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1st International Conference on Modern and Advanced Research

July 29-31, 2023 : Konya, Turkey

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Preparation and Characterization of Eco-friendly Plywood Produced with Waste Polystyrene

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Abstract – In this study, polystyrene (PS) has been melted using gasoline and used as an adhesive in Plywood production. Nowadays, thermoset resins which have formaldehyde emission are used in Plywood production. This study aims to enable the recycling of waste polystyrene and produce eco-friendly Plywood. Beech veneer (BC) with a thickness of 2 mm is used as the wood material. On top of the BC, PS sheets with the same width and length dimensions, but with a thickness of 5 mm, were placed. Then, gasoline was sprayed onto the PS sheets. In this way, 6 layers of BC and 5 layers of PS plates were overlapped together and cold-pressed under 4 bar pressure for 24 hours without using any heat during the process. Similarly, 3 pieces of 3 mm Medium Density Board (MDF) and 10 mm PS plate (20 kg/m^3) were overlapped each other and then cold-pressed. MDFs bonded with polyurethane (PU) and polyvinyl acetate (PVA) were also prepared in 3 layers. Afterward, analysis samples were cut from these materials. Mechanical and physical characterization of the samples was conducted according to TSE (Turkish Standards Institution) standards, including bending, tensile, screw holding, density, water absorption, and thickness swelling analyses. According to results, it has been determined that the sample produced with PU has the highest mechanical strength and physical durability. The samples produced using melted PS exhibit mechanical strength and physical resistance above the standards. As a result of the study, it is concluded that waste PS, after being melted with gasoline, can be used as an adhesive in plywood production. Thus, eco-friendly plywood without formaldehyde emissions can be manufactured.

Keywords – Wood, Polystyrene, Adhesive, Plywood, Polyvinyl Acetate, Polyurethane

I. INTRODUCTION

The rapid increase in the human population has led to a rapid growth in industrialization [1]. This phenomenon is causing the natural resources of the world to deplete rapidly [2]. In order to address this issue, humanity has begun to develop eco-friendly composite materials made from recycled materials [3]–[7]. Among these materials, the most important ones that can be used as substitutes for wood are particle board (PB), medium-density board (MDF), plywood, wood sandwich panels, and wood-plastic composites [8]–[12].

The wood-based composites industry plays a vital role in many countries' economies, with plywood being widely utilized in construction, furniture manufacturing, transportation, packaging, and decorative purposes. Plywood offers several advantages over solid wood, including enhanced dimensional stability, uniformity, higher mechanical strength, larger sizes availability, better appearance, and environmental benefits. However, a significant drawback of plywood production is its heavy reliance on adhesives, which can account for up to 20 % of its total mass [13], impacting its ecological balance and making it less environmentally friendly compared to solid wood. Global plywood production in 2020 reached 118 million m^3 [14], necessitating the use of approximately 15 million tons of synthetic thermosetting resins, typically derived from phenol, urea, formaldehyde, and isocyanates. These resins have formaldehyde emissions and harmful to human health. Many studies are being conducted to develop healthier and more environmentally friendly adhesives [15]. Veneer bonding experiments utilized various thermoplastic polymers, including HDPE [16]–[18], polystyrene [19]–[21], polypropylene [22], [23], or poly(vinyl chloride) [24]. These polymers were employed in different forms, such as textile fiber waste like polyurethane and polyamide-6 [25], recycled plastic shopping bags [26]. Also, in this study, eco-friendly plywood production has been investigated by using polystyrene.

In some studies, conducted using PS; Demirkir et al. [27] conducted a study to investigate the technological properties of polystyrene composite plywood made from different density polystyrene as the adhesive material. Beech (*Fagus orientalis* Lipsky) and alder (*Alnus glutinosa* subsp. *Barbata*) veneers were used to produce polystyrene composite plywood. In the production of polystyrene composite plywood, three different densities (10, 16, and 20 kg/m^3) of polystyrene were used as adhesives. The experiments resulted in finding that the mechanical properties of the panels produced with low-density polystyrene generally provided the highest values among all groups, and these values decreased as the density of polystyrene increased.

El-Bashir [28] manufactured wood plastic nanocomposites composed of palm tree fibers (PTF) filled into polystyrene (PS) nanocomposites. It was reported that the incorporation of a coupling agent significantly influenced the adhesion between PTF and PS/SiO_2 nanocomposites, particularly at low nanosilica concentrations, leading to variations in flexural strength, impact resistance, abrasion resistance, and water absorption properties of the nanocomposite sheets.

In this study, PS was dissolved by gasoline and used for plywood production. The aim of the study was to establish a new method for recycling polystyrene waste. This way, it is possible to contribute to preventing environmental pollution and produce water-resistant eco-friendly plywood.

II. Materials and Method

Materials and methods used when conducting the study were described below.

A. *Materials*

In the study, plywood was produced using two different wood veneers and three different adhesives. Beech (*Fagus orientalis*) veneer and medium density fiberboard (MDF) veneer were used as wood materials. The adhesives were used polystyrene (PS), polyvinyl acetate (PVA), and polyurethane (PU) adhesives. Lead-free gasoline was used to melt the PS. PS was obtained from the local market [29]. The beech (*Fagus orientalis*) veneers used in plywood production have been purchased from an online market [30]. The veneers were 2 mm thick, 200 mm wide, and 300 mm long. They were dried up to 2 % moisture content in a drying oven. MDF with one side painted, measuring 1700 mm x 2100 mm and 3 mm thick, was purchased from the local market [31]. The painted coating on the MDF with 6 % moisture content was sanded off from the surface to be glued. Polystyrene (PS) with a thickness of 5 mm, a width of 800 mm, and a length of 1250 mm was purchased from the local market. PVA adhesive (D3 class) and PU adhesive (D4 class) were also purchased from the local market [32].

B. *Preparation of samples*

A total of 4 sample groups were prepared (1. $PS_{(MDF)}$, 2. $PS_{(BC)}$, 3. $PVA_{(MDF)}$, and 4. $PU_{(MDF)}$) (Table 1). For the $PS_{(MDF)}$ samples, 2 mm $PS_{(BC)}$ were cut into 200 mm x 200 mm pieces. Along the grain direction of the veneer, 5 mm thick PS was placed. Gasoline was sprayed onto the PS using an air gun to melt it. Afterward, another veneer was placed on the melted PS. The veneers were stacked on top of each other with their grain directions perpendicular, and this process was repeated 6 times to obtain a plywood draft with a thickness of 9.5 mm (Fig. 1). The plywood draft was cold-pressed at 4 bars for 24 hours without applying heat.

For the $PS_{(MDF)}$ samples, three pieces of MDF with dimensions of 200 mm x 200 mm and one side painted white were used. PS (10 mm thick) was melted between the MDF layers by spraying gasoline using an air gun. The paint on the surface of the MDF used on the outside was not removed, but the paint on the surface of the MDF used in the middle was sanded off. A plywood draft with a thickness of 9.5 mm was obtained and pressed at 4 bars for 24 hours without applying heat.

Table 1. Materials ratios of samples

Group	Sample code	BC thick. (mm)	MDF thick. (mm)	PS thick. (mm)	PVA (g/m²)	PU (g/m²)
1	PS (MDF)	-	3	10	-	-
2	PS (BC)	5	-	5	-	-
3	PU (MDF)	-	3	-	-	250
4	PVA (MDF)	-	3	-	250	-

For the $PVA_{(MDF)}$ and $PU_{(MDF)}$ samples, three pieces of 200 mm x 200 mm MDF were used for each. The MDF pieces were bonded together using 250 g/m^2 of PVA and PU adhesives. The samples were pressed at 4 bars for 24 hours without heating.

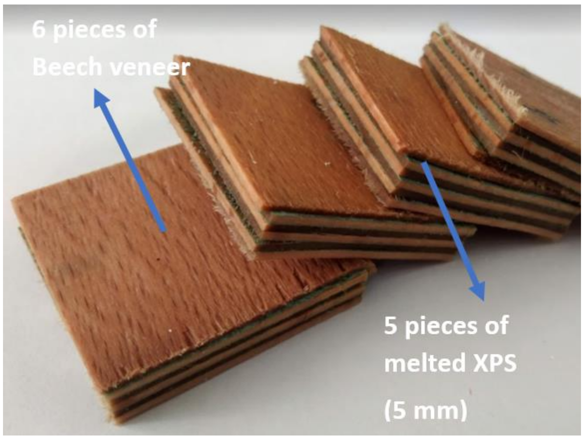

Fig. 1 $PS_{(BC)}$ samples

C. *Analysis methods*

The mechanical characterization of the plywood samples was performed according to TS EN 310 [33], TS EN 320 [34], and TS EN 319 [35] for Modulus of Rupture (MOR), Screw Withdrawal (SW), and Internal Bond (IB) analyses, respectively.

The physical analyses, including Density (DN), Thickness Swelling (TS), and Water Absorption (WA) analyses, were conducted according to TS EN 323 [36], TS EN 317 [37], and TS EN 317 [37], respectively.

D. *Statistical analysis*

The analysis results were analyzed using the SPSS software package. One-way ANOVA analysis was used to determine whether there were significant differences between the groups at a 95 % confidence interval (P<0.05). Duncan analysis was used to identify similarities among the groups.

III. RESULTS

The mechanical analysis results were given in Table 2. It has been determined that the sample produced with PU ($PU_{(MDF)}$) adhesive has the highest mechanical strength, while the sample ($PVA_{(MDF)}$) with PVA adhesive has the lowest mechanical values. There was no significant similarity between density and mechanical properties.

Table 2. Mechanical characteristics of samples

Samples	SW (N/mm)	MOR (N/mm²)	IB (N/mm²)
PS (MDF)	103 a* (±5)	13 b (±1,5)	1,45 c (±0,8)
PS (BC)	140 b (±14)**	10 a (±0,9)	1,02 b (±0,2)
PU (MDF)	179 c (±9)	19 d (±1,5)	1,85 d (±0,2)
PVA (MDF)	143 b (±8)	17 c (±1)	0,27 a (±0,4)

*: Duncan Analysis groups, **: Standard deviations

The physical analysis results were given in Table 3. It has been determined that the MDF sample bonded with PU adhesive ($PU_{(MDF)}$) is the most resistant to swelling and water absorption. On the other hand, it has been found that the beech sample bonded with PS adhesive ($PS_{(BC)}$) is the least resistant to water.

Table 3. Physical characteristics of samples

Samples	DN (kg/m³)	TS_{2h} (%)	TS_{24h} (%)	WA_{2h} (%)	WA_{24h} (%)
PS (MDF)	823 b* (±5)**	1,8 a (±0,1)	7,4 b (±0,4)	14 a (±0,1)	30 c (±0,1)
PS (BC)	683 a (±12)	5,8 bc (±0,1)	41 a (±0,1)	8,5 c (±0,2)	52 d (±0,3)
PU (MDF)	837 c (±17)	4,1 b (±0,1)	6,4 a (±0,2)	9,9 a (±0,1)	19 a (±0,1)
PVA (MDF)	843 c (±6)	6,1 c (±0,2)	11 b (±3)	14 b (±0,1)	22 b (±0,3)

*: Duncan Analysis groups, **: Standard deviations

IV. DISCUSSION

In Figure 2, it was observed that the samples produced with MDF had higher MOR strengths. Among them, the beech sample ($PS_{(BC)}$) exhibited the lowest bending strength. There is a correlation between bending strength and moisture content. Eser et al. [38] reported that moisture content significantly influenced the bending strength and tension zones of the wood material. They observed that an increase in moisture content led to a more uniform distribution of deformation throughout the wood material.

When the IB strength was examined, it was noticed that the samples produced with PVA adhesive had lower IB strength compared to those produced with PU and PS adhesives. The IB strength of the samples bonded with PS was close to that of the PU sample. This indicates that melted PS can be used in plywood production. One of the most critical analyses in the board industry is "screw withdrawal." When examining the screw withdrawal (SW) forces of the samples, it was observed that $PU_{(MDF)}$ had the highest value. The SW forces of the samples bonded with PS were above the standard value. Consequently, it is evident that the samples bonded with PS can be considered for plywood production.

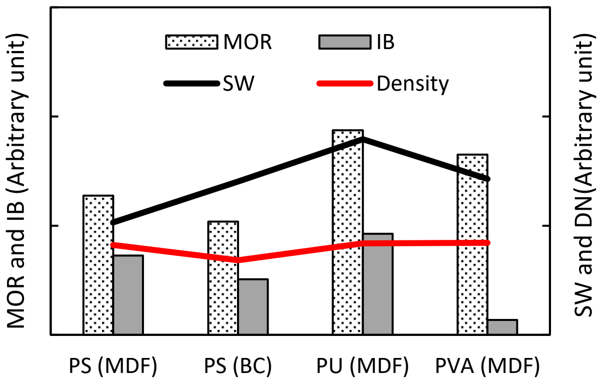

Fig. 2 Mechanical properties

When examining Figure 3, it was observed that the samples bonded with PU adhesive were the most water-resistant. Although the water resistance of the samples bonded with PS was lower than that of PU and PVA, they still exhibited TS (Thickness Swelling) and WA (Water Absorption) values above the standards. It was also noticed that the samples produced with MDF were more water-resistant compared to the ones produced with beech (BC). When the top surface of the beech samples was coated with a water-resistant coating, it becomes evident that water-resistant plywood can be produced using PS adhesive.

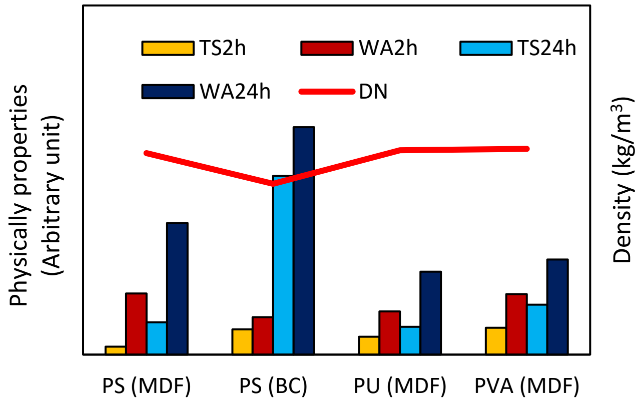

Fig. 3 Physically properties

V. CONCLUSION

In this study, Plywood was produced using Expanded Polystyrene (PS), Polyvinyl Acetate (PVA), and Polyurethane (PU). As wood materials, 2 mm beech veneer and 3 mm medium density fiberboard (MDF) were utilized. The potential of using waste polystyrene in plywood production was evaluated in present study. To use PS as an adhesive, it was sprayed with gasoline using an air gun. The dissolved PS with gasoline was then used to bond the beech veneers. Additionally, three pieces of 3 mm MDF were bonded together using PU and PVA adhesives. Mechanical analyses, including Modulus of Rupture (MOR), Screw Withdrawal (SW), and Internal Bond (IB), as well as physical analyses, including Density (DN), Thickness Swelling (TS), and Water Absorption (WA), were conducted on the samples.

Based on the obtained results, it was determined that plywood produced with PS exhibited mechanical and physical properties similar to plywood produced with PU. Consequently, the findings suggest that PS dissolved with gasoline can be utilized in plywood production. Further research in this area indicates that recycling waste PS could be beneficial for creating value-added products.

ACKNOWLEDGMENT

This study was conducted in the laboratory of Mudurnu Süreyya Astarcı Vocational School, Bolu Abant Izzet Baysal University.

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