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EFFECT OF ULTRA-LOW TEMPERATURE ON SOME MECHANICAL PROPERTIES OF PAINTED AND FILM-COATED PLYWOOD

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ABSTRACT

Plywood is used for insulation systems in liquid natural gas cargo ships because of its good thermal properties. However, there are only a few research investigating the mechanical properties of plywood exposed to ultra-low temperatures. This study aims to determine how plywood reacts when exposed to ultra-low temperatures, such as - 196 °C. To achieve this purpose, the present study investigated the bending strength, modulus of elasticity, and tensile-shear strength of painted and film-coated plywood under ultra-low temperatures. The mechanical properties of plywood were discovered to be significantly impacted by the ultra-low temperature as a result of this research. Moreover, not only the bending strength of the painted and film-coated plywood increased with decreasing temperature, but also the modules of elasticity of the painted and film-coated plywood increased. At decreasing temperature, the tensile shear strength of the painted and film-coated oven-dried plywood increased, but the ensile-shear strength of painted and film-coated air-dried plywood decreased. The tensile shear strength of air-dried plywood was determined to be more sensitive to the temperature change. Therefore, attention should be paid to plywood used in liquefied natural gas cargo ships with high humidity.

Keywords: Bending, birch, modulus of elasticity, plywood, tensile shear strength.

INTRODUCTION

The plywood is a large-surface engineered wood product which has uniform strength properties, lower shrinking and swelling and could be defect-free. Phenol formaldehyde (PF) resin is frequently used as an adhesive for outdoor plywood to improve water resistance, however, melamine-urea formaldehyde (MUF) adhesives are preferred for plywood production due to their low cost. However, it has been noticed that plywood bonded with MUF resin is less durable than plywood bonded with PF resin in outdoor conditions (Öncel *et al*. 2019).

Mechanical properties such as bending strength (Kim *et al.* 2015, Kim *et al.* 2018), modulus of elasticity (Kim *et al.* 2015, Kim *et al.* 2018), tensile strength (Kim *et al.* 2015) and compression strength (Cha *et al.* 2020) have been found to increase during freezing in plywood made of the MUF and PF resins. Similarly, it has been discovered that compression strength and bending strength values increased in wood composites with decreasing temperatures (Ayrilmis *et al.* 2010, Bekhta and Marutzky 2007). However, mechanical properties of plywood such as the bending strength (BS), modulus of elasticity (MOE), and tensile-shear strength (TSS) decreased by low thermal cyclic shock (Kim *et al.* 2015, Kim *et al.* 2018).

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As the strength of the ice increases as the temperature decreases, it is thought to contribute to the increase of the mechanical properties of the wood. On the other hand, the increase in mechanical properties caused by the freezing of oven-dried wood can be explained by factors other than water. These can be shown as the hardening of wood cell walls due to low-level freezing (Zhao *et al.* 2015). In addition, at low temperatures, the intermolecular distance of the material decreases, so the intermolecular strength increases, and more energy is necessary for the breaking down of the sample (Zhao *et al.* 2015, Zhao *et al.* 2016). Ultra-low temperature applications stabilize the crystalline structure and reduce residual stress, making materials (such as metals, alloys, plastics, and composites) stronger and more durable (Kalia 2010). For example, it was found that the BS of a wooden baseball bat increased by 26 % when it was cryogenically treated to a temperature of -190 ºC for 24 h (Kendra and Cortez 2010).

The variations between the adhesives and thermal properties of wood will cause performance concerns when the structure is subjected to significant changes in temperature. The design must account for differential part movement while maintaining structural integrity. The efficiency of glue lines is well established at elevated temperatures. There is little information on the stability of glue lines at low temperatures, particularly extremely cold temperatures, although there have been some studies of timber bridges in cold climates. Work on adhesive films at cold temperatures combined with the effect of moisture content should also be studied. Specimens are required for further research on the effect of temperature changes on the integrity of the bond surface (Wang *et al.* 2015).

Plywood has recently, become popular in ultra-cold conditions, such as liquid natural gas (LNG) cargo ships (Cha *et al.* 2020, Kim *et al*. 2015, Kim *et al.* 2018). Even though previous studies have focused on the effects of ultra-low temperature on BS, MOE and compressive strength on plywood, there is no study on tensile shear strength at ultra-low temperature for plywood. Therefore, the aim of this study was to determine how plywood react when exposed to ultra-low temperatures, such as -196 °C. In this paper, the mechanical properties such as modulus of rupture, modulus of elasticity, and tensile shear strength of plywood were tested at the ultra-low temperature.

MATERIALS AND METHODS

Materials

The birch plywood samples coated with film and paint were obtained from EKOL Plywood Company (Kastamonu, Turkey). Painting and coating were applied to only one side of 9-layer plywood that were unprotected exterior types and produced using phenol formaldehyde resin from rotary cut veneers. In the production of plywood, a single surface of the veneer was glued by using an amount of 150 g/m^2 phenol formaldehyde resin. The pressure was set to 0,7 MPa, the temperature 110 °C, and the pressing time was 17 minutes. All plywood test samples were obtained from commercially produced boards and cut in the longitudinal direction of the boards. The moisture content of the film-coated and painted plywood boards were 8,33 % and 9,77 %, respectively. Ten samples were prepared for the bending strength test with the dimensions of 280 mm × 50 mm × 12 mm (L x W x T). Ten samples for the tensile-shear tests were prepared with dimensions of 150 mm × 25 mm × 12 mm (L x W x T).

Determination of density

The densities of air-dried and oven-dried plywood materials were determined according to TS EN 323 (1999). Ten samples with dimensions of 50 mm × 50 mm × 12 mm (L x W x T) were prepared to determine density of the materials. To determine the oven-dried density of samples, the samples were dried up to 103 ºC ± 2 °C until they were in constant weight and were weighed with a precision of 0,001 g on an analytical balance. To determine the air-dried density of samples, the samples were kept in the climatized room adjusted to a temperature of 20 °C and relative humidity of 65 % until they reached consistent weight. Subsequently, the wood material dimensions were measured with a digital caliper with precisions of 1 % sensitivity, and volumes were determined by a stereo-metric method.

Freeze treatment

The oven-dried conditioned samples were dried up to 103 ºC ± 2 °C until they reached constant weight. After drying, each sample was placed into a container filled with liquid nitrogen (LN_2) for 10 minutes (Figure 1a). Samples were taken out from the container just before testing. Air-dried samples were conditioned for four weeks at 20 ºC ± 2 °C and relative humidity of 65 % ± 5 %. After conditioning, each sample was placed into a container filled with LN_2 for 10 minutes. The samples were taken out from the container just before testing.

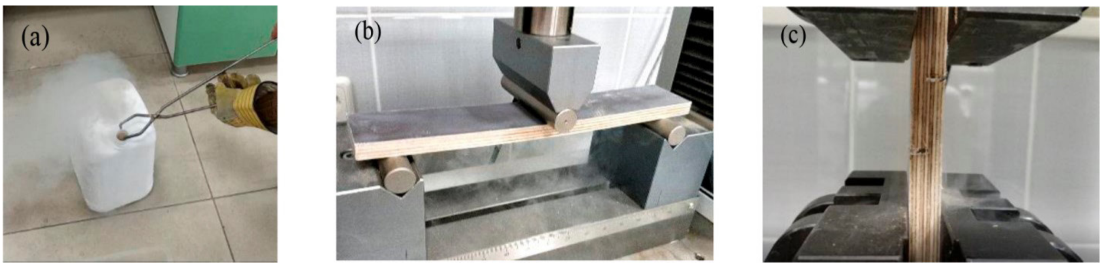

Figure 1: (a) Freezing treatment of plywood samples, (b) bending test, (c) tensile-shear test.

Mechanical test

The bending strength and tensile-shear strength tests of plywood samples were performed at 2.5 mm/min speed on Shimadzu™ AG-IC 20/50 KN STD Universal Testing machine (Figure 1b). The experiment time between removing wood samples from LN_2 and performing mechanical tests was calculated as one minute. The bending strength was conducted according to TS EN 310 (1999). Painted and film-coated plywood surfaces were tested in the tensile zone in the bending strength test. Calculation of BS of the 280 mm × 50 mm × 12 mm (L x W x T) specimens was made according to Equation 1:

$$BS = \frac{3 \times Fmax \times L}{2 \times b \times h^2} \qquad (1)$$

Where *Fmax*: max. load (N), *L*: span (mm); *b*: width of cross-section (mm); *h*: dept of cross-section (mm)

According to TS EN 310 (1999) standard, modulus of elasticity was carried out. Calculation of MOE of the prepared specimens was made according to Equation 2:

$$MOE = \frac{(F_2 - F_1) \times L^3}{4 \times b \times h^3 \times (d_2 - d_1)} \qquad (2)$$

Where F_2-F_1: increment of load on the straight-line portion of the deformation curve (N), *L*: span (mm), *b*: width of cross-section (mm), *h*: dept of cross-section (mm), d_2-d_1: increment of deformation corresponding to F_2-F_1 (mm).

The tensile-shear strength was performed according to TS 3969 EN 314-1 (1998) standards (Figure 1c). Calculation of tensile-shear strength of the prepared specimens was made according to Equation 3:

$$\text{ó} = \frac{F}{A} = \frac{F}{(L \times b)} \qquad (3)$$

Where σ: Tensile shear strength (MPa), F: maximum load (N), L: shear plate length (mm), b: shear plate width (mm).

Data analysis

The statistical parameters like an analysis of variance (ANOVA) were calculated with SPSS 23 (IBM 2020).

RESULTS AND DISCUSSION

Density

The oven-dried painted plywood samples of 0,728 g/cm^3 were kept at 20 ºC ± 2 °C for 2 weeks at 60 % ± 5 % and brought to 9,77 % balance humidity and the air-dried density value was 0,763 g/cm^3. The film-coated plywood samples with the oven-dried density of 0,703 g/cm^3 were kept at 20 ºC ± 2 °C for 2 weeks at 60 % ± 5 % and brought to 8,33 % balance humidity, and the air-dried density value was 0,738 g/cm^3.

Effect of freezing on the mechanical properties of plywood

Table 1 shows the effect of ultra-low temperature on the BS, MOE, and tensile-shear strength (TSS) of the plywood.

Table 1: Mechanical properties of plywood at ultra-low temperature.

Plywood type	Temperature °C	Bending strength BS (MPa)		Modules of elasticity MOE (MPa)		Tensile shear strength TSS (MPa)	
		Oven dry	Air dry	Oven dry	Air dry	Oven dry	Air dry
Painted	+ 20 (Control)	97,34^{CD}	86,99^{DE}	12170,61^{D}	9943,59^{F}	1,929^{C}	3,012^{A}
	- 196	121,87^{B}	146,27^{A}	14744,47^{B}	15647,96^{A}	2,319^{B}	2,262^{B}
	Percent %	+ 25,20	+ 68,10	+ 21,10	+ 57,40	+ 20,20	- 24,90
Coated	+ 20 (Control)	81,32^{E}	84,71^{E}	10810,84^{E}	10101,60^{F}	1,487^{D}	2,488^{B}
	- 196	112,09^{B}	101,05^{C}	12848,16^{C}	14682,15^{B}	1,984^{C}	1,980^{C}
	Percent %	+ 37,80	+ 19,30	+ 18,80	+ 45,40	+ 33,40	- 20,40

Groups with the same letters in the column indicate that there was no statistical difference ($p \leq 0,05$) between the specimens according to Duncan's multiply range test.

Figure 2a and Figure 2b show the fracture characteristics of the outer layer during the room and ultra-low temperature in the bending test. At room temperature, the outermost layer of the plywood fractured flat, while at ultra-low temperature a more fragmented fracture occurred. Temperature affects the type of failure mechanism. The bonding force between the layers and the resin is not very strong at room temperature. As a result, the ambient samples fail relatively easily at the resin-layer interface, explaining the low MOE and MOR values. On the other hand, the resin is hardened and the bonding force is relatively strong at cryogenic temperatures compared to ambient temperatures (Kim *et al.* 2015).

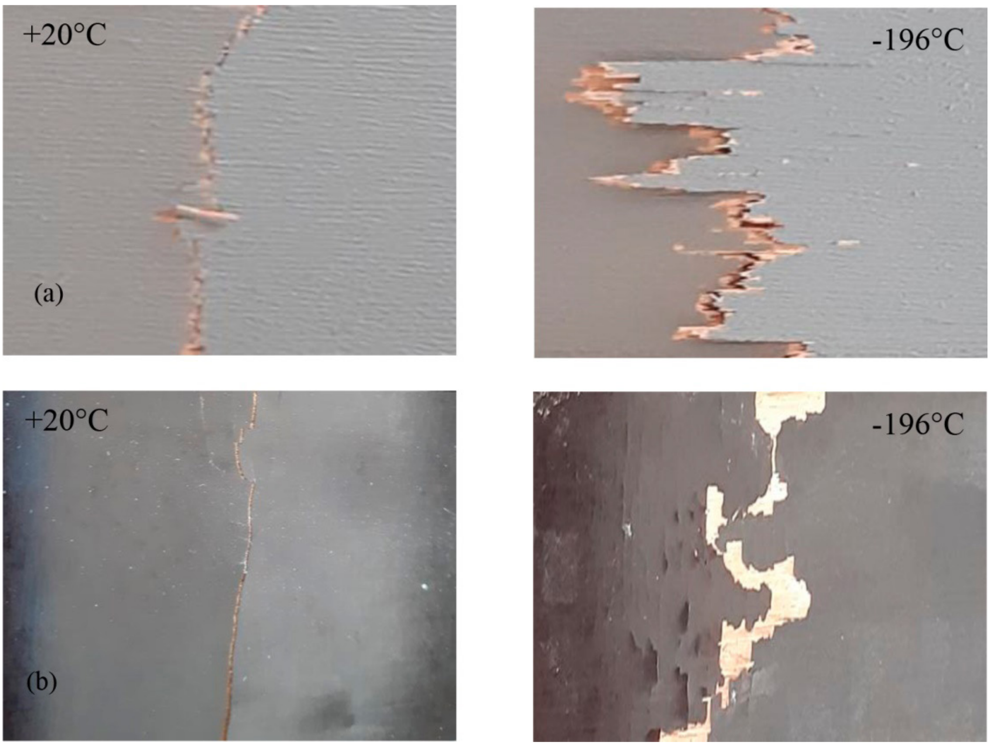

Figure 2: (a) Fracture characteristics of painted and (b) film-coated plywood between room temperature (+20 °C) and ultra-low temperature (-196 °C).

Figure 3 shows the effect of the ultra-low temperature on the bending strength. The BS of the painted and film-coated plywood increased with decreasing temperature. For oven-dried and air-dried painted plywood samples, with decreasing temperatures from +20 to -196 °C, the average BS was increased by 25,2 % and 68,1 %, respectively. For oven-dried and air-dried film-coated plywood samples, with decreasing temperatures from +20 °C to -196 °C, the average BS was increased by 37,8 % and 19,3 %, respectively. There was a statistically significant difference in the BS changes between +20 °C and -196 °C painted and film-coated plywood for oven-dried and air-dried humidity. However, the BS values did not significantly differ between oven-dried and air-dried film-coated at the temperature of 20 °C.

A previous study by Ayrilmis *et al.* (2010) reported that the BS values in plywood increased by 21,9 % when the temperature decreased from +20 °C to -30 °CSimilar trends were followed for MDF and OSB specimens because of increase in stiffness of the specimens at colder temperatures which may be attributed to ice crystals being formed on wood cell walls (Ayrilmis *et al.* 2010). Also, several researchers reported similar increases of BS and MOE with decreasing temperature in particleboard (Bekhta and Marutzky 2007), in solid beech wood (Özkan 2021). Drake *et al.* (2015) investigated the shear behavior of glulam beams with the four-point bending test between -40 and +20 °C. As a result of cooling from +20 to -40 °C, the strength and stiffness of the beams increased with decreasing temperature.

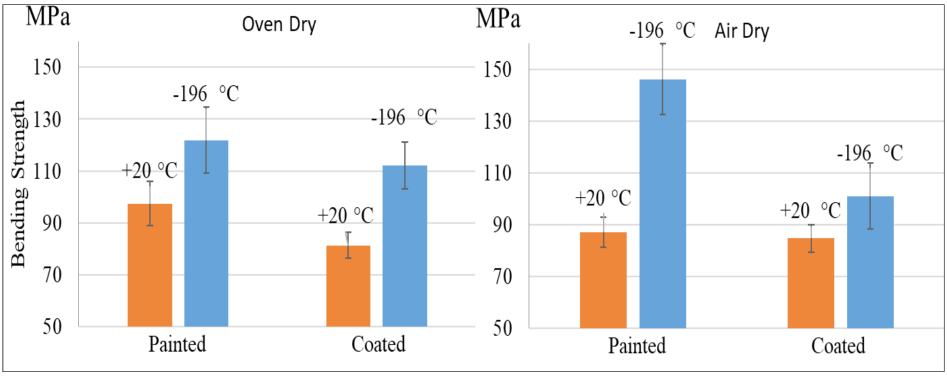

Figure 3: The effect of ultra-low temperature on the bending strength of the painted and film-coated plywood.

Figure 4 shows the effect of the ultra-low temperature on the modules of elasticity. The MOE of the painted and film-coated plywood increased with decreasing temperature. For oven-dried and air-dried painted plywood samples , the average MOE was increased by 21,1 % and 57,4 %, respectively with decreasing temperatures from +20 to -196 °C whereas the average MOE was increased by 18,8 % and 45,4 %, respectively for oven-dried and air-dried film-coated plywood samples. There was a statistically significant difference in the MOE changes between +20 °C and -196 °C painted and film-coated plywood for oven-dried and air-dried humidity.

Bekhta and Marutzky (2007) examined BS and MOE values changes between -40 and +40 °C in particleboards with 12 % humidity. As a result of cooling from +40 to -40 °C, the BS and MOE values increased by 34 % and 38 %, respectively. Cha *et al.* (2020) found that the MOE of plywood increased with decreasing temperature. Zhao *et al*. (2015) studied the MOE of water-saturated, fresh-cut, air-dried, and oven-dried birch (*Betula platyphylla*) wood under the temperatures at +20 °C and -196 °C. The results showed that the MOE of birch wood with different MCs increased with low-temperature treatment. Furthermore, the low-temperature application had more effect on specimens with higher MC than specimens with lower MC.

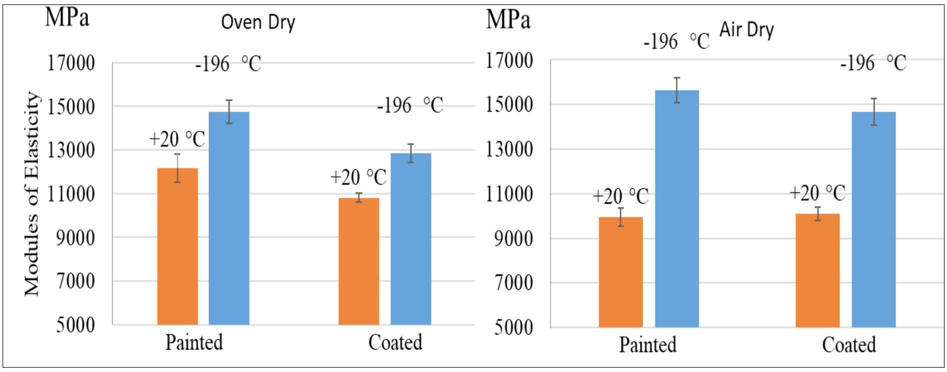

Figure 4: The effect of ultra-low temperature on the modules of elasticity of the painted and film-coated plywood.

Figure 5 shows the effect of the ultra-low temperature on the tensile shear strength. The TSS of the painted and film-coated oven-dried plywood increased with decreasing temperature. But, the TSS of painted and film-coated air-dried plywood decreased with decreasing temperature. For oven-dried painted and film-coated plywood samples, with decreasing temperatures from +20 °C to -196 °C, the average TSS was increased by 20,2 % and 33,4 %, respectively. For painted and film-coated air-dried plywood samples, with decreasing temperatures from +20 °C to -196 °C, the average TSS declined by 24,9 % and 20,4 %, respectively. There was a statistically significant difference in the TSS changes between +20 °C and -196 °C painted and film-coated plywood for oven-dried and air-dried humidity. However, there was no a statistically significant difference in the TSS between oven-dried and air-dried plywood at -196 °C.

Wang *et al*. (2015) investigated the shear strength of Norway spruce (*Picea abies*) joints, which were glued with seven different commercially available adhesives and evaluated at six different temperatures: -60, -50, -40, -30, -20, and +20 ºC. the temperature changes have a considerable impact on the shear strength of wood joints in general. For example, as temperature dropped, the shear strength of wood joints bonded with different adhesives also reduced. Using polyurethane adhesive gave the highest shear strength, while the adhesive with the lowest shear strength was melamine urea-formaldehyde.

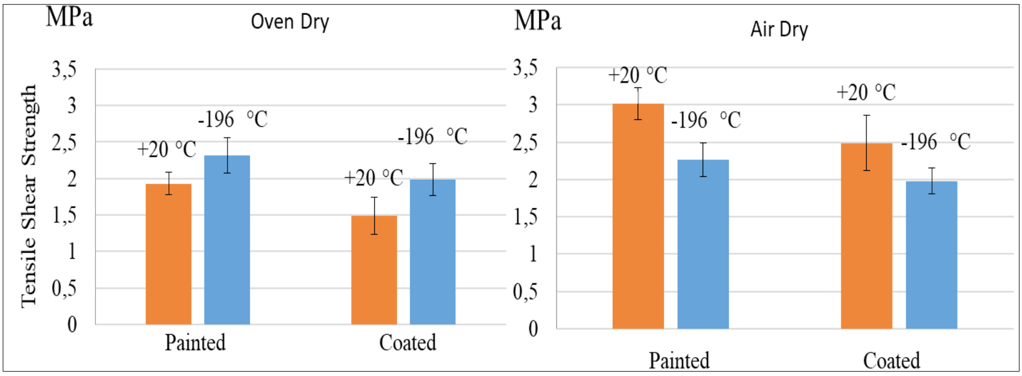

Figure 5: The effect of ultra-low temperature on the tensile shear strength of the painted and film-coated plywood.

CONCLUSIONS

In the present study, the mechanical and fracture characteristics of the painted and film-coated plywood were investigated at ultra-low temperatures. The main conclusion is as follows:

The mechanical and fracture characteristics of the PF resin plywood used in ultra-low temperatures were determined in oven-dried and air-dried humidity.

The painted air-dried plywood showed the highest bending strength, tested at -196 °C temperature while film-coated air-dried showed the weakest bending strength tested at +20 °C temperature.

The painted air-dried plywood had the highest MOE value when tested at -196 °C temperature, while film-coated air-dried and painted air-dried panels had the lowest MOE value tested at +20 °C temperature. As a result, the brittleness of the wood increases during freezing as the bending strength increases,.

The tensile-shear strength of plywood at temperatures of +20 and -196 °C was studied. Generally, the tensile-shear strength of painted plywood resisted the effects of ultra-low temperature better than that of film-coated plywood. It was also determined that there was a decrease in the tensile-shear strength of air-dried samples due to the temperature decrease. It shows that the water in the wood material harms the adhesion strength of the glue in cold climates.

The findings of this study support the design of LNG containers using plywood for structural safety at ultra-low temperatures. Also, this study gives an idea about the ultra-low temperature resistance of PF resin plywood. As a result, PF resin plywood can be used in an ultra-low temperature environment depending on the humidity.

AUTHORSHIP CONTRIBUTIONS

M. O.: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Supervision, Writing-original draft. O. E. O.: Investigation, Resources, Writing-original draft.

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