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ORIGINAL ARTICLE

Effects of cryogenic temperature on some mechanical properties of beech (*Fagus orientalis* Lipsky) wood

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Abstract

It is important to know the changes in the mechanical properties of wood during freezing for engineering calculations of the wood material to be used in cold environments. Although this is important, the mechanical properties of wood at temperatures below − 100 °C have rarely been studied. In this study, the effects of cryogenic temperature (− 196 °C) on the bending strength, modulus of elasticity in bending and compression strength parallel to the grain of oven-dried and air-dried beech wood was investigated. As a result of the experiment, the mechanical strength properties of the wood increased during freezing. The increase in bending strength and modulus of elasticity values were higher in air-dried wood than those in oven-dried wood. However, the increase in compression strength values was determined at the same rates as 61% for air-dried and oven-dried wood. This increase in mechanical strength properties of wood during freezing could be explained by freezing of water in the wood, hardening of wood cell walls, decreasing intermolecular distance, increasing intermolecular force and stabilization of crystalline structure.

1 Introduction

The most abundant lignocellulosic building material in the world is still the wood raw material. Unique features of wood are its low carbon footprint as it emits less greenhouse gases in production processes compared to other building materials such as steel and concrete, and the fact that its use allows for energy-efficient structures (He et al. 2020). Moreover, the fact that wood is an eco-friendly building material due to its renewable and carbon storage properties increases the interest in it recently (Churkina et al. 2020). Engineering wood products such as glued-laminated timber (glulam), laminated veneer lumber (LVL), structural-composite lumber (SCL), and cross-laminated timber (CLT), are increasingly used in the construction industry in Europe and America (Wang et al. 2016b). However, in these widespread areas of use, wood can face extremely cold situations. In such cases, it is necessary to know the mechanical characteristics of wood, such as bending strength, in terms of engineering (Gerhards 1982).

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There are many areas where wood must withstand the effect of low temperature such as in ships up to − 163 °C that are carrying liquid natural gas (Kim et al. 2015, 2016, 2018), in structural roofing materials (Ayrilmis et al. 2010), in logging and timber fields stored in open areas in winter (Campean et al. 2008), in bridges up to − 45 °C that are manufactured with cross-laminated timber (CLT) in Canada and Sweden (Wang et al. 2016a), in railroad sleepers (Medvedev et al. 2019) and in bridges manufactured with stress-laminated decks (Wacker et al. 1996). The wood may also need to withstand ultra-cold conditions in environments such as the Moon and Mars with cold climates where wood is likely to be used in the future.

Low environmental temperatures affect the mechanical properties of wood (Gerhards 1982; Zhao et al. 2015a). Here, two types of temperature effects on wood can be mentioned. When wood is heated or cooled quickly and then tested at the adjusted temperature, the changes in the mechanical property is called immediate or reversible effect, that is, when the wood temperature returns to the room temperature, the mechanical property returns to its original value. Permanent or irreversible change of properties can also occur when the wood is heated to high temperatures or frozen while its moisture is above fiber saturation. When this wood is tested at room temperature, permanent decreases in its properties occur (Green and Evans 2008; Ates et al. 2017; Özkan et al. 2017).

Some earlier studies have found that some of the wood mechanical properties such as compression strength (Gerhards 1982; Jiang et al. 2014), bending strength (Zhao et al. 2015a, 2016) and modulus of elasticity (Green and Evans 2008; Zhao et al. 2015a) increase during freezing. Similarly, it has been found that compression strength and bending strength values increase in wood composites with decreasing temperatures (Bekhta and Marutzky 2007; Ayrilmis et al. 2010). Furthermore, as a result of freezing, an increase in Young's modulus values has been found to occur as a cause of breaking of the branches of woody plants due to snow and wind load (Umbanhowar et al. 2008). Almost all mechanical properties of wood were affected by the low-temperatures (Gerhards 1982; Ayrilmis et al. 2010).

There may be more than one reason for the reversible increase in the mechanical properties of wood during freezing. The most important one is that the water in the wood increases the mechanical properties of the wood during freezing. Furthermore, the increasing moisture and the decrease in temperature enhance the rate of the increase in mechanical properties of wood during freezing (Gerhards 1982; Jiang et al. 2014; Zhao et al. 2015a, 2016). As the strength of the ice increases with the decreasing temperature, it is thought to contribute to the increase in mechanical properties of wood (Zhao et al. 2015a). In contrast, the increase in mechanical properties caused by freezing in oven-dried wood can be explained by other factors rather than water. These can be shown as hardening of wood cell walls as a result of freezing (Zhao et al. 2015a). Furthermore, the intermolecular distance of the material decreases at low temperature, thus the intermolecular force increases, resulting in more energy needed to break the sample (Zhao et al. 2015a, 2016). Moreover, it is made stronger and more durable with low-temperature applications (cryogenic processing) in order to stabilize the crystalline structure and reduce residual stress in materials such as metals, alloys, plastics and composites (Kalia 2010).

The permanent effects of freezing on the wood are generally observed if the wood moisture level is higher than the fiber saturation point. Liu et al. (2015) reported in an earlier study that the tensile strength parallel to grain, compression strength parallel to the grain, bending strength, and modulus of elasticity in static bending values of *Eucalyptus* spp. wood, which has a 40% humidity rate, have decreased after the pre-freezing process. Another study found decreases in bending strength, compression strength parallel to the grain and impact maximum strength values after freezing *Eucalyptus* spp. wood, which has a humidity ratio of 70% (Missio et al. 2016). Japanese wood species (balsa, sugi, spruce, katsura, karamatsu, and keyaki) had minor losses in bending strength and modulus of elasticity of air-dried samples after freezing between 15 and 45 min. at − 140 to − 20 °C, but large decreases in bending strength and modulus of elasticity values were observed in water-saturated wood (Mishiro 1990).

When freshly cut wood (above fiber-saturation point) is cooled below 0 °C, cell walls swell because ice forms in the cell lumens, resulting in physical damage to the wood cell walls. As a result, the mechanical properties of wood may be adversely affected (Zhao et al. 2015b). In addition, the pressure created by the ice expanding during the freezing of the water in the wood may cause some bonds to break in the wood. In this case, micro-cracks occur in the wood cell walls, which can affect the mechanical properties of the wood (Szmutku et al. 2013). The freezing rate is also an important factor in green wood. Fast freezing (− 10 °C/h), compared to slow freezing, does not significantly affect wood strength, but slow freezing (− 1 °C/H) has been found to negatively affect bending strength by 24%, compression strength by 31% and tensile strength by 10%. The deterioration caused by the large-size ice crystals formed with slow freezing rate on the wood cell walls was shown as the reason for the decrease in the mechanical resistance properties of wood (Szmutku et al. 2013).

While some tree species die during freezing, others can withstand cryogenic temperatures such as − 196 °C (Burke et al. 1976). Among the wood obtained from different tree species, the effects of cold climatic conditions are also different. For example, in one species between room temperature and Antarctic climate, there is a 10% difference in mechanical resistance values, while in another species there might be a 40% difference. A safe structural design is based on such information (Gerhards 1982). Although it has caused such significant changes, wood strength has been rarely studied at cryogenic temperatures such as − 100 to − 196 °C (Zhao et al. 2015b). The aim of this study is to determine the effects of cryogenic temperature on the bending strength, modulus of elasticity and compression strength values of oven-dried and air-dried beech wood.

2 Materials and methods

2.1 Materials

Beech (*Fagus orientalis* Lipsky) sapwood with an average oven dry density of 0.61 ± 0.01 g/cm^3 without any coloration, rot, knot or similar defects was obtained from local timber companies in Kastamonu. The sapwood was cut into the size of test samples (300 × 20 × 20 mm and 30 × 20 × 20 mm) to determine the mechanical properties. Ten replicates were used for each test group. The oven-dried wood has been kept for 2 weeks until it reaches constant weight at 103 ± 2 °C in the oven, while the air-dried wood has been kept for 3 weeks at

20 ± 2 °C 65% ± 5 relative humidity. Liquid nitrogen with a density of 0.808 g/cm^3, boiling point of − 195.8 °C and melting point of − 210 °C was obtained from Kastamonu University Centre Research Laboratory.

2.2 Methods

2.2.1 Freeze treatment

The oven-dried and air-dried wood samples were immersed in liquid nitrogen filled containers for 10 min.

2.2.2 Mechanical test

The wood samples were taken out from the containers just before testing. The wood samples thickness and width were measured prior to mechanical testing. The experiments were carried out at a speed of 5 mm/min on the Shimadzu™ AG-IC 20/50 KN STD Universal Test device. The time between removing wood samples from liquid nitrogen and performing mechanical tests was 2 min. Bending strength (BS) ISO 13061-3 (2014) and modulus of elasticity in bending (MOE) ISO 13061-4 (2014) of the samples of 300 × 20 × 20 mm were calculated according to the following formulas;

$$BS = \frac{3.Fmax.L}{2.b.h^2}\left(\mathrm{N/mm^2}\right)$$

where *Fmax*: max. load, *L*: span; *b*: width of cross section; *h*: dept of cross section

$$MOE = \frac{\left(F_2 - F_1\right).L^3}{4.b.h^3.(d2 - d1)}\left(\mathrm{N/mm^2}\right)$$

where F_2–F_1: increment of load on the straight line portion of the deformation curve, *L*: span,; *b*: width of cross section; *h*: depth of cross section, d_2-d_1: increment of deformation corresponding to: F_2–F_1.

Compression strength (CS) test was carried out in samples of 30 × 20 × 20 mm according to ISO 13061-17 (2017);

$$CS = \frac{Fmax}{a.b}\left(\mathrm{N/mm^2}\right)$$

where *Fmax*: max. load*, a*: dept of cross section, *b*: width of cross section.

3 Results and discussion

3.1 Effect of freezing on the mechanical properties of beech wood

Table 1 shows the effect of cryogenic temperature on the BS, MOE and CS of the beech wood. All mechanical properties of beech wood tested during freezing have increased. For oven-dried wood samples, with decreasing temperature from + 20 to − 196 °C, the average BS, MOE and CS were increased by 32.76%, 24.17% and 60.58%, respectively. For air-dried wood samples, with decreasing temperature from + 20 to − 196 °C, the average BS, MOE and CS were increased by 51%, 34.79% and 60.91%, respectively. Previous studies have also found that the mechanical properties of wood increased while under the influence of low temperature (Gerhards 1982; Jiang et al. 2014; Zhao et al. 2015a, 2016).

When the temperature of air-dried beech wood was decreased from + 20 to − 196 °C, the bending strength increased by 51% while it was 32.76% in oven-dried wood (Fig. 1). According to this result, it can be said that when comparing oven-dried and air-dried wood, moisture has a positive effect on increasing the bending strength during freezing. Previous studies have found that when temperatures of water-saturated, air-dried and oven-dried *Betula platyphlla* wood was reduced from 0 to − 110 °C, the bending resistance values increased by 273%, 49% and 12%

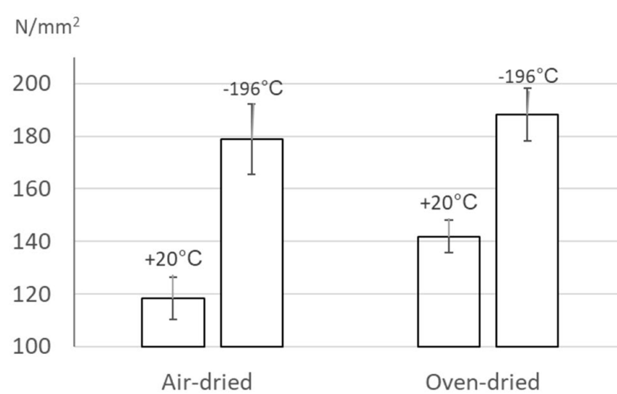

Fig. 1 Effect of cryogenic temperature on the bending strength of beech wood

Table 1 Mechanical properties of wood at cryogenic temperature

Temperature °C	Bending strength (N/mm^2)		Modules of elasticity (N/mm^2)		Compression strength (N/mm^2)	
	Oven-dried	Air-dried	Oven-dried	Air- dried	Oven-dried	Air-dried
+ 20	141.86	118.39	11,920.85	11,500.59	73.62	59.91
+ 196	188.34	178.76	14,801.55	15,502.20	118.22	96.40
Percent improvement %	32.76	51.00	24.17	34.79	60.58	60.91

respectively (Zhao et al. 2016). BS of the frozen wood (−50 °C) was increased by 18%, 35%, 60% and 110% at a moisture content ≤ 4%, 11–15%, 18–20% and %28, respectively (Gerhards 1982). Wood with a high moisture content is known to be more affected in terms of increased mechanical properties during freezing (Gerhards 1982; Zhao et al. 2015a, 2016). Because of decreasing temperature, the frozen water molecules stiffened cellulose fibers as adhesives. Thus, the mechanical properties of wood composites increase (Ayrilmis et al. 2010).

The modulus of elasticity value of air-dried and oven-dried wood increased by 37.79% and 24.17% respectively, during freezing (Fig. 2). Gerhards (1982) reported that the MOE of the frozen wood (−50 °C) was increased by 11%, 17% and 50% at a moisture content of 0%, 12% and > 30%, respectively. The reason for this increase in MOE is the shortening distance between the molecules at the time of freezing in the internal molecular structure of wood and increased bonding forces (Zhao et al. 2015a, 2016).

Zhao et al. (2015b) examined the modulus of elasticity and crystalline changes of water-saturated, green, air-dried and oven-dried birch wood frozen at −196 °C for 72 h and conditioned at room temperature for 24 h, and repeated this cycle four times. As a result, it was found that the four time repeated freezing of birch wood did not statistically significantly affect the modulus of elasticity. When this situation is compared with concrete, tensile strength, compression strength and modulus of elasticity values of concrete decreased with cyclic treatment of freezing (Dahmani et al. 2007; Zhao et al. 2015b). It has been observed that the wood performs better than concrete in cold regions. The reason for this could be the fact that molecules converge together with the drop in temperature and the stabilization of the crystalline structure. In previous studies, crystalline measurements on wood, which are balanced at 20 °C 65% relative humidity after liquid nitrogen application, were performed with X-ray diffraction. As a result, it has been found that the low temperature does not affect the crystalline structure of the wood (Zhao et al. 2015a, b, 2016). In these studies, the X-ray diffraction device measured the crystallinity of wood in room conditions. However, similar to the increase in reversible mechanical properties in wood during freezing, the structure of the crystal must also be measured when it is cold, due to the possibility that it will change only at the time of freezing.

The compression strength of air-dried and oven-dried wood increased by about 61% at cryogenic temperature (Fig. 3). Previous studies have found that the compression strength of the frozen wood (−50 °C) was increased by 20% and 50% at moisture content 0% and 12–45%, respectively (Gerhards 1982). Jiang et al. (2014) examined the compression strength values of air-dried oak wood at −196 °C. As a result of the experiment, a linear increase in their mechanical properties was found when the temperature of the wood decreased from + 20 to −196 °C. This increase was 283.91% in compression strength and 146.30% in compression modulus of elasticity. The reason for this is that the cellulose fibrils are tightened as a result of freezing water in the wood cell walls and the water acts as glue.

4 Conclusion

The main objective of this study was to evaluate the mechanical properties such as bending strength, modulus of elasticity in bending and compression strength values of beech wood when frozen at cryogenic temperature compared to room temperature. When the temperature of the wood was reduced from + 20 °C (room temperature) to −196 °C (cryogenic temperature), all mechanical property values increased between 24.17 and 60.91%. The reason for this could be the freezing of the water in the wood, hardening of the wood cell walls, decreasing the intermolecular distance, increasing the intermolecular force and stabilization of the

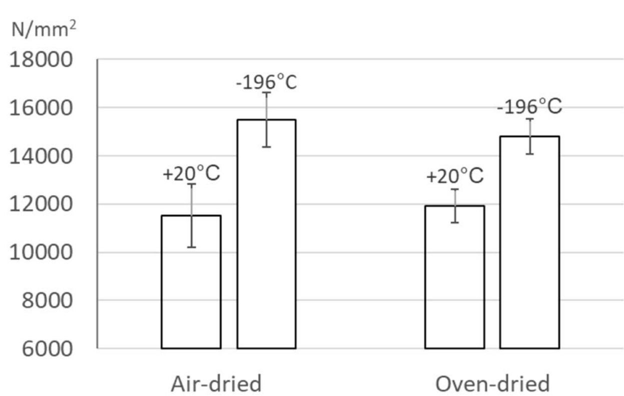

Fig. 2 Effect of cryogenic temperature on the modules of elasticity in bending of beech wood

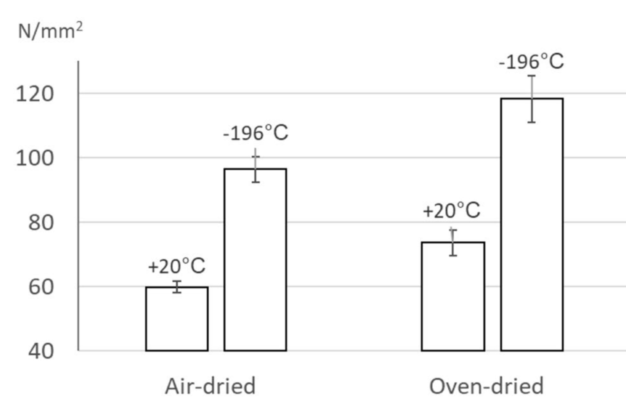

Fig. 3 Effect of cryogenic temperature on the compression strength of beech wood

crystalline structure. Wood shows a good performance in terms of its mechanical strength properties at low temperatures. The increased mechanical strength performance of the beech wood at cryogenic temperatures allows applications in dry environments that can be exposed to low temperature. However, as a result of wrong insulation in buildings, wood materials can absorb water in humid areas. If these parts are exposed to gradual freezing due to climatic factors, they may be subject to permanent damage.

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