IDENTIFICATION OF FACTORS INFLUENCING THE MAXIMUM FLEXURE OF BEECH WOOD PLASTICIZED BY MICROWAVE HEATING

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This paper reports on the influence of selected factors and their interactions on maximum flexure after plasticizing beech wood by microwave heating. To our knowledge, the use of microwave heating has not been reported for plasticizing wood yet. Therefore, a proper procedure was developed to verify the use of microwave heating for the purpose of plasticizing. The determination of maximum flexure was based on the principle of static bending with three-point loading. Maximum flexure was monitored in beech test samples with dimensions of 25 x 25 x 400 mm (cross-sectional dimensions were selected according to standard testing samples). Samples were divided into three groups of initial moisture contents of 65%, 30% and 20%. Our research confirmed only the influence of plasticizing time and moisture content on the maximum flexure of wood plasticized by microwave heating, exactly as we expected. The other two factors, orientation (radial and tangential) and placement (in the center or on the side), had small or no effect on the value of maximum flexure. Microwave heating is quite intense, therefore for this kind of heating, it is better to have higher moisture content in an appropriate power device and minimal plasticizing time. The biggest advantage of microwave heating is the short plasticizing time, a few minutes, while steaming requires tens of minutes or even hours.

Keywords: microwave heating, plasticizing, maximum flexure, moisture content, plasticizing time, orientation, placement

INTRODUCTION

The purpose of this work was to contribute to the knowledge on the use of microwave heating for wood plasticizing to develop and accelerate the process of wood bending.

The main aim of the process of plasticizing wood before forming it is the temporary change in its mechanical and physical properties, which achieve optimal conditions for forming. For the forming technology, the condition that needs to be met is for the wood to reach the highest level of plasticity, while the components of the lignin–polysaccharide matrix should remain the least damaged.[1-3] The achievement of the desired state is also dependent on the method of plasticizing.[4]

Steaming is one of the oldest and most widely used types of plasticizing, but the conditions are not always suitable for the production process. The benefit of the method is good plasticity of the wood and only a slight deterioration caused by the longer time of plasticizing. The drawbacks of steaming are poor working environment, low technology readiness and heat transfer from the surface zones to the inner zones, which in poor thermal conductivity of wood causes slowness in the process of plasticizing. Because of these drawbacks, there has been a search for other principles of plasticizing that might improve or replace steaming, while maintaining the benefits it brings. Any new method is compared with steaming for wider application and better results.[5-6]

The research was intended to test a method permitting to improve and accelerate the process of plasticizing and thus actual wood bending. Our research was aimed at determining plasticizing conditions during microwave heating depending upon factors that could influence it: initial moisture content, plasticizing time, orientation and placement of wood, and also at verifying the results of plasticizing by maximum flexure tests. The maximum flexure of wood, after plasticizing by microwave heating, was the final monitored feature.

EXPERIMENTAL

The research was based on the investigation of the impact of selected factors on the maximum flexure y_{max} of beech wood plasticized by microwave heating.

The experimental beech trees (*Fagus sylvatica* L.) were 70 years old, grown in the Javorie mountains area in central Slovakia, southeast from Zvolen city. The zones suitable for sampling were cut from the trunk at a height of 2 m from the stump. The zones from the middle of the distance between the pith and bark were chosen for sample preparation. From these parts 1 m long sections were cut. For experiments, clear beech samples with dimensions of 25 × 25 × 400 mm were used. All the samples were air-conditioned in the conditioning room for more than five months before moisture conditioning.

The air-conditioned samples were divided into two groups in relation to treatment – samples for microwave heating and samples for steaming. The samples for steaming served as a reference standard. The entire research was based upon 400 samples. Furthermore, all samples were divided into three groups according to initial moisture content, namely 20, 30, and 65%. The samples with initial moisture content below or equal to the fiber saturation point – FSP (20 and 30%) were conditioned in a conditioning chamber by achieving the equilibrium moisture content (EMC). The conditioning chamber provided different conditions in relation to relative humidity of air and temperature (20% – 86±3%, t = 20±2 ºC and 30% – 97±3% and t = 20±2 ºC). An EMC above FSP (65%) was achieved by water soaking. The actual EMC of each sample was measured by weighing after conditioning.

Plasticizing time of microwave heating was set to 2, 4 and 6 min for all samples.[5] All moisture contents and plasticizing times were chosen based on preliminary tests. It was further determined to carry out plasticizing with only one piece of sample in order to prevent the absorption of radiation by other samples.

The **placement** of the samples in the plasticizing space was center placement – **c** and side placement – **s**. Sample **orientation** during microwave heating, considering the virtual line of magnetrons, was radial – **R** and tangential – **T**. The device power was set constant at 700 W per magnetron.[5]

A reference test was also realized along with this test – steam plasticizing. **Steaming** was carried out in a steaming device (the device has been designed by us), which contained water on the bottom. Before testing, the water was preheated to the boiling point, and then the samples were inserted into the steaming device. The samples were placed on a metal grate over the water. During heating, the temperature in the device was kept at about 95 ºC. Plasticizing of samples took 20 min. The samples plasticized by steam, as well as the samples plasticized by microwave heating, were loaded and tested.[5]

Maximum flexure of wood plasticized by microwave heating

The investigation of maximum flexure was followed by plasticizing by microwave heating, which was carried out in a plasticizing device (Fig. 1). During heating, the sample was placed on wooden trestles 5 mm above the water (Fig. 2).

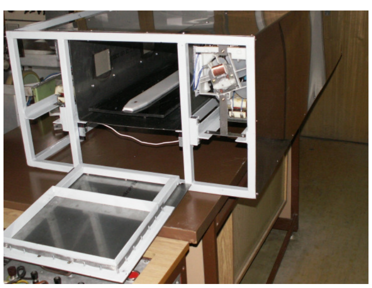

Figure 1: Microwave plasticizing device: a) overview; b) placement of magnetrons

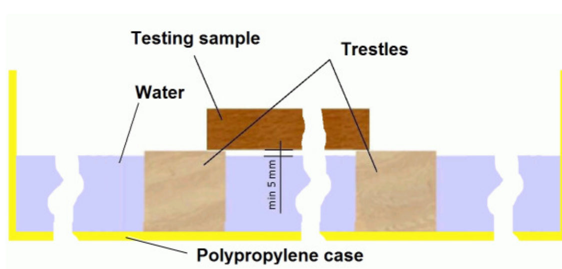

Figure 2: Schematic demonstration of testing sample positioned during plasticizing by microwave heating

On the bottom of the polypropylene case, water was added to moisturize the environment, limit the loss of moisture of the test samples, and provide an environment with higher water content with respect to the relative moisture of the environment. The temperature in wood was controlled by a thermal teflon-coated sensor and kept at 95 ºC during heating. After plasticizing, the temperature was also verified by thermocouple.[7-10]
The determination of maximum flexure was based on the principle of static bending with three-point loading. During testing on the bending machine, the sample was placed so that the loading force acted radially in relation to the grain direction on cross-section. The maximum flexure was measured at the center of the test sample with an accuracy of 0.1 mm.

RESULTS AND DISCUSSION

Table 1 contains the values of the ANOVA test, which reflect the statistical significance of individual factors and their mutual combinations. Based on these values, it may be stated that all factors were statistically significant, except the placement of samples.

Table 1
Influence of individual factors and their interactions on maximum flexure (4-factor analysis of variance)

Monitored factor	Sum of squares	Degree of freedom	Variance	Fisher's F - Test	Significance level P
Intercept	227,533.6	1	227,533.6	30,887.6	0.000
plasticizing time	3,764.0	2	1,882.0	255.5	0.000
moisture content	8,021.8	2	4,010.9	544.5	0.000
orientation	499.8	1	499.8	67.8	0.000
placement	5.2	1	5.2	0.7	0.401
plasticizing time*moisture content	243.0	4	60.7	8.3	0.000
plasticizing time*orientation	25.9	2	12.9	1.8	0.174
moisture content*orientation	283.2	2	141.6	19.2	0.000
plasticizing time*placement	3.5	2	1.8	0.2	0.787
moisture content*placement	91.9	2	45.9	6.2	0.002
orientation*placement	414.7	1	414.7	56.3	0.000
plasticizing time*moisture content* orientation	75.1	4	18.8	2.6	0.039
plasticizing time*moisture content* placement	33.3	4	8.3	1.1	0.341
plasticizing time*orientation*placement	107.7	2	53.9	7.3	0.001
moisture content*orientation*placement	115.5	2	57.8	7.8	0.000
plasticizing time*moisture content*orientation*placement	152.1	4	38.0	5.2	0.000
Error	2386.8	324	7.4		

Figure 3 shows the impact of plasticizing time on the maximum flexure of wood. The results show that the highest maximum flexure was achieved at a plasticizing time of 2 minutes, while the lowest values were found for a plasticizing time of 6 minutes, which means that an increase in plasticizing time leads to a decrease in maximum flexure, which is probably caused by the higher moisture loss.[11,12]

Figure 4 shows the impact of initial moisture content. The moisture content of wood had a positive effect on maximum flexure, i.e. the higher the moisture content, the higher the maximum flexure reached. This fact can be confirmed by results – the highest values of maximum flexure were achieved at a moisture content of 65%. On the other hand, the lowest values of maximum flexure were reached at a 20% moisture content.

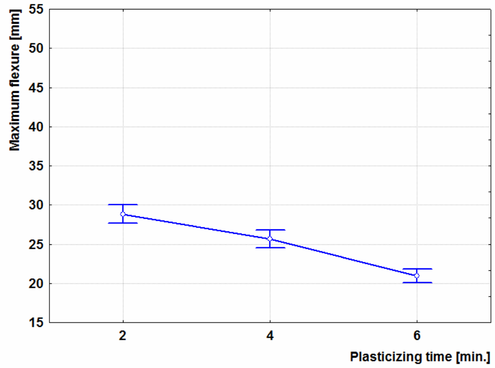

Figure 3: Influence of plasticizing time on maximum flexure (95% confidence intervals)

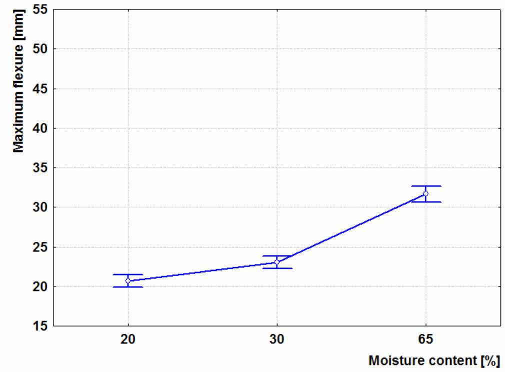

Figure 4: Influence of moisture content on maximum flexure (95% confidence intervals)

The orientation of samples considering the virtual line of two opposing magnetrons was another influencing factor. The influence of sample orientation on maximum flexure is shown in Figure 5. Orientation is also a statistically significant factor. The highest maximum flexure was measured on samples tangentially oriented, whereas the lowest values were achieved for radial orientation.

The placement of samples in the plasticizing space during heating was the last examined factor. The samples were placed either in the center or on the side of the plasticizing space. Figure 6 shows that the placement was not a statistically significant factor, because the values were not too high for individual placements.

These results confirm that the density of microwave radiation in the space of the plasticizing device is fairly uniform or with only slight differences. On the other hand, it is difficult to determine the direction of microwave propagation in the space, given their chaotic motion and reflections of radiation from the metal walls of the device. Placement depends on similar conditions as those of the previous factor – orientation.

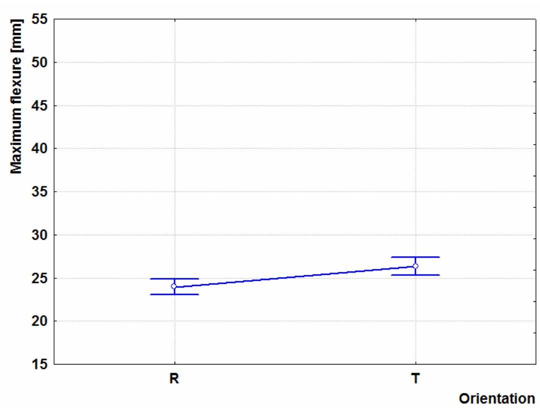

Figure 5: Influence of orientation on maximum flexure (95% confidence intervals)

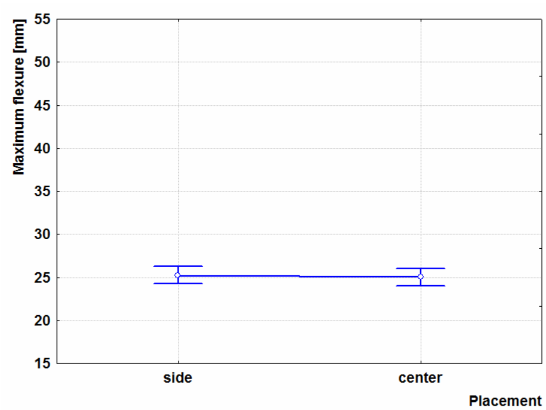

Figure 6: Influence of placement on maximum flexure (95% confidence intervals)

Further, Figure 7 shows the influence of plasticizing time and moisture content on maximum flexure, which was statistically significant. Moisture content had a positive effect on maximum flexure, while plasticizing time, on the contrary, had a negative impact. The largest differences in the values of maximum flexure were recorded between 65% moisture content and other moisture contents.

The impact of plasticizing time and orientation (radial and tangential), as illustrated in Figure 8, was not statistically significant. Higher maximum flexure was achieved in tangential orientation for all plasticizing times.

Even though higher values were found for tangential orientation, differences were not great and the course of the curves was very similar in both cases.

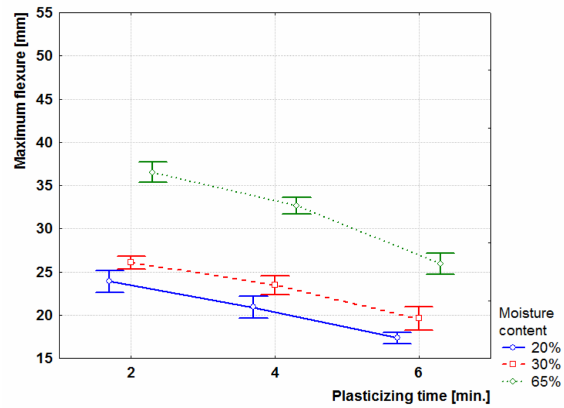

Figure 7: Influence of plasticizing time and moisture content on maximum flexure (95% confidence intervals)

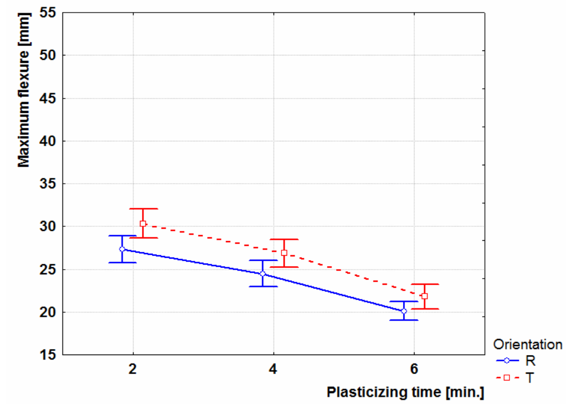

Figure 8: Influence of plasticizing time and orientation on maximum flexure (95% confidence intervals)

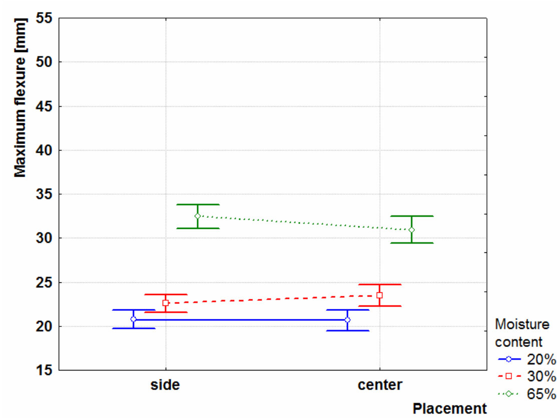

Figure 9: Influence of placement and moisture content on maximum flexure (95% confidence intervals)

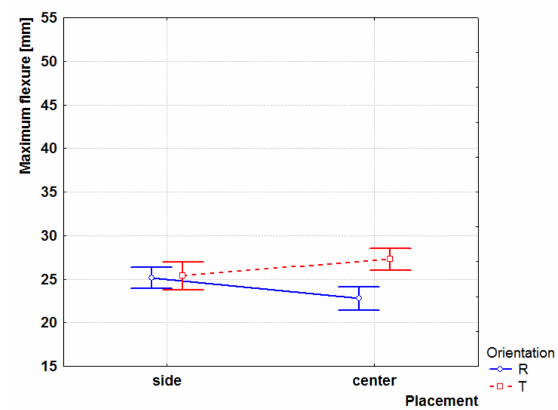

Figure 10: Influence of placement and orientation on maximum flexure (95% confidence intervals)

The influence of moisture content and sample placement on maximum flexure is displayed in Figure 9. This combination of factors was statistically moderately significant. Significant differences in the values of maximum flexure were recorded between 65% moisture content and other moisture contents, while the differences between the moisture contents of 20% and 30% were negligible. Based on these results, it is irrelevant where the wood is placed during plasticizing by microwave heating.

The effect of the interaction of placement and orientation is shown in Figure 10. This combination of factors is statistically significant. The maximum flexure values of wood with radial and tangential (R and T) orientation and side placement were almost identical, but greater differences were recorded for wood placed in the center. For center placement, the curves of maximum flexure presented an opposite character.

Figure 11 shows the influence of placement and plasticizing time. Individual curves are almost identical, although slightly higher values of maximum flexure were achieved for side placement. However, these values decreased with increasing plasticizing time. Given these results, we can conclude that this factor combination is statistically insignificant.

The impact of the interaction of moisture content and orientation on maximum flexure is shown in Figure 12 and, as the graph shows, it is statistically significant. The highest maximum flexure was achieved at 65% moisture content and tangential orientation. The same fact (i. e. the highest maximum flexure achieved for tangential orientation) was also confirmed at 20% moisture content. At a moisture content of 30%, the maximum flexure values were almost the same for both types of orientation. So, we can state that the highest maximum flexure was achieved on samples with 65% moisture content, for both orientations.[13]

Then, we investigated the effect of a three-factor combination including moisture content, plasticizing time and orientation. As can be noted in Figure 13, it is statistically less significant. The maximum flexure of wood oriented radially rose uniformly with the increase in moisture content. This increase was less uniform for the tangential orientation. However, the plasticizing time had a negative effect on the value of maximum flexure for both orientations.

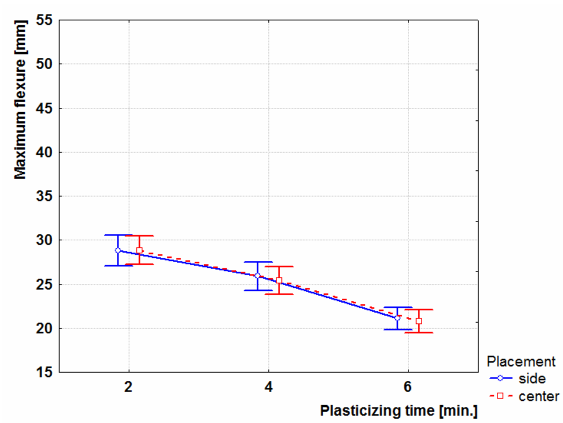

Figure 11: Influence of plasticizing time and placement on maximum flexure (95% confidence intervals)

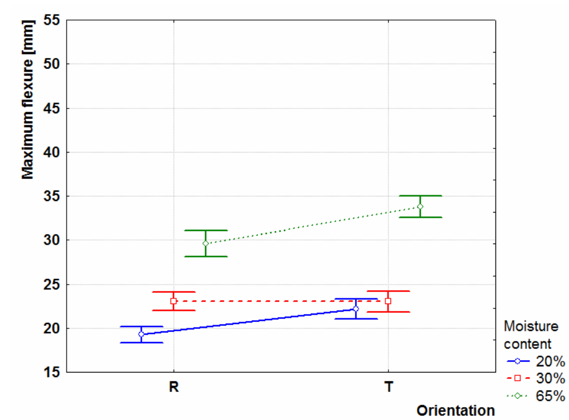

Figure 12: Influence of orientation and moisture content on maximum flexure (95% confidence intervals)

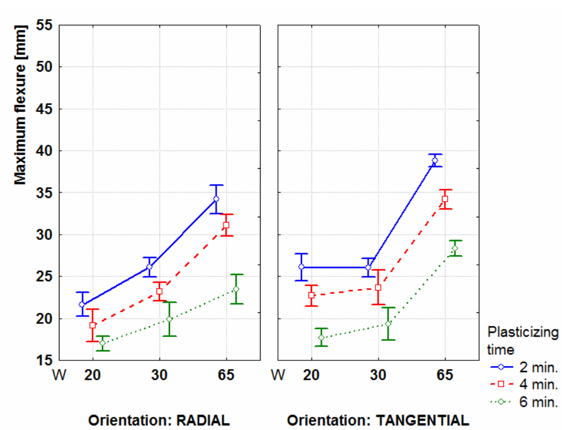

Figure 13: Influence of orientation, plasticizing time and moisture content on maximum flexure (95% confidence intervals)

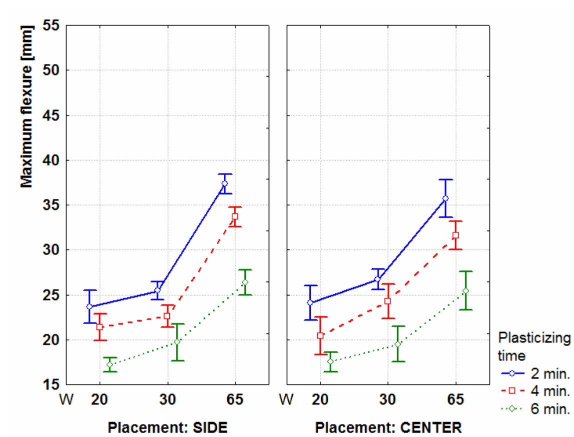

Figure 14: Influence of placement, plasticizing time and moisture content on maximum flexure (95% confidence intervals)

The influence of placement, plasticizing time and moisture content is shown in Figure 14. This three-factor combination is statistically insignificant. The differences in the values of maximum flexure for various placements are negligible.

Figure 15 shows the impact of plasticizing time, placement and orientation on maximum flexure. Based on the results of the F-test, it is clear that the combination is statistically significant. While maximum flexure was always higher for radial orientation and central placement, the behavior for side placement was not so clear.

For both types of placement, it has been confirmed that with increasing plasticizing time the value of maximum flexure decreased.

Figure 16 represents the influence of moisture content, orientation and placement on maximum flexure – a combination that also had a statistically significant effect. The highest maximum flexure was achieved for 65% moisture content and both placements. Higher values were always reached for wood with radial orientation and central placement. On the other hand, the wood with side placement had higher maximum flexure in tangential orientation only at moisture contents of 65% and 20%. However, maximum flexure had an opposite behavior for 30% moisture content.

The last combination investigated included all four factors simultaneously, which, for a better understanding, has been represented by two graphs in Figures 17 and 18. This combination was statistically significant.

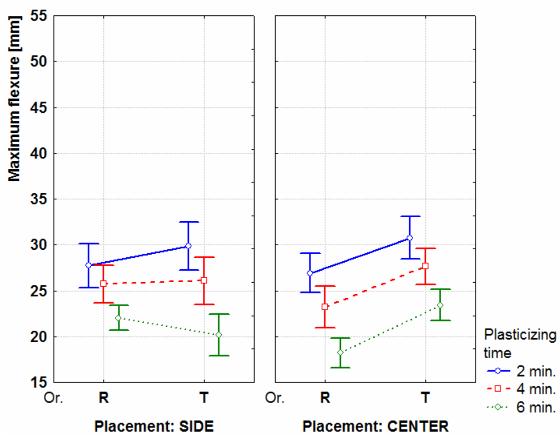

Figure 15: Influence of orientation, placement and plasticizing time on maximum flexure (95% confidence intervals)

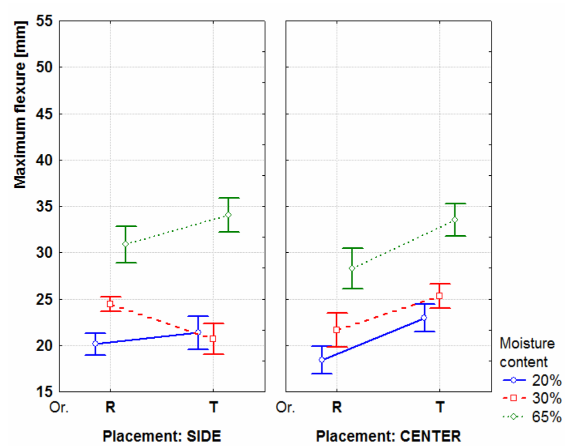

Figure 16: Influence of placement, moisture content and orientation on maximum flexure (95% confidence intervals)

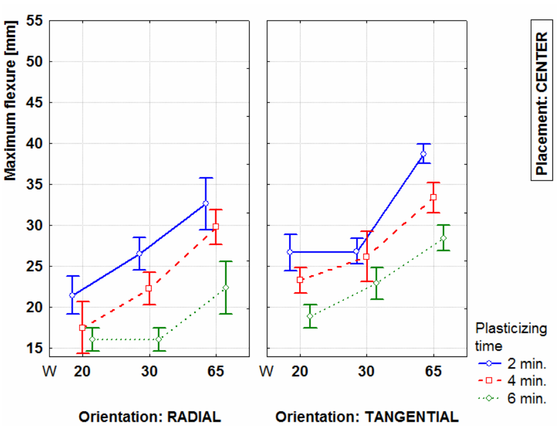

Figure 17: Influence of orientation, moisture content, plasticizing time and placement at center on maximum flexure (95% confidence intervals)

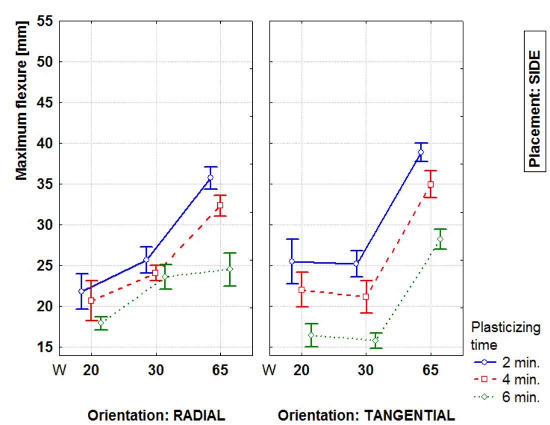

Figure 18: Influence of plasticizing time, orientation, moisture content, and placement at side on maximum flexure (95% confidence intervals)

Figure 17 describes the influence of all factors on maximum flexure for central placement. In general, higher maximum flexure has been found for tangential orientation. The negative impact of plasticizing time on maximum flexure was also confirmed in this case. The maximum flexure increased with increasing moisture content, but not uniformly and not in all cases.

Figure 18 describes the impact of all factors on maximum flexure for side placement. The curves are similar in nature as in the previous case.We did not find clear difference between radial and tangential orientation for side placement.

In general, maximum flexure decreases with increasing plasticizing time. This decrease can be explained by the higher amount of energy absorbed by wood, and thus by the more intense temperature inside wood. The high moisture loss is associated with the sharp increase in the temperature inside wood, which grows in a few minutes up to 100-130 °C.[17-19] Temperature causes the extrusion of a larger amount of water to the surface. The loss of moisture is a key factor that affects the final moisture content of wood. A suitable final moisture content of wood is an important and necessary condition for good and qualitative bending.[20,21]

Higher maximum flexure was probably reached because of better penetration of microwave radiation through the radial faces of the samples, respectively, the lower moisture loss for this orientation. Differences between tangential and radial orientation grew with increasing moisture content and reducing plasticizing time. During heating, the microwaves do not pass through the wood only in a certain direction, they move in all directions due to the reflections from the metal walls of device, and this is the reason why radiation density is so high in the whole plasticizing space. Therefore, it is not possible to determine clearly the exact direction in which the microwaves penetrate into the wood. Another fact is that the wood intended for bending does not always have purely tangential or radial faces, depending on grain angle, wood age etc. This is the reason why this factor is of little significance for practical use.[21]

The maximum flexure of wood with central and side placement did not show large differences. Based on these results, we can state that placement does not have a significant impact on the final maximum flexure of wood.

It is necessary to consider the effects of microwave heating or plasticizing on the basic characteristics of wood, such as modulus of elasticity, ultimate tensile strength, bending strength and compression strength, density, etc., which will be the subject of our next research.

CONCLUSION

Based on the results described above, we can summarize the following conclusions:

- our results confirm the fact that moisture content has the highest and most positive influence on the maximum flexure of wood;
- plasticizing time is an important factor with a significant influence on the results of maximum flexure achieved. Longer plasticizing time increases the amount of microwave energy delivered to wood, on the other hand, the higher amount of energy also causes a higher moisture loss. Therefore, a suitable plasticizing time should be chosen, according to the dimensions of wood and device performance;
- although the orientation factor was statistically significant, differences in the values for different types of orientation were not considerable. In general, plasticized wood with tangential orientation achieved higher values of maximum flexure;
- in general, placement is not a statistically significant factor, which was also confirmed by our results.

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