Effect of Freezing Temperature on Impact Bending Strength and Shore-D Hardness of Some Wood Species

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Wood is exposed to variable environmental conditions during its use. Low temperature is one of the most important environmental factors affecting the behavior of wood in use. Contrary to other mechanical properties, there are not enough studies on how the impact bending strength is affected during freezing of wood. This study evaluated the effect of various freezing temperatures (-20, -40, -78.5, and -196 °C) on the impact bending strengths of beech (*Fagus orientalis* Lipsky), Scotch pine (*Pinus sylvestris* L.), fir (*Abies nordmanniana* subsp. *bornmulleriana*), and spruce (*Picea orientalis* L.) wood in comparison with non-frozen wood (+20 °C). During the freezing, the impact bending strength generally increased in softwood species but decreased in hardwood. The highest drop in impact bending strength value of -30.6% was found at -196 °C for beech wood. For this reason, precautions should be taken when using beech wood at ultra-low temperatures, due to substantial decreases in impact bending strength values. The good impact bending strength properties of the softwood while frozen allows application in low temperature environments.

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INTRODUCTION

Human beings have used wood in many different ways from past to present. In Anatolia, wood is expressed as a most versatile raw material that is needed from cradle to grave. Wood has been used for thousands of years and has emerged as an important sustainable building material to potentially replace steel and concrete because of its economic and environmental advantages, which include energy savings, low carbon emissions (15 kg/m^3), and high carbon storage (250 kg/m^3) (Wimmers 2017; Temiz *et al.* 2020). The popularity of the use of wood in space is also increasing. Currently, there is talk of projects in which a wooden satellite will provide an advantage in preventing space litter. Actually, the space travel of wood has started before. First, in 1962 as part of the NASA mission, spheres made of balsa wood were used as impact-limiters in probes to be sent to the Luna (URL-1). In addition, China used wood for insulation purposes in space shuttles in 1966 (URL-2). Finally, Newton's apple tree wood traveled into space in 2010 with the Atlantis space shuttle (URL-3).

Wooden elements in airplanes, vehicles, machines, sports equipment, ladders, tool handles, as well as construction deteriorate more frequently under the influence of impact stress than static overload. An impact stress only acts for a short time (a few microseconds). The behavior of wood against impact stress is called shock resistance. High shock resistance of wood can be equated with toughness, whereas low shock resistance is associated with brashness (Kollmann and Côté 1968). Wooden members in timber structures are frequently subjected to both static and impact loads. Information on static and impact bending properties is essential for the design of wooden structures and the maintenance of an adequate level of safety. Toughness is the opposite of brittleness or brashness, and is defined as the ability of wood to withstand the shock of a suddenly applied load, which causes stresses that exceed the proportional limit. Toughness is defined as the energy required by a pendulum impact hammer to rapidly cause complete failure in a centrally loaded bending specimen (Adamopoulos and Passialis 2010). Flexural strength and impact bending strength are especially important for load-bearing structural components (Bal 2016).

When wood is cooled below room temperature, its mechanical properties tend to increase (Jiang *et al.* 2014). There are some previous studies about the influence of cold temperatures on wood properties, including bending strength (Gerhards 1982; Jiang *et al.* 2014; Zhao *et al.* 2016; Özkan 2021), modulus of elasticity (Bekhta and Marutzky 2007; Ayrilmis *et al.* 2010; Zhao *et al.* 2015; Özkan 2021), and compressive strength (Gerhards 1982; Jiang *et al.* 2014; Özkan 2021). These studies found significant increase of modulus of elasticity (MOE), compression strength, and bending strength with decreasing temperature. However, there have been limited studies on dynamic bending strength of wood at low temperatures. Özkan (2021) has reported that the bending strength of frozen *Fagus orientalis* wood having a moisture content of 12% at -196 °C was 178.8 N/mm^2 while it was found as 118.4 N/mm^2 at 20 °C. Gerhards (1982), found that the bending strength of the frozen wood (-50 ºC) was increased 18%, 35%, 60%, and 110% at moisture contents of ≤ 4%, 11% to 15%, 18% to 20%, and 28%, respectively. Zhao *et al.* (2016), found that when the temperature was decreased from 0 °C to −110 °C, the bending strength of *Betula platyphylla* wood increased 70%, 33%, and 11% for water-saturated, air-dried, and oven-dried samples, respectively. Ayrilmis *et al.* (2010), investigated the changes in some mechanical resistance properties of wood-based boards, such as oriented strand board (OSB), medium-density fiberboard (MDF), and plywood at 12% humidity and temperature range -30 °C and +30 °C. As a result, the bending strength and elasticity modulus of wood increased with increasing coldness. The reason for this has been explained as the freezing of the water in the cell walls of the wood, and thus the adhesion property of the water due to its polar structure strengthened with freezing and the molecules approach each other upon cooling. Bekhta and Marutzky (2007) investigated the changes in bending and MOE values between -40 and +40 ° C in chipboards with 12% humidity. As a result of cooling from +40 to -40, bending and MOE values of chipboards increased 34% and 38%, respectively. Özkan (2021) found that the MOE of the frozen from +20 °C to -196 °C beech wood increased 24.17% and 34.79% at moisture contents of 0% and 12%, respectively.

Birch woods with different humidity levels were kept at -196 °C for 72 h, then kept at room temperature for 24 h, and this cycle was repeated 4 times. As a result, it was determined that the freezing event repeated 4 times in birch wood did not significantly affect the MOE (Zhao *et al.* 2015). When this situation is compared with the previous studies on concrete in the literature (Yamane and Zhao 1980; Dahmani *et al.* 2007), considering that concrete's tensile strength, compressive strength, and MOE values decrease significantly with repeated freezing, it has been said that wood performs better in cold regions. Özkan (2021), found that the compression strength of the frozen beech wood from +20 °C to -196 °C increased 60.58% and 60.91% when moisture contents were at 0% and 12%, respectively. Jiang *et al.* (2014) found that when temperature decreased from

23 °C to -196 °C, the compression strength and compression MOE of oak (*Quercus mongolica*) wood increased 283.9% and 146.3%, respectively. Gerhards (1982) found that the compressive strength of the frozen wood (-50 ºC) increased 20% and 50% at different moisture contents. Szmutku *et al.* (2013) froze the fresh logs with 150% humidity to -25 °C with cooling rates of -10 °C/h and -1.0 °C/h for one week. As a result, the decrease in the mechanical properties of the suddenly cooled wood was lower than the slow cooled wood. The reason for this was because the damage to the cell walls caused by the large ice crystals formed during slow freezing may be larger. Therefore, fast freezing was preferred in this study.

To the best of the author's knowledge, no study has been reported in the literature concerning the pendulum impact bending strengths and Shore-D hardness of wood samples at ultra-low temperature. For this reason, the aim of this study was to determine the effects of freezing (-20, -40, -78.5, and -196 ℃) on the impact bending strength and Shore-D hardness of beech, scotch pine, fir, and spruce wood samples.

EXPERIMENTAL

Materials

Beech (*Fagus orientalis* Lipsky), Scotch pine (*Pinus sylvestris* L.), and fir (*Abies nordmanniana* subsp. *bornmulleriana*) wood samples were obtained from Kastamonu, Türkiye, and spruce (*Picea orientalis* L.) wood was obtained from Trabzon, Türkiye as a single trunk. The trunk was initially cut into 10 cm x 10 cm x 100 cm wood samples and stored under room conditions at 20±2 ℃. The test samples were prepared from defect-free (without knots, cracks, reaction wood, and color change) wood. Charpy impact test samples of all wood species were divided into five groups and designated for four freezing temperatures (-20, -40, -78.5, and -196 °C) and one control (+20 °C) group. Each group contained 10 samples, so that in total there were 50 samples per wood species. The whole test involved 200 samples. Unlike the Charpy impact test, the number of samples in the shore-D hardness was taken as 3 per group.

Methods

The Charpy impact test (CIT) was determined according to the ISO 13061-10 (2017) and ISO 148-1 (2016) standard with some modification such as the size of the specimens (Epmeier *et al.* 2004; Kuzsella and Szabó 2007; Guo *et al.* 2019). The CIT was performed using an impact tester (Hardway, JBW-300B, Shandong, China). The support span width was 40 mm. The dimensions of test samples were 55 mm × 10 mm × 10 mm (L × R × T), unnotched. Impact bending test values were determined for radial surface. Impact velocity was 5.2 m/s, and the maximum impact energy was 300 J. The wood samples were conditioned in a climate-controlled room at 20 ± 2 °C and 65 ± 5% relative humidity to a constant weight before testing to reach a moisture content of roughly 12%. Afterward, they were conditioned according to their individual temperature level with a laboratory freezer (-20 and -40 °C), dry ice (-78.5 °C), and liquid nitrogen (196 °C). According to the ISO 148-1, there was a period of maximum 5 seconds between removing the samples from cooling container and placing it in the device and performing the test. A total of 10 replicates were used for CIT. The CIT tests were performed on tangential direction of the woods. Before the test, the dimensions of the samples were measured using a digital caliper to a precision of 0.01 mm.

The impact bending strength was calculated according to Eq. 1,

$$A_w = \frac{1000 \times Q}{b \times h} (kJ.m^{-2}) \quad (1)$$

where Q is the energy required to break the test piece (J), and b and h are the dimensions of the test piece in the radial and tangential directions (mm).

The Shore-D hardness measurements of control and frozen samples were carried out according to the ASTM D2240-15 (2021) standard with Shore-D hardness device Hardmatic HH-334, Mitutoyo, (Neuss, Germany) (Esteves *et al.* 2021). The dimensions of Shore-D test samples were 30 mm × 20 mm × 20 mm (L × R × T). Shore-D hardness values were determined for tangential surface.

RESULTS AND DISCUSSION

Charpy Impact Test

An overview of the obtained impact bending strength values at the tested temperature levels is given in Table 1.

Table 1. Influence of Freezing Temperature on the Impact Bending Strength and Shore-D Hardness of Wood Species

Wood Species	Temperature(°C)	Impact Bending Strength (J/cm^2)*					Shore-D Hardness*				
		n	X	±	COV	P (%)	n	X	±	COV	P (%)
Beech	+20	10	11.20	0.95	8.50	-	3	61.00	4.10	6.73	-
	-20	10	8.95	0.83	9.30	-20.14	3	61.38	2.84	4.62	0.61
	-40	10	7.98	0.86	10.79	-28.74	3	62.78	3.09	4.92	2.91
	-78.5	10	10.20	0.60	5.87	-8.93	3	65.78	3.44	5.23	7.83
	-196	10	7.77	0.71	9.13	-30.60	3	72.50	2.54	3.51	18.85
Scotch Pine	+20	10	5.63	0.51	9.14	-	3	49.60	4.44	8.94	-
	-20	10	6.84	0.78	11.43	21.38	3	56.18	4.44	7.91	13.26
	-40	10	5.58	0.59	10.50	-0.95	3	52.90	3.64	6.88	6.65
	-78.5	10	8.85	0.92	10.41	57.10	3	52.63	5.00	9.50	6.10
	-196	10	6.55	0.40	6.08	16.27	3	62.75	6.44	10.26	26.51
Fir	+20	10	5.98	0.23	3.91	-	3	49.12	2.81	5.72	-
	-20	10	6.26	0.50	7.96	4.69	3	41.78	1.74	4.17	-14.95
	-40	10	6.67	0.50	7.56	11.57	3	51.00	4.87	9.54	3.83
	-78.5	10	8.89	0.84	9.49	48.72	3	47.60	4.65	9.77	-3.09
	-196	10	7.73	0.73	9.50	29.26	3	55.60	4.27	7.68	13.20
Spruce	+20	10	4.85	0.48	9.89	-	3	45.63	4.32	9.48	-
	-20	10	4.74	0.41	8.73	-2.36	3	40.48	1.75	4.33	-11.30
	-40	10	5.02	0.46	9.13	3.54	3	47.68	4.23	8.87	4.47
	-78.5	10	5.53	0.85	15.33	13.88	3	41.63	3.61	8.68	-8.78
	-196	10	6.09	0.57	9.33	25.47	3	56.11	2.87	5.12	22.95

*n: Sample number; X: mean; ±: standard deviation; COV: coefficient of variation; and P: percent change compared to +20 °C

The impact bending strength values of control (non-freezing) samples were 11.20 J/cm^2 for beech wood, 5.63 J/cm^2 for Scotch pine, 5.98 J/cm^2 for fir, and 4.85 J/cm^2 for spruce wood. Kuzsella and Szabó (2007) found that the impact bending strength of beech (*Fagus sylvatica* L.) wood was 8.85 J/cm^2 at +20 °C. Gaff *et al.* (2019) found that the impact bending strength of Norway spruce (447 kg/m^3) was 6.4 J/cm^2. The result of the pendulum impact bending strength is affected by various properties of the sample, such as density, ring direction of the wood, moisture content, and temperature (Bal 2016). Impact bending strength, as well as some other mechanical properties of wood, increased with density (Bučar and Merhar 2015).

Table 1 shows that the impact bending strength of beech wood was reduced with freezing. However, the impact bending strengths of other wood samples are generally increased with freezing. With decreasing temperature from +20 °C to -20, -40, -78.5, and -196 °C the impact bending strength of beech wood was changed by -20.14%, -28.74%, -8.93%, and -30.60%, respectively. However, in beech woods, there was no linear decrease as the temperature decreased, but a fluctuating decrease was observed. With decreasing temperature from +20 °C to -20, -40, -78.5, and -196 °C, the impact bending strength of Scotch pine wood was changed by 21.38%, -0.95%, 57.10%, and 16.27%, respectively. The biggest difference with freezing occurred in Scotch pine with an increase of 57.1% at -78.5 °C. Kollmann and Côté (1968**)** found that the impact strength of air-dry pine wood at low temperature (-20 °C) increases considerably. With decreasing temperature, the impact bending strength of fir wood was increased by 4.69%, 11.57%, 48.72%, and 29.26% at -20, -40, -78.5, and -196 °C, respectively. Thus, with decreasing temperature the impact bending strength of spruce wood was increased by 2.36%, 3.54%, 13.88%, and 25.47%, respectively. These results indicate that the impact bending strength values of beech wood with high density were affected worse than other wood samples with low densities during freezing. This is because the effect of temperature is essentially greater in denser woods than in lighter woods (Kollmann and Côté 1968).

Table 2 shows a statistical evaluation of the influence of wood species and temperature on impact bending strength. Wood species, temperature, and 1*2 were statistically significant ($P<0.05$).

Table 2. Statistical Evaluation of the Factors Influencing the Impact Bending Strength

Source	Sum of Squares	Degrees of freedom	Mean Square	F-value	Significance level
Intercept	8205,447	1	8205,447	19325,593	,000
Wood species (1)	292,459	3	97,486	229,602	,000
Temperature (2)	69,116	4	17,279	40,696	,000
1 * 2	122,613	12	10,218	24,065	,000
Error	66,236	156	,425		

Shore-D Hardness

An overview of the obtained Shore-D values at the tested temperature levels is given in Table 1. The Shore-D hardness values of non-freezing samples were 61.0 for beech wood, 49.6 for Scotch pine, 49.1 for fir, and 45.6 for spruce wood. Beech showed the highest and spruce indicated the lowest hardness values of all studied wood species. For beech wood samples, with decreasing temperature from +20 to -196 °C, the average Shore-D hardness was increased 0.61%, 2.91%, 7.83% and 18.8%, respectively. With freezing, Shore-D hardness increased for all the beech samples. The increase was higher in samples with lower temperature (-196 ℃). Shore-D values of Scotch pine samples was increased by 13.26%, 6.65%, 6.10% and 26.51% for -20, -40, -78.5, and -196 °C, respectively. It can be said that Shore-D values of all Scotch pine samples increased with freezing. However, Shore-D values of fir and spruce woods both decreased and increased later with freezing. Shore-D values of fir samples changed by -14.95%, 3.83% -3.09% and 13.20% for -20, -40, -78.5, and -196 °C, respectively. From this, it was observed that Shore-D values of the fir samples decreased at -20 °C and -78.5 °C and increased at -40 °C and -196 °C. Shore-D values of spruce samples changed by -11.30%, 4.47% -8.78% and 22.95% for -20, -40, -78.5, and -196 °C, respectively. Similar to the fir samples, it was observed that Shore-D values of spruce woods decreased at -20 °C and -78.5 °C, and increased at -40 °C and -196 °C.

Table 3 shows a statistical evaluation of the influence of wood species and temperature on Shore-D hardness. Wood species, temperature and 1*2 were statistically significant ($P<0.05$) on Shore-D hardness values.

Table 3. Statistical Evaluation of the Factors Influencing the Shore-D Hardness

Source	Sum of Squares	Degrees of freedom	Mean Square	F-value	Significance level
Intercept	1122095,209	1	1122095,209	72858,543	,000
Wood species (1)	19374,185	3	6458,062	419,327	,000
Temperature (2)	6881,486	4	1720,371	111,705	,000
1 * 2	1898,358	12	158,197	10,272	,000
Error	5713,775	371	15,401		

CONCLUSIONS

1. The effects of the low temperatures on the impact bending strength and Shore-D hardness of five different wood species were investigated. When the temperature of the wood was reduced from +20 °C, the impact bending strength values decreased in hardwood and were increased in softwood. This can be attributed to the density value, which is higher for hardwood than that of softwood. Thus, hardwood is more negatively affected by temperature changes. The effect of wood species and temperature on impact bending strength were statistically significant ($P<0.05$).
2. It is known from the literature that the mechanical properties of wood increase during freezing. In this study, contrary to other mechanical properties, it was determined that there was a decrease of up to 30% in the impact bending strength values.
3. Shore-D hardness values increased in hardwood with decreasing temperature. For all wood species maximum Shore-D hardness values were obtained from at -196 °C. The effect of wood species and temperature was statistically significant ($P<0.05$) relative to Shore-D hardness values.

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