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Mechanical Performance of Linseed Oil Impregnated Pine as Correlated to the Take up Level

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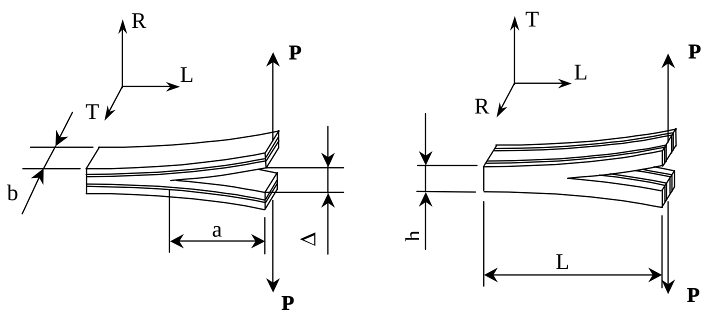
Abstract

The mechanical performance of pine sapwood, impregnated with linseed oil to different take up levels, is evaluated using several test methods. The reduction of mechanical properties is attributed to a) localized cell wall damage in the ray region that facilitates longitudinal inter-cell split in L-R plane (macrocrack) initiation and propagation; b) submicroscopical cracking in the S1 sublayer that reduces the resistance to Mode I and Mode II inter-cell splitting at any location where the oil front has passed. Mechanical testing shows that the Mode I fracture toughness in L-T and L-R planes, the flexural strength in R-T and T-L planes as well as flexural modulus are reduced due to impregnation. 3-point flexural tests reveal only minor changes of longitudinal and shear modulus.

Introduction

The use of toxic chemicals is becoming increasingly questioned for environmental reasons. Linseed oil, traditionally used as a surface coating is a natural, organic and hydrophobic chemical, can be used as a wood preservative.



a) b)

Fig. 1. Scheme of DCB tests specimens and loading. The annual rings are shown as a sequence of dark and white layers. a) is called 0-test b)is called 90-test.

It has been established by Thuvander-1998 and Kifetew-1998 [1] that the wood drying from green state introduces high stresses in- and between the cell wall layers. The highest shear stresses are created in layer S1. The combination of transverse tensile stress and shear stress in S1 layer is more favorable for cracking than in other layers. As a consequence, submicrocracks are developed in layers with subsequent decrease of mechanical properties. Any impregnation of the wood's porous structure requires high pressure and/or a long treatment time which can also cause microstructural damages in the material which further degrades the mechanical performance of the wood.

The objective of this paper is to study the effect of the impregnation process corresponding to certain oil take up on the mechanical performance of the material. Thus, a damage hypothesis is introduced which states that the mechanical properties of the impregnated wood are related to the specific level of take up, understanding implicitly that not the oil itself but rather the impregnation procedure is the reason for degradation. The weight fraction of the oil is used as a process variable.

1. Mechanical Test Methods and Data Reduction

1.1. DCB test

Coordinate in the longitudinal direction (growing direction, cell direction) is denoted by L, R is the radial direction and T is the tangential direction. Plane specimens with L, T, and R axis running parallel to the specimen axis have been used in order to determine the stiffness and strength properties as effected by the impregnation process and the presence of linseed oil. The test procedure and the data reduction scheme is described in [2], [3] and schematically shown in Fig.1. This test may be used to determine the critical strain energy release rate (fracture toughness) of the material in Mode I– the energy needed to create a unit of fracture surface Two types of tests, see Figure 1 are curried out in order to characterize performance in planes R-L and L-T. Details see [3].

1.2. 3-Point Flexural Test

Timoshenko beam theory [3, 4, 5, 6] assuming parabolic shear stress distribution across the beam thickness is used. According to Timoshenko theory the flexural modulus can be used to extract elastic modulus $E_i, \quad i = L, T, R$ and shear modulus $G_{ij}, \quad i, j = L, T, R$ for relative comparison of elastic properties as effected by linseed oil. Detailed data reduction scheme can be found in [3].

1.3. T-0 and T-90 tests

The test setup is shown in Fig.2. From these tests we can obtain flexural modulus in radial E_{Rfl} and tangential E_{Tfl} directions and tensile strength in radial and tangential directions.

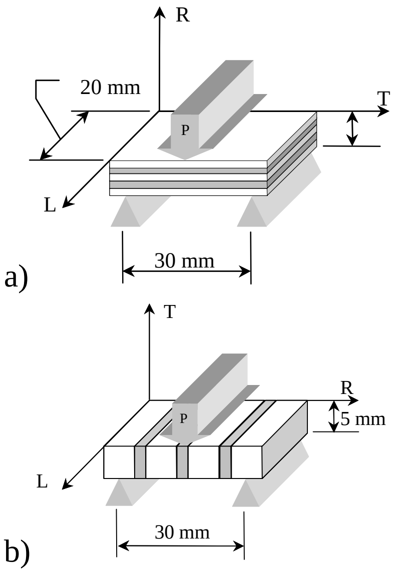


Fig.2. Scheme of 3-point flexural tests. Orientation of the specimens with respect to supports and applied load. a) T-0 test; b) T-90 test.

1.4. L-0 and L-90 tests

The specimen orientation with respect to the load and supports is shown in Fig.3. The span length in this test was varied from 160 mm to 35 mm, the specimen thickness 5.5 mm and the specimen width 11 mm. From these tests the longitudinal modulus E_L, and shear modulus G_{LT} as well as G_{LR} were obtained. Since the compressive strength is much lower than the tensile, the premature damage appeared in the load application zone earlier than in the tension zone. Hence, this test was not suitable to determine tensile strength.

2. Results and Discussion

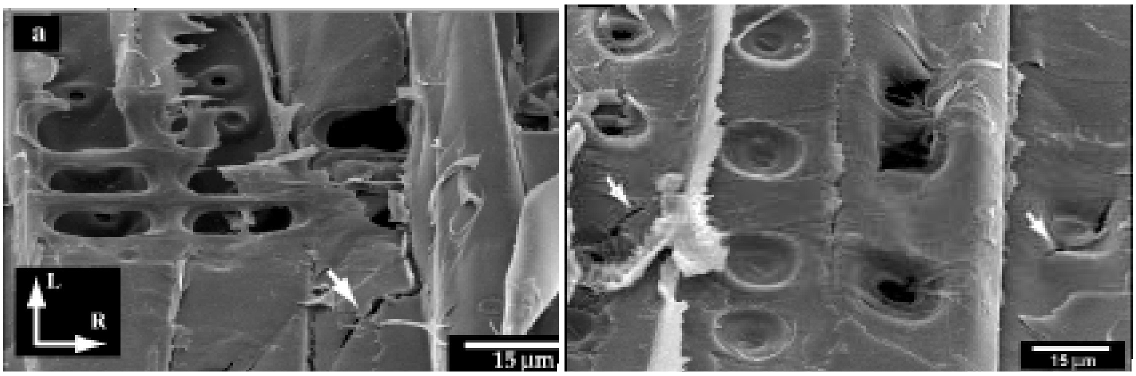
2.1. Location of the Penetrant and Microdamage Due to the Impregnation

Three significantly different levels of take up of linseed oil were obtained following the impregnation procedure. These were called Low, Intermediate and High, with characteristic macroscopic increase of weight (percent)25-40, 50-80 and 90-120 respectively. It has earlier been shown [7] that the specimens exhibited a gradient from the surface into the specimen which resulted in higher concentration near the surface, than the average values.

*Low take up level.*Linseed oil is predominantly found in small clusters. The clusters are ranging from a few filled tracheids and up to about ten or twelve in size. Furthermore, the clusters are often found to be located nearby a radial extending ray.

There was no significant evidence of morphological changes when comparing impregnated and unimpregnated microtome cut fracture surfaces originated from this level of take up.

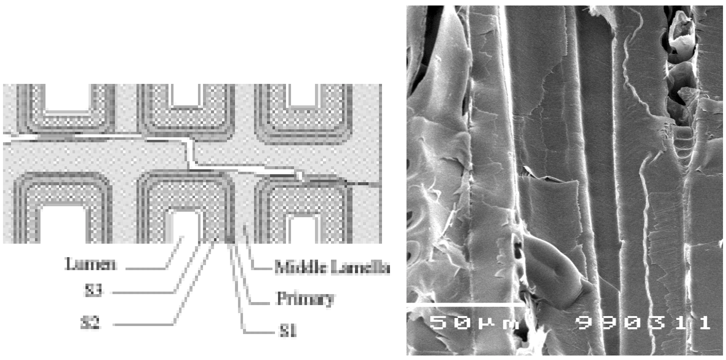
Intermediate take up level. Clusters have apparently expanded in the tangential directions. Damage related to the impregnation process can be found at this level. The damage are predominately found as small cracks in the cell wall (a few micrometers) near the cross field pits in the earlywood.



a) b)

Fig. 4. Damage related to the impregnation process (marked with white arrows)

High take up level. Oil is dispersed throughout the annual ring. The morphological changes are significant at this level. Referring to Figure 4a, showing the L-R plane near the cross field pit region, cracks in the cell wall extend in the longitudinal direction (marked wiht white arrows). The sharp density gradient between latewood and earlywood is localised in the right part of 4a. The investigation of mechanically non-loaded specimens showed that the most severe damages were located near this density gradient. Cell wall cracks are occasionally located near the bordered pits, see Figure 4b.



a) b)

Fig. 5. Inter-cell splitting crack. a) Schematic showing of a splitting in direction transverse to wood cells, b) Splitting crack surface in L-T plane.

The reduction of mechanical properties discussed below can not be explained by the described microcracks localized in the ray region only. It indicates that when the oil front passes through the cell an additional damage at submicroscopical scale (submicrocracking) takes place. These submicrocracks are cracks located in cell wall layers. Previously it was shown using modeling [1, 8] that cell wall layers must have such submicrocracks caused by material drying. The combination of transverse tensile stress and shear stress in S1 layer is more favorable for cracking than in other layers. It may explain the fact that the most severe damage was located near the highest density gradient between earlywood and latewood. The mechanical constraint applied from the stiffer and thicker latewood cell to the deformation of the earlywood cell, filled with the oil during the oil take up, causes additional damage in cell wall layers. The submicrocracks of cell wall layers (mainly in S1–layer) can reduce the material resistance to inter-cell splitting due to local tensile and/or shear stresses during mechanical loading (the inter-cell shear strength and tensile strength are reduced). The cell wall damage localized in the ray region facilitates the macrocrack initiation and propagation through the ray in radial as well as in longitudinal direction (splitting). The inter-cell splitting is cracks moving partially in the middle lamella between cells and partially in outer layers of the cell wall as shown in Fig.5. Both Mode I and Mode II failure my be effected because for this kind of cracking. The propagation of a macrocrack in L-R plane is illustrated in Fig.6. The main mechanism is the inter-cell splitting. During impregnation even up-to low oil level the inter-cell shear strength in region 2 in Fig.6. is the most weakened. Severe cell wall damages close to the ray in region 1, Fig.6. may also facilitate the crack propagation by allowing the crack path to deviate from the ray plane, if it is energetically favorable.

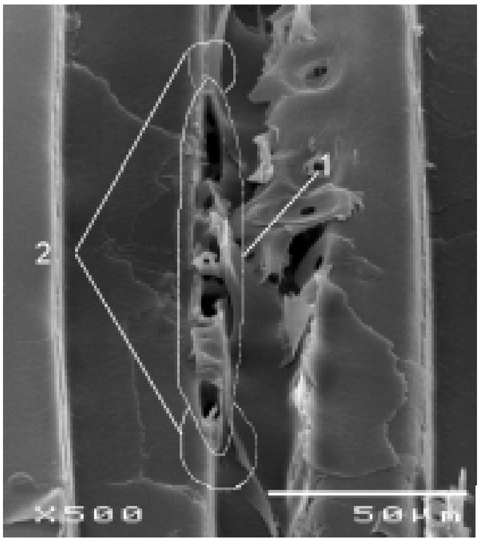


Fig. 6. Crack plane deviation initiated by cell wall damage close to the ray in case of longitudinal splitting crack in L-R plane. Damage regions: 1-weak region at the ray ends, 2-damaged cells at the ray.

2.2. DCB test

The critical strain energy release rate, G_{IC} (fracture toughness) for Mode I longitudinal splitting in L-T plane, dependence on impregnation level, is shown in Fig. 7. It is decreasing with increasing oil content. Longitudinal split in L-R plane runs through both latewood and earlywood layers and is in some sense an average G_{IC} of both earlywood and latewood layers. The fracture surface observation in L-R plane by SEM, reveals that the basic failure mechanisms (longitudinal splitting and shift of the crack plane) described in the beginning of this section are present in both 0-test and 90-test. The fracture surface of an impregnated specimen is smoother with parallel shifts of the crack plane in ray regions. This observation confirms that the inter-cell shear strength is reduced and cells are damaged in the ray region. Since the failure mechanism is the same, we can expect that the reduction of fracture resistance will be approximately equal in both tests. Fig.7 confirms this prediction.

2.3. T-0 and T-90 3-point flexural tests

Effect of the oil content on flexural mechanical properties is analyzed comparing flexural data in radial and tangential direction [3].

The flexural failure strain dependency on the oil content in specimens is not certain and the observed decrease is comparable with the data scatter. The failure stress in T-0 test is overestimated, because of hydraulic pressure of the oil in the compression zone. The pure failure stress (after accounting for the hydraulic effect) should be lower. Since in the region of the oil content V_{oil}<60% the presented flexural strength is constant, we conclude that the pure flexural strength decreases with the oil content. This means that there

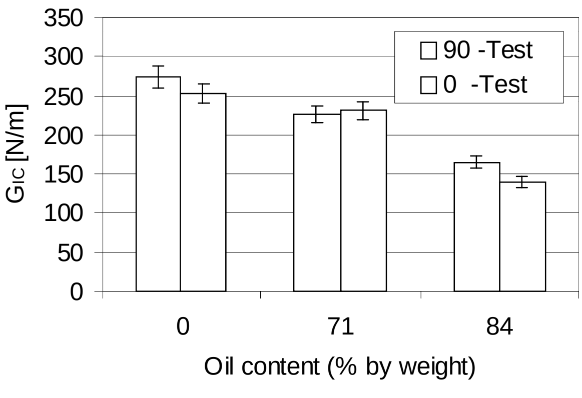


Fig. 7. Critical strain energy release rate dependence on oil content in pine, 90-test, and 0-test.

is a small damage and an associated strength reduction in the specimen in region of oil content V_{oil}<60%.

The macrocrack propagating in R-direction is initiated at the specimen bottom surface in a ray, which at this position may be considered as a macrocrack that is loaded in tension transverse to the crack plane. Stress concentration on both tips of the ray leads to its growth in L-direction as a Mode I splitting crack. After reaching a certain size this crack starts to propagate in Mode I in R-direction. This mechanism is the same for all oil contents and the observed difference in fracture stress is related to the reduction of the inter-cell fracture resistance caused by impregnation.

The flexural modulus E_{Tfl}, is increasing slightly or is constant in the region of oil content V_{oil}<60%, $\approx 0.22 \pm 0.025 [GPa]$. It can be explained by the hydraulic effect, which in this region is more significant than the microdamage created by oil passing through rays. The main damage responsible for reduction of flexural modulus is the increased submicrocrack density in cell wall layers generally and an additional local increase of microcracks and submicrocrack density in ray regions. In the region of oil content V_{oil}>60% the damage based E-modulus reduction dominates over to hydraulic effect. The hydraulic effect is still increasing but the damage (splitting, microcraks in the ray region and increased submicrocrack density) becomes more significant and finally the E_{Tfl} is reduced, from $E_{Tfl} \approx 0.21$ [GPa] to $E_{Tfl} \approx 0.18$ [GPa].

In the unimpregnated specimen, T-90, not always the crack starts in the earlywood, but its propagation is always along a “zigzag” path between the earlywood and the transitionwood. In impregnated specimens it is most often found near the interface between earlywood and latewood. This confirms our hypothesis that the largest microstructural changes actually occur at this interface.

The flexural modulus E_{Rfl} is reduced slightly, $\approx 20\%$, which implies that there is a balance between hydraulic and damage effects.

2.4. L-0 test and L-90 tests

For the longitudinal modulus from L-0 and L-90 tests, almost the same values are obtained in both tests and there are almost no changes in stiffness as the oil content increases. In both tests part of the cells are loaded in longitudinal compression and a part in tension. The S2 sub layer takes most part of the load. The new submicrocracks in this layer caused by impregnation do not effect longitudinal stiffness much, because of the orientation of fibrils in this layer. The submicrocracks in S1 and S3 layers have an orientation that may cause the reduction of stiffness. However, the sub-layers S1 and S3 are rather thin as compared to S2 and the influence on stiffness is small. The decrease of shear modulus may be underestimated as a result of the hydraulic effect. Both shear moduli seems to be similarly influenced by the impregnation procedure.

Conclusions

The mechanical performance of pine sapwood, impregnated with linseed oil to different take up levels, is evaluated using several test methods. The observed reduction of mechanical properties due to impregnation has been explained by a) localized microcracks in the ray region; b) submicroscopical cracks accumulating mainly in the S1 cell wall layer at any location where the oil front has passed. It is suggested that the most severe cell wall layer damage is located near the highest density gradient between earlywood and latewood.

In mechanical loading the presence of submicrocracks in S1 layer reduces the resistance to Mode I and Mode II inter-cell splitting. The microcracks in the ray region facilitate the macrocrack initiation and propagation. The extend of damage depends on the take up level, increasing with increasing oil content. Damage is predominantly located in earlywood.

The Mode I fracture toughness G_{IC} in L-T and L-R planes is significantly lowered by the damage introduced during impregnation. The crack propagation mechanism is longitudinal splitting. The flexural strength as well as flexural modulus in R- and T-directions are reduced due to impregnation. The crack path in impregnated specimens is different, being in T-0 test more rough with a large number of separated cells leading to “zigzag” deviation of the crack plane from planarity. The crack in T-90 test in unimpregnated specimens grows in a “zigzag” form in both earlywood and transitionwood layers but becomes more smooth in impregnated specimens and is located at the interface between earlywood and latewood which is most damaged. The reduction of longitudinal modulus E_L and shear moduli G_{LT} and G_{LR}, caused by damage is rather small and is compensated by hydraulic effects of the oil.

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