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Deformation properties of Finnish spruce and pine wood in tangential and radial directions in association to high temperature drying. Part III. Experimental results under drying conditions (mechano-sorptive creep)

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The set of papers (Part I–IV) sums up the results of an extensive project to quantify primarily the creep characteristics but also other deformation properties of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) wood under conditions relevant in the high temperature drying process. This paper reports the experimental results obtained for creep in tension under drying conditions at temperatures 95–125 °C. The results are compared to other researchers' measurements of mechano-sorptive creep at conventional drying temperatures (up to 80 °C). Based on this comparison the effect of temperature on the perpendicular to grain mechano-sorptive creep compliance is quantified.

Verformungseigenschaften von finnischem Fichten- und Kiefernholz in tangentialer und radialer Richtung unter Bedingungen der Hochtemperaturtrocknung. Teil 3: Experimentelle Ergebnisse unter Trocknungsbedingungen (mechano-sorptives Kriechen)

In dieser Artikelserie werden Ergebnisse eines Forschungsprojektes zur Quantifizierung des Kriechverhaltens aber auch anderer Verformungen an Fichten- und Kiefernholz beschrieben, und zwar unter Bedingungen, wie sie bei der Hochtemperaturtrocknung vorliegen. In diesem Beitrag werden die Ergebnisse des Kriechens unter Spannungsbelastung während der Trocknung bei 95–125 °C vorgestellt. Die Ergebnisse werden mit Messungen des mechanisch-sorptiven Kriechens verglichen, die andere Forscher unter konventionellen Trocknungsbedingungen (bis zu 80 °C) erhalten haben. Aufgrund dieser Daten wird der Temperatureinfluß auf das mechanisch-sorptive Kriechen senkrecht zur Faser quantifiziert.

1 Introduction

In the project "High temperature creep of wood", conducted at VTT (Technical Research Centre of Finland) during 1994–95, the creep properties of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) under conditions appropriate for a high temperature drying process were investigated in an extensive experimental programme. The experiments were carried out as tension creep tests with tangential and radial specimens in both saturated wet conditions and drying conditions at temperatures 95–125 °C. The first paper (Hanhijärvi 1998) of this series dealt with the experimental methods and reported the results concerning shrinkage, hygrothermal deformation, modulus of elasticity and strength. The second one (Hanhijärvi 1999) reported the results on viscoelastic creep. This paper reports the results under drying conditions (the mechano-sorptive creep). The results are compared with earlier results obtained by other researchers and the effect of temperature on the mechano-sorptive creep compliance is studied and quantified.

Some more details about the experiments can also be found in Hanhijärvi (1997).

1.1 A look at some earlier results

In a literature survey made during the project, no references could be found concerning the mechano-sorptive behaviour in high temperature conditions. However, results are available of quite a few recent investigations that were carried out at the conventional drying temperatures (up to c. 80 °C).

At VTT, prior to this project, creep in conventional drying temperatures was investigated by Kangas (1990) and Ranta-Maunus (1992). Both investigations were summarised by Ranta-Maunus (1993). Kangas (1990) investigated the creep of drying spruce and pine wood at temperatures 40, 60 and 80 °C under tensile load. Ranta-Maunus (1992) measured the force which is generated by a circular ring cut from wood along the annual rings when the shrinkage deformation is prevented.

Hisada (1986) performed an extensive study on the deformation behaviour of makanba (*Betula maximowicziana Reg.*) and hinoki (*Chamaecyparis obtusa Sieb.*) specimens (tangential) during drying under variable loads, including zero load. Drying conditions included the constant temperatures 20, 30, 50, 70 and 80 °C. The experiments included different loading schemes, in which the load was applied in the beginning of drying and removed in the latter part of it, or was only applied at different stages of drying.

Svensson's (1995, 1996) results contain both drying strain measurement results (under load or zero-load) and restrained shrinkage force results, giving a considerably better picture of the deformation behaviour than creep results alone. Temperatures include 60 and 80 °C.

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Wu and Milota (1995, 1996) measured the tangential mechano-sorptive deformation of Douglas-fir at 65.5 °C under monotonous desorption and monotonous adsorption.

The work of Joyet (1992) is directed towards investigating creep in service conditions (~room temperature) but provides useful fundamental information about the mechano-sorptive creep, especially concerning the effect of many repeated moisture cycles.

2
Test conditions and analysis of data

In this project, drying condition creep results at 95–125 °C were obtained from tests carried out in a drying condition test chamber. The design of the chamber, the test set-up, the specimens preparation and the drying schedules were reported in detail in the first paper (Hanhijärvi 1998), so here these techniques will not be touched on, only some aspects concerning the test conditions, quality of measurements and data processing.

2.1
Scope of tests

Altogether 45 tests were made in the drying condition chamber embracing more than 100 creep-specimen–dummy pairs of which a drying condition (mechano-sorptive) creep curve could be determined. The specimens were taken from three tree trunks, two spruce ones (labelled K and S) and one pine trunk (M). The density values of each specimen were measured after test runs and a summary of the density results has been given earlier (Hanhijärvi 1999).

2.2
Accomplishment of conditions

The climate (drying schedule) was controlled in the manner described in the first paper. All tests contained an initial drying period during which the specimens (initially in green condition) were brought to a moisture content near fiber saturation point (FSP). Before the end of this period, the specimens were loaded and after a few hours the actual drying below FSP (and consequent shrinkage) started. In most tests, the drying below FSP was done in such a way that moisture content was first taken down to an intermediate level (10–13%) followed by some remoistening and then by final drying to a moisture content of 2–5%. However, some tests were carried out with many (fairly small sized) drying–moistening cycles and some as monotonous drying. The climate control system (regulation of dry bulb and wet bulb temperature) functioned most of the time satisfactorily, although in some tests there were deviations from the desired drying schedule, mainly temperature peaks, which caused some unplanned moisture cycles to occur during few tests.

2.3
Processing and quality of measurements

Mårtensson (1994) and Svensson (1994) have introduced the approach of presenting creep curves obtained in drying condition tests as plotted against zero-load shrinkage measured in the same test, rather than against moisture content. This approach is advantageous for many reasons. First of all, shrinkage is easier to measure than moisture content. Furthermore, shrinkage measurement itself corrects possible influence of uneven moisture content distribution within the specimens, because the same moisture content distribution is present in the zero-load shrinkage specimens. This is also supported theoretically, if the findings of Hunt (1986) concerning the correlation of longitudinal mechano-sorptive creep and longitudinal hygroexpansion hold also for the transverse directions. On the other hand, if and when the amount of shrinkage can be considered linearly proportional to moisture content change below fiber saturation, the two approaches are principally equivalent. So, although the moisture content was monitored during the tests, the compliance curves were determined as function of zero-load shrinkage rather than time or moisture content. Strain vs. time and moisture content vs. time plots of the results can be found in Hanhijärvi (1997).

The displacement measurements required two transducers measuring one specimen, because in practise there is always some uneven shrinkage causing warping, so that the employment of the average of the displacements measured on two sides is necessary. With this arrangement the measurement of displacements functioned well.

The displacement measurements of each creep and zero-load specimen were processed by taking first the average of the two transducer readings and transforming it to strain. Then the compliances were calculated by determining first an estimate for the zero-load behaviours of each creep (loaded) specimen and subtracting those from the measured strains under load. For each creep specimen, the estimated zero-load behaviour was based on its matched dummy pair (zero-load specimen), whose origin was adjacent to that of the creep specimen. The basic idea in the estimation was that the shrinkage behaviour of the adjacently cut pair is the same, so that if there is enough time for them to dry and for the moisture content to reach equilibrium, their shrinkages will be equal. The estimated zero-load behaviour was determined as a new curve which before loading moment follows the measured strain of the creep specimen but after loading gradually begins to approach the measured strain curve of the dummy and reaches it at the first equilibrium moisture level during drying, Fig. 1. In some rare cases, when it was seen that the above procedure would not give the best result, the estimated zero-load behaviour after loading was assumed to follow directly the length changes of the dummy.

Even if the specimens and their dummies are matched (=adjacently cut), their shrinkages can be different due to the inevitable variability of wood material. This causes scatter to the final compliance curves. This seems to be unavoidable; but with results from a sufficient number of pairs, the average result is reliable.

Besides the errors caused by the difference of the final shrinkage values of the specimen and its dummy, there can be errors caused by differences in their drying speeds and consequent shrinkage rates. Contrary to the above, these effects can be corrected in the final compliance curves. The shrinkage rate difference, which can also be described as a

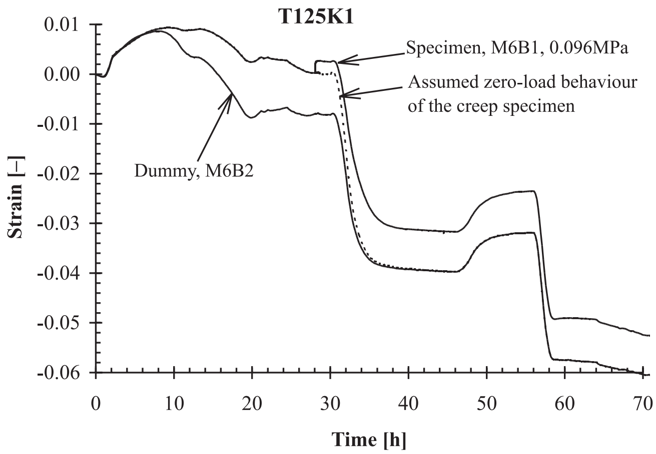


Fig. 1. An example of the estimation of the zero-load shrinkage behaviour for a loaded creep specimen based on the measurement of the shrinkage of a dummy specimen, which has been cut adjacent to the creep specimen. The estimation is based on the idea that if there is enough time for both specimens to dry and their moisture contents to reach equilibrium, their shrinkages will be equal

Bild 1. Beispiel für die Schätzung des Schwindungsverhaltens ohne Belastung anhand der Messung eines Prüfkörpers, der unmittelbar neben der Probe entnommen wurde. Die Schätzung beruht auf der Annahme, daß bei genügend langer Trocknungszeit und jeweiliger Gleichgewichtsfeuchte die Schwindung für beide Proben gleich groß ist

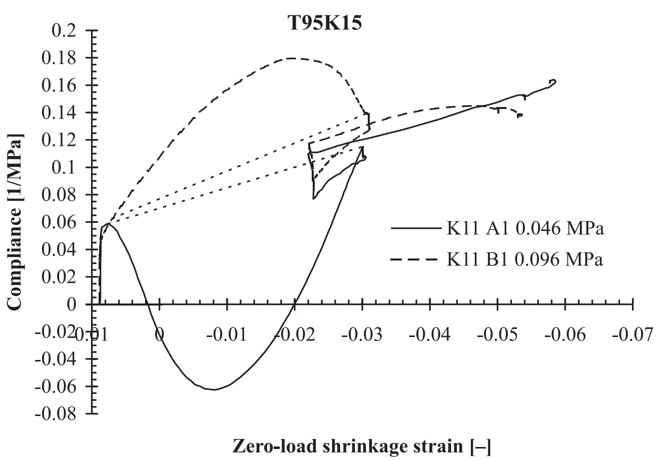


Fig. 2. Example of the error in the compliance caused by the difference between the shrinkage rates of the creep specimen and its dummy. This difference induces a 'mountain' or a 'valley' onto the compliance curve depending on whether the dummy or the specimen shrinks faster. The error can be easily corrected (dotted lines)

Bild 2. Beispiel für den Fehler beim Bestimmen der Dehnungszahl, verursacht durch den Unterschied zwischen den Kriechraten des Prüfkörpers und einer Kontrollprobe. Dieser Unterschied verursacht einen 'Berg' oder ein 'Tal' im Kurvenverlauf, je nachdem ob die Kontrolle oder die Probe schneller trocknet. Der Fehler kann leicht korrigiert werden (gestrichelte Linien)

'phase shift' between the shrinkages, causes a 'mountain' or 'valley' onto the compliance curve during a rapid shrinkage period. These errors can be easily detected and corrected as is shown in Fig. 2.

3 Mechano-sorptive creep results

Compliance vs. zero-load shrinkage results of individual specimens are presented in Figs. 3a–g and 4a–g, grouped according to the different trunks and the maximum temperature values reached during test. For clarity, the obscuring effect has been corrected which is caused by the 'phase shift' as explained above. The correction has been done whenever it was considered to be possible and to make the Figures clearer. Whenever the correction was done, the corrected range is plotted with dashed line. The Figures contain all the results regardless of the type of drying schedule (drying with one intermediate moistening cycle, many moisture cycles or monotonous drying) or loading pattern (with or without unloadings or recovery periods).

Each compliance curve starts at zero compliance and the loading moment is seen as a sudden increase of compliance at approximately zero shrinkage value. The loading may also occur at a negative shrinkage (=swelling) value for tangential specimens due to the hygrothermal effect. After loading the compliance continues to grow with drying and increasing shrinkage. Wetting periods are seen in the curves as diminishing shrinkage (in other words as a horizontal move to the left). Unloadings and re-loadings are seen as sudden changes in the compliance value (vertical drop or rise). Short unloading–reloading successions are seen as streaks downwards.

Even with the above corrections some of the Figures and curves are not very clear. This is partly due to the scatter of the results, entanglement of the curves and vague behaviour of individual specimens. The radial results are clearer than the tangential ones, which can be explained by the fact that it is easier to produce truly radially oriented specimens, causing less scatter. Due to the intricacy of Figs. 3 and 4 they are not suitable for the study of very sophisticated aspects of the mechano-sorptive creep but rather for the magnitude of it. A few more sophisticated aspects will be treated later by considering results of some individual specimens.

Apparently, the large scatter is mostly due to the procedure of processing the measurement data, from which the difference of the total strain and the shrinkage strain must be taken. This difference is very sensitive to error in determining the zero-load shrinkage. And, due to natural variability, there is always some difference between the shrinkage of the creep specimen and its dummy, even if they were chosen to match well. Another cause for the large scatter is the fairly low stress level that a significant portion of the specimens was loaded to. Low stress level makes the results more susceptible to error regarding the estimation of the zero-load behaviour. Nevertheless, since the number of tested specimens is quite high, the average magnitude of the mechano-sorptive compliance can be quite confidently obtained.

Figures 3 and 4 contain also estimated curves for combined elastic–viscoelastic compliance and average total compliance. Estimation of the average mechano-sorptive compliance can be obtained as the difference of

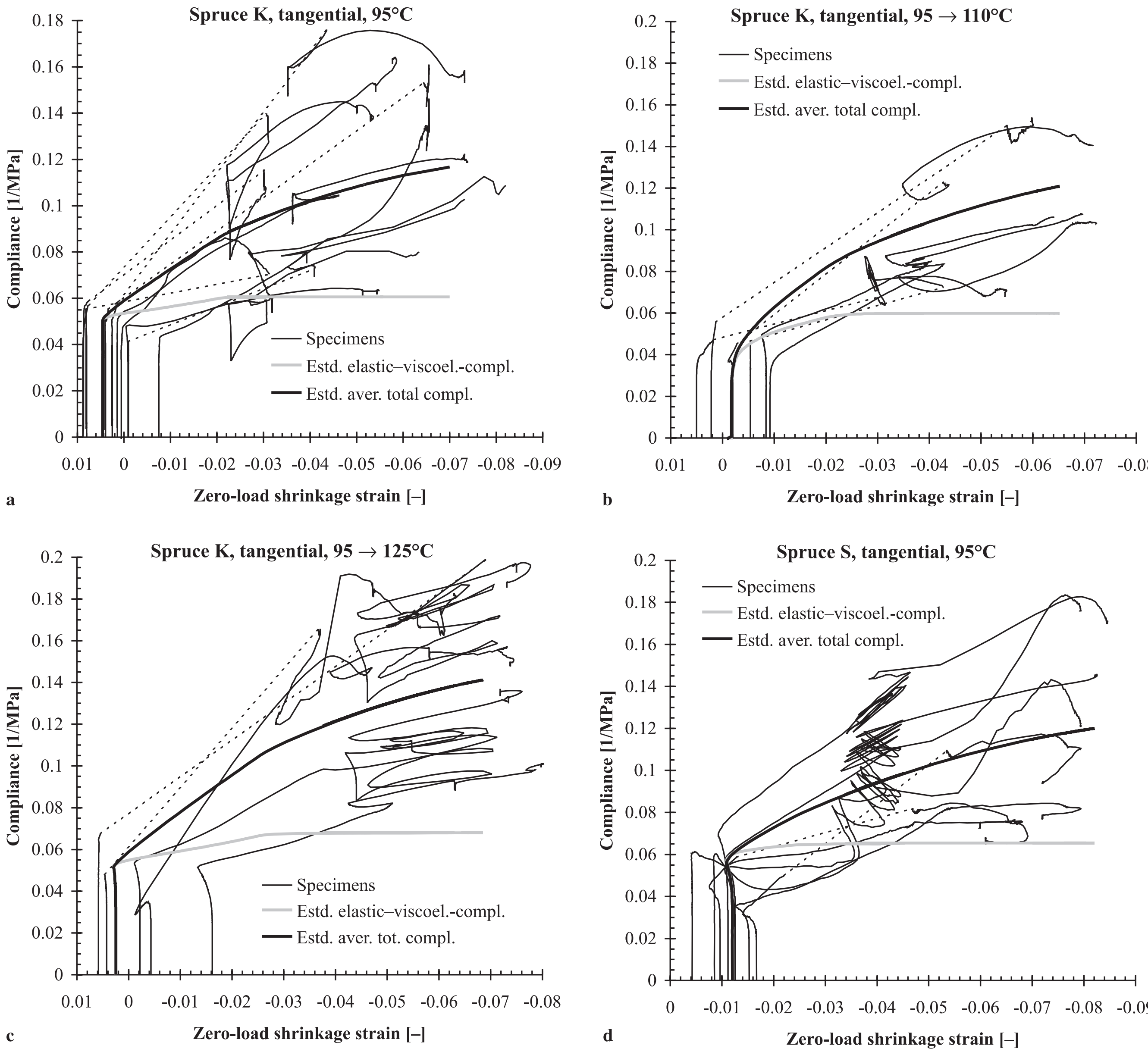


Fig. 3a–g. Compliance results vs. zero-load shrinkage strain for tangential specimens in the tests at 95 °C and tests with maximum temperature 110 and 125 °C for pine and spruce wood. The estimated elastic–viscoelastic compliances are also plotted as well as the estimated average total compliance, which is based on all tangential results (is the same in all graphs)

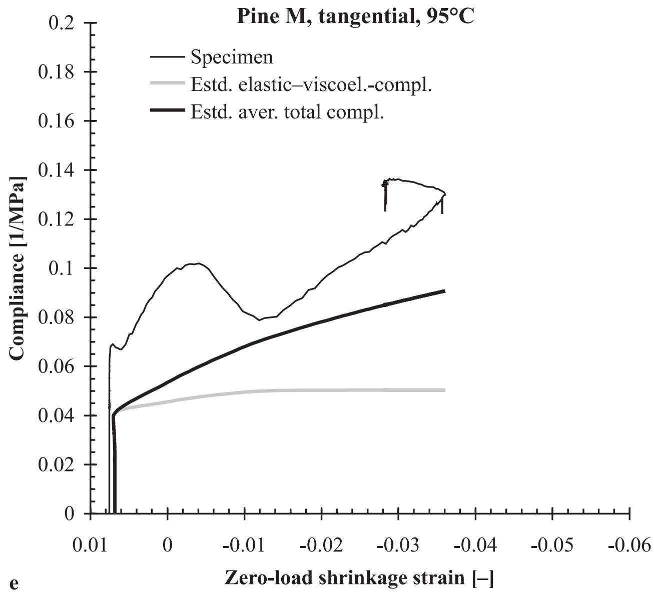
Bild 3a–g. Dehnungszahl von tangentialen Fichten- und Kiefernproben in Abhängigkeit von der Schwindspannung ohne Belastung bei 95 °C und maximalen Temperaturen von 110 und 125 °C. Die geschätzten Werte sowie der Gesamtmittelwert sind ebenfalls dargestellt

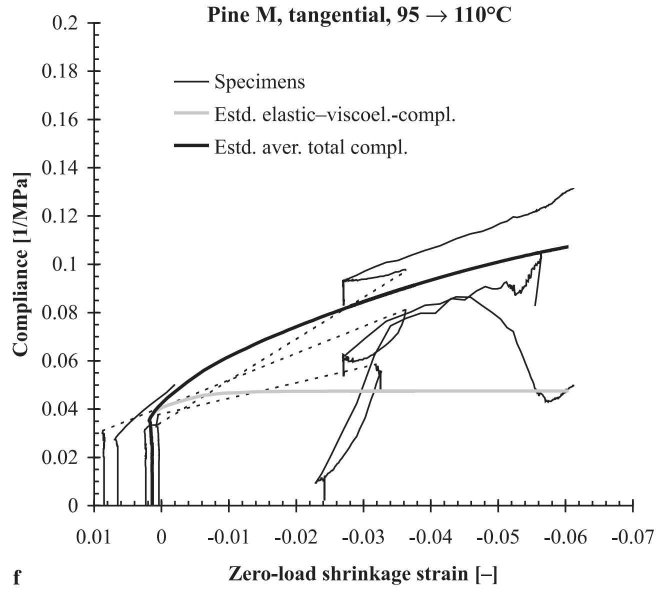
the two curves. The elastic-viscoelastic compliances were determined using the Master curve given previously (Hanhijärvi 1999) in constant load case. The average total compliance curves are graphical estimations (no calculated means) based on all results in the proper direction. For instance, the estimated total compliances for tangential cases were estimated based on all tangential test results, and not on the results in a single Figure only. Furthermore, the average total compliances were assessed assuming monotonous drying and constant load, which was not the case for the majority of the tests.

All cases clearly show that the elastic–viscoelastic compliance curves level out, so that they become practically horizontal after loading and some viscoelastic creep during the early drying stage. Thus, the slope of the total compliance curve after the early drying is a good estimate of the magnitude of the mechano-sorptive creep development.

3.1
Magnitude of mechano-sorptive creep

The results did not give reason to determine the mechano-sorptive compliance separately for spruce and pine as their responses seem to be of equal magnitude. However, if the scatter was not as large, the possible difference between the two species might be detectable.





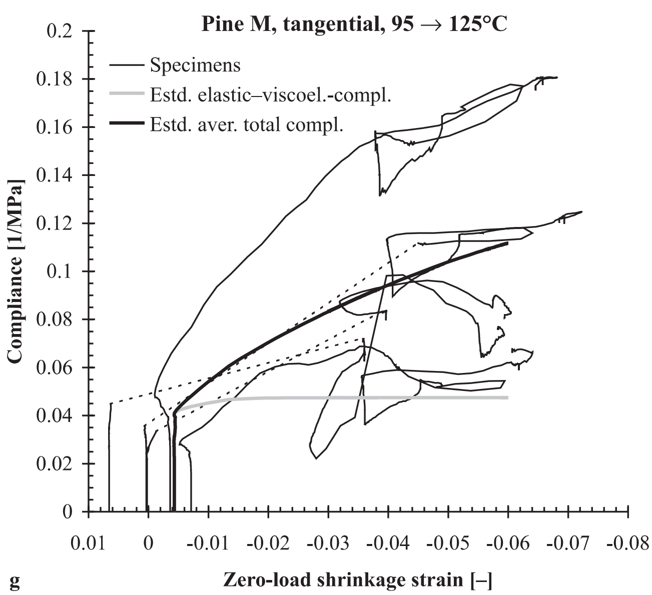


Fig. 3. (Contd.)

The magnitude of the mechano-sorptive creep compliance at 95 °C was estimated based on Figs. 3 and 4:

$$J_{\mathrm{ms,T}} = \left(-1.2(\varepsilon_\mathrm{s} - \varepsilon_\mathrm{s,loading}) - 6(\varepsilon_\mathrm{s} - \varepsilon_\mathrm{s,loading})^2\right)\frac{1}{\mathrm{MPa}} \tag{1}$$

$$J_{\mathrm{ms,R}} = \left(-1.2(\varepsilon_\mathrm{s} - \varepsilon_\mathrm{s,loading}) - 12(\varepsilon_\mathrm{s} - \varepsilon_\mathrm{s,loading})^2\right)\frac{1}{\mathrm{MPa}} \tag{2}$$

where the subscripts T and R refer to tangential and radial directions. ε_s is the zero-load shrinkage strain and $\varepsilon_\mathrm{s,loading}$ is its value at the time of loading. It should be noted that these compliance magnitudes have been determined for continuous loading and monotonous drying at 95 °C.

The results cannot be directly used to study any possible effect of temperature on mechano-sorptive creep, because in the tests with the maximum temperature of 110 and 125 °C, the temperature was not constant, and a large part of the drying took place at much lower temperatures.

3.2
Effect of temperature on mechano-sorptive creep

To obtain a better picture of the effect of temperature and to quantify the mechano-sorptive creep as function of temperature, the results were compared to other researchers' results obtained at lower temperatures. For this, the estimated average total compliance in the tangential direction at 95 °C was compared with the results of Hisada (1986), Wu and Milota (1995), Svensson (1996) and Kangas (1990), Figure 5. Kangas' results were slightly re-processed and an estimated average compliance was determined in the same manner as for the new results. Fig. 5 indicates clearly that temperature has an effect on the amount of mechano-sorptive creep. Based on the slope of the compliance curves (after loading and initial

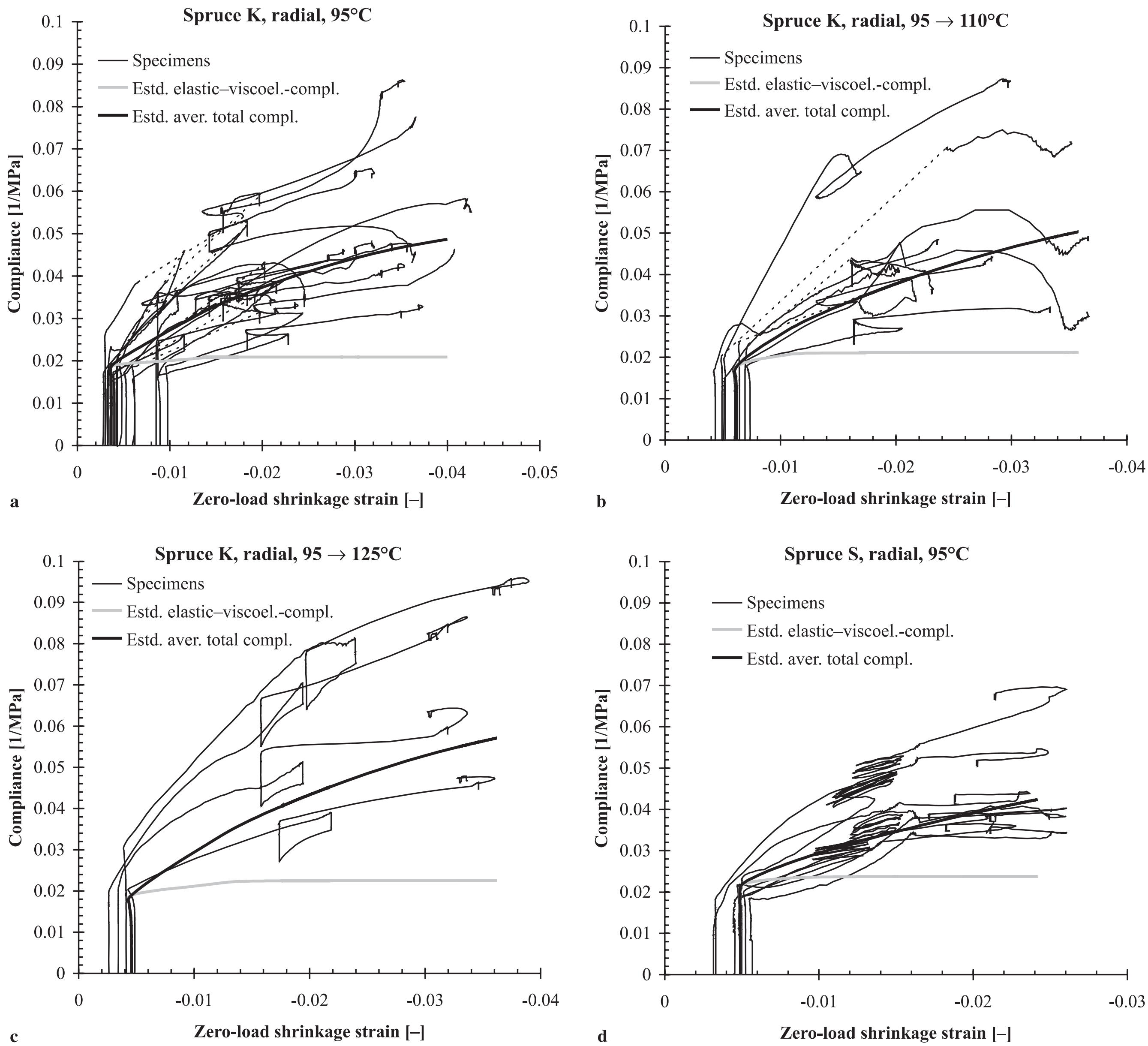


Fig. 4a–g. Compliance results vs. zero-load shrinkage strain for radial specimens in the tests at 95 °C and tests with maximum temperature 110 and 125 °C. The estimated elastic–viscoelastic compliances are also plotted as well as the estimated average total compliance, which is based on all radial results (is the same in all graphs)

Bild 4a–g. Dehnungszahl von radialen Fichten- und Kiefernproben in Abhängigkeit von der Schwindspannung ohne Belastung bei 95 °C und maximalen Temperaturen von 110 und 125 °C. Die geschätzten Werte sowie der Gesamtmittelwert sind ebenfalls dargestellt

deformation at early drying), the dependence of the mechano-sorptive creep magnitude was estimated as function of temperature, Fig. 6. The mechano-sorptive creep magnitude as function of temperature was also expressed in numbers, by writing the magnitude of the mechano-sorptive creep development as relative to that at 95 °C:

$$\frac{J_{\mathrm{ms}}(T)}{J_{\mathrm{ms}}(95\,^\circ\mathrm{C})} = 1 + 0.014\,^\circ\mathrm{C}^{-1}(T - 95\,^\circ\mathrm{C}) + 0.00007\,^\circ\mathrm{C}^{-2}(T - 95\,^\circ\mathrm{C})^2 \quad (3)$$

This equation is based on experiments at temperatures 20–95 °C, but it is assumed that its application range can be extended to somewhat above 95 °C.

3.3 Effect of moisture cycling on mechano-sorptive creep

One important aspect in the quantification of the mechano-sorptive effect is the effect of repeated moisture cycles. This feature was studied by experiments that consisted either of a single monotonous drying or of several drying-moistening cycles. Figure 7 shows an example of the resulting compliance curve of both drying schedule

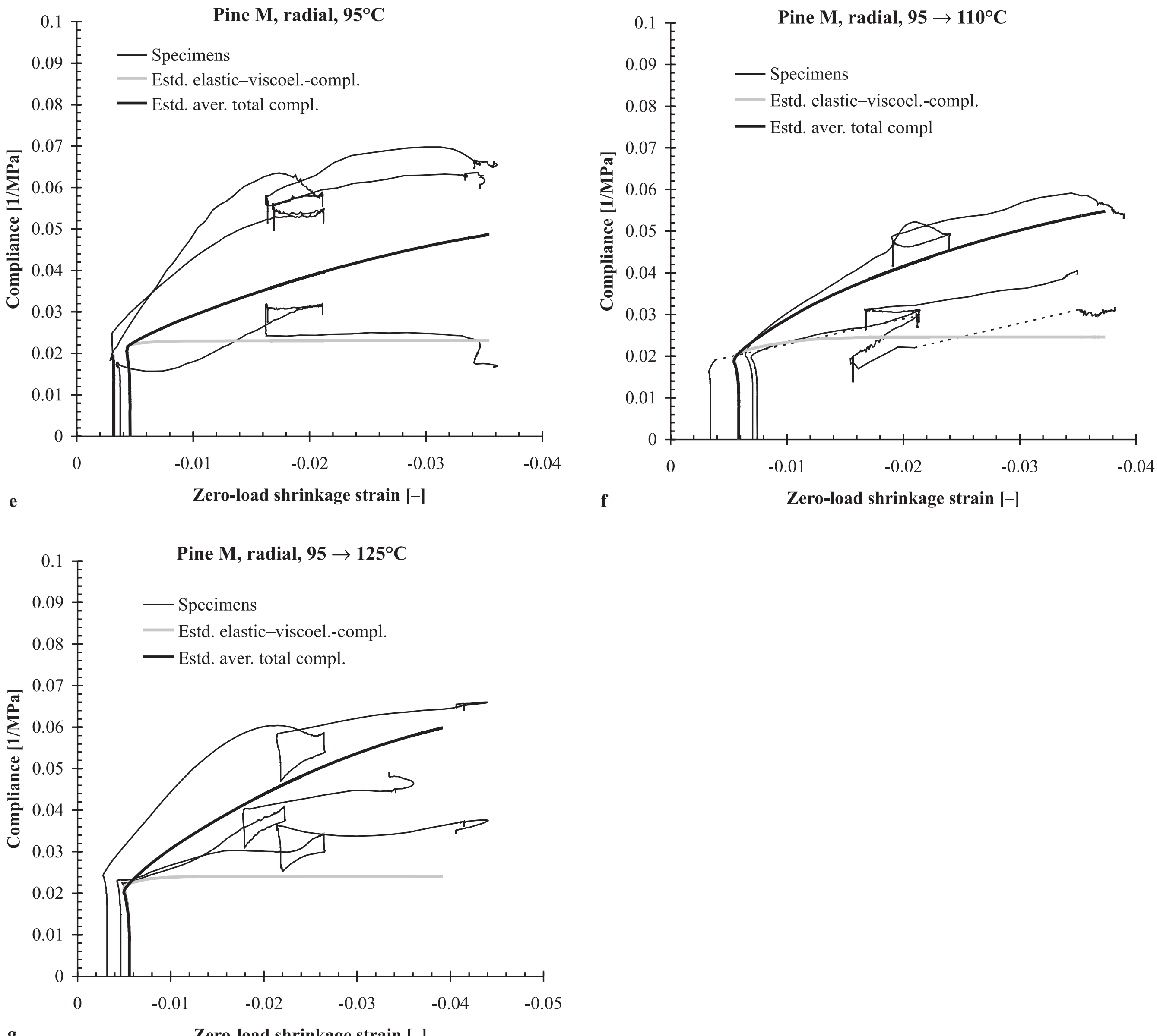


Fig. 4. (Contd.)

types. The curves are chosen so that they resemble each other as much as possible except for the presence or lack of the moisture cycles. The curves indicate that there is some more creep development due to the moisture cycles but the effect is not very strong.

3.4 Recoverability of mechano-sorptive creep

Another interesting aspect of the mechano-sorptive creep in conjunction with drying is the recoverability. In Kangas' (1990) experiments it was found that mechano-sorptive creep is largely recoverable during re-wetting. In the present project, recovery was investigated in a test in which the load was removed at about halfway of the drying. In Fig. 8, the compliance of two specimens is compared; the first one of them was loaded throughout the entire experiment, whereas from the second one, the load was removed halfway through the test. Except for the load history, the specimens were chosen to show a very similar response. It can be seen that there is very little recovery during drying, if any at all. This is a somewhat surprising result, because it has been frequently assumed that mechano-sorptive creep is recoverable by any moisture change regardless of its direction.

4 Discussion and conclusions

The tests reported here give novel information about the basic deformation properties of wood in conditions that have not been investigated before or have been subject to a very limited amount of research effort. This kind of knowledge is essential for the understanding of the deformation phenomena and stress development occurring in timber during high temperature drying. The results reported in this paper lead to the conclusions described in the following.

In the early stages of drying, when the moisture content is still high, the viscoelastic creep is significant for the total

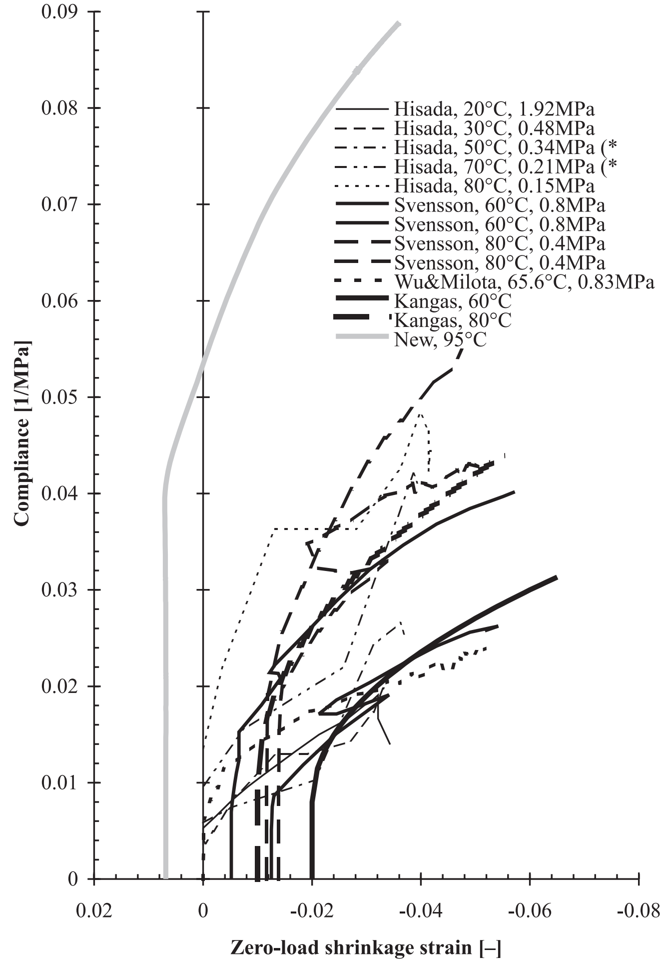


Fig. 5. Effect of temperature on tangential compliance during drying showing results from several researchers. Hisada's (1986) results [∗) zero-load shrinkage estimated by the author] are on hinoki (*Chamaecyparis obtusa*). Wu and Milota's (1995) results are on Douglas fir (Pseudotsuga menziesii). Svensson's (1996) and Kangas' (1990) results are on Scots pine (*Pinus sylvestris*). Note that the curve of the new results begins at a positive shrinkage strain value due to the hygrothermal effect

Bild 5. Temperatureinfluß auf die Dehnungszahl in tangentialer Richtung während der Trocknung. Ergebnisse mehrerer Autoren. Die Werte von Hisada (1986) wurden an Hinoki gemessen [∗) die Schwindmaße ohne Belastung wurden vom Autor geschätzt]. Die Werte von Wu und Milota (1995) wurden an Douglasie gemessen, die Werte von Svensson und Kanga (1990) an Kiefer. Man beachte, daß die Kurve mit den neuen Ergebnissen aufgrund des hygrothermalen Effekts bei positiver Schwindungsspannung beginnen

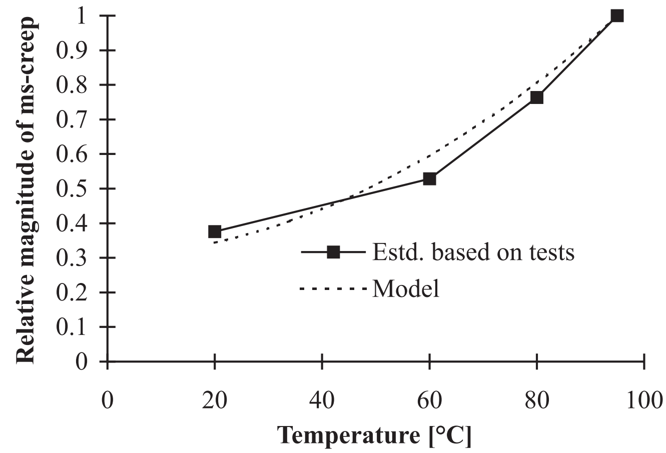


Fig. 6. Estimated magnitude of the mechano-sorptive creep development at different temperatures relative to its magnitude at 95 °C. The experimental points are based on estimation of curve slopes in Fig. 5

Bild 6. Geschätzte Größe des mechanisch-sorptiven Kriechens bei verschiedenen Temperaturen im Verhältnis zu ihrem Wert bei 95 °C. Die experimentellen Punkte beruhen auf Schätzungen des Anstiegs der Kurven in Bild 5

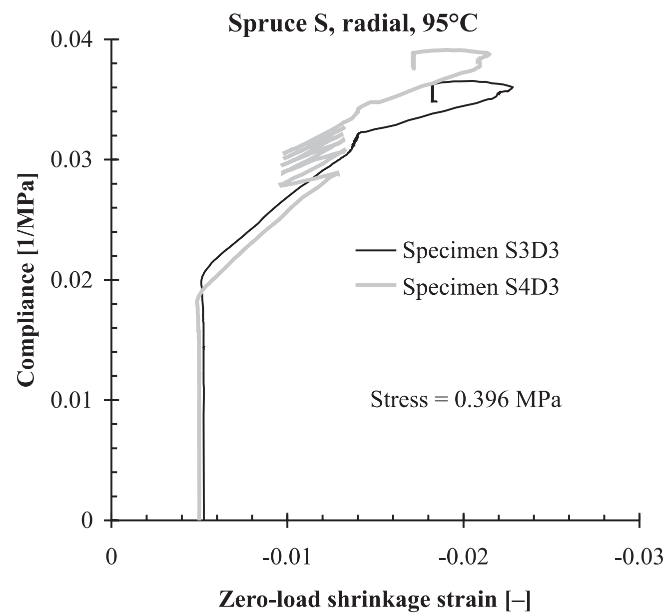


Fig. 7. Effect of moisture cycling on mechano-sorptive creep development. Comparison between two specimens that underwent a monotonous drying or a drying with moisture cycles

Bild 7. Einfluß des Wechselklimas auf die Entwicklung des mechanisch-sorptiven Kriechens. Vergleich zwischen kontinuierlicher Trocknung und wechselnder Befeuchtung

compliance, but as drying proceeds and moisture content drops increasingly, the development of viscoelastic creep becomes negligible compared to the amount of the mechano-sorptive creep.

The measurements clearly show that raise in temperature increases mechano-sorptive creep compliance substantially. The comparison of the results of many researchers given in this paper provides a good quantitative estimate for the temperature effect.

The analysis of the magnitude of the mechano-sorptive creep also indicates that mechano-sorptive creep development is not directly proportional to the amount of shrinkage but a slight decrease of creep development occurs when shrinkage increases. This could be an effect of moisture content level, but much more probably indicates that the accumulated creep inhibits the creep development.

The results also indicate that moisture cycles induce additional creep compared to monotonous drying, but the magnitude of the additional creep development was smaller than expected. According to the results, very little

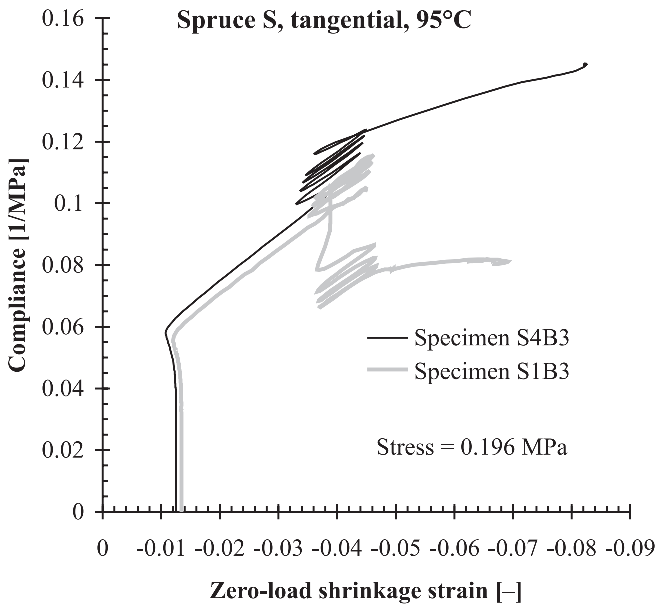


Fig. 8. Test of recoverability of mechano-sorptive creep if load is removed at about halfway of drying. The two specimens have been chosen to resemble each other as much as possible in the response except that the other one had the load on through the whole experiment and the other one had it removed at about halfway

Bild 8. Prüfung der Erholung des mechanisch-sorptiven Kriechens, nachdem die Belastung nach etwa der Hälfte der Trocknungsperiode entfernt wurde. Es wurden zwei Proben mit möglichst ähnlichem Verhalten ausgewählt. Die eine war während der gesamten Trocknung belastet, die andere bis etwa zur Hälfte

recovery takes place when the load is removed in the middle of the drying process and drying is continued. This is an opposite behaviour in comparison with the previous investigation (Kangas 1990, conventional drying temperatures), in which substantial recovery was recorded if the specimens were re-wetted after removal of load.

The set of three papers on experimental results that this paper completes provides the knowledge – also in quantitative terms – on the deformation properties of the studied wood species needed for the simulation of the stress development in the high temperature drying process. However, this is not yet sufficient regarding function-based numerical simulations, because the knowledge needs to be transferred into a mathematical form (material model, constitutive equation) describing the behaviour as function of the time lapse and as influenced by the other variables. This will be the subject of the fourth and final paper.

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