The influence of acetylation of Radiata pine in structural sizes on its strength properties

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ABSTRACT

In much of the literature on the properties of wood that is enhanced by acetylation, the strength properties are said to be not affected. In many cases this has been measured with a flexure test, determining strength (MOR) and stiffness (MOE) of small pieces of clear wood. In the calculation of constructions, structural engineers need to work with more realistic values.

In this study Radiata pine of structural sizes was tested in a 4-point flexure test according to EN 408, in order to assess MOR and MOE. Firstly, the MOE was determined non-destructive for untreated timber. Secondly, the same pieces were acetylated to 20% acetyl content. Thirdly, these pieces were tested in order to determine the MOE and MOR after treatment. The MOR and MOE of untreated Radiata pine were also determined using pieces of the same origin. The density of all test specimens was recorded as well.

According to EN 338 the characteristic strength and stiffness values of (North) European softwood can be determined based on the MOR, MOE and the density. It is not clear if the same relationships can be used for (treated) Radiata pine. The verification of these relations will be subject of study in the near future using the same material as used for the four point bending tests described in this paper.

INTRODUCTION

The past decades, extensive research has been done on acetylation with uncatalysed acetic anhydride to upgrade the durability and dimensional stability of not-durable wood species (Beckers et al. 1998, Beckers and Militz 1994, Beckers et al. 1994, Goldstein et al. 1961, Larsson and Simonson 1994, Larsson-Brelid et al. 2000, Rowell et al. 1989, Singh et al. 1992).

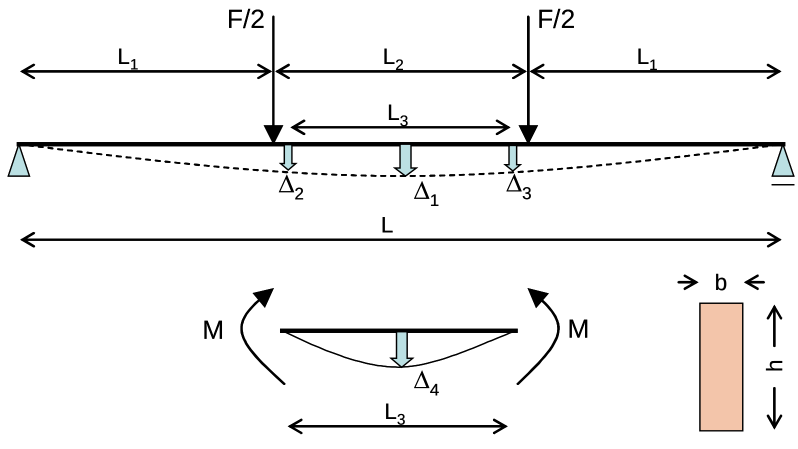
For load-bearing applications, of which outdoor structures, like timber bridges, are most interesting regarding the durability properties, the mechanical properties of acetylated wood are of major importance. According to literature the mechanical properties are not significantly altered by acetylation (Akitsu et al. 1993, Bongers and Beckers 2003, Dreher et al. 1964, Goldstein et al. 1961, Larsson and Tillmann 1989). In many cases this has been measured with a bending test, determining strength (MOR) and stiffness (MOE) of small pieces of clear wood. In the calculation of constructions, however, structural engineers need to work with more realistic values, based on the properties of structural seizes.

In this study, Radiata pine of structural sizes was tested in a 4-point bending test according to EN 408, in order to determine these characteristic bending stiffness (MOE) and –strength values (MOR) of untreated as well as acetylated Radiata pine.

EXPERIMENTAL

Radiata pine (*Pinus radiata* D. Don) boards of 50 mm thickness, 155 mm width and 4 m length, visually graded as No 2 Clear and Better (one face and both edges have no visible defects), grown in New Zealand, are used in this study to determine the bending stiffness and –strength according to EN 408.

After conditioning at 65% relative humidity and 20 °C during 3 weeks, all boards have been visually assessed on wood quality parameters such as distortion, knots, slope of grain, etc. The moisture content and weight of the boards was also measured. Further the static bending stiffness (Modulus of Elasticity MOE) of 44 boards Radiata pine is (non-destructively) determined by 4-point flexure test over a span of 2.8 m, which was classified as the "weakest" part of the board by visual assessment. This part is loaded to approximately 40% of the estimated bending strength to determine the bending stiffness before acetylation. In Figure 1 a schematic overview of the test set-up is given.



$$M = L_1 F / 2$$

$$\Delta_4 = \Delta_1 - \frac{\Delta_2 + \Delta_3}{2}$$

$$MOE = \frac{3FL_3^2 L_1}{4bh^3\Delta_4} \quad \text{or}$$

$$MOE = \frac{F\left(16L_1^3 + 24L_1^2 L_2 + 9L_2^3\right)}{8bh^3\Delta_1}$$

$$MOR = \frac{3FL_1}{bh^2}$$

Figure 1: Test set-up to determine the modulus of elasticity in bending (MOE) and the bending strength (MOR).

In Figure 1 two different equations for the determination of the modulus of elasticity (MOE) are shown. Since the ratio $\frac{L}{h} \approx 18$, and, consequently, the shear deformation is of minor importance, both equations can be used. In this paper Eqn. 1 is used.

$$MOE = \frac{3FL_3^2 L_1}{4bh^3 \Delta_4} \qquad (1)$$

With: F — $F_{0,4} - F_{0,1}$ [N] defined in figure 1

Δ_4 — $\Delta_{4;0,4} - \Delta_{4;0,1}$ [mm] defined in Figure 1

0,4 — at approximately 40% of the failure load

0,1 — at approximately 10% of the failure load

b — beam width [mm]

h — beam height [mm]

L_1; L_3 — defined in Figure 1 [mm]

The bending strength (MOR) was calculated according to equation (2).

$$MOR = \frac{3FL_1}{bh^2} \qquad (2)$$

With: F — load at failure defined in figure 1

The boards have been acetylated by Titan Wood using an industrial process. After acetylation and conditioning the modulus of elasticity (MOE) in bending and bending strength (Modulus of Rupture MOR) of the boards has been determined; these tests were also carried out according to Figure 1.
Besides the acetylated boards the MOE and MOR of 44 boards of untreated Radiata pine were determined. After breaking of the samples, the density and moisture content of the boards was determined by weighing and drying. Below a general flow diagram of the research program is given.

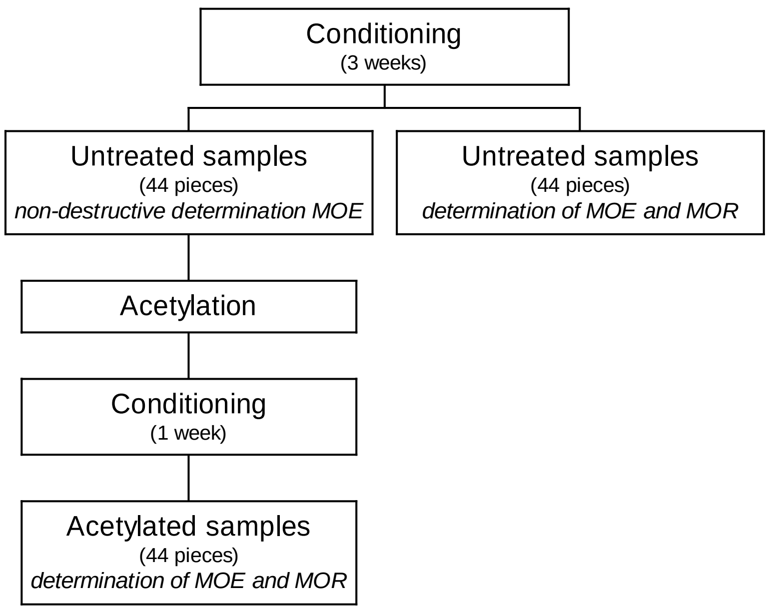


Figure 2: Test overview

RESULTS AND DISCUSSION

In Table 1 the average results of the acetylated and untreated Radiata pine are given. Due to acetylation the oven-dried density has increased by approximately 20%, and the (equilibrium) moisture content (EMC) has been reduced from 13 to 5%. The reduction in EMC is similar to values found in literature, however the increase of oven-dried density is larger. Dreher et al. (1964) and Larsson and Tillmann (1989) found values from 7 to 10% increase of oven-dried density. There can be some bias on these results, since the density before acetylation is determined on the whole boards, whereas the density after acetylation is determined on a small section of the board only. The modulus of elasticity in bending (MOE) of the acetylated boards stays nearly the same (averaged reduction 3%) compared to the identical boards before acetylation.
The untreated series had a 10 % higher average bending strength (MOR) compared to the acetylated series. However, the untreated series also had a 7% higher MOE compared to the other (not yet treated) series. Figure 6 indicates that the relation between MOE and MOR does not change due to the acetylation process and that, consequently, the expected MOR for the untreated series is higher than for the acetylated series. On the other hand, Table 1 indicates that the variation in MOR is increased after acetylation, which, together with a slightly lower average MOR, results in a significant lower characteristic value. The characteristic value for the bending strength, based on the 44 tests carried out, for the untreated Radiata pine is approximately $f_{m;0;k}$ = (43 – 1,72*10) = 25,8 N/mm^2 while the characteristic value for the bending strength for the acetylated wood is approximately $f_{m;0;k}$ = (39 – 1,72*13) = 16,6 N/mm^2. This is caused mainly by the increased variation for the acetylated wood. This phenomenon is subject for further study, in which the type of fracture is taken into account. Another remark is that some of the boards are loaded to 71% of their strength before acetylation in stead of the intended 40%. None of the presented values have been corrected for (equilibrium) moisture content. The reason for this is that the relationship between mechanical properties and moisture content is not known for acetylated wood, in contrast to untreated wood, for which at least some research was carried out in the past (Tsoumis 1991, Madsen 1992).

Dreher et al. (1964) found for Ponderosa pine and Red oak a reduction in bending strength, while the modulus of elasticity in bending, or bending stiffness, remained unchanged after acetylation. Almost no change in bending stiffness and –strength due to acetylation was found by Larsson and Tillmann (1989) for small clear samples Norway spruce and Scots pine. Work of Bongers and Beckers (2003) shows that the effect of acetylation on the mechanical properties is heavily depending on the acetylation process. The reduced EMC and increased density “upgrades” the mechanical properties. On the other side, the reduction of the amount of fibres and lignocellulose per volume (due to swelling) and possible hydro-thermal effects during the acetylation process, result in a decrease of mechanical properties.

Table 1: Average density, moisture content, bending stiffness (MOE) and bending strength (MOR) before and after acetylation (between brackets standard deviation)

Treatment	**Before acetylation**				**After acetylation**			
	Oven dried density [kg/m^3]	**Moisture content [%]**	**MOE [N/mm^2]**	**MOR [N/mm^2]**	**Oven dried density [kg/m^3]**	**Moisture content [%]**	**MOE [N/mm^2]**	**MOR [N/mm^2]**
Acetylated	411 (38)	13.1 (1.5)	9064 (2268)	-	492 (48)	5.2 (3.1)	8788 (2320)	39 (13)
Untreated	417 (25)	12.2 (1.3)	9664 (2130)	43 (10)	-	-	-	-

All above values are averaged results. For a better investigation of the results, and to be able to determine the effect of acetylation upon the bending stiffness and -strength, individual values need to be studied. In Figure 3 the effect of acetylation upon the bending stiffness (MOE) is shown in a frequency diagram. The MOE before acetylation is defined as 100%. In this figure, as well as in Figure 4, it can be seen that for the individual boards the tendency in MOE change is slightly negative (the regression coefficient in Figure 4 is slightly lower than 1).

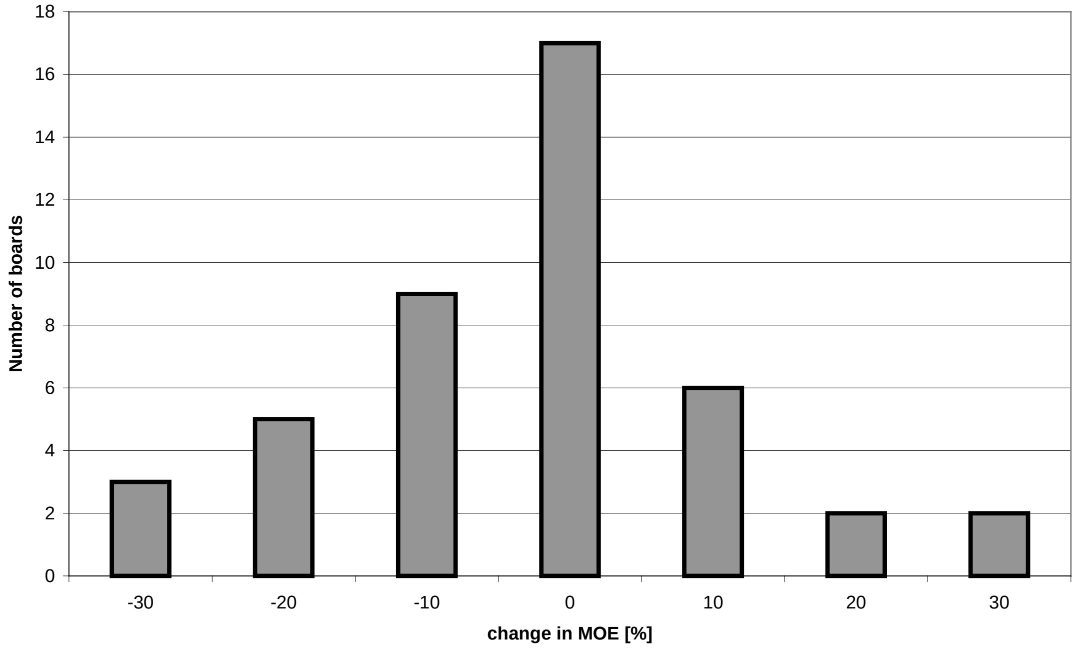


Figure 3: Change in modulus of elasticity (MOE) in bending due to acetylation

Remark: -30% : the absolute change is more than 25%
-20% : the change is between -15% and -25%
-10% : the change is between -5% and -15%
0% : the change is between -5% and +5%
10%: : the change is between 5% and 15%
20% : the change is between 15% and 25%
30% : the change is more than 25%

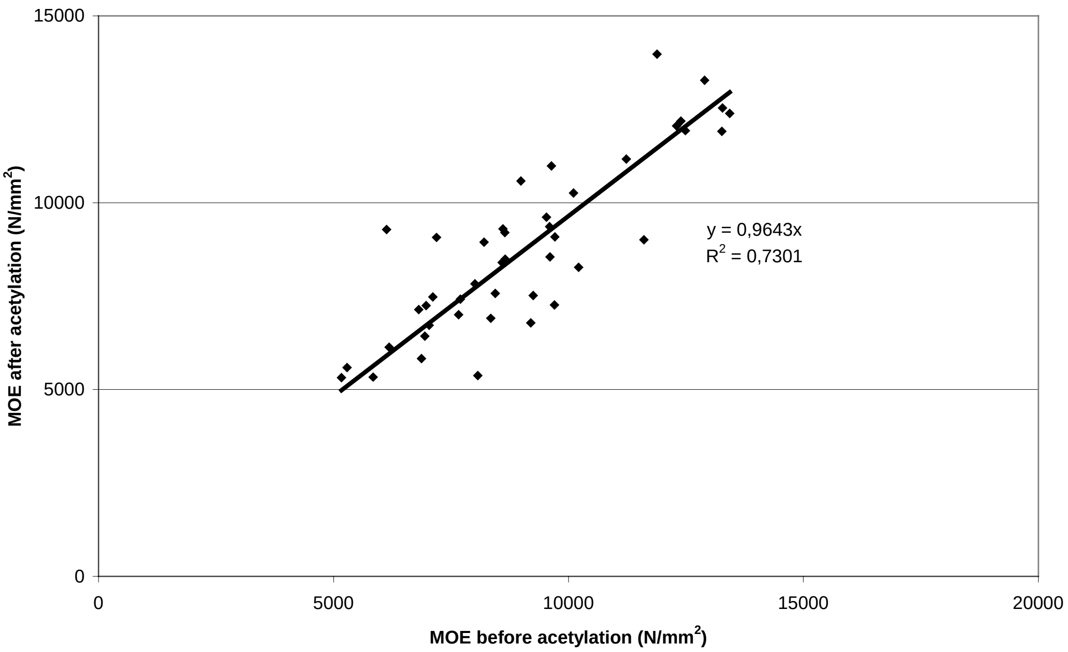


Figure 4: Bending stiffness (MOE) before and after acetylation

In Figure 5 the distribution of the bending strength (MOR) of untreated and acetylated Radiata pine is shown. This figure shows that the distribution of the bending strength is rather scattered. Due to this scatter an effect of the acetylation upon the bending strength (distribution) is not clearly visible. Grading and sorting of the timber before acetylation could result in a less scattered distribution and would therefore be beneficial for commercial exploitation of acetylated wood in load-bearing applications. Sorting and grading of timber before and after acetylation by (non-destructive) determination of the bending stiffness is possible, even in a mechanical way, since the relation between bending stiffness and –strength is unchanged by acetylation (see Figure 6). On the other hand the coefficient of determination (R^2) for the relation MOR-MOE for untreated Radiata Pine is so low that mechanical grading based on the relation MOR-MOE alone is not accurate enough; other parameters as knots and growth disturbances must most probably also be considered. Density does not clearly correlate with bending stiffness nor bending strength.

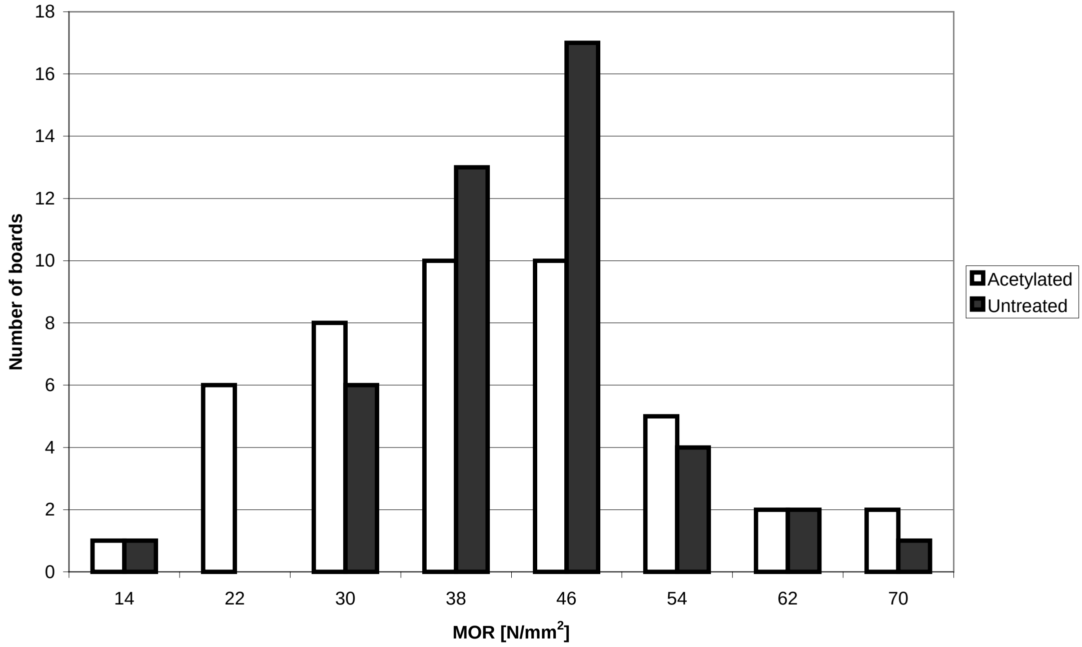


Figure 5: Frequency diagram of bending strength of untreated and acetylated Radiata pine.

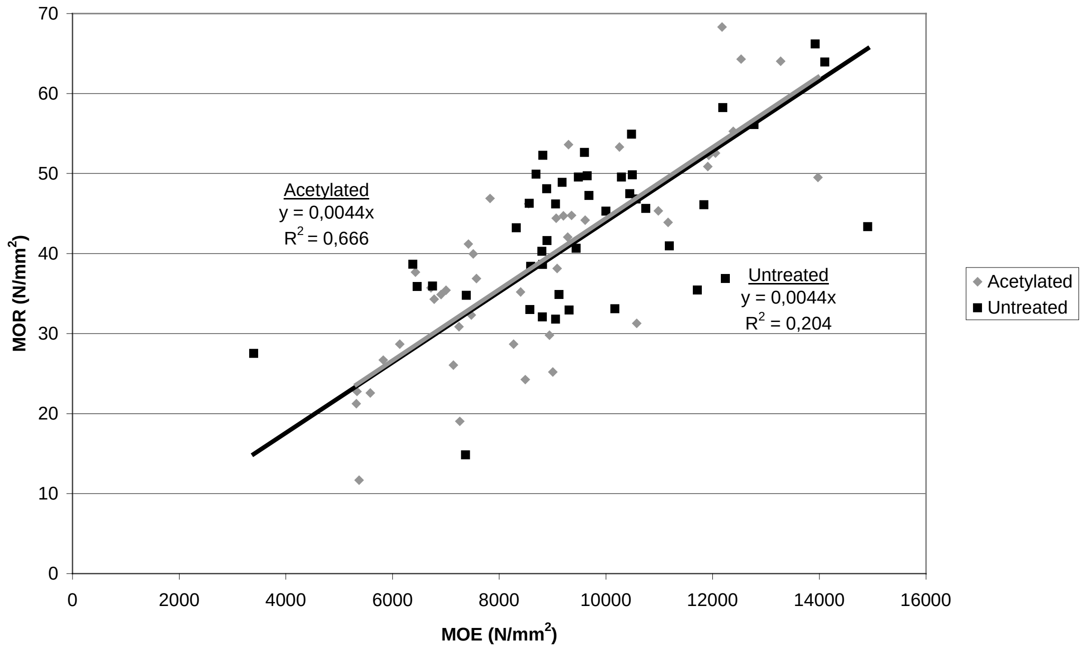


Figure 6: Relation between bending stiffness and –strength for untreated and acetylated Radiata pine

CONCLUSIONS

Acetylation of Radiata pine in structural sizes does most probably not significantly influence the modulus of elasticity (MOE) in bending negatively. The acetylation process does not alter the relationship between modulus of elasticity in bending and bending strength (MOR). The bending strength of the tested material was lower for the acetylated wood compared to the untreated wood. The mean value of MOR is only slightly lower for the acetylated material, however, due to an increase in variation, the characteristic value drops significantly. This is still subject for further research. The data will be analysed in more detail and a/o visual characteristics (knot area ratio, slope of grain, type of fracture) will be taken into account. Besides the bending stiffness and strength, further research is targeting various other mechanical properties (tensile, compression, impact bending and embedded strength) on the same material. A more thorough study of the effect of moisture content (and temperature) on the mechanical properties of acetylated wood is desirable for calculation purposes in structural engineering.

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REFERENCES

Akitsu, H., Norimoto, M., Morooka, T. and Rowell, R.M. (1993). Effect of humidity on vibrational properties of chemically modified wood. Wood and Fiber Science, 25(3), 250-260.

Beckers, E.P.J., Meijer, M. de, Militz, H. and Stevens, M. (1998). Performance of finishes on wood that is chemically modified by acetylation. Journal of Coatings Technology, 70(878), 59-67.

Beckers, E.P.J. and Militz, H. (1994). Acetylation of solid wood. Initial trials on lab and semi industrial scale. In: Second Pacific Rim Bio-Based Composites Symposium, Vancouver, Canada, November 6-9 1994, 125-133.

Beckers, E.P.J., Militz, H. and Stevens, M. (1994). Resistance of acetylated wood to basidiomycetes, soft rot and blue stain. In: International Research Group on Wood Preservation, Document no. IRG/WP 94-40021.

Bongers, H.P.M. and Beckers, E.P.J. (2003). Mechanical properties of acetylated solid wood treated on pilot plant scale. In: Van Acker, J. and Hill, C. (eds.). Proceedings of the First European Conference on Wood Modification, 3-4 April 2003, Ghent, Belgium, p. 341-350.

EN 338 (2003). Structural timber - Strength classes.

EN 384 (2004). Structural timber - Determination of characteristic values of mechanical properties and density.

EN 408 (2003). Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties.

Dreher, W.A., Goldstein, I.S. and Cramer, G.R. (1964). Mechanical properties of acetylated wood. Forest Products Journal, 14(2), 66-68

Goldstein, I.S., Jeroski, E.B., Lund, A.E., Nielson, J.F. and Weaver, J.W. (1961). Acetylation of wood in lumber thickness. Forest Products Journal, 11(8), 363-370.

Larsson, P. and Simonson, R. (1994). A study of strength, hardness and deformation of acetylated Scandinavian softwoods. Holz als Roh- und Werkstoff, 52, 83-86.

Larsson-Brelid, P., Simonson, R., Bergman, O. and Nilsson, T. (2000). Resistance of acetylated wood to biological degradation. Holz als Roh- und Werkstoff, 58, 331-337.

Larsson, P. and Tillmann, A.-M. (1989). Acetylation of lignocellulosic materials. In: The International Group on Wood Preservation, Document No. IRG/WP/3516.

Madsen, B. (1992). Structural behaviour of timber. Timber Engineering Ltd. North Vancouver, Canada. ISBN: 0-9696162-0-1.

Rowell, R.M., Imarura, Y., Kawai, S. and Norimoto, M. (1989). Dimensional stability, decay resistance, and mechanical properties of veneer-faced low-density particleboards made from acetylated wood. Wood and Fiber Science, 21(1), 67-79.

Singh, S.P., Dev, I. and Kumar, S. (1992). Chemical modification of wood with acetic anhydride. Journal of the timber Development Association of India, 38(1), 5-8.

Tsoumis, G.T. (1991). Science and technology of wood: structure, properties, utilization. Van Nostrand Reinhold, New York. ISBN: 0-442-23985-8.