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Determination of Shear Strength and Fire Performance of Plywood Supported by Woven E-Glass Fiber

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***Abstract*— The aim of this study was to determine the shear strength and fire performance of beech *(Fagus orientalis)* plywood supported (SP) by woven E - glass fiber (WGF). After providing 1.5 mm thickness beech veneers from a commercial company, they were manufactured as five layers. WGFs were placed bottom of the surface layers of plywood. Urea formaldehyde resin which contains 64% solid content was used approximately at a rate of 170 g/m². Adhesive mixture was spread on single surfaces of veneers by using roller brush. Shear strength tests were performed on the bond line 1 (contained WGF) and bond line 2 (not contained WGF) according to TS EN 314-1 as air dried and immersed in water. Fire performance tests were carried out according to ASTM E-69 by using fire tube test. SP samples have increased in reach to maximum temperature approximately three minutes. In bond line 1, shear strength values of control plywood (CP) samples have showed 7% higher shear strength properties than SP samples in air dried. In bond line 2, shear strength values of SP samples which are immersed in water have increased by 45%.**

Keywords—Plywood, shear strength, fire performance, woven glass fiber, bonding strength, urea formaldehyde

I. INTRODUCTION

Plywood is widely used in the building industry and furniture manufacturing. But the flammability of plywood limits its applicability because of the possible heavy casualties or the uncountable damage to the property caused by a fire accident. Although many relatively efficient flame retardants have been used in the plywood, they also have several technical and ecological disadvantages [1]. Many of the treatments may have adverse effects on other wood properties. Fire retardant treated (FRT) wood often becomes moisture sensitive, discolored or corrosive. The mechanical strength of wood might be reduced. Most of the treatments are not durable in exterior applications. They may also cause brittleness or obstruct or interfere with glues or paints. Most of these adverse effects are associated with certain types of impregnation treatments, but some of them, e.g. inferior durability and corrosion, occur also for surface coatings and chemicals added during the manufacture of board materials [2]. The use of minerals as fire retardants has also been suggested in the literature as an alternative to health and environmental concerns [3, 4 and 5].

The design of wood composite with high strength and durability is always an important issue in construction. Advances in fiber-reinforced plastics motivated researchers to evaluate the feasibility of manufacturing reinforced wood composites with high-performance synthetic fibers [6]. Initially reinforcing in wood elements glass fibers have been used [7, 8, 9 and 10]. Then carbon fiber, basalt and aramid were offered in the market, and the number of studies carried out using these materials applied in the reinforcement of wood and wood composites [11, 12, 13 and 14].

Bal, [15] concluded that reinforced laminated veneer lumber (RLVL) with woven glass fiber have increased modulus of rapture (MOR) and modulus of elasticity (MOE) of control LVL samples. He has also reported that density of WGF used in study have effected properties of RLVL and suggested using stronger adhesive than phenol formaldehyde such as resorcinol formaldehyde, epoxy adhesive, or isocyanate adhesive. Rosa García et al. [16] have determined systems of wooden pine beams reinforced with basalt and carbon FRP glued at the exterior and found that the ultimate tensile strain of the reinforcement is increased 50% for carbon fiber and 21% for basalt fiber. In another study, Triantafillou and Deskovic, [17] found that carrying capacity of beams reinforced with unidirectional carbon fiber reinforced plastic (CFRP) can increase between 20% and 40% when compared to the control samples.

Reinforced wood and wood elements have generally used in building construction occupied by people. However, in these studies fire performance of supporting materials and reinforced wood and wood composites have been disregarded.

The fire-retardant chemicals most used for wood products contain phosphorus, especially monoammonium phosphate (MAP) and diammonium phosphate (DAP). These phosphates are among the oldest known fire-retardant systems. They are usually included in proprietary systems used for wood. Boron compounds are considered to be effective flame retardants that exert less impact on mechanical properties compared with some other flame retardant chemicals [18]. Apart from fire-retardant chemicals, there has been intumescent fire retardant [19], polymer materials [20] and paints [21].

Boric acid (BA), disodium octoborate tetra hydrate (DOT) and alumina trihydrate (ATH) which are

significant fire retardant compounds have negative effected on flexural strength [22]. Boric acid which has been as fire retardant have decreased splitting strength, static bending strength in grain direction, modulus of elasticity in static bending, compression strength in tangential direction of laminated beech veneer lumber at rate of 58.02%, 5.12%, 3.75% and 35.48% respectively [23]. As seen in published studies, chemical fire retardants have reduced mechanical properties while increased fire performance.The main objective of this work is to improve fire performance of plywood by supporting it woven E- glass fiber (WGF) which has contained chemicals aluminum oxide, boron oxide and magnesium oxide. Contrary to chemical compounds, WGF material is used physical material among the layers. Another objective is to determine the effect of woven glass fiber on the bonding quality of plywood by means of lap joint shear tests.

II. MATERIAL AND METHODS

A. *Materials*

Beech veneers were supplied from Basoglu Orman Urunleri Sanayi ve Ticaret A.S., Zonguldak in Turkey. 1.2 thickness veneers obtained by rotary method were cut to1200 x 500 mm dimensions. Moisture content of veneers was determined as 7%. Five beech veneers were used in manufacturing Control Plywood (CP) plates. In Supported Plywood (SP) plates, five plies veneers and two plies WGF were used. WGF materials were placed at the bottom of veneers which were located in faces of plywood plates. Plan of layers utilized in supported plywood board manufacturing was shown in Figure 1.

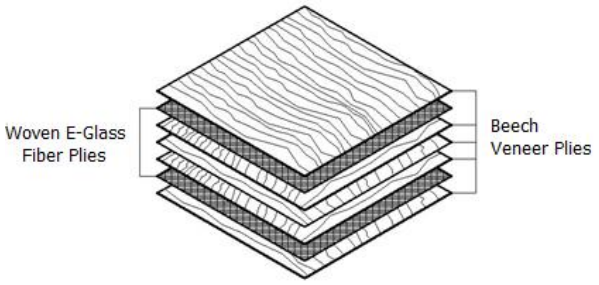

Figure 1. Plan of layers utilized in Supported Plywood (SP) plate manufacturing

Urea formaldehyde (UF) glue resin which contains 64% solid content was spread on single surfaces of veneers by using roller brush. Adhesive amount for each surface was applied at rate of 170gr/m^2. Hot press time and pressure were used 5 min and 15 kg/cm² respectively. Press temperature was 120 °C in the manufacturing of plywood panels. Woven (E) glass fibers (GW300T 2x2 TWILL) used in this study contains 54% silica, 17.5% calcium oxide, 14% aluminum oxide, 8% boron oxide and 4.5% magnesium oxide. Figure 2 shows overview of WGF.

Figure 2. Overview of WGF used in the study

B. *Methods*

Fire performance of plywood's was determined according to ASTM E 69 using fire tube test. Samples were cut to 7.2 x 19 x 1016 mm dimensions. Two variations (CP and SP) and eigth replicates totally sixteen samples were tested for during 20 minute. Digital scales having 0.01 g sensitivity was used for determination of mass reduction of plywood's when they were burnt. Butane gas was used to make an ignition flame. The distance between the bottom of the test samples and the top of the gas pipe were adjusted as 2.54 cm. In result of tests, mass loss of samples, temperature, CO, O_2 and NO release values were determined.

Shear strength tests were carried out on the bond line 1 and bond line 2 of CP and SP samples according to TS EN 314-1. Manufactured plywood's (CP and SP) have contained four bond lines. WGF materials were located in bond line 1 and bond line 4 of SP samples. Test samples were cut 150 x 25 x 7.2 mm (thickness) dimensions. Bond lines of CP samples in Figure 3-a, bond lines of SP samples have showed in Figure 3-b. Overview of shear strength sample test for SP bond line 1 was shown in Figure 4.

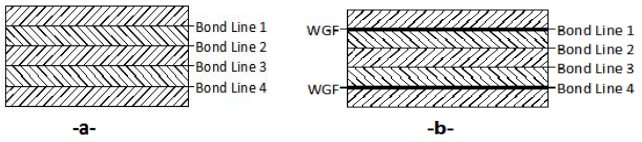

Figure 3. Bond lines of CP (a) and SP (b) samples.

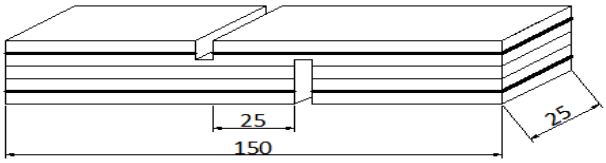

Figure 4. Overview of shear strength test specimen for SP bond line 1.

Tests were carried out on the bond line 1 (contained WGF) and bond line 2 (not contained WGF). Shear strength tests were conducted as air dried and immersed in water for the each variation. Samples immersed in water were waited 24 h at temperature of 25 ± 3 ^{0} C. By using two different types plywood (CP and SP), two different glue line (BL1 and BL2), two different condition (air dried and in water) and fourteen replicates have applied for each combination and totally (2x2x2x14) 112 shear tests were carried out. One-way analysis of variance was

used for determining the differences between the groups and Duncan test was carried out to determine whether the differences had any significant level.

III. Result and Discussion

A. *Fire performance Tests*

Fire performance of the all of the samples was carried out by using fire tube test. Temperature, mass loss, O2, NO and CO values were determined (Table 1).

Table 1. Fire test results of samples

Samples	Temperature (^{0} C)	Mass loss (%)	O_2 (%)	NO (ppm)	CO (ppm)
(CP)	248.62 (±25.54)	62.11 (±9.63)	19.50 (±0.07)	35.81 (±2.79)	220.08 (±29.5)
(SP)	255.12 (±20.64)	57.28 (±8.94)	19.67 (±0.09)	41.18 (±3.15)	175.08 (±18.4)

The maximum temperatures have determined 476 ^{0} C for CP and 450 ^{0} C for SP samples. The mean temperatures are measured 248.62 ^{0} C and 255.12^0 C for CP and SP samples respectively. Yapıcı et al.[24] reported that the mean temperatures of oriental beech wood treated with impregnation chemicals boric acid, Tanalith –E and borax, as varnish materials polyurethane, acid hardener, synthetic and water-based varnishes the average temperature 341 ^{0} C and minimum 288 ^{0} C for Tanalith-E + polyurethane and Borax + acid hardener samples respectively. While boron chemicals are important fire retardant, WGF used in this study have showed the fire performance better than these chemicals. As shown in Figure 5, SP samples which are included WGF have decreased the maximum temperature value by 5% and extended the time of reach to maximum temperature from 10th min. to 13th. Upon analyzing the temperature curves, similar behavior were observed in both CP and SP samples until 5th minute. In this stage, face combustion of samples have been observed. After this stage, bond line 1 and 4 in SP samples have showed its effect. The decreasing the time of reach to maximum temperature of SP is very important factor during fire for evacuating people from inside of building.

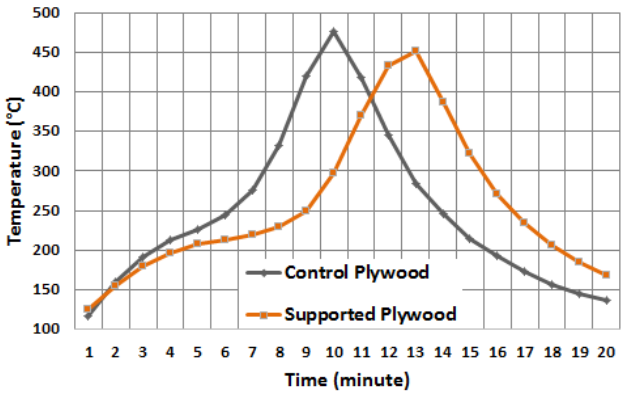

Figure 5. The maximum temperature curves of CP and SP samples.

Mass loss curves are given in Figure 6. Mass losses of samples have showed similar properties as maximum temperature curves. This situation can be explained as effect of the WGF. From 4th min. to 15th slowdown in mass loss values was shown. Decreased mass loss is especially important in wooden buildings because of the load carrying capacity.

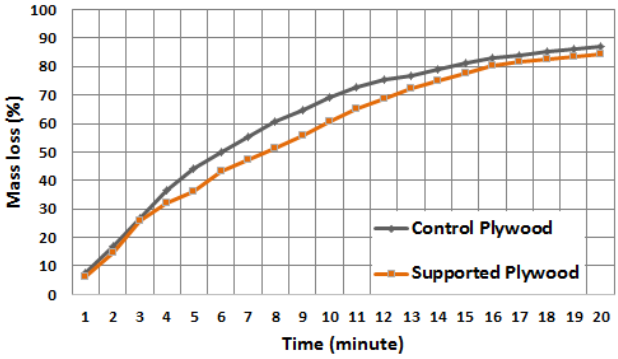

Figure 6. Mass loss curves of CP and SP samples.

At the beginning and end of the fire tube tests, the proportion of O_2 in air was observed as 21%. The amount of O_2 of CP and SP are very close to each other. The average O_2 values are 19.51 ppm and 19.68 ppm for CP and SP samples respectively. O_2 values of samples are given Figure 7.

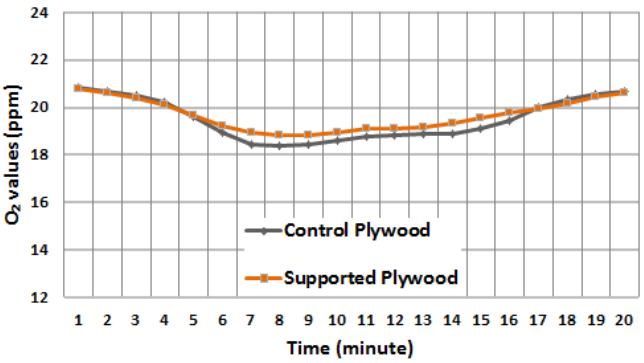

Figure 7. Amount of O_2 of CP and SP samples during fire test.

The formation of NO emission can be explained with two reasons. One is the high temperature resulted during combustion and the other is the nitrogen in the materials [25]. In materials used in this study are not nitrogen and so formation of NO is derived from high temperature. Generally, NO release values of SP samples higher than CP samples. The average NO values are 35.82 ppm and 41.18 ppm for CP and SP samples respectively. NO values of samples have shown Figure 8.

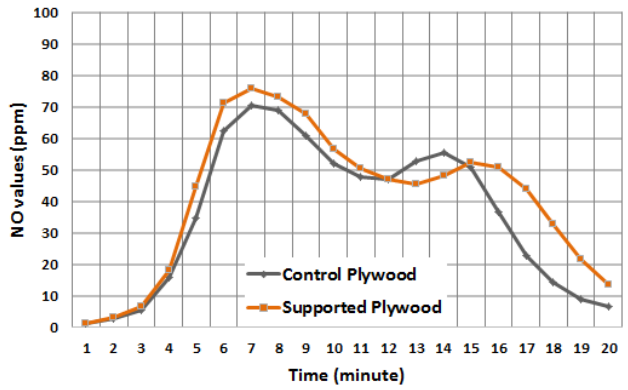

Figure 8. NO release values of CP and SP samples.

During in a fire, the prime toxic product is carbon monoxide (CO) together carbon dioxide (CO_2). The formation of CO in fires occurs at low temperatures in the early stages of fire development (as seen in Figure 9) mainly due to incomplete combustion of the pyrolysed fuel volatiles [26]. CO release have showed similar to temperature curves for CP and SP samples until 13th minute. However, after the 14th minutes, amount of CO has decreased in SP samples. This state is considered to result from chemical changes and content of the glass fiber during the glass fiber burning. The amount of CO released into the atmosphere during combustion is given in Figure 9.

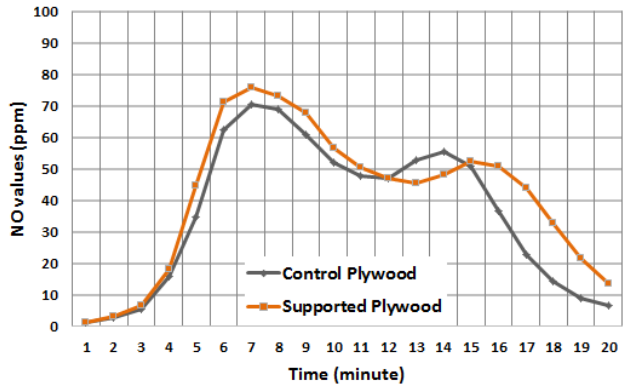

Figure 9. CO release values of CP and SP samples.

B. Shear Strength Tests

In all of the shear strength tests, air dried (A) samples have shown higher values than immersed in water samples (W). The highest shear strength value was obtained for CP samples in bond line 2 air dried samples. Densities of CP and SP samples, shear strength test results were shown in Table 2.

Table 2. The average shear strength values of CP and SP

Samples	Density (gr/cm^3)	Bond line 1 (N/mm^2)		Bond line 2 (N/mm^2)	
		Aired dry	24 hours in water	Aired dry	24 hours in water
(CP)	0.68	2.60 (±0.31)	2.17 (±0.21)	2.86 (±0.43)	1.77 (±0.26)
(SP)	0.72	2.42 (±0.32)	2.12 (±0.32)	2.63 (±0.33)	2.59 (±0.30)

Results showed that to place WGF have decreased shear strength of plywood's in both bond line 1 (BL1) and bond line 2 (BL2). In a similar study, Bal [15] have indicated that WGF have decreased shear strength of LVL approximately 16% in air dried samples. In samples placed in water, WGF layer has increased shear strength about 45% in BL2 because of prevented the transfer of water to the inner layer. On the other hand in BL1, CP samples have shown higher shear strength values than SP samples. Results of shear strength tests were shown Figure 10.

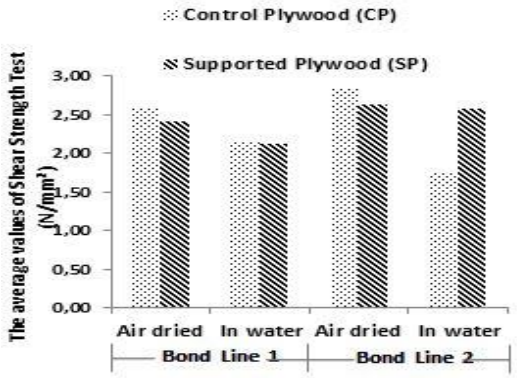

Figure 10. Results of shear strength tests.

There is a significantly difference between shear strength (Fratio=17.013; Pvalue=0.000<0.05) according to analysis of variance. Duncan test results were presented in Table 3.

Combinations	Number of samples	A	B	C	D
PC+BL2+ W	14	1.77			
SP +BL1+W	14		2.12		
PC+BL 1+W	14		2.17		
SP +BL1+A	14			2.42	
SP +BL2+W	14			2.59	
PC+BL1+ A	14			2.60	
SP +BL2+A	14			2.63	2.63
PC+BL2+A	14				2.86

PC+BL2+A samples have located in the highest group D together with SP+BL2+A. Lowest group A was formed by PC+BL2+ W samples. In the shear strength tests samples placed in the water have shown lower shear strength values (group A and B) than air dried samples because of effect of water on bonding properties. However, SP +BL2+W combination have located in group C unlike other immersed samples.

Generally, two types of failures have formed in the shear tests. *Type 1*; breaking in the adhesive line and *Type 2*; breaking in the wood. Type 1 failure was seen in the samples which are contained SP, while type 2 was seen in the control samples. Figure 11 have shown failure types observed shear strength in air dried tests.

a-SP Bond Line 1 b-CP Bond Line 2

Figure 11. Failure types *(a- Type 1, b- Type 2*) of shear strength test.

IV. Conclusion

Fire performance test and shear strength test of plywood supported with woven glass fiber were determined by using fire tube test and lap joint shear test respectively. In shear strength tests have carried out air dried and immersed water. It was also determined on the BL1 (contained WGF) and BL2 (not contained WGF).

In fire tube tests, the maximum temperature was reached at 10 min in CP samples. This time in SP samples was lengthened approximately 3 min. The glass fiber used in this study contains 54% silica, 17.5% calcium oxide, 14% aluminum oxide, 8% boron oxide and 4.5% magnesium oxide. During the combustion interaction of these chemicals can be decrease the amount of CO. It's our recommendation that different gas emissions other than O_2, CO and NO can be determined during the combustion in future studies.

Samples which are contained WGF (SP) have increased the shear strength test results by 45% in water tests. Declines in other samples have varied between 2.3% and 8%. Placed WGF among beech veneers have decreased bonding performance of layers. However, in water samples, WGF have prevented progress of water inside of the plywood. Decreasing in shear strength test can be overcome by using better strong adhesive than urea formaldehyde. In the future studies, different types of WGF which are cropped and dust of glass fiber can be investigated in terms of applicability in other wood composites.

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