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Variation of moisture induced movements in Norway spruce (*Picea abies*)

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Abstract – This paper deals with the variability of moisture induced movements in Norway spruce wood. Totally 987 specimens from 12 well defined trees, six from a fast-grown and six from a slow-grown stand, were studied in detail. A large variation in moisture induced movements was found. The swelling coefficients in the longitudinal direction (α_l) varied between 0.001 and 0.035, in the tangential direction (α_t) between 0.18 and 0.46 and in the radial direction (α_r) between 0.07 and 0.28. Especially for α_l there was an individual variation with distance from the pith for each of the studied trees. For α_t and α_r there was a difference between the trees but no clear variation with distance from the pith. By excluding specimens containing knots and/or compression wood, the variability in swelling coefficients was decreased, especially for α_l. The eigenfrequency in the longitudinal direction was the single best parameter, measured in this study, to predict swelling coefficients in all three directions. The variation in eigenfrequency explained 52% of the variations in α_l, 67% of the variations in α_t and 52% of the variations in α_r. Specimens from the fast-grown stand and specimens containing compression wood were less anisotropic than the other specimens.

shrinkage / swelling / eigenfrequency / raw material properties / variability

Résumé – **Variation des mouvements induits par l'humidité dans l'Épicéa (*Picea abies*)**. Ce papier traite de la variabilité des mouvements induits par l'humidité dans le bois d'Épicéa. En tout 987 échantillons provenant de 12 arbres bien identifiés, 6 d'un site à croissance rapide et 6 d'un site à croissance lente, ont été étudiés en détail. Une variation importante des mouvements induits par l'humidité a été trouvée. Le coefficient de gonflement (exprimé en % de déformation par % de variation d'humidité du bois) dans la direction longitudinale (α_l) varie entre 0.001 et 0.035, celui de la direction tangentielle (α_t) entre 0.18 et 0.46, celui de la direction radiale (α_r) entre 0.07 et 0.28. Dans le cas de a_l une variation individuelle avec la distance à la moelle a été constatée pour chacun des arbres étudiés. Pour α_t et α_r il y a une différence entre les arbres mais pas de variation nette en fonction de la distance à la moelle. En excluant les échantillons contenant des nœuds et/ou du bois de compression, on diminue la variabilité du coefficient de gonflement, spécialement pour α_l. Dans cette étude, le seul paramètre explicatif des coefficients de gonflement dans les trois directions était la fréquence de résonance dans un essai de vibration dans la direction longitudinale. Les variations de cette fréquence de résonance expliquent 52 % des variations de α_l, 67 % de celles de α_t, 52 % de celles de α_r. Les échantillons provenant du site à croissance rapide et ceux contenant du bois de compression étaient moins anisotropes que les autres échantillons.

retrait / gonflement / fréquence de résonance / propriétés du matériau / variabilité

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1. INTRODUCTION

1.1. Background and aim

If the behaviour of wood material, for example creep or distortion is being modelled, a good knowledge of the variation in the raw material properties is required. Detailed models, such as finite element models, require accurate input data of wood properties and their variations. Earlier studies have shown that the shrinkage and swelling properties influence both the shape stability [9, 10] and the creep behaviour [3, 4] of structural timber.

The aim of this paper is to evaluate the shrinkage and swelling properties of Norway spruce (*Picea abies*) and to see how these properties are affected by the variability of the wood raw material. It is not within the scope of this study to examine the properties of clear wood specimens, but to evaluate how large the variations in moisture induced movements can be. The specimens used in the study were very well defined with respect to growth conditions, position in the log and some physical material parameters and the measurements of shrinkage/swelling properties were made in great detail. This study is a part of a larger study, where the influence of raw material parameters on the creep behaviour of wood is studied, see [1–5].

The variation in the wood raw material can be very large. Therefore, a meaningful comparison between the behaviour of different specimens is difficult to perform. In this study, the measured properties are related to material data. This coupling is important both for the understanding of the behaviour of the wood material and for obtaining data which can be used to model mechanical properties or distortion.

1.2. Literature

In [14] measurements of shrinkage coefficients, density and modulus of elasticity for small specimens, $10 \times 10 \times 300$ mm^3, were reported. These specimens were cut along the south-north diameter at three heights of eleven Norway spruce trees from four different site classes in the south of Sweden. The longitudinal shrinkage decreased with increasing distance from the pith. Radial and tangential shrinkage displayed small variations with respect to distance from the pith.

Common facts presented in the literature for shrinkage and swelling in the different directions of softwood are $\alpha_{rad}=\alpha_{tang}/2$ and $\alpha_{long}=\alpha_{tang}/10$, see for example [12]. These relationships do not always seem to be true. For the data presented in [14] the relationship between radial and tangential shrinkage and swelling was approximately 1: 2 and the relationship between longitudinal and tangential shrinkage and swelling was more like 1:100.

In [13] and [8] moisture induced dimensional changes for specimens made of pine (*Pinus Radiata* and *Pinus Sylvestris*) with different microfibril angles were presented. Specimens with a large microfibril angle showed larger dimensional changes.

Measurements presented in [18] on Norway spruce wood also showed that the longitudinal shrinkage/swelling was largest close to the pith and decreased with increasing distance from the pith. Longitudinal shrinkage also seemed to increase higher up in the trees.

In [15] a large influence of knots and compression wood on the longitudinal shrinkage of specimens made of Norway spruce was found. The material used in that study came from the same stands as the material used in this more detailed study.

From this literature survey, which was limited to results of interest for this study, it can be concluded that even though a quite large amount of data on shrinkage/swelling properties of Norway spruce wood is present, the coupling between this data and easily measurable material parameters is missing. This coupling should be useful when using the data in practical applications.

2. MATERIALS AND METHODS

2.1. Test material and specimen preparation

The test material came from two well documented Norway spruce stands, one fast-grown stand (characterised by an average annual ring width of 4.7 mm) and one slow-grown stand (characterised by an average annual ring width of 2.8 mm). The origin of the test material was accurately described in [11] and [16].

The sawing pattern for the specimens is shown in *figure 1*. The centre part of the butt logs were cut into six three meter long battens 45×70 mm^2 in cross section. From each batten 15 small specimens, $11 \times 11 \times 200$ mm^3, were cut. All specimens from one tree were cut from the same height of the tree. Specimens from six trees from the fast-grown stand and six trees from the slow-grown stand were included in the study. For five of the trees from each stand, the entire cross section, as in *figure 1*, was studied. For one of the trees from each stand, only half a cross section was included. Thus, the total amount of 990 specimens was obtained.

At the ends of each of the small specimens, small rivets were placed in order to define the measurement points for dimensional measurement in the longitudinal direction. On the sticks with a pure radial/tangential plane (≤ 3 specimens per batten, totally 180 specimens) the dimensions in the radial and tangential directions were also measured. For these sticks, the cross section was locally, over 20 mm, reduced from a squared to a circular one by turning. These two steps were performed in order to get well defined surfaces for the measurements.

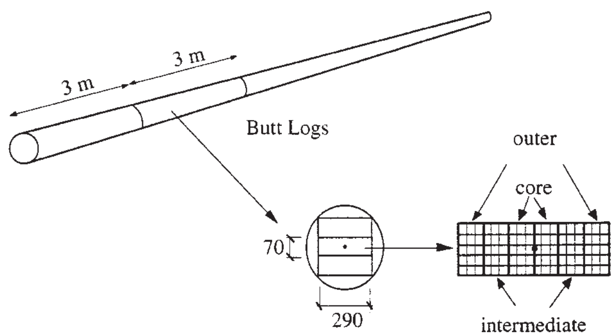

Figure 1. Sawing pattern for the specimens.

2.2. Measurement of shrinkage and swelling

The small specimens were placed in a climate room and subjected to a cyclic relative humidity (RH) of 30%–90% and a constant temperature of 22 °C. The length of the moisture cycles was four weeks, which means that the small specimens reached equilibrium moisture content (MC) during each cycle. The tests were performed as four test series. The levels of RH were checked to be the same between the test series.

The free shrinkage and swelling were measured in a device specially designed for these measurements, see *figure 2*. The maximum deviation for repeated measurements in the longitudinal direction was 0.003 mm and in the radial and tangential directions the maximum deviation was 0.01 mm. The measurements were carried out inside the climate room to maintain the moisture content in the specimens. The weight of the specimens was registered at the same time as their dimensions were measured. After testing, the specimens were oven dried and weighed and the MC was calculated. The moisture content (u), the strain (ε), and the shrinkage and swelling coefficient (α) were calculated as :

$$u = \frac{m_u - m_0}{m_0} \times 100 \qquad [\%] \tag{1}$$

where m_u is the weight of the specimen at the moisture content u and m_0 is the weight in the oven dry condition.

$$\varepsilon = \frac{L_{90} - L_{30}}{L_{90}} \times 100 \qquad [\%] \tag{2}$$

where L_{90} is the dimension (in the longitudinal, tangential or radial direction) at equilibrium MC at 90% RH and L_{30} is the dimension at equilibrium MC at 30% RH.

$$\alpha = \frac{\varepsilon}{u_{90} - u_{30}} \qquad [\%/\%] \tag{3}$$

It is worth noting that when calculating the strain (ε) it did not make any difference, practically, if L_{90} or L_{30} was chosen as the reference. In the following, the α-values will be denoted swelling coefficients.

For 54 of the 990 specimens, randomly chosen, the dimensional measurements were repeated during two or more moisture cycles to study the reversibility of the shrinkage and swelling while for the other specimens the dimensions were only measured once at 30% RH and once at 90% RH. In the latter cases, the specimens were subjected to at least one moisture cycle prior to the dimensional measurements.

2.3. Other measured parameters

The specimens were characterised by the parameters annual ring width (RW), distance from the pith, modulus of elasticity (E) and density. Density and E were measured both at equilibrium MC at 30% RH and at equilibrium MC at 90% RH. The results of the E-measurements were presented in [2]. Modulus of elasticity was measured with a dynamic test method, see [2]. Mean values of some material parameters for the specimens, from each of the trees, can be found in *table I*.

The 15 specimens from each batten were classified as either juvenile, intermediate or mature wood. This classification was made under the assumption that the 0–15 first annual rings consisted of juvenile wood and the wood nearest to the bark was assumed to be mature wood. With a few exceptions, the 30 specimens cut closest to the pith (core specimens in *figure 1*) were assumed to contain juvenile wood and the 30 specimens cut closest to the bark (outer specimens in *figure 1*) were assumed to contain mature wood.

a)

b)

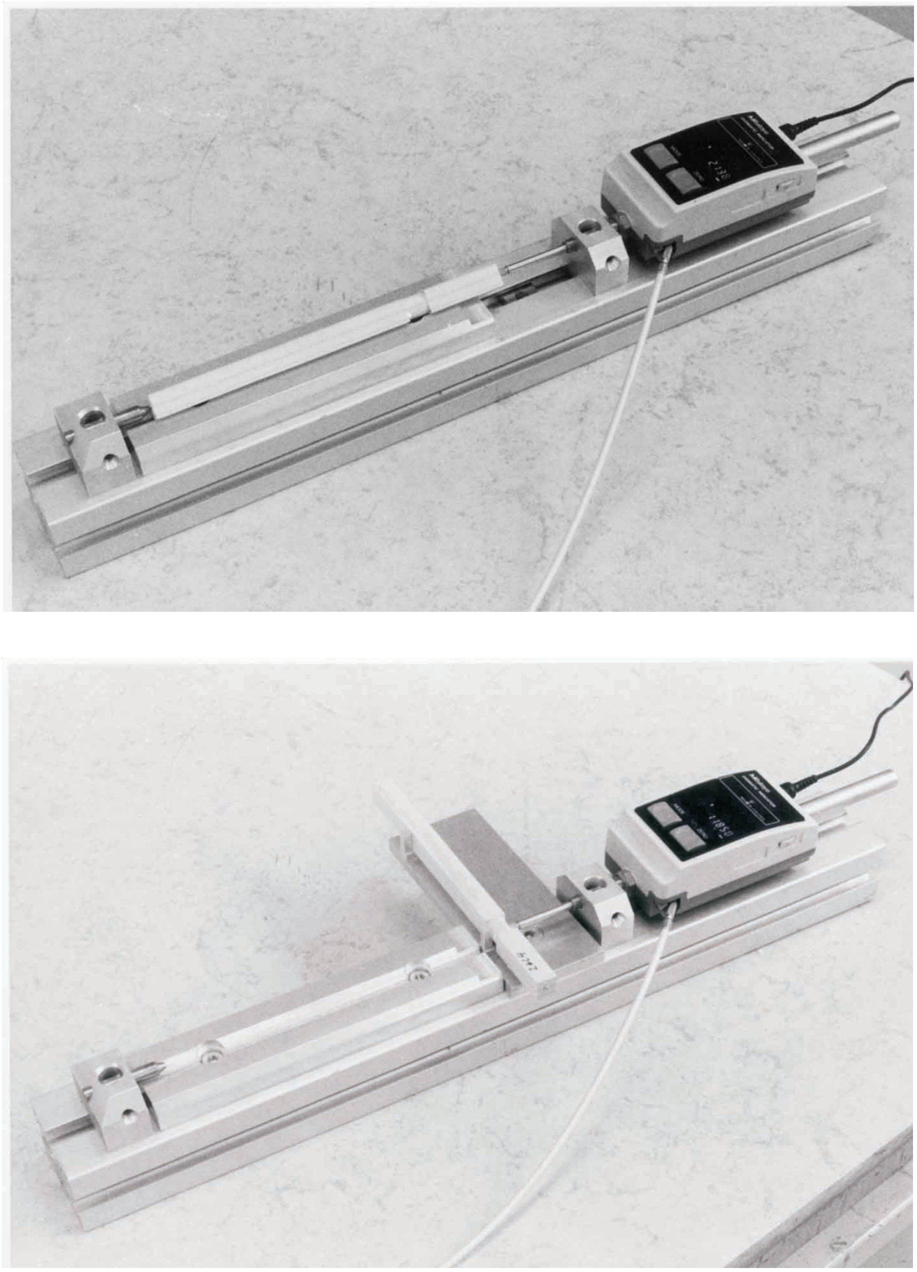

Figure 2. a) Measurement of shrinkage and swelling in the longitudinal direction; b) Measurement of shrinkage and swelling in the radial and tangential directions.

Tree numbers beginning with "s" correspond to trees from the slow-grown stand and tree numbers beginning with "f" correspond to trees from the fast-grown stand.

The specimens were examined visually with respect to compression wood and grouped into three groups:

CW-0: No visible compression wood;

CW-1: Widened latewood band in one or several growth rings;

CW-2: Dominating latewood band in one or several growth rings.

Table I. Mean values of some material parameters for the specimens from each of the trees. Two specimens from tree s3 and one specimen from tree f62 are missing and therefore the total amount of tested specimens was 987.

Tree	Number of specimens	Growth site	RW [mm]	Density (90% RH) [kg m^{-3}]	Density (30% RH) [kg m^{-3}]	MC (90% RH) [%]	MC (30% RH) [%]
s1	90	slow	2.9	430	408	20.0	8.2
f2	90	fast	4.4	435	412	20.0	8.4
s3	43	slow	2.4	566	547	19.8	8.4
f4	45	fast	7.1	421	400	18.7	8.3
s12	90	slow	2.6	445	432	18.0	7.9
f22	90	fast	4.1	439	424	18.3	8.1
f32	90	fast	4.7	382	362	18.8	8.5
s42	90	slow	3.4	405	386	18.6	8.2
f52	90	fast	5.2	365	350	18.8	8.2
f62	89	fast	4.3	369	355	18.5	8.3
s72	90	slow	2.7	493	477	18.5	8.2
s82	90	slow	3.3	472	458	18.6	8.1

This type of visual examination of compression wood was also used in [15]. Problems with this classification occurred when there was a gradual change in the width of the latewood bands of the annual rings between specimens cut just beside each other and for specimens with very narrow annual rings.

Knot area ratio (KAR) was used as a parameter describing the size of the knots. Knot area ratio is defined as the percentage of the area of the cross section that is covered by a projection of the knot(s). The groups were:

KAR-0: KAR = 0% (knot-free specimens);

KAR-1: 0 < KAR ≤ 33%;

KAR-2: KAR > 33%.

Also this parameter was used in [15].

The grain angle was not measured for all the specimens but a visual examination indicated that none of the specimens displayed extreme values of the grain angle.

3. RESULTS

The significance tests referred to below were performed using t-tests. For these tests p-values less than 0.05 were considered as statistically significant.

3.1. Reversibility of swelling

The reversibility of the free longitudinal shrinkage and swelling is important for the modelling of spring and bow deformations of structural timber [10]. Also for mechano-sorptive creep, both in tension, compression and bending, the free longitudinal shrinkage and swelling have shown to be of importance. Much of the typical deformation pattern for mechano-sorptive creep, due to moisture cycling, was erased after the free longitudinal shrinkage and swelling had been subtracted from the creep curve, see [3] and [4].

For 54 specimens from four trees (two fast-grown trees, f2 and f4, and two slow-grown trees, s1 and s3) the shrinkage and swelling were measured, in all three directions, during two or more moisture cycles to study the reversibility of shrinkage and swelling. For most of these specimens, the shrinkage and swelling during the first moisture cycle differed slightly from the shrinkage and swelling during the following moisture cycles. Thereafter, the dimensional changes of the specimens were practically reversible between the moisture cycles. This statement is true for both the longitudinal, the radial and the tangential directions. *Figure 3a* shows the length variation of some specimens from tree s1 measured during four moisture cycles and *figure 3b* shows the tangential width variation of some specimens from tree f2, also

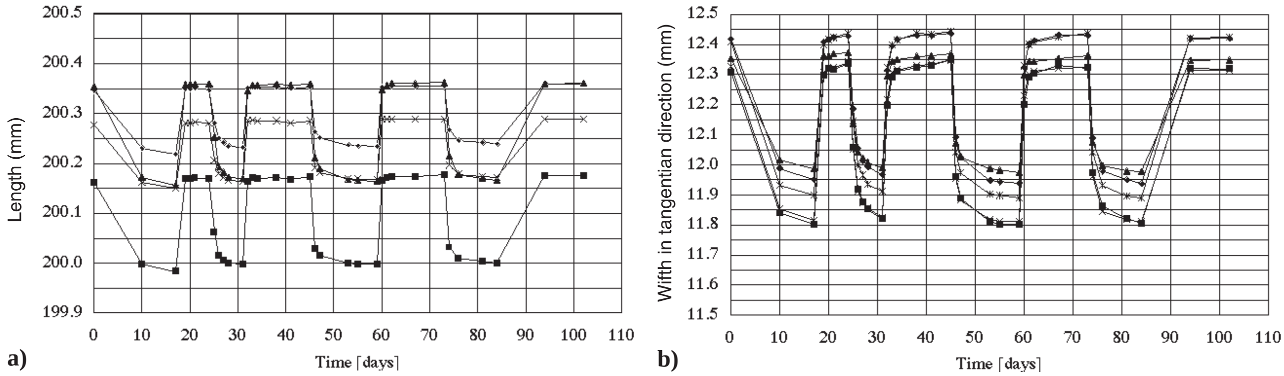

Figure 3. a) Length of some specimens from one slow-grown tree (s1). The first drying period was 17 days then the following moisture cycle was only two weeks (instead of four) due to unexpected problems with the climate room; b) Width in the tangential direction of some specimens from one fast-grown tree (f2).

measured during four moisture cycles. It can also be seen that after each change in relative humidity the dimensional changes occurred very fast, especially in the longitudinal direction.

For some specimens a slight decrease in longitudinal swelling was obtained during the two weeks at 90% RH. This behaviour was not found in the tangential and radial directions.

Also the amount of water (in gram) adsorbed and desorbed during the moisture cycles was very reversible during the moisture cycles. The first moisture cycle differed slightly from the following cycles.

3.2. Radial variation of swelling

In *table II* the swelling coefficients in the different directions are given as mean values and standard deviations for the specimens from the different trees. Note that the radial and tangential swelling coefficients were measured only for specimens with a clear radial-tangential plane and these measurements were therefore made for only 180 specimens. Swelling coefficient in the longitudinal direction is denoted by α_l and swelling coefficients in the tangential and radial directions are denoted by α_t and α_r.

Table II. Mean values and standard deviations () of swelling coefficients in the different directions for the specimens from the different trees. Longitudinal swelling coefficient, α_l, was measured for all 987 specimens, Tangential and radial swelling coefficients, α_t and α_r, were measured for 180 specimens.

Tree	α_l [%/%]	α_t [%/%]	α_r [%/%]
s1	0.006 (0.002)	0.33 (0.05)	0.16 (0.02)
f2	0.005 (0.002)	0.35 (0.03)	0.14 (0.02)
s3	0.004 (0.001)	0.39 (0.02)	0.22 (0.02)
f4	0.013 (0.002)	0.23 (0.02)	0.10 (0.01)
s12	0.006 (0.002)	0.35 (0.04)	0.20 (0.03)
f22	0.006 (0.002)	0.36 (0.06)	0.17 (0.05)
f32	0.012 (0.007)	0.25 (0.04)	0.10 (0.02)
s42	0.006 (0.002)	0.28 (0.03)	0.13 (0.02)
f52	0.010 (0.002)	0.31 (0.03)	0.15 (0.02)
f62	0.009 (0.002)	0.34 (0.03)	0.18 (0.02)
s72	0.006 (0.002)	0.37 (0.05)	0.22 (0.03)
s82	0.005 (0.003)	0.38 (0.04)	0.20 (0.04)

3.2.1. Longitudinal direction

For the relationship between the swelling coefficients in the longitudinal direction, α_l, and the distance from the pith, for all 987 specimens together, the correlation coefficient was very poor ($R = -0.24$), see *table III*. Furthermore, if that relationship was examined for the specimens from each of the stands separately, the coefficient of determination for the specimens from the fast-grown stand was $R^2 = 0.004$, see Figure 4b, and for the specimens from the slow-grown stand $R^2 = 0.55$, see *figure 4a*. In *figures 4a* and *4b* it is clearly shown that the variation in α_l was largest for the specimens from the

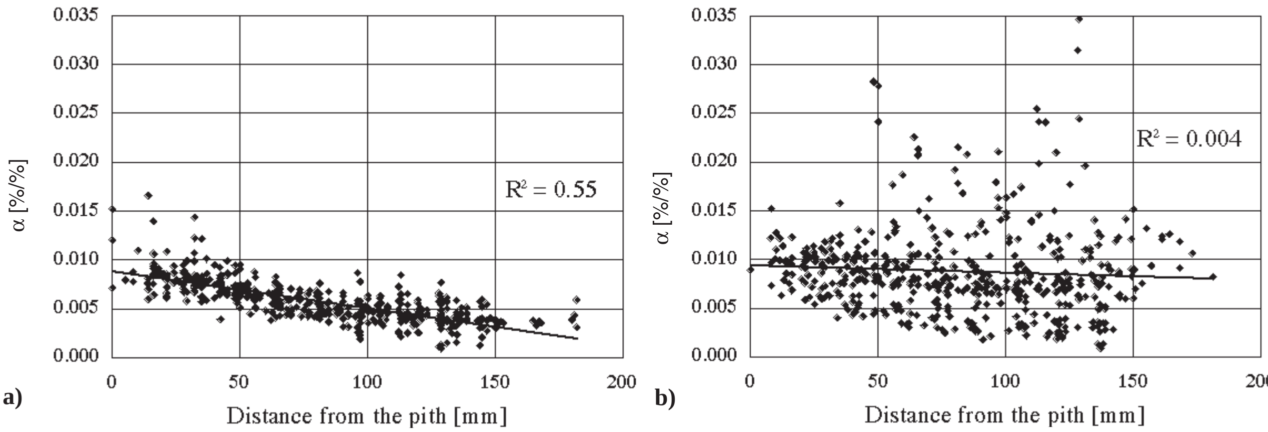

Figure 4. a) Swelling coefficients in the longitudinal direction, α_l, for specimens from the slow-grown stand; b) Swelling coefficients in the longitudinal direction, α_l, for specimens from the fast-grown stand.

fast-grown stand. One possible reason to this large variation is that more specimens from the fast-grown stand contained knots than specimens from the slow-grown stand. The amount of specimens assumed to contain compression wood was approximately the same for the both stands. The specimens from the fast-grown stand (mean value of $\alpha_l = 0.009$) displayed significantly larger α_l than the specimens from the slow-grown stand (mean value of $\alpha_l = 0.006$).

The poor correlation between α_l and distance from the pith for all specimens as one group is explained by the difference in level of α_l between specimens from the different trees, see *table II*, and by the difference in variation pattern between the different trees. For trees number s1, s12, f22, s42 and s82 the coefficient of determination (R^2) between α_l and distance from the pith was larger than 0.50.

If the specimens were grouped with respect to radial position (juvenile, intermediate, mature) there was a statistically significant difference in α_l between the three groups. The specimens containing juvenile wood showed the largest α_l and the specimens containing mature wood showed the smallest α_l. The variation within the groups was large, however.

Figures 5 and *6* show swelling coefficients in the longitudinal direction for specimens from four trees. For specimens from some trees there was a large variation in α_l between the pith and the bark and for specimens from some trees there was nearly no variation in α_l at all. In *figure 5b* the specimen containing the pith displayed an α_l that was more than two times larger than the α_l of the other specimens. Otherwise the variation in α_l was small for the specimens from this tree. The specimens in *figure 6b* displaying large α_l were assumed to contain compression wood. That was also the case for some specimens in the corner of *figure 6a*. However, the magnitude of the swelling coefficients of the compression wood specimens in *Figure 6b* was 2–3 times larger than the magnitude of the swelling coefficients for the compression wood specimens in *figure 6a*. This large variation radially in a tree should lead to circumspection when using swelling coefficients for modelling the behaviour of timber.

Table III shows correlation coefficients (R) between α_l and some material parameters. The dynamic E-modulus at 30% and at 90% RH were evaluated in [2]. The strongest correlation for α_l was achieved with respect to the eigenfrequency in the longitudinal direction (measured at 90% RH, the relationships were approximately the same if the values measured at 30% RH were used). One possible explanation for this strong correlation between α_l and the eigenfrequency is that the eigenfrequency is a measure of E/density (sometimes called specific modulus). Further, E is quite well correlated with microfibril angle, see [6, 7, 17]. Consequently, the strong relationship between eigenfrequency and α_l confirms the fact that swelling properties in the longitudinal direction are influenced by the microfibril angle.

If RW and density were combined by multiple regression to predict α_l the correlation coefficient was 0.59. Adding also the radial position (Dist.) did not improve the correlation coefficient. If either density, RW or radial position was combined with the eigenfrequency to

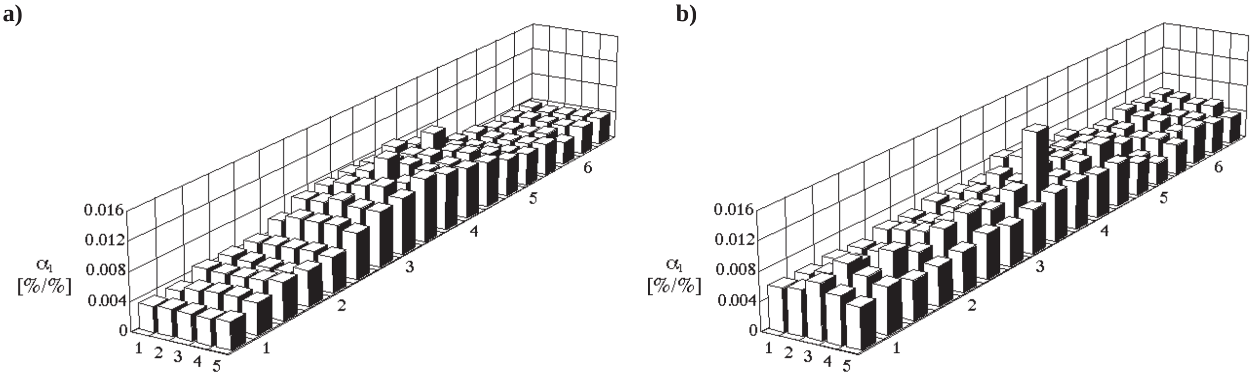

Figure 5. a) Swelling coefficients in the longitudinal direction for specimens from tree s1; b) Swelling coefficients in the longitudinal direction for specimens from tree s72.

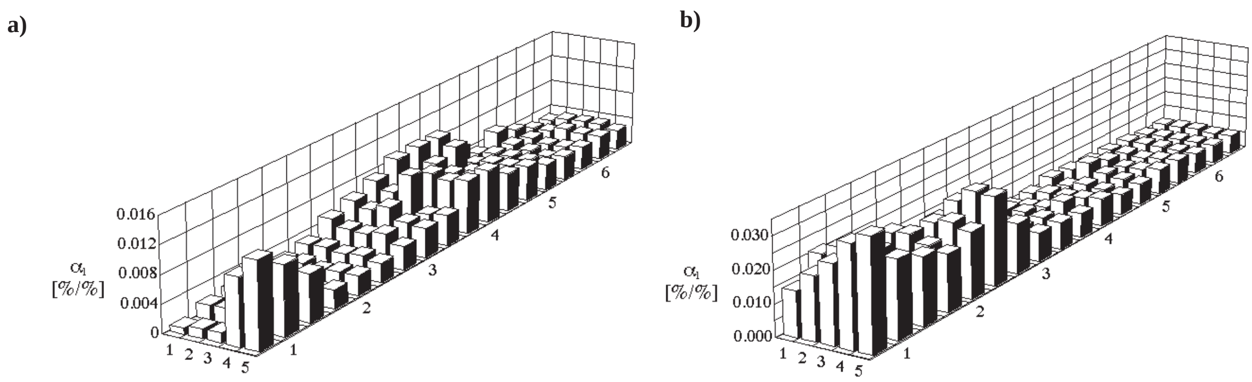

Figure 6. a) Swelling coefficients in the longitudinal direction for specimens from tree f2; b) Swelling coefficients in the longitudinal direction for specimens from tree f32. Note the difference in scale between *figure 6a* and *figure 6b*.

predict α_l, the correlation coefficient was only marginally affected compared to R = –0.72 for eigenfrequency and α_l (the sign shifted).

3.2.2. Tangential and radial directions

For swelling coefficients in the radial and tangential directions, α_r and α_t, the radial variation was less pronounced than for swelling coefficients in the longitudinal direction. This can be seen in *figures 7a* and *7b* with α_r and α_t versus distance from the pith for the specimens from two trees. The correlations between radial position and α_r and α_t were very weak if all specimens were studied together (R = 0.24 and 0.29 respectively), see *table IV*. This is partly explained by the fact that the magnitudes of swelling coefficients differed between the trees, see *table II*. It can especially be noted that the specimens from trees f4 and f32, on the average, displayed swelling coefficients in both the radial and tangential directions that were smaller than the swelling coefficients of the specimens from the other trees.

The magnitude of the swelling coefficients presented in this paper were of the same order as coefficients presented in other studies of Norway spruce wood [14, 15]. The slow-grown material had significantly larger swelling coefficients in the tangential and radial directions (α_t = 0.35 and α_r = 0.18) than the fast-grown material (α_t = 0.32 and α_r = 0.15).

Table IV shows a correlation matrix for α_r, α_t and other properties measured on the 180 sticks. It can be seen that also the swelling coefficients in the radial and tangential directions correlated well with eigenfrequency, measured in the longitudinal direction. By combining density and RW the correlation coefficient (*R*) for α_t increased to 0.59 and for α_r the correlation coefficient increased to 0.72. Adding also distance from the pith to density and RW gave a very small improvement of the correlation coefficient for α_r, namely to R = 0.74.

Table III. Correlation matrix (*R*) for swelling coefficients in the longitudinal direction (α_l) and some material parameters (987 specimens included). RW = annual ring width, E = dynamic modulus of elasticity (measured at 90% RH), Freq. = eigenfrequency in the longitudinal direction, Dist. = distance from the pith.

	α_l	RW	*E*	Density	Freq.	Dist.
α_l	1.00	0.58	–0.68	–0.41	–0.72	–0.24
RW		1.00	–0.75	–0.57	–0.69	–0.44
E			1.00	0.78	0.87	0.40
Density				1.00	0.38	0.39
Freq.					1.00	0.28
Dist.						1.00

Table IV. Correlation matrix (*R*) for the 180 specimens with swelling coefficients measured in the radial and tangential directions (α_r and α_t). Abbreviations see *table III*.

	α_t	α_r	Freq.	α_l	Dist.	Density	*E*	RW
α_t	1.00	0.79	0.82	–0.62	0.29	0.56	0.83	–0.51
α_r		1.00	0.72	–0.44	0.24	0.69	0.84	–0.61
Freq.			1.00	–0.68	0.20	0.42	0.85	–0.56
α_l				1.00	–0.21	–0.37	–0.62	0.49
Dist.					1.00	0.42	0.38	–0.50
Density						1.00	0.82	–0.65
E							1.00	–0.70
RW								1.00

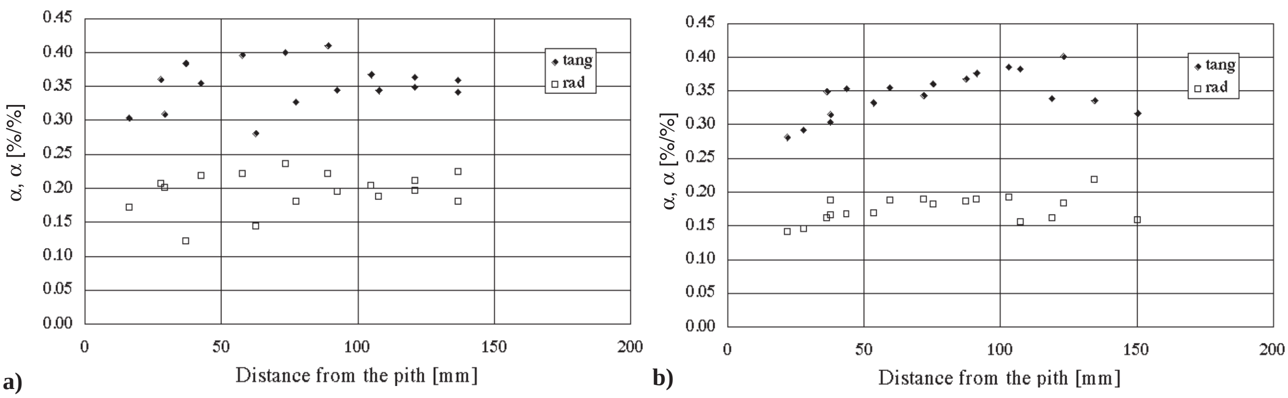

Figure 7. a) Swelling coefficients in the tangential and the radial directions, α_r and α_t, versus distance from the pith for the specimens from tree s12; b) Swelling coefficients in the tangential and the radial directions, α_r and α_t, versus distance from the pith for the specimens from tree f62.

A combination of eigenfrequency and density resulted in correlation coefficients for α_t and α_r of 0.86 and 0.84 respectively. Further improvement of the correlation coefficients by combination of eigenfrequency and other parameters measured in this study was not possible to achieve.

Moisture induced movements in the tangential direction have shown to be of importance for prediction of twist of structural timber, see [9]. As mentioned before, this study of moisture induced movements is a part of a larger study concerning mechano-sorptive creep in wood. Each 15 specimens were sawn at the end of a creep test specimen, 1.10 m long. For 48 creep test specimens the longitudinal eigenfrequency was measured before the creep tests started. The mean values of the radial and tangential swelling coefficients of the small specimens corresponding to these 48 creep test specimens were correlated with longitudinal eigenfrequency measured on the large creep test specimens. These coefficients of determination were $R^2 = 0.46$ for α_t and $R^2 = 0.58$ for α_r. As a very preliminary study this is interesting, as there are commercial grading machines which measure the longitudinal eigenfrequency already in operation. Adding the density of the creep test specimens did not improve the above mentioned correlation coefficients.

3.3. Anisotropy of swelling in the different directions

Table V shows the anisotropy of the swelling coefficients in the different directions for the specimens from the two stands. The common fact presented in the literature with $\alpha_r = \alpha_t/2$ was valid, at least approximately, for the spruce specimens studied here. The difference in this relationship was statistically significant between the specimens from the two stands.

The relationship between α_l and α_t (1 : 10) reported in literature was not valid for the material studied here, see *table V*. There was a quite large difference in the relationships α_r/α_l and α_t/α_l between the specimens from the two stands. Also for these two cases the differences between the specimens from the two stands were statistically significant.

Table V. Anisotropy of the swelling coefficients for specimens divided by stands. Mean values and standard deviations () are shown.

	Fast-grown	Slow-grown
Specimens	89	91
α_t/α_r [-]	2.2 (0.4)	1.9 (0.3)
α_r/α_l [-]	23.4 (18.1)	36.9 (21.7)
α_t/α_l [-]	52.1 (43.1)	68.8 (37.2)

When examining the anisotropy of the swelling coefficients in the different directions for specimens from the 12 different trees it is clearly shown that the anisotropy varies not only between the specimens from the two stands but also between specimens from the different trees. The specimens from tree f2 were, on the average, the most anisotropic ($\alpha_t/\alpha_l = 113.4$) and the specimens from tree f4 were the least anisotropic ($\alpha_t/\alpha_l = 18.9$). Furthermore, when these relationships were examined for individual specimens very large variations were found. Possible causes for the large variations will be discussed in section 3.4.

3.4. Influence of knots and compression wood on swelling

In Sections 3.2 and 3.3 no difference was made between defect free specimens and specimens containing knots and/or compression wood. However, it is reasonable to assume that visual defects as knots and compression wood can explain a part of the large variations presented above.

3.4.1. Longitudinal direction

Knots seemed to influence the swelling coefficients in the longitudinal direction especially within the compression wood groups CW-0 and CW-1 as can be seen in *figure 8*. For specimens classified as CW-0 (no compression wood) the difference in α_l was statistically significant

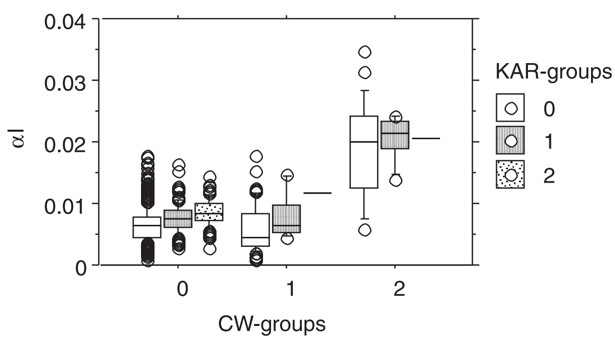

Figure 8. Swelling coefficients in the longitudinal direction (α_l) for specimens classified with respect to occurrence of knots and compression wood. See also *table VI*.

between all three KAR-groups. Mean values and standard deviations of the data shown in *figure 8* can be found in *table VI*. In the box plots the 25th, 50th and 75th percentiles are shown.

The influence of compression wood on the longitudinal swelling coefficients was larger than the influence of knots. Specimens classified as CW-2 displayed swelling coefficients in the longitudinal direction that were more than twice as large as for specimens classified as CW-0. The difference in α_l between specimens classified as CW-0 and CW-1 was small. The reason for this is probably that the classification used for compression wood was not accurate enough.

In this study, no significant influence of compression wood on density was found which also indicates that the visual identification of compression wood was not accurate enough.

Even if the presence of knots and/or compression wood explained the largest swelling coefficients in the longitudinal direction, there was still a large variation in α_l within the 580 specimens with no knots and no compression wood. For this group, the minimum α_l was 0.001 and the maximum α_l was 0.018. Differentiating these defect free specimens with respect to stand or radial position (juvenile, intermediate and mature) reduced the variation within each of the groups. There was a statistically significant difference between the groups but the "outliers" were still spread out in all the groups. Placing all specimens with RW ≤3 mm in one group gave a group with quite small variation in α_l, however the variation within the other group (RW > 3 mm) was still large.

Table VI. Swelling coefficients in the longitudinal direction, α_l. Mean values and standard deviations () for specimens classified with respect to appearance of knots and compression wood are shown.

CW-group	KAR-group	Specimens	α_l [%/%]
0	0	580	0.007 (0.003)
0	1	162	0.008 (0.002)
0	2	95	0.009 (0.002)
1	0	104	0.006 (0.004)
1	1	11	0.008 (0.004)
1	2	1	0.012 (–)
2	0	25	0.019 (0.008)
2	1	7	0.020 (0.004)
2	2	1	0.021 (–)

For the defect free specimens, the correlation matrix involving the same parameters as *table III* looked approximately in the same way as for all specimens studied together. The only difference was the correlation between α_l and RW. For the defect free specimens that correlation increased to $R = 0.69$, compared to $R = 0.58$ for all specimens, which was nearly equal to the correlation between α_l and freq. Eigenfrequency in the longitudinal direction was still the best parameter, measured in this study, to predict α_l.

3.4.2. Tangential and radial directions

Swelling coefficients in the tangential and radial directions were measured locally in a knot free section of the specimens. The influence of knots on these coefficients was therefore negligible.

The influence of compression wood on α_t and α_r is shown in *figure 9* and in *table VII*.

Occurrence of compression wood (CW-2) significantly decreased the swelling coefficients in the tangential and radial directions. The decrease in α_t and α_r was, on the average, more than 30% compared to specimens without compression wood (CW-0). The same result was obtained in [15]. As for α_l, the swelling coefficients in the transverse directions displayed only a small difference between the compression wood groups CW-0 and CW-1.

There was a large variation in α_t and α_r ($0.19 \le \alpha_t \le 0.46$, $0.09 \le \alpha_r \le 0.28$) also within the group of specimens without compression wood (CW-0). A correlation matrix with only these 148 specimens, including the same parameters as *table IV*, showed only very small differences compared to *table IV*, where all 180 specimens were included. The correlations were slightly weaker, probably due to the decreased variability in α_t and α_r. Grouping the specimens with respect to stand or radial position did not reduce the variability within the groups satisfactorily (these values are not shown in the paper).

3.4.3. Anisotropy of swelling in the different directions

The anisotropy of the swelling coefficients in the different directions for the three compression wood groups of specimens can be found in *table VII*. Compression wood showed no significant influence on the relationship between α_t and α_r. But for the relationships α_t/α_l and α_r/α_l compression wood significantly decreased the values, see *table VII*. Compression wood clearly makes the wood less anisotropic. This conclusion agrees well with the fact that compression wood displays large microfibril angles.

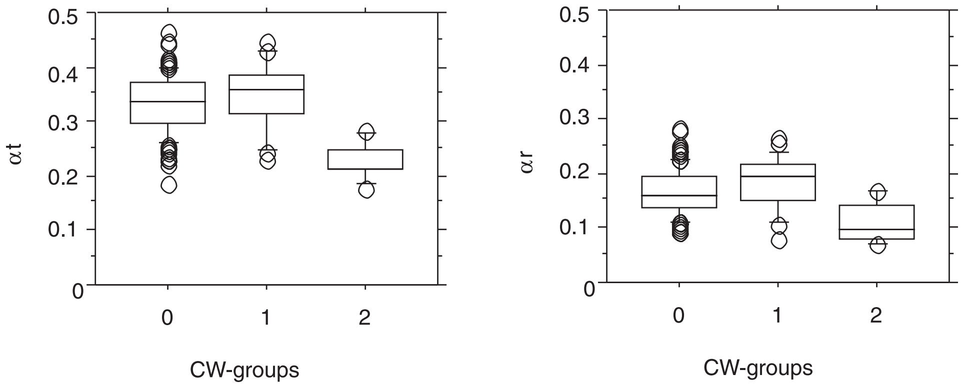

Figure 9. a) Swelling coefficients in the tangential direction (α_t) for specimens classified with respect to compression wood; b) Swelling coefficients in the radial direction (α_r) for specimens classified with respect to compression wood.

Table VII. Influence of compression wood on swelling coefficients in the tangential, α_t, and radial, α_r, directions and on the relationships between swelling coefficients in the different directions. Mean values and standard deviations () are shown.

CW-group	Specimens	α_t [%/ %]	α_r [%/ %]	α_t/α_r [–]	α_t/α_l [–]	α_r/α_l [–]
0	148	0.33 (0.05)	0.17 (0.04)	2.1 (0.3)	57.9 (30.7)	28.4 (14.0)
1	25	0.35 (0.06)	0.18 (0.05)	2.0 (0.3)	89.6 (71.6)	47.3 (37.9)
2	7	0.23 (0.04)	0.11 (0.04)	2.26 (0.6)	12.4 (6.4)	6.2 (4.6)

4. DISCUSSION

This paper has clearly pointed out a large variation in moisture induced movements, between equilibrium MC at 30% RH and equilibrium MC at 90% RH, for the studied spruce material. The variation was largest for swelling coefficients in the longitudinal direction. For the entire material (987 specimens) α_l varied between 0.001 and 0.035.

Each of the 12 studied trees showed an individual variation in α_l between the pith and the bark. This individual variation is found also for other wood material parameters as for example spiral grain angle, annual ring width and modulus of elasticity. The general trend is, however, larger α_l for specimens cut near the pith of the tree than for specimens cut near the bark.

The variation in α_l was smaller for the specimens from the slow-grown stand than for the specimens from the fast-grown stand. For the specimens from the slow-grown stand 55% of the variation in α_l could be explained by distance from the pith. For the specimens from the fast-grown stand the corresponding figure was 0.4%.

The eigenfrequency measured in the longitudinal direction was the single best parameter, measured in this study, to predict α_l for the entire test material. That parameter could explain approximately 52% of the variation in α_l.

It was possible to reduce the variation in α_l by taking occurrence of knots and compression wood into account. Then the variation was nearly halved. On the average, occurrence of compression wood (CW-2), more than doubled the value of α_l. The influence of knots on α_l was not so large.

Also within the group of 580 defect free specimens there was still a large variation in α_l, see *figure 8*. The eigenfrequency in the longitudinal direction was the best predictor of α_l also within this group. For these specimens annual ring width was nearly as good as eigenfrequency for predicting α_l (R^2 = 0.48).

For the swelling coefficients in the tangential and the radial directions there were not such clear differences between the specimens from the two stands in terms of variation between the specimens as for α_l. None of the variations with distance from the pith were pronounced. However, there was a statistically significant difference in α_t and α_r between the specimens from the two stands (larger α_t and α_r for the specimens from the slow-grown stand).

Occurrence of compression wood, on the average, decreased α_t and α_r with 30%. The variability within the group of compression wood free specimens was only slightly decreased compared to the whole group of specimens. Also for α_t and α_r the single best predictor, measured in this study, was the eigenfrequency in the longitudinal direction. Density was nearly as good as the eigenfrequency for predicting α_r. For the entire test material the relationship α_t/α_l varied between 5.7 and 285.6. The specimens from the fast-grown stand were less anisotropic than the specimens from the slow-grown stand. Also specimens containing compression wood showed less anisotropy than the other specimens. The reason for this is probably the large microfibril angle for specimens from the fast-grown stand and for specimens containing compression wood. This conclusion was strengthened by the fact that the eigenfrequency in the longitudinal direction was the best predictor of swelling coefficients in all three directions as the eigenfrequency can be seen as related to the microfibril angle.

With background of the results obtained in this study, the eigenfrequency in the longitudinal direction seems to be useful for predicting moisture induced movements. The parameter was applicable both for small defect free specimens and for small specimens containing knots and compression wood. Whether the eigenfrequency in the longitudinal direction is useful also for predicting moisture induced movements of large specimens is not possible to decide from this study.

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