The influence of wood moisture content on dynamic modulus of elasticity measurements in durability testing

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Der Einfluss von Holzfeuchteänderungen auf das dynamische E-Modul bei Dauerhaftigkeitsversuchen

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Die herkömmlichen Methoden, um Pilzbefall unter Feldtestbedingungen zu beurteilen, ~~sind oftmals zu ungenau, um einen frühzeitigen Befall quantifizieren zu können.~~ Bestimmungsmethoden, bei denen Festigkeitsverluste oder Veränderungen der elastischen Eigenschaften gemessen werden, bieten hierbei Vorteile.
In den vorliegenden Versuchen wurde der Einfluss unregelmäßiger Holzfeuchteverteilungen (wie in der Praxis von Feldversuchen üblich) auf das dynamische E-Modul bestimmt. Hierzu wurden E-Moduländerungen bei unterschiedlichen Holzfeuchten mittels dynamischen und statischen Messverfahren verglichen. Wie erwartet, verändert sich der E-Modul bei sich ändernden Holzfeuchtigkeiten. Statische und dynamische Messungen zeigen hierbei vergleichbare Trends. Jedoch für praktische Feldmessungen ist die Beobachtung wichtig, dass bei einer Vernachlässigung der Einbeziehung der sich durch Holzfeuchteänderung verursachten Dimensionsänderungen der dynamische E-Modul viel weniger von den Holzfeuchteänderungen beeinflusst wird als der statische E-Modul.

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Methods for analysing fungal attack in wood under field test conditions (e.g., splinter test, sounding with a hammer, visual examination, etc.) are often not sufficiently sensitive to detect early stages of fungal decay. However, strength testing or testing elastic properties of timber can fulfil the demands of a quantitative and objective test for assessing incipient wood decay.
This study investigated the influence of wood moisture content upon the modulus of elasticity determined by a dynamic vibration method. Elastic changes in wood specimens were calculated by conventional static and dynamic techniques. The density, natural frequency of free transverse vibration and static flexural stiffness were measured on small specimens of Beech and Scots pine conditioned to different moisture levels.
The results of this study indicate that the natural frequency determined in the hardwood and softwood specimens decreased, as expected, with increasing moisture content. The static and dynamic MOE measurements followed the same trend, regardless of the wood moisture content. Furthermore, this research shows that if dimensional changes that occur during shrinkage/swelling of wood are neglected, the calculated dynamic MOE stayed practically constant within the whole range of moisture content, from oven dry to fully saturated. Applied to natural durability testing, this technique could provide a fast and reliable tool for the on site inspections of the fungal attack in field trials as well as in laboratory unsterile soil bed tests.

Field stake tests methods based upon EN 252 and laboratory unsterile soil bed test are well established to prove the efficacy of wood preservatives and the natural durability of timber in contact with the ground. Methods generally applied to assess wood decay in field trials (e.g., splinter test, sounding with a hammer, visual examination, etc.), although relatively simple, are often not sufficiently sensitive to detect early decay.

Strength testing by determining the modulus of rupture (MOR) in combination with the evaluation of the elastic properties of wood could provide a quantitative and objective test mean for assessing fungal attack (Hardie, 1980; Gray, 1986). In particular, the determination of the modulus of elasticity (MOE) bears some advantages; e.g., sensitivity to early stages of wood decay, repeatability, reduction of test material (Machek et al., 1997).

Static methods are described in most standards for MOE determination (eg. EN 408, DIN 52 186). An alternative method for the determination of MOE uses resonant vibration non-destructive testing. This technique involves mechanically vibrating test specimen as dynamic reaction of a material to an external impact in a torsional, transverse and longitudinal vibration mode. The dynamic flexural MOE was calculated based on the equation derived by Hearmon (1966) [eq. 1]. This mathematical expression uses the natural frequency of wood together with the density and the data describing the shape of a specimen [Eq. 1]:

$$MOE_{dyn} = \frac{4 \times \pi \times l^4 \times f^2 \times \rho \times A}{m_1^4 \times I} * [1 + I/(l^2 x A) \times K_1]$$

I ... moment of inertia (mm^4)
A ... area of the cross section (mm^2)
f ... frequency (kHz)
ρ ... density (kg/m^3)
l ... length (mm)
$K_1 = 49.48$
$m_1 = 4.72$

For wood, the density ρ is a combined figure of the mass and the moisture content at given conditions. From experiments on dry wood done by others, it is known that the longitudinal stress wave technique yields higher MOE values compared to a flexural vibration estimation (Bell et al., 1977; Gerhards, 1975; Miller and Tardif, 1967).

The elastic moduli determined by both the static and the dynamic approach in conditioned sound wood samples have been reported to be well correlated (Machek et al., 1997; Blass & Gard, 1994, Perstorper, 1994; Gerhards, 1975). In general dynamic Young's modulus over-estimate static bending by 5 to 15%. These findings also agree with results obtained by Machek et al. (1998) for several wood species decayed to various extents.

Little research has been reported on the effect of the moisture content (mc) on the natural frequency of wood. Burmester (1965) reported on speed of longitudinal stress waves (C_L) in pine in relation to the moisture content ranging from zero to fibre saturation point (FSP) and farther to fully saturated condition. This research showed linear reduction in C_L between in range 9 to 27% of wood mc. For additional increase of mc up to 152%, Burmester observed 14% reduction in speed. James (1964) reported an effect of the mc on the speed of longitudinal stress waves within the hygroscopic range below fibre saturation point (FSP) in clear Douglas-fir specimens.

In this study a significant correlation between the elastic moduli determined statical-

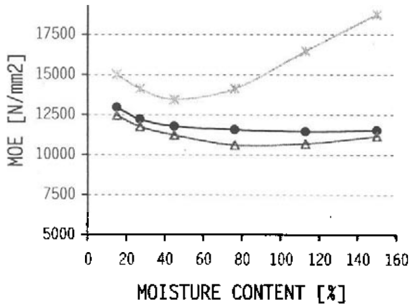

Fig. 1. Moisture content and modulus of elasticitv calculated from Gerhards (1975) data for sweetgum samples analysed by, static MOE (-•-), dynamic MOE flexural vibration (-∆-) and dynamic MOE longitudinal vibration (-*-)

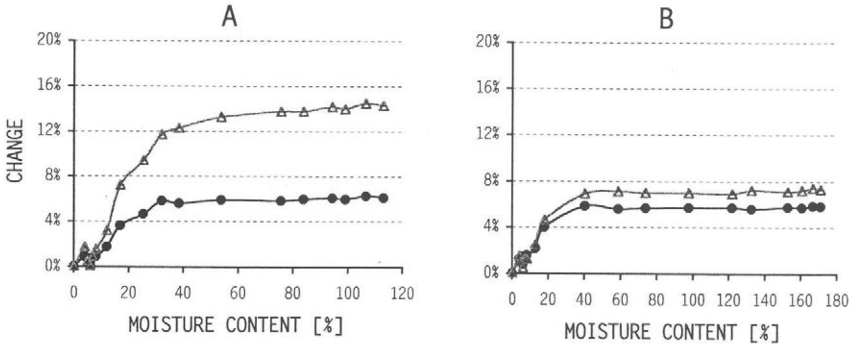

Fig. 2. Cross-section dimensions of beech (A) and Scots pine (B) specimens during drying from fully saturated stage to 0 % moisture content (mc). Width (-•-) and height (-∆-)

ly and dynamically (longitudinal vibration) in the wood moisture range from about 12 to 28% mc was observed but the regression coefficients appeared to depend upon moisture content. Gerhards (1975) evaluated the effect of wood mc varying from 15 to 150% on the speed of longitudinal and flexural stress waves and calculated the corresponding MOE values from stress wave principles. The author reported that the longitudinal MOE differs considerably from the static MOE and that the longitudinal stress wave technique should not be used to assess the static MOE without any correction. Furthermore, as shown in Figure 1, the static MOE was found to be somewhat higher than the dynamic flexural modulus. Gerhards assumed that the inconsistency between these results and other literature data might be explained by the previous use of softwoods whereas he experimented with hardwoods (sweetgum). Gerhard assumed that the difference between the two types of dynamic MOE may partly be due to neglecting of the correction factor in the elementary Timoshenko (1953) formula for flexural MOE (longitudinal MOE is about 20% higher than the flexural MOE in the hygroscopic mc range).

This study was set up to evaluate the effect of moisture content, varying from oven dry to fully saturated wood, on the modulus of elasticity using as well the static and the dynamic approach. A low dependency of the measurements on varying moisture contents would be of great importance for stake field test trials, because the actual wood mc varies along the stake length and the moisture gradient will be very difficult to predict.

Materials and Methods

The material consisted of twenty specimens (10 x 5 x 100 mm^3) of beech (Fagus sylvatica) and Scots pine (Pinus sylvestris) sapwood.

The experimental equipment for the determination of the dynamic modulus of elasticity was a commercial GrindoSonic MK5 „industrial" (J.W.Lemmens N.V., Leuven, Belgium). The equipment and measurement procedure are described in detail in a previous study by Machek et al. (1998). Flat-wise static MOE in the tangential plane was determined using a 3-point bending test in accordance with the German standard (DIN 52 186) using a universal testing machine (type Roell & Korthaus). The applied load was adjusted to cause a deflection of 0.75 mm.

The test stakes were impregnated with water. For this purpose, stakes were submerged in water, for approximately 50 hrs, in a vacuum vessel. After impregnation excess water was wiped from the specimen surface and the measurements were performed in the following order: weighting of the samples, measurement of dynamic MOE and static MOE and, finally, determination of sample dimensions. The wood specimens were then dried stepwise in a conditioned chamber.

The first 9 stages of reconditioning, at moisture content (mc) above FSP were performed at a temperature of 26°C and a relative humidity (rh) of 95%. The time between individual stages of measurements was approximately 24 hours. When the moisture content reached ca. 30%, the test material was conditioned at 26°C to moisture contents of about 18% (rh 85), 12% (rh 70), 8% (rh 45), 7% (rh 40), 6% (rh 30), 5% (25) and 4% (rh 15). The last stage of the measurements was oven dry condition, performed at 103°C

The measurement procedure was repeated after each of seventeen stages of reconditioning.

Results and Discussion

Changes in the elastic behaviour and other wood properties (density, fundamental frequency and dimensional changes) under various moisture content levels were assessed with beech and Scots pine samples.

In Fig. 2 the dimensions (width and height) of Scots pine are plotted against the wood moisture content. Both curves show that samples began to shrink at approximately 40% mc during the reconditioning stage. This early shrinkage will be due to surface drying effect, occurring even at an average mc of the whole sample above fibre saturation point.

Figure 3 shows how weight, density and natural flexural frequency of beech and Scots pine samples were affected by moisture content. While the weight of the specimens increased linearly with the moisture content (the highest mc tested for beech was 113% and for Scots pine was 170%), the volume increased up to the maximum capacity of the wood cell wall to swell was reached (FSP of beech around 18%, Scots pine 12%), and then it remain constant regardless of further increase in the moisture content. As a result, the density increased with increasing moisture content. The natural frequency decreased with increasing moisture content level. The decrease in the frequency is partly due to the higher density and party due to the lower MOE of the moist wood. These results are in agreement with previous reports (Kollmann and Krech, 1960; Gerhards, 1975).

Figure 4 relates the modulus of elasticity calculated from both static and dynamic approaches to the wood moisture content. The static MOE determined for both beech (A) and Scots pine (C) revealed the expected general trend. The MOE is reduced with increasing moisture content up to approximately fibre saturation point. In both cases for beech and pine, the dynamic MOE values followed the same trend as those obtained by the static measurements. These findings agree closely with results reported earlier by Kollmann and Krech (1960).

Comparison of the absolute values of the MOE calculated by both, the static and the dynamic approaches showed that the static MOE values are lower than those measured dynamically. The static MOE values observed for beech in the range from dry to fibre saturation point are ca.17% lower than the values obtained by the dynamic approach. Above ca. 30% mc, the static MOE is about 30% lower than the dynamic flexural MOE. Concerning pine wood, this difference is even more evident (ca. 25% below FSP and ca. 40% above FSP, respectively). This phenomenon is known and agrees with previous reports (Hearmon, 1966; Goerlacher, 1984; Bass et al., 1994). Cracks and other imperfections in the specimen structure have been suggested to account for the lower values in the static modulus. Similar conclusions were drawn by Ide (1935) as a result of experiments on rocks. In our study the difference seems excessive compared to the literature. The inconsistency can partly be explained by the fact that the static MOE measurements are examining only a small area around the central loading point, while the dynamic MOE measurements are examining the entire samples. In the static bending test, the deflection

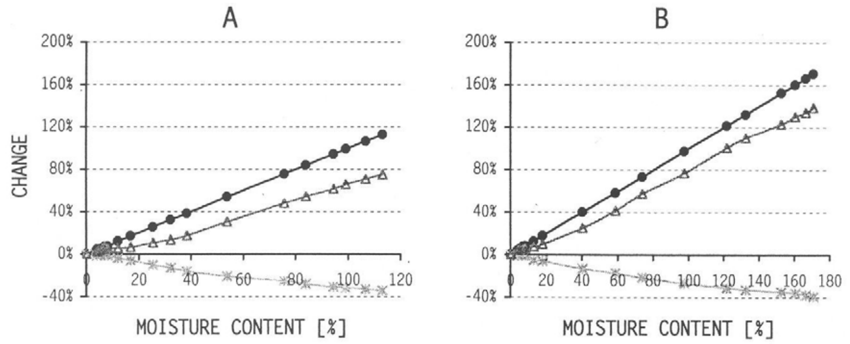

Fig. 3. Effect of wood moisture content (mc) on weight (-•-), density (-Δ-) and natural frequency (-*-) of beech (A) and Scots pine (B) specimens

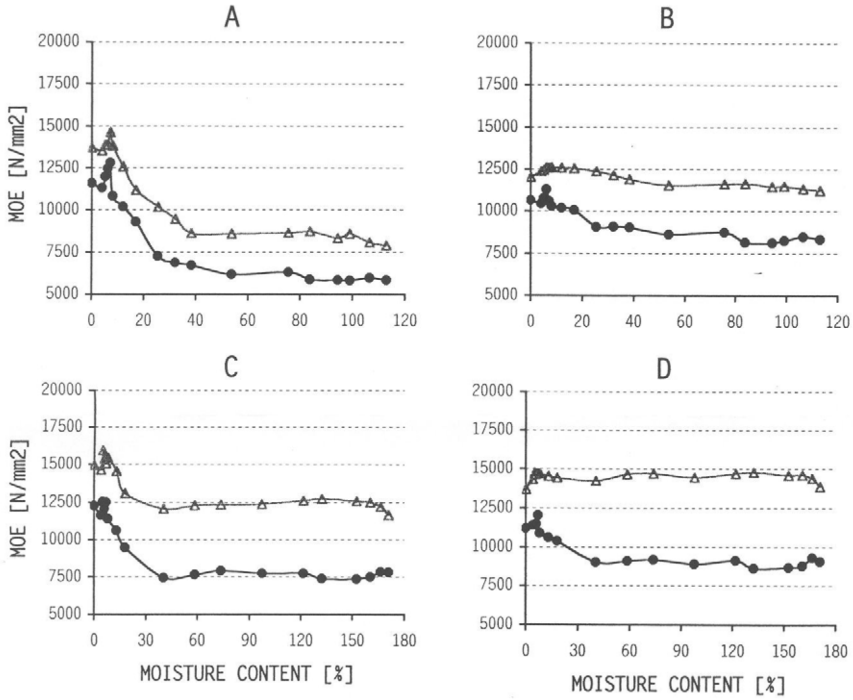

Fig. 4. Effect of wood moisture content (mc) on the modulus of elasticity (MOE) calculated by both static (-•-) and dynamic (-Δ-) approaches. Beech samples (A and B), Scots pine(C and D). The initial dimensions of test samples (12% mc).were used to calculate the MOE values in chart B and D

was determined only as load displacement. Furthermore, part of the difference in the two types of elasticity constants may be due to neglecting of shear and rotary inertia in the dynamic MOE calculation.

In an ideal system, ie., uniform beam, evenly distributed load throughout the beam, impulse excitation, the equation 2 is valid (Gerhard, 1975) [Eq. 2]:

Figure 4B and 4D show the MOE values calculated for beech and Scots pine from both the static and the dynamic approach. However, the MOE values plotted in latter figures (B and D) were calculated according to [eq. 1], using the initial dimensions at ca 12% wood moisture content rather than actual dimensions of a specimen at a certain wood mc.

When the dimensional changes occurring below FSP are neglected, then only the frequency and mass from Timoshenko MOE dynamic equation [eq.1] will change with changing moisture content (fig. 4). As these two magnitudes change linearly over the whole range of moisture content. Based on this equation, the dynamic MOE should stay constant when dimensional changes in the hygroscopic range are not considered.

The results obtained with beech and Scots pine wood specimens indicate that the changes in the elastic behaviour (MOE) differ considerably between static and dynamic methods. Generally, the static MOE losses show the same trend as when calculated with the actual dimensions at a certain mc (Fig. 4A and 4C). However, the observed values are influenced by the ratio of dimensional changes of a particular wood species. In contrast, the extent to which the dynamic MOE changes is very small. The average value observed for beech above and below fibre saturation point differs approximately by 6%, while in the case of Scots pine it only shows a difference of ca. 0.5%.

In this study the actual moisture gradient across the cross section of stakes after each phase of reconditioning was not determined. It was assumed that the liquid moisture, as well as the vapour in the cell wall, were evenly distributed throughout the specimens. In practice, this assumption will not be completely true due to uneven drying of the stakes, starting with surface drying effect. The fact that the dynamic MOE calculated for beech (average value 12.076 MPa, standard deviation 498 Mpa) and Scots pine (median value 14.614 MPa, std. 301 MPa) was not consistent may be due to that uneven drying effect.

Conclusions

From the results of this research it can be concluded that for both timber species (beech and Scots pine) the modulus of elasticity in the hygroscopic range was found to be highly dependent on the moisture content of the samples. Above fibre saturation the dynamic MOE was much less dependent on further moisture uptake, whereas the static MOE was only dependent on the load to deformation rate.

Furthermore, if the dimensional changes

$$(f_1/f) = \frac{\rho}{\rho_1}$$

f ... initial frequency (Hz)
ρ ... initial sample density (kg/m^3)
f_1 ... changed frequency (Hz)
ρ_1 ... changed sample density (kg/m^3)

which occur during the drying or wetting process are neglected, the dynamic elastic constant was constant to different mc's, confirming the theoretical assumptions. These findings might be of importance for field trials of natural durability or wood preservatives testing, where for obvious reasons the stakes can not be conditioned before measurements are taken in the field.

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