FLAMMABILITY AND MECHANICAL PROPERTIES OF WOOD-BASED COMPOSITES

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Abstract
In this study the influence of type of resin, veneers lay-up and addition of fiberglass textile on mechanical properties and fire performance of plywood were investigated. PN-EN310 standard was used to evaluate tensile strength and bending strength of plywood panels. The flammability of the plywoods was determined by testing limiting oxygen index according to ISO 4589 and smoke characteristic according to PN-K02501. From the obtained result, it showed that type of resin used has a significant influence on the modulus of elasticity and also on fire performance of plywood. It was found that plywood reinforced by fiberglass textile of lower areal weight showed better mechanical properties.

1. Introduction

Plywood is used in many applications due to its strength, stability and tolerance to changes in temperature and moisture. In addition, wood-based composites are in the group of environmentally friendly materials. Plywood can be made from either softwoods or hardwoods. It is always constructed with an odd number of layers with the fibers direction of adjacent layers oriented perpendicular to one another [1]. In the production of plywood the adhesives with increased resistance to heat and moisture are used. The most common adhesives used in wood-based panel production are amino resins based on urea-formaldehyde condensation. Due to low price and the most beneficial functional features the urea-formaldehyde (UF) and melamine-urea-formaldehyde (MUF) resins have the biggest share in the production of wood composites, even up to 90% [2, 3]. The adhesives used in plywood have become a point of concern. There are many investigations on modification of urea- or phenol-formaldehyde resin and also on new type of resin usage to improve the final product properties [2, 4, 5]. In this study an attempt to investigate the melamine-urea-phenol-formaldehyde (MUPF) resin used in plywood board production was made. Due to the potential application of plywood as a construction material with an improved properties and lower production cost many investigations of a various modifications of traditional plywood panels are conducted [6-8]. In this study the reinforcement in the form of glass fiber textile was used to strengthen the plywood. The glass fiber textiles are commonly used as a reinforcing agent for many polymer products to form a very strong and light composite material [9-11]. Although not as strong or as rigid as carbon fiber, it is much cheaper and significantly less brittle. It is possible to apply the glass fiber textile as one of the layers in plywood panels [9, 12]. Layer of glass fiber in the plywood might also constitute a protective layer during burning. The aim of this study was to determine properties of newly developed two types of plywood materials and theirs combination with fiberglass textiles.

2. Materials and methods

2.1. Materials

For manufacturing new types of plywood the following components were used: beech veneers with thickness of 1.5 mm (*Fibra spol. s r. o., Slovakia*); two types of resin: melamine-urea-phenol-formaldehyde (MUPF) (*Melfemo®510, Silekol Sp. z o.o., Poland*) and melamine-urea-formaldehyde (MUF) *(MUF system 1231, Akzo Nobel Casco Adhesives, Sweden)*; two types of glass fiber textiles (GFT) with different areal weight 150 and 250 g/m^2 (*TG Textilglas GmbH, Germany*). Beech veneers plywood (thirteen-ply) glued with urea-formaldehyde (UF) resin (*Kronocol U300, Czech Republic*) was used as a reference sample.

2.2. Preparation of plywood

The plywood boards were prepared by the following procedure:
(1) Drying: the beech veneers were cut to the dimensions of 400 mm x 400 mm x 1.5 mm and dried to approximately 6-12 wt% moisture content.
(2) Adhesive application: the adhesive was applied to the both sides of a every second sheet of veneer using a glue applicator roller.
(3) Lay-up: the veneers were arranged in a specific configuration in the 13-layer plywoods (without GFT) and the 15-layer plywoods reinforced with glass fiber textiles.
(4) Hot-pressing: the glued plywood boards were hot-pressed at specific pressure of 1.5 MPa and temperature of 100ºC over 15 minutes.
(5) Conditioning and cutting: to relieve drying stresses plywood boards were conditioned in a conditioning room maintained at a relative humidity of 60% and temperature of 23ºC for 6 days prior to properties evaluation.
Altogether, nine types of plywood were prepared as shown in Table 1.

No	Code	Adhesive type	Number of beech veneers	Lay-up type	GFT type
0	UF_t1	UF	13	type 1	-
1	MUF_t1	MUF	13	type 1	-
2	MUF_t2			type 2	-
3	MUF_t3_GFT150			type 3	150 g/m^2
4	MUF_t3_GFT250				250 g/m^2
5	MUPF_t1	MUPF	13	type 1	-
6	MUPF_t2			type 2	-
7	MUPF_t3_GFT150			type 3	150 g/m^2
8	MUPF_t3_GFT250				250 g/m^2

Table 1. The enumeration of produced plywoods

Three types of veneers lay-up were examined: type 1 – classical cross-graining, adjacent plies having their wood grain rotated relative to adjacent layers by 90 degrees (grain direction changing 90^o with each layer); type 2 – wood grains in two first and two last layers in the same direction; type 3 – second and fourteenth ply of fiber glass textile.

2.3. Mechanical testing

Mechanical properties commonly taken into consideration in the general usage of plywoods were investigated in this study: tensile strength, modulus of elasticity, bending strength and deflections of plywood. A minimum number of 5 samples were tested in each case.

2.3.1. Tensile test

The static tensile test was performed according to PN-EN ISO 527-1 using MTS 810 universal testing stand. The tensile test was carried out using dogbone-shaped specimens with standard dimensions. Samples were loaded by a maximum force of ±25kN at a 5 mm/min crosshead speed and a maximum piston traverse was ±40 mm. The tensile strength was investigated in samples cut out in two directions parallel and perpendicular to the orientation of outer layers and all odd-numbered layers in plywood.

2.3.2. Bending test

The three-point bending test was performed according to PN-EN 310:1994P using MTS 858 universal testing stand. The bending test was carried out using rectangular strips with dimensions of 150 mm x 10 mm x 13 mm (impact of the addition of glass fiber textile on the plywood's thickness is negligible). Samples were tested at a crosshead speed of 5 mm/min and span between supports of 100 mm. The deflection was recorded basing on crosshead displacement measurement.

2.4. Flammability testing

In the present study, the investigation of flammability property has been done by measuring the limiting oxygen index (LOI) and optical density of smoke. The obtained materials were classified according to ISO 4589.

2.4.1. Limiting Oxygen Index test

Limiting Oxygen Index is defined as the minimum concentration of oxygen, expressed as volume percent, in a mixture of oxygen and nitrogen that will just support flaming combustion of a material initially at room temperature [14]. The test was carried out in accordance with EN ISO 4589. The specimens had a standardized shape of rectangular strips with dimensions of 100 mm x 10 mm x 13 mm (length, width, thickness respectively). Measurements were carried out at room temperature ±23^{o}C and a relative humidity was 61%.

2.4.2. Smoke properties

The test of smoke properties of obtained materials was performed in accordance with PN-K-02501:2000 in a smoke chamber (NBS Smoke Density Chamber). This test measure the loss of light transmission through a collected volume of smoke produced under controlled conditions [15]. The specimens with dimensions of 120 mm x 100 mm x 13 mm were exposed to a radiant heat source of 25 kW/m^2, in a closed chamber, with the use of a pilot flame. A minimum of 3 samples were tested for each type of plywood. The average light intensity (E) after 4 minutes was determined. The calculation of the irradiation (S) which is the amount of light supplied at a specific time to the illuminated surface was achieved using the following equation:

$$S = \int_0^t E dt \quad (1)$$

3. Result and discussion

3.1. Tensile test

The mean values of tensile strength of plywood panels are given in Figure 1. The tensile strength of panels prepared using standard UF resin are lower than those obtained using another two types MUF and MUPF adhesive.

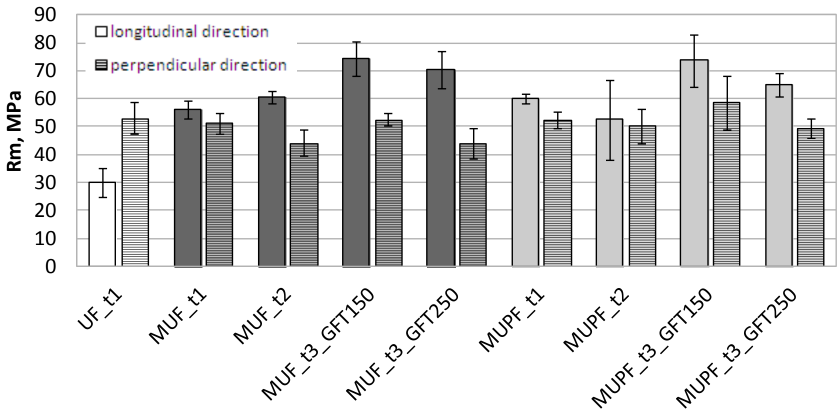
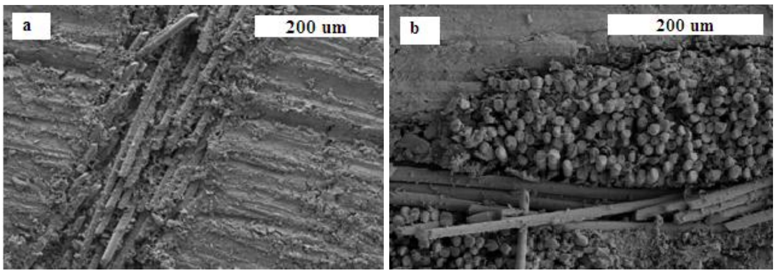


Figure 1. The tensile tests results

The tensile strength of samples oriented in the longitudinal direction is higher than in perpendicular, which indicates that the obtained structures of the plywood are anisotropic [16]. Generally, the plywood with MUPF resin base, has lower difference between these values. The difference between tensile strength in these two direction also shows dependence on the type of veneers lay-up and for type 1 is about 10%, for type 2 and 3 is about 30% for MUF and about 20% for MUPF. The highest values of tensile strength was obtained for composites with MUF and MUPF resins reinforced with glass fiber textile with areal weight of 150 g/m^2. It has been found that the glass fabric of a lower density is better wetted by resin, which affects into higher strength properties. A glass fiber layer in the plywood samples are shown in the SEM images in Fig. 2. For the samples with the fabric layers of 250 g/m^2 a density, areas where delamination occurs at the borders of the fabric plywood interface were observed. It was also observed that the fibers are not wetted by the resin (Fig. 2c-d). For samples with a lower fabric areal weight a much better connection between the resin and fibers was observed.



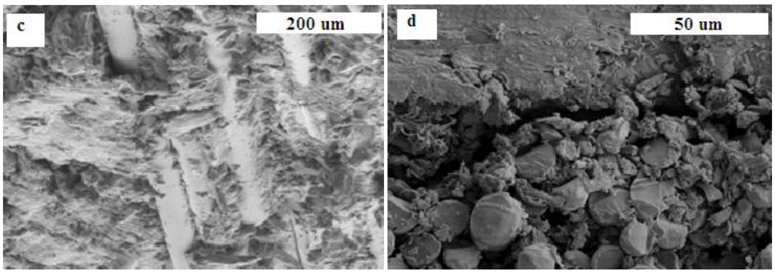


Figure 2. SEM images of cross section of type 3 samples: a, b – MUF_t3_GFT150 and c, d – MUF_t3_GFT250

3.2. Bending test

Bending tests results are reported for plywood with three type of resin and three type of veneers lay-up. Table 2 shows the bending strength and bending modulus of plywood with MUF and MUPF resin as compared to plywood with UF resin measured in two directions parallel and perpendicular to the wood fibers orientation of outer layers.

No	Code	Bending strength (MPa)		Bending modulus (GPa)		Deflection value (mm)	
		Longitudinal direction	Perpendicular direction	Longitudinal direction	Perpendicular direction	Longitudinal direction	Perpendicular direction
0	UF_t1	91.5 (6.5)[a]	68.1 (5.4)	3.4 (0.2)	3.1 (0.2)	3.9 (0.2)	3.5 (0.2)
1	MUF_t1	80.3 (7.0)	60.6 (5.7)	3.0 (0.5)	3.2 (0.2)	3.8 (0.9)	2.7 (0.4)
2	MUF_t2	94.1 (9.5)	49.2 (4.5)	3.2 (0.2)	2.3 (0.1)	4.1 (0.3)	3.0 (0.3)
3	MUF_t3_GFT150	99.6 (3.3)	54.4 (3.7)	3.3 (0.3)	2.1 (0.1)	4.2 (0.4)	3.5 (0.3)
4	MUF_t3_GFT250	97.7 (6.1)	57.5 (2.8)	3.1 (0.2)	2.0 (0.2)	4.4 (0.4)	3.9 (0.6)
5	MUPF_t1	91.7 (8.9)	70.3 (3.4)	3.3 (0.3)	2.6 (0.3)	4.0 (0.4)	3.8 (0.6)
6	MUPF_t2	103.2 (10.4)	56.9 (7.2)	4.0 (0.2)	2.4 (0.3)	3.7 (0.4)	3.5 (0.6)
7	MUPF_t3_GFT150	108.1 (6.0)	69.3 (3.9)	4.3 (0.5)	2.7 (0.1)	3.5 (0.6)	3.5 (0.3)
8	MUPF_t3_GFT250	93.8 (2.9)	61.1 (9.7)	3.7 (1.1)	2.2 (0.2)	3.8 (1.0)	4.0 (0.9)

[a] values in parenthesis are standard deviations

Table 2. The bending tests results

The results showed that, as expected, that the bending properties were generally higher for the plywood measured in samples cut out in the parallel directions to the wood fibers of outer layers [17]. Higher values of bending modulus were found for panels made using melamine-urea-phenol-formaldehyde compared to panels made using urea-formaldehyde and melamine-urea-formaldehyde. This may be because the MUPF resin has the highest fracture toughness, when properly cured [3]. Generally, resins commonly used in plywood production are tougher than the wood itself and results in a higher bending properties [18]. The bending strength and modulus of plywoods reinforced with GFT of areal weight 150 g/m^2 were found to be higher than those with GFT of areal weight 250 g/m^2. The differences in such properties due to usage of GFT with various areal weight could be the result of a poor connection of glass fabric with the plywood. Delamination and discontinuities were revealed on the border of glass fibers and plywood layers (Fig. 2). The use of higher-density fabric reduces the bending strength and increases the deflection of the specimen during bending test.

3.3. Limiting Oxygen Index test

With the purpose of determining the effect of the usage of different adhesives on fire performance of plywood and impact of glass fiber textiles on LOI the selected types of plywood were investigated. The experimental results are shown in Table 3.

No	Code	LOI (%)
0	UF_t1	29.5
1	MUF_t1	29.2
3	MUF_t3_GFT150	30.7
5	MUPF_t1	29.8
7	MUPF_t3_GFT150	30.6

Table 3. Result of Limiting Oxygen Index test

Results of the experiments showed that obtained wood-based composites have a high level of oxygen index. As can be seen from these results, usage of glass fiber textiles caused slight increase (3-5%) of LOI levels. The higher oxygen index for the GFT reinforced plywood could be the result of slowing down the process of plywood delamination. In this case the flame has more difficult access to the deeper layers of this plywood. As a result, all tested materials can be classified into fire retardant or fire resistance material group according to ISO 4589. It is well known that each of the used resins have superior fire retardant properties [19-21], while the raw wood is high flammable material and its LOI is around 22.4 to 24.6 percent [22]. Therefore as expected, the high level of oxygen index for plywood is an effect of combination of the flammable properties of these components [23].

3.4. Smoke properties

Smoke emission is one of the basic parameters for characterizing a materials performance subjected to fire. The combustion conditions under which smoke is produced – flaming, pyrolysis and smoldering – affect the amount and characteristic of the smoke [24]. In this study the light intensity transmitted through smoke as a function of time, under flaming and smoldering conditions was measured. In Fig. 3 the E – time curves for selected materials are presented.

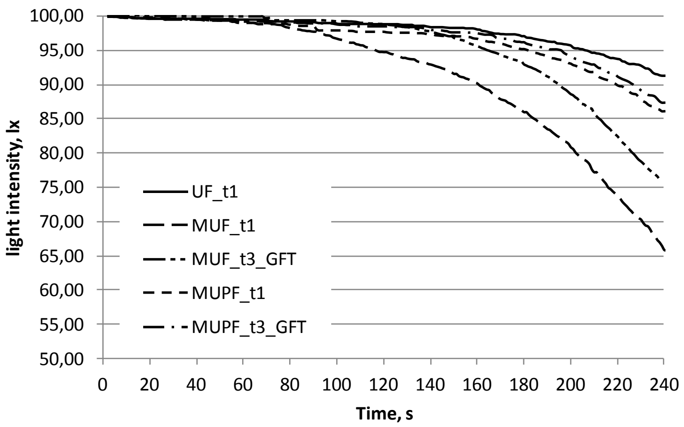


Figure 3. Smoke emission curves (E – time)

The irradiation (S) corresponds to the area under the graph and the higher S value the better smoke properties of material.

No	Code	Irradiation, S (lx·min)	Light intensity, E (lx)
0	UF_t1	392.3	91.3
1	MUF_t1	364.6	65.9
3	MUF_t3_GFT150	381.3	76.2

5	MUPF_t1	386.8	86.0
7	MUPF_t3_GFT150	389.5	87.4

Table 4. The results of optical smoke density tests

The values of irradiation and light intensity obtained after 4 min from ignition for each selected materials are shown in Tab. 4. Generally the smoke production characteristics of tested plywoods revealed good enough level and all those materials according to PN-K-02501:2000 can be used in a railway industry. The results also showed that the type of resin has an influence on smoke emission of investigated materials. The plywood with the UF resin shows slightly better smoke characteristic than other. It can be an effect of melamine appearance on resin composition. The melamine component cause improvement of fire resistance but also increase of smoke emission [25, 26]. It can be also seen that usage of GFT reduces amount of produced smoke for the same reasons which are described before.

4. Conclusions

In this study the influence of type of resin, veneers lay-up and addition of fiberglass textile on mechanical properties and fire performance of plywood were investigated. It can be concluded from the obtained results that the type of resin has an influence on the mechanical properties. The highest values of bending and tensile strength were found for the plywood based on melamine-urea-phenol-formaldehyde (MUPF) resin. It was also found that addition of glass fiber textile (GFT) of areal weight 150 g/m^2 in opposite to GFT of 250 g/m^2 causes an improvement of the mechanical properties. From SEM images it has been found that the glass fabric of a lower density is better wetted by resin, which affects into higher mechanical properties. The arrangement of the two first and two last veneer layers in the same wood fibers direction (lay-up type 2) causes an slight increase of mechanical properties. The limiting oxygen index (LOI) test results showed that all obtained wood-based composites can be classified into fire retardant or fire resistance material group (according to ISO 4589). The smoke production test results showed that the type of resin has an influence on smoke emission of investigated materials. The plywood based on urea-formaldehyde (UF) resin has slightly better smoke characteristic than other. It was found that the melamine component cause improvement of fire resistance but also increase of smoke emission. The addition of GFT increases LOI level and reduces amount of produced smoke by slowing down the process of plywood delamination.

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