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Wood shrinkage: influence of anatomy, cell wall architecture, chemical composition and cambial age

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Abstract The influence of microfibril angle (MfA), density and chemical cell wall composition on shrinkage varied between the longitudinal and tangential directions as well as between wood types, namely compression wood (CW), mature wood (MW) and juvenile wood (JW). At the same MfA, CW exhibited a lower tangential shrinkage than JW, indicating the influence of the chemical composition on wood shrinkage. The chemical composition measured via FTIR microspectroscopy has been shown in conjunction with density to be an alternative to MfA data for shrinkage predictions. This was particularly true for wood of young cambial age for which the MfA did not correlate to shrinkage. The results indicate a possibility to reduce distortion of sawn timber by segregation using infrared (IR) and X-ray in-line measurements.

Schwindverhalten von Holz: Einfluss von Anatomie, Zellwandarchitektur, chemischer Zusammensetzung und Alter des Kambiums

Zusammenfassung Der Einfluss des Mikrofibrillenwinkels (MfA), der Rohdichte und der chemischen Zusammensetzung der Zellwand auf das Schwindverhalten variiert sowohl zwischen longitudinaler und tangentialer Richtung als auch zwischen Druckholz (CW), juvenilem (JW) und adultem Holz (MW). Die geringere Tangentialschwindung von CW im Vergleich zu JW bei gleichem MfA weist auf den Einfluss der chemischen Zellwandzusammensetzung auf das Schwindverhalten hin. Es konnte gezeigt werden, dass die chemische Zellwandzusammensetzung, gemessen mittels Mikro-FTIR-Spektroskopie, eine Alternative zum MfA für die Vorhersage des Schwindmaßes darstellt. Dies galt insbesondere für JW, für welches keine Korrelation zwischen Schwindmaß und MfA gefunden wurde. Diese Ergebnisse zeigen eine Möglichkeit zur Reduzierung der Verformung von Schnittholz durch Sortierung basierend auf Infrarot- und Röntgenmessungen.

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1 Introduction

Even the strongest piece of timber is not saleable as construction material if it is distorted and therefore dimensional stability is of huge economic value for the forest industry (Johansson et al. 1994, Eastin et al. 2001). Spring and bow are forms of timber distortion which cannot be predicted from macroscopic wood characteristics like ring curvature or spiral grain (e.g., Simpson and Gerhardt 1984, Skaar 1988, Johansson 2002). They are the result of heterogeneous shrinkage within a piece of timber (Simpson and Gerhardt 1984), which can vary considerably in a random way within a batten (Kliger et al. 2003, Johansson 2003). Models based on high-resolution longitudinal shrinkage data do give good predictions of spring and bow (Simpson and Gerhardt 1984, Ormarsson 1999, Stanish 2000, Kliger et al. 2003, Johansson 2003, Johansson et al. 2003). In order to make use of these models to improve timber quality by segregation, non-destructive techniques for measurement of longitudinal shrinkage are required. Currently, such techniques do not exist.

Dimensional changes of wood caused by water adsorption are anisotropic and in the first instance dependent on the anatomical direction in the wood (as summarised by Skaar 1988). While the longitudinal shrinkage (LS) of sound timber is generally small (< 1%), the radial and tangential shrinkage (TS) is of considerable magnitude varying between 2–5% and 6–8% for conifers, respectively (as summarised by Suchsland 2004). However, wood shrinkage also depends on microstructural and molecular features of the cell wall. These include the microfibril angle (MfA) (Koehler 1931, Barber and Meylan 1964), the angle at which the cellulose fibrils wind in the tracheid cell walls, as well as the physical properties of the surrounding matrix. Theoretical models describing the influence of the MfA on the TS and LS have been developed based on a hygroscopic isotropic matrix consisting of hemicelluloses and lignin which is reinforced with rigid cellulose fibrils (Barber and Meylan 1964, Barrett et al. 1972, Cave 1972, Koponen et al. 1989, Yamamoto 1999). These theoretical models, refined over the years (e.g. incorporating more cell wall layers and MfA distributions) predict principally similar influences of MfA on shrinkage behaviour. The models are generally in accordance with the rather scarce experimental data and illustrate the complex relationship between MfA and shrinkage (Yamamoto et al. 2001). TS is high at low MfA and steeply decreases with MfA above 30°. LS is fairly constant for MfA below 30°, showing a slight decrease (or even longitudinal expansion for MfA around 25°), and then increases rapidly. TS and LS are of same magnitude at MfA = 45°, beyond which TS and LS exchange their behaviour.

The model developed by Yamamoto et al. (2001) also demonstrates the crucial influence of the matrix properties. Varying the swelling potential of the matrix has a major influence on the TS at low MfA, while the same is true for LS at high MfA. The implication is that the correlation between shrinkage and MfA is strong only over a narrow MfA range (30–40°) (Floyd 2005).

The mechanical properties of the matrix are sensitive to changes in the moisture content. Moreover, each matrix polymer (i.e., lignin and the various hemicelluloses) responds differently to moisture changes (Cousins 1976, 1978, Akerholm and Salmén 2004, Olsson and Salmén 2004). This causes in conjunction with the variable chemical composition of individual wood types (e.g., galactan in compression wood (Timell 1986), high xylan content in juvenile wood (Bertaud and Holmbom 2004)) a swelling behaviour that is not entirely dependent on the MfA (Barber and Meylan 1964). Wooten et al. (1967) following comments by Kelsey (1963) reported that the LS of compression wood (CW) is almost an order of magnitude bigger than for JW with comparable MfA. They attributed this to a thicker S1 layer, which after re-evaluating the published microscopy images is in fact the S2(L) layer (as summarised by Timell 1986). The S2 layer in severe CW tracheids separates in an outer S2(L) and an inner S2 layer. TEM photographs taken after the selective removal of polysaccharides or lignin, respectively, demonstrate that the outer S2(L) layer is highly lignified and almost devoid of cellulose fibrils (Casperson 1962, Côté et al. 1968). Recently, the β-1-4-galactan present in CW has been localised in the outer cell wall layers by immunolabelling (Altaner et al. 2007). Combining those observations, a cell wall layer consisting predominantly of lignin and β-1-4-galactan can be postulated in CW. This emphasises the influence of physical matrix properties on shrinkage.

Traditionally shrinkage has been correlated with density (e.g. Suchsland 2004). This correlation is not particularly strong and represents a general trend for sound wood of different species. Watanabe and Norimoto (1996) proposed a hyperbolic relationship between LS and specific MOE (MOE/density). However, the form factors of the curve were different for normal wood (NW) and CW. A robust regression for predicting LS by MfA was reported for example in loblolly pine (*Pinus taeda*) if cambial age was included (Lu et al. 1994). Johansson et al. (2003) developed a model for the prediction of LS from colour and 'tracheid effect' measurements. The model uses six variables obtained from on-line measurements and was able to predict 81% of the variation in longitudinal shrinkage in Norway spruce (*Picea abies*).

Recently, Floyd (2005) proposed an alternative model to predict LS of wood. It is based on the assumption that the longitudinal shrinkage can be expressed as a ratio of a driving force (hemicelluloses) and a resisting force (microfibril network):

$$\text{Predicted LS} = (\text{Density/MOE}) \times (\alpha \times \text{Glucose content} + \beta \times \text{Galactose content}) + c$$

where α and β are constants expressing the relative importance of the resisting and driving forces. It is likely that these constants are species dependent. For loblolly pine (*Pinus taeda*) the influence of the driving force was more than five times that of the resisting force. The model could explain 92% of the variation in LS.

Shrinkage predictions have to be based on non-destructive on-line measurements if they are to be used for improvement of the quality of timber by segregation. Present measurement techniques for MfA, local MOE, or galactose and glucose contents do not fulfil these requirements. High resolution density scanners are already used in the forest industry to predict timber quality in terms of strength and stiffness but not with respect to distortion. Infrared spectroscopy (IR) yields information on the chemical composition and is used in the high frequency range (NIR) in industrial processes for quality control (So et al. 2004, Tsuchikawa 2007). However, NIR has shown weak correlations, in particular for galactose, when used to predict the chemical composition of wood (Jones et al. 2006). Calibration of IR spectroscopy to physical wood properties like density, MfA or MOE has also been reported (e.g. Thygesen 1994, Hoffmeyer and Pedersen 1995, Schimleck et al. 2002, Nuopponen et al. 2006). NIR has been used for shrinkage predictions. For 5-year old *Eucalyptus urophylla* × *E. grandis* hybrids TS could be modelled with 82% accuracy by NIR (Bailleres et al. 2002). The weak correlations with radial shrinkage (RS) (0.45) and LS (0.35) precluded similar predictions in these directions. 63% of the variation in volumetric shrinkage of mahogany (*Swietenia macrophylla*) could be predicted by NIR (Taylor et al. 2008). This weak correlation, compared to density and extractives content ($R^2 = 0.81$ and 0.67, respectively), was probably caused by their counteracting effects on shrinkage.

The authors have recently reported the possibility of measuring CW severity by mid-range IR scanning microscopy (Altaner et al. 2009), utilising the unique chemical composition of CW. Purpose of this study was to investigate if the FTIR CW-indicator can be used to improve shrinkage predictions.

2 Materials and methods

55 specimens were prepared from a 36 year old Sitka spruce (*Picea sitchensis* (Bong.) Carrière) tree grown at Kershope, Northumbria, UK and selected for the presence of severe compression wood as well as normal juvenile and mature wood (McLean 2007). From a radial strip samples for FTIR CW-indicator, X-ray density and transmitted light measurements were prepared according to Altaner et al. (2009). From the remainder small samples (~1.5 mm (*R*) × ~21 mm (*L*) × ~15 mm (*T*)) for shrinkage measurements were split. Dimensional change between fully saturated (submerging for 2 d in deionised water including 5 vacuum cycles) and oven dry (3 d at 105 °C) conditions were measured with a micrometer (±1 µm precision). The MfA was determined by analysing the 002 χ-profile of the X-ray diffraction patterns according to Cave (1966) ('2T-method').

3 Results and discussion

3.1 Radial profile

Figure 1 illustrates the variation of longitudinal (LS) and tangential (TS) shrinkage in a radial strip of Sitka spruce containing severe CW. The biggest variation coincided with the occurrence of CW as identified in transmitted light or by IR spectroscopy. Noticeable differences in shrinkage could be recognized between MW and JW. Those agree with the differences in MfA as could be expected from the reinforced matrix theory discussed above (Barber and Meylan 1964, Cave 1972, Barrett et al. 1972, Koponen et al. 1989, Yamamoto 1999). The difference in shrinkage between MW

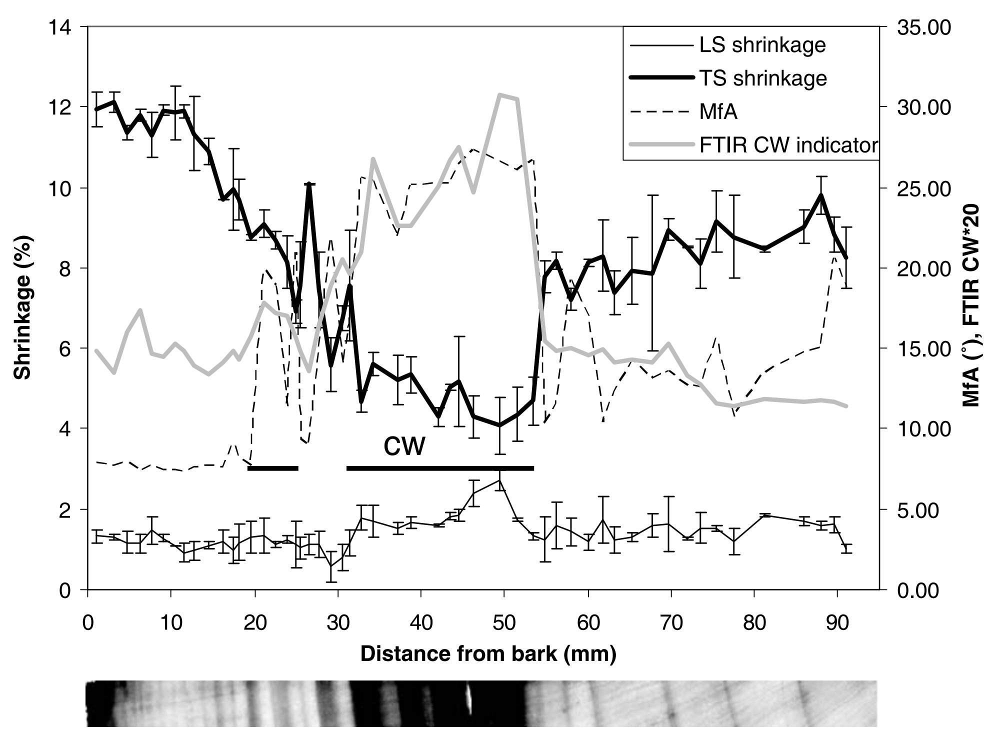


Fig. 1 MfA, FTIR CW-indicator and shrinkage in a *P. sitchensis* radius. The photograph shows the cross section in transmitted light for CW identification. The samples regarded as CW are marked. JW samples are from 55 mm onward

Abb. 1 MfA, FTIR CW-Indikator und Schwindmaß in einem Radius von *P. sitchensis*. Das Foto zeigt den Querschnitt im Durchlicht zur Identifikation von Druckholz (CW). Die als Druckholz identifizierten Proben sind mit einem schwarzen Balken markiert. Proben jenseits von 55 mm wurden als juveniles Holz (JW) klassifiziert and JW was not mirrored by the FTIR CW-indicator, which gave similar values for both wood types. Density (data not shown) was higher for MW than JW samples. This offered the possibility to predict shrinkage from a combination of FTIR CW-indicator and density values, two measurements potentially available for sawn timber. In order to be of value for wood quality assessment in the timber industry measurements have to be done on-line and reliably cope with JW, the major wood type produced in fast growing plantation forestry.

3.2 Shrinkage

As expected, MW differed statistically from CW and JW at alpha ≤ 0.05 in its tangential as well as longitudinal shrinkage behaviour (Table 1). JW and CW, both characterised by a high MfA, did not differ significantly in LS, but did so in TS. Figure 2 visualises the different relationship between LS and TS shrinkage for the wood types investigated. CW, JW and MW samples were found in separated clusters. Particularly the different shrinkage behaviour in the longitudinal and tangential directions for CW demonstrates that shrinkage is influenced not only by one wood characteristic, i.e., MfA, but also by the morphology or chemical composition. Secondly it shows that the influence of those wood features is different for the longitudinal and tangential directions. This is consistent with theoretical considerations on the influence of morphological (Cave 1972) and physical cell wall properties on shrinkage (Yamamoto et al. 2001). It is not only the composition of the cell wall matrix that varies in wood (among others β-1-4 galactan is present in CW (Timell 1986) and JW is enriched in xylan (Bertaud and Holmbom 2004)) but also the cell morphology (i.e., cell shape, cell wall thickness, rays etc.) differs. Therefore, the relationship between LS and TS can be expected to vary between wood types.

Table 1 Longitudinal shrinkage (LS), tangential shrinkage (TS), microfibril angle (MfA), FTIR CW-indicator (FTIR) and density of mature wood (MW), compression wood (CW) and juvenile wood (JW) in Sitka spruce; Average values with standard deviation in parentheses

Tabelle 1 Längsschwindmaß (LS), Tangentialschwindmaß (TS), Mikrofibrillenwinkel (MfA), FTIR CW-Indikator (FTIR) und Rohdichte von adultem Holz (MW), Druckholz (CW) und juvenilem Holz (JW) in Sitkafichte. Mittelwerte mit Standardabweichung in Klammern

	All	MW	CW	JW
Number of samples	53	16	19	18
LS (%)	1.46 (0.37)	1.16 (0.15)	1.50 (0.51)	1.46 (0.23)
TS (%)	8.37 (2.33)	10.76 (1.34)	5.94 (1.60)	8.37 (0.65)
MfA (°)	14.2 (6.74)	7.9 (0.64)	22.1 (4.91)	14.2 (3.03)
FTIR (AU)	0.67 (0.25)	0.74 (0.05)	1.11 (0.23)	0.67 (0.08)
Density ($g\,cm^{-3}$)	0.45 (0.12)	0.59 (0.06)	0.54 (0.13)	0.45 (0.11)

Three wood features have been correlated to shrinkage of different Sitka spruce wood types. The MfA is a measure of the cell wall anisotropy, recognised as an important factor influencing wood shrinkage (Koehler 1931). Density represents a morphological characteristic that has been associated with volumetric and cross-sectional shrinkage (e.g. Panshin and de Zeeuw 1980). The FTIR CW-indicator provides a measure for the chemical composition of the wood, which has also been predicted to influence its shrinkage

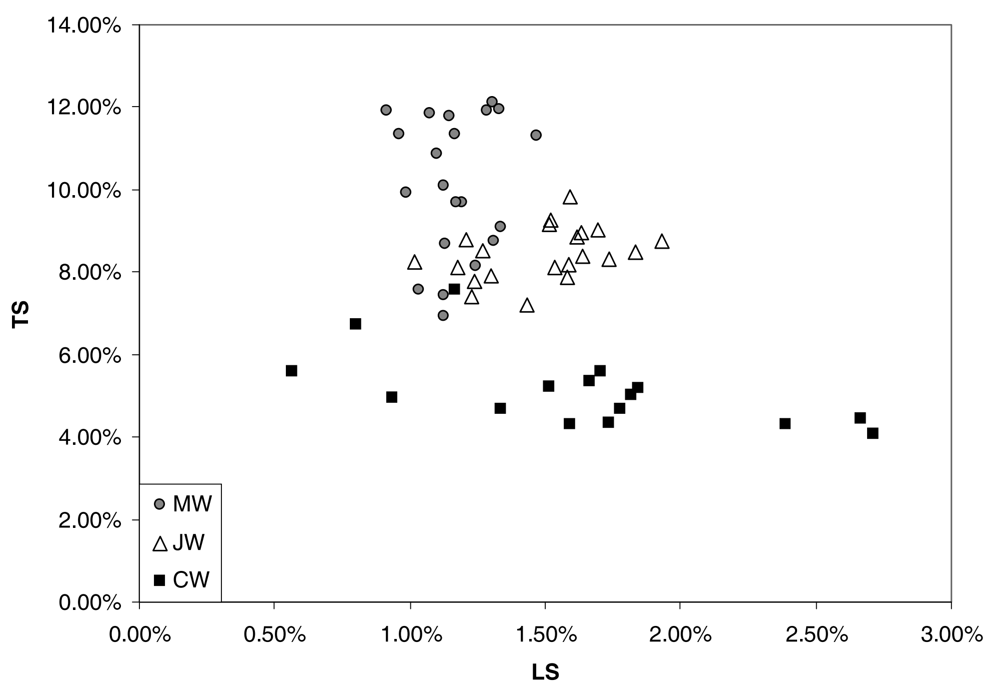


Fig. 2 Relationship between longitudinal and tangential shrinkage in Sitka spruce

Abb. 2 Zusammenhang zwischen Längsschwindmaß und Tangentialschwindmaß in Sitkafichte

Table 2 Linear correlation factors (R^2) between shrinkage and wood properties (and linear combinations thereof) for different Sitka spruce wood types
Tabelle 2 Lineare Korrelationsfaktoren (R^2) zwischen Schwindmaß und Holzeigenschaften (sowie deren linearen Kombinationen) für unterschiedliche Holztypen

Feature	All samples	MW	CW	JW	MW + CW	CW + JW	MW + JW
				Longitudinal			
MfA	0.28***	0.06^{ns}	0.45***	0.01^{ns}	0.39***	0.16**	0.20**
FTIR	0.24***	0.00^{ns}	0.56***	0.00^{ns}	0.55***	0.20***	0.10*
Density	0.05^{ns}	0.02^{ns}	0.46***	0.02^{ns}	0.20**	0.19**	0.17**
MfA + FTIR	0.31***	0.06^{ns}	0.60***	0.02^{ns}	0.55***	0.20*	0.21*
MfA + Density	0.33***	0.06^{ns}	0.61***	0.04^{ns}	0.25***	0.25*	0.24*
FTIR + Density	0.24***	0.02^{ns}	0.63***	0.02^{ns}	0.64***	0.25**	0.20*
All features	0.33***	0.06^{ns}	0.66***	0.04^{ns}	0.65***	0.26*	0.24*
				Tangential			
MfA	0.77***	0.44**	0.65***	0.01^{ns}	0.85***	0.67***	0.43***
FTIR	0.54***	0.00^{ns}	0.61***	0.37**	0.71***	0.79***	0.06^{ns}
Density	0.00^{ns}	0.74***	0.25*	0.05^{ns}	0.01^{ns}	0.26***	0.35***
MfA + FTIR	0.79***	0.45**	0.73***	0.38*	0.86***	0.82***	0.45***
MfA + Density	0.77***	0.74***	0.67***	0.06^{ns}	0.86***	0.70***	0.49***
FTIR + Density	0.65***	0.75***	0.61***	0.38*	0.80***	0.79***	0.35***
All features	0.80***	0.75***	0.73***	0.40*	0.88***	0.52***	0.52***

^{ns} Not significant at alpha ≤ 0.05
* Significant at alpha = 0.05
** Significant at alpha = 0.01
*** Significant at alpha = 0.001

behaviour (Yamamoto et al. 2001). The linear correlation coefficients between these wood features and shrinkage for several wood types including their significance are listed in Table 2. The results differed between LS and TS, with a tendency for stronger correlations for the latter, as could be expected from theoretical considerations (Barber and Meylan 1964). While genuine differences in the shrinkage behaviour between LS and TS in relation to wood features exist, the higher accuracy of the TS measurements due to their higher values should not be neglected especially for MW.

When all samples, i.e., wood types, were considered, the MfA (0.28 (LS) and 0.77 (TS)) showed a slightly stronger correlation than the FTIR CW-indicator (0.24 (LS) and 0.54 (TS)) to shrinkage. Wood density, the parameter of wood quality historically used, did not correlate to dimensional changes. The commonly reported correlation between density and volumetric shrinkage (as summarised by Skaar 1988) is an interspecies observation and based on small clear samples corresponding to MW in this study. For MW, density was strongly ($R^2 = 0.74$) correlated to TS (Table 2).

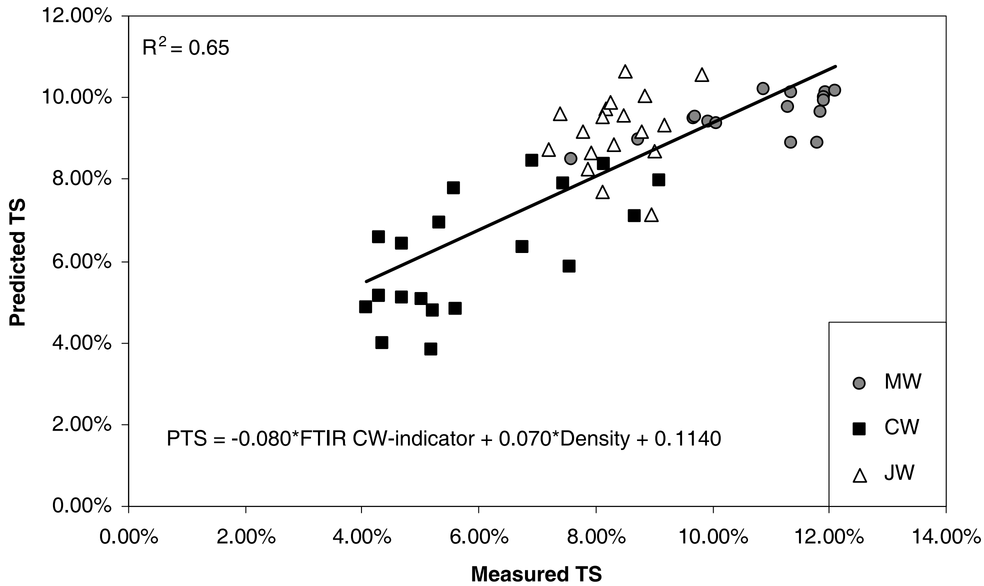
The influence of the individual cell wall features on shrinkage varied between the wood types. For CW all three wood features had an influence on shrinkage LS and TS. For MW and JW, correlations were found only for TS. In the case of MW, density and to a lesser degree MfA was connected to TS but in CW, the FTIR CW-indicator correlated to TS. The varying influence of the individual wood features on shrinkage implies that it is unlikely that shrinkage in practice can be accurately predicted from one wood feature alone. However, in this dataset, a linear combination of MfA, density and FTIR CW-indicator improved the accuracy of wood shrinkage prediction only slightly, to 0.33 and 0.80 for LS and TS, respectively (Table 2) for all samples. Non-linear models, as suggested by theoretical considerations, might improve the accuracy. With the inclusion of density, MOE, glucose as well as galactose content, a correlation of up to 0.92 could be achieved for *Pinus taeda* (Floyd 2005).

3.3 Predicting shrinkage

If all samples were considered TS could be modelled with similar accuracy by a linear combination of density and FTIR CW-indicator ($R^2 = 0.65$) as with the MfA ($R^2 = 0.77$) alone (Table 2). For LS the FTIR CW-indicator ($R^2 = 0.24$) explained a proportion of the variation in shrinkage similar to MfA ($R^2 = 0.28$). In this case a linear combination of density and the FTIR CW-indicator did not improve the model for LS. The model which avoids MfA for TS prediction is displayed in Fig. 3. The correlation is likely to be improved if experimental difficulties could be overcome. Changes in moisture content during sample preparation and measurements resulted in alignment inaccuracies of the radial profiles due to the variable tangential swelling (Fig. 1). As Bailleres et al. (2002) point out further advances in small size shrinkage measurement could improve results.

If timber quality in terms of dimension stability is to be improved by segregation, it is necessary to predict wood shrinkage from data accessible on-line in the timber production process. Despite the strong correlation of the MfA to wood shrinkage it is not suitable for shrinkage predic-

Fig. 3 Predicted TS from FTIR CW-indicator and density
Abb. 3 Aus FTIR CW-Indikator und Rohdichte berechnetes Tangentialschwindmaß



tion because of the difficulty of measurement. Shrinkage prediction based on X-ray density and/or chemical composition measured by infrared spectroscopy could provide an alternative. Compared to the on-line set up reported by Johansson et al. (2003) based on six variables (i.e., colour and 'tracheid effect') which is able to predict LS in Norway spruce with 81% accuracy, LS predictions based on density and FTIR CW-indicator were weak. However colour measurements are most likely to be less effective in species with a coloured heart wood like Sitka spruce. Floyd's (2005) model which explains 92% of shrinkage in loblolly pine is based on density, MOE as well as glucose and galactose contents. The MOE is tightly related to MfA, which gives the model an advantage over the ones based on online measurements. Incorporating MfA into the model for TS and LS prediction in Sitka spruce increases the accuracy to 80% and 33%, respectively (Table 2). Bailleres et al. (2002) used NIR for the prediction of shrinkage in young eucalyptus. Correlation was strong for TS ($R^2 = 0.82$) while prediction of LS was inaccurate ($R^2 = 0.35$). The difference between TS and LS predictability is consistent with the data reported here on Sitka spruce. However, their samples did not contain MW. When the MW samples were excluded from the Sitka spruce dataset reported here the correlation between the FTIR CW-indicator and TS increased to an almost identical value of $R^2 = 0.79$. Our findings suggest that the correlations could be improved by incorporating X-ray based density measurements. Considering the work of Taylor et al. (2008) this is especially the case for wood species with a low extractive content. They could predict volumetric shrinkage of mahogany by NIR with only 63% accuracy due to the counteracting effects of density and extractives content on shrinkage.

3.4 Cambial age and shrinkage

The fact that shrinkage of individual wood types is influenced to different degrees by the wood features described above is of importance when dealing with young trees. Short rotation plantation forestry of fast growing tree species, like *Eucalyptus* spp., radiata or loblolly pine and Sitka spruce, has gained importance in timber production. Wood of such origin can consist exclusively of JW. JW has a tendency to low stiffness and high distortion, wood properties generally less desired by the timber industry. Thus not only is shrinkage prediction of increased importance to improve the quality of such timber but also it is necessary to deal with the special physical characteristics of JW described above. Much knowledge on timber quality is related to wood from old growth forests and therefore relates to MW. Because such knowledge is of limited value to the increasingly important short rotation forestry, timber quality assessments on young trees has been subject of more recent studies (e.g. Koshy and Lester 1994, Bailleres et al. 2002, Chauhan and Walker 2006). The determination of wood properties in young trees is also an important issue when considering the improvement of wood quality through breeding. The earlier that wood quality can be determined in a tree seedling, the shorter breeding cycles can be.

The correlation of MfA and density to TS found for MW breaks down when JW is considered (Table 2). A similar observation was made for stiffness and density correlations in young *Pinus radiata* (Chauhan and Walker 2006). It is particularly of interest that the MfA, showing the strongest correlation to shrinkage when all samples are considered, did not correlate at all to LS or TS for JW. In this respect the fact that the FTIR CW-indicator was the only wood feature which correlated to TS in JW is of value (Table 2). Table 2 also lists the correlation factors for combinations of the classified wood types, representing wood of 'old' (MW + CW), 'young' (JW + CW) and 'defect-free' (MW + JW) trees. When the samples representing a young tree were considered the FTIR CW-indicator accounted for 79% of the variation in TS and was also found to be significant for LS with alpha ≤ 0.001. Considering samples resembling wood from 'old' trees the modelling of shrinkage by the FTIR CW-indicator was improved if density was considered as additional parameter and in the case of LS was then superior to models involving MfA. Shrinkage in 'defect free' wood was the most difficult to model and none of the wood features showed strong correlations within this subsample. However, this is of minor relevance since shrinkage in such samples is low and less problematic to the timber industry in terms of timber distortion.

Conclusion

Longitudinal and tangential shrinkage of CW, MW and JW of Sitka spruce is governed to different degrees by MfA and chemical composition. The lower tangential shrinkage of CW compared to JW at similar MfA indicated the influence of the chemical composition on wood shrinkage. FTIR micro-spectroscopy, a fast measurement of the chemical composition, has been shown to be an alternative to MfA data for shrinkage predictions when corrected for density. This was particularly true for wood of young cambial age for which the MfA did not correlate to shrinkage. Accordingly, infrared and X-ray in-line measurements in saw mills could have the potential to reduce distortion of sawn timber by segregation.

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