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Effects of Different Adhesive Ratios on Selected Panel Properties of High-Density Fiberboard (HDF) Produced from Fir and Beech Chips

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High-density fiberboard (HDF) has been utilized in various forest-based industries for centuries. This study investigated the effects of different adhesive ratios on the properties of HDF through a series of tests. The panels, designed in particular for this study, had been produced in a laboratory putting the usage of a combination of 70% fir (*Abies nordmanniana* subsp. *bornmulleriana*) and 30% beech (*Fagus orientalis* L.) fibers sourced from the western Black Sea area of Turkey. Two adhesive levels were tested: 10.73% for panel I and 11.30% for panel II, both calculated based on dry fiber weight. We assessed several physical and mechanical properties, including density, modulus of rupture (MOR), modulus of elasticity (MOE), internal bonding (IB), hardness, water absorption, and through-thickness swell, in accordance with standard testing methods. The results indicated that both adhesive levels produced panels meeting the general performance requirements for HDF. Panel II, which contained slightly more adhesive, demonstrated marginally better performance in specific strength and dimensional stability tests. Overall, the findings suggest that optimizing adhesive usage in industrial HDF production can help establish a balance between the performance requirements of the boards and cost-effectiveness in production.

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Introduction

Wood is widely used as a building material due to its unique structure, high density, and excellent thermal insulation. In addition, it is durable, stylish, and requires minimal maintenance. When used indoors, excellent thermal insulation reduces heating and cooling costs. The thermal conductivity and the value of wood products depend on the type of wood, and are therefore important factors to consider [Richardson, 1976; Kang et al., 2015].

Wood fiber synthesis methods are often divided into wet and dry. Fiber definitions are specified in the European Standard [EN 622-5, 2006]. Initially, fibers were classified according to their release mode: liquid fibers dispersed in water, and air-dispersed fibers [Halvarsson, 2010].

Cutting and processing wood by splicing, joining, and gluing allows the construction of wood-based structures with structural stability and reliability. In addition to the properties of the wood particles or fibers, factors such as bonding, compression pressure, compression time, and bonding quality play a significant role in determining the cost and performance characteristics of wood-based composite panels. It is important to note

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that cold-formed fibers require little or no bonding due to the bonding of the fibers [Mahrt et al. 2017].

Wood and wooden composites play a crucial role in engineering generation because of their flexibility and potential to be custom-designed to character needs, making them appropriate for a huge variety of applications. Wood composites may be tailor-made to particular overall performance requirements, and they provide an extra environmentally friendly opportunity in comparison to strong wooden [Kristaki et al. 2021].

In recent years, the demand for different wood-based products (such as particleboard, plywood, and wood fiber) has increased worldwide. Fiberboard (FBM) is a wood-based material produced by hot-pressing wood fibers under high temperature and pressure [Toemen et al. 2010; Hong et al. 2017].

Based on density, fiberboard is divided into two types: medium-density fiberboard (MDF) and high-density fiberboard (HDF). While MDF is known to have a density between 400 and 900 kg/m^3, HDF has been reported to have a density exceeding 900 kg/m^3 [EN 316 1999; Dominguez-Robles et al. 2018].

HDF is a modified material obtained by combining lignocellulosic fibers with synthetic fibers under high pressure and temperature [Irle and Barbu, 2010; Badin et al., 2018]. High-quality wood composites containing minimal chemical additives [Henke et al. 2022; Majeed and Hussein, 2024a]. In addition to its excellent mechanical properties, excellent deformation resistance, high fiber adhesion, high quality, and resistance to cracking, HDF is one of the most popular composite materials in the furniture industry [Wei et al. 2018].

Adhesives are materials used to bond materials together, which can be obtained from natural or synthetic sources. Adhesives are mainly composed of synthetic or polymeric materials [Kvira, 2015; Majeed and Hussain, 2024b].

An adhesive is a substance used to bond or be a part of gadgets collectively and may be derived from natural or artificial sources. Primarily, adhesives are composed of polymeric materials, both naturally occurring or synthetically produced [Sunday, 2015; Majeed and Hussein, 2024b]. In the wooded area merchandise industry, the maximum commonly used thermosetting adhesives for wood-primarily based totally composites are urea-formaldehyde (UF) resins and melamine-changed UF resins (MUF). UF resins belong to a category of thermosetting adhesives referred to as amino resins [Pizzi, 1983]. The number one characteristic of adhesives is to facilitate load switch and distribution among additives, thereby improving the very last material's power and modulus. The performance of strain switch among additives relies upon the power and quantity of bonds formed [Frihart and Hunt, 2010; Espinosa et al., 2021].

Studies in the literature by various authors on HDF panels produced using different mole ratios, different production stages, different adhesives, and chips from different wood species are available. These studies report mechanical, physical, and formaldehyde tests on the produced panels [Çamlıbel and Ayata, 2020; Hasanah et al., 2024; Çamlıbel, 2020a;b; Antov et al., 2021; Majeed and Hussein, 2024a;b; Mihajlova and Savov, 2018; Wei et al., 2018; Mahrdt et al., 2017; Espinosa et al., 2021; Badin et al., 2018].

This paper investigates the consequences of various adhesive ratios on diverse board homes of HDF panels produced the use of fir and beech wooden chips.

Materials and methods

Fir (*Abies nordmanniana* subsp. *bornmulleriana*) and beech (*Fagus orientalis* L.) wood were used in this study. Raw materials were obtained from the warehouses of the Western Black Sea Forest Management Directorate. The UF adhesive used in the study was produced at the Kastamonu Integrated Adhesive Facility.

An aggregate of fir (70%) and beech (30%) turned into used as uncooked substances within the manufacturing of HDF. The logs have been shredded in a chipper and transferred to softwood and hardwood chip silos. The aggregate of 70% spruce chip and 30% beech chip turned into fed into the manufacturing line through a discharge screw. The blended chips have been robotically screened the usage of a dyne screen device and sized for manufacturing.

The properties of the UF resin are shown in Table 1: solids content: 64±10, urea-formaldehyde (U: F) mole ratio: 0.92, density (20°C): 1.227 (g/cm^3), viscosity (25°C cps): 15-35 s, gel time (100°C) (20% $(NH_4)_2SO_4$): 40-75 s, pH: 6.9-8.5, free formaldehyde: 0.20% max, methylol groups: 12-15% and shelf-life: 80 days.

The chips had been pre-steamed within the pre--steaming silo at 130°C and 2.30 bar steam pressure. The steamed chips had been transported to the Andritz defibrator machine through a screw conveyor. In the Andritz defibrator, the chips had been steamed for 3 minutes at 188°C and 8.10 bar steam pressure. Before defibrillating, the softened chips had been coated with liquid paraffin. Fibers had been produced in defibrillator segments, and inside the blowing line, binder and UF resin had been applied to the fibers. The fibers had then been dried to 12% moisture content. After drying, the fibers were transferred to hoppers used to ensure a homogeneous mixture. The fibers had then been laid out on mats on the mat-forming station.

The production parameters of HDF panels (panel I and panel II) are shown in Table 1.

In the pre-pressing process, cold pressing was applied to the mats with a pressure of 120-140 kg/cm^2. The mats were then passed through a continuous hot-press production line, where the press temperature was

Table 1. Production parameters for HDF panels (panel I and panel II)

Variable	Panel - I	Panel - II
Wood composition (fir + beech)	70% + 30%	70% + 30%
Adhesive solid content (m^3 basis)	81 kg/m^3	85 kg/m^3
Adhesive solid content (dry fiber basis)	10.73%	11.30%
Hardener content (dry fiber basis)	0.80%	0.80%
UF molar ratio	F:U: 0.92	F:U: 0.92
Paraffin content (dry fiber basis)	1.17%	1.17%
Pres model	Siempelkamp ContiRoll Hot Press 2008 Model, (Krefeld, Germany)	
Continuous press temperature	220°C	220°C
Continuous press speed	820 mm/s	820 mm/s
Pressing time	54 s	54 s
Continuous press pressure	31 kg/cm^2	31 kg/cm^2
Panel dimensions (mm)	7.4 X 2097 X 7365	7.4 X 2097 X 7365

220°C, the press time was 54 seconds, the press speed was 820 mm/s, and the press pressure was 31 kp/cm^2, resulting in the production of HDF panels.

The panels were climatized in a star cooler. The panels were sized to 7.4 mm x 2097 mm x 7365 mm dimensions at the sizing unit. After production, the panels were stored in a stock area for a 5-day resting period. Once rested, both the top and bottom surfaces of the panels were sanded using 40, 80, and 140 grit sandpaper, resulting in panels with a final thickness of 7.4 mm. The test panels were stored on a block on a smooth concrete floor, away from airflow. The HDF panels were conditioned to a moisture content of 12% according to the TS 642-ISO 554 [1997] standard under conditions of 65±5% relative humidity and 20±2°C. Air conditioning operations were carried out for approximately 2 weeks.

The applied test standards are as follows: ASTM D 1037-12 [2020] for surface Janka hardness strength measurements of panels, TS 642-ISO 554 [1997] for conditioning and/or standard atmosphere properties for testing, TS EN 326-1 [1999] for the selection, cutting, inspection, and presentation of test panel samples, TS EN 324-1 [1999] for thickness measurement of panels, TS EN 322 [1999] for moisture content measurement, TS-EN 317 [1999] for determining immersion of particleboard and fiberboard in water, TS-EN 323 [1999] for determining the specific gravity of wood-based panels, TS-EN 325 [2012] for determining the dimensions of test specimens of wood-based panels, TS EN 310 [1999] for measuring the mechanical properties of panels, including bending strength and modulus of elasticity, TS EN 319 [1999] for testing the perpendicular tensile strength of panels, and TS EN 320 [2011] for testing the screw withdrawal resistance of edges.

The standards specified for both physical and mechanical properties in this study were chosen not only because they are internationally recognized and used in studies on this subject, but also because they are widely used in similar studies, allowing comparison of the results obtained in the study.

To ensure statistical validity in the study, 10 test samples were prepared from each group. The measurement results of these samples are given in the tables. Each sample was cut and prepared to fit the relevant test. Relevant standards were used in this regard. A statistical software was used to calculate: standard deviation values, mean results, coefficient of variation, and minimum and maximum result values. A one-way ANOVA test was performed on the data obtained in the study using an SPSS program.

Results and discussion

The thickness, moisture, and density check outcomes for HDF panels with exclusive adhesive ratios are offered in Table 2. The assessments carried out within the observation had been achieved according to TS EN 324-1 [1999], TS EN 322 [1999], and TS EN 323 [1999]. As proven in Table 2, the same old restricted values for HDF panels are created in 7±0.2 mm thick observe, 4 to 11% and 870±5 kg/m^3. According to the check outcomes, the 2 panels have given very similar outcomes of popular restricted values. In addition, the thickness of panel I and panel II is decided to be between 7.28 mm to 7.40 mm. The common thickness values calculated were 7.34 mm for panel I and 7.35 mm for panel II, and each is proven to be the same old thickness targeted. The moisture check confirmed that the moisture of panel I degrees from 6.35% to 6.78% and panel II, from

Table 2. Results of strength, density, and hardness values of HDF panels produced using different adhesives

Tests	Thickness		Moisture		Density	
Test Standards	TS EN 324-1 [1999]		TS EN 322 [1999]		TS EN 323 [1999]	
Standard limit values for HDF boards	7±0.2 mm		4-11%		870±5 kg/m³	
Test Sample Number	Panel - I	Panel - II	Panel - I	Panel - II	Panel - I	Panel - II
1	7.36	7.36	6.68	7.53	881.87	886.09
2	7.40	7.40	6.76	7.09	885.02	859.46
3	7.36	7.36	6.35	7.26	877.13	856.24
4	7.35	7.35	6.78	7.26	880.87	856.37
5	7.35	7.36	6.66	7.19	872.28	886.09
6	7.28	7.30	6.45	7.36	867.90	869.46
7	7.35	7.41	6.58	7.35	865.33	856.24
8	7.33	7.45	6.56	7.58	851.67	856.37
9	7.36	7.32	6.45	7.19	876.29	857.46
10	7.29	7.22	6.71	7.16	861.03	876.76
Mean	7.34	7.35	6.60	7.29	871.94	866.05
Standard Deviation	0.04	0.06	0.15	0.16	10.46	12.59
Minimum Result	7.28	7.22	6.35	7.09	851.67	856.24
Maximum Result	7.40	7.45	6.78	7.58	885.02	886.09
Coefficient of Variation	0.48	0.87	2.21	2.18	1.20	1.45

7.09% to 7.58%. The moisture content of the 2 panels is proven to be within the targeted popular restrict. The average moisture content of the dashboard is 6.60% and for panel II – 7.29%. The density tests have shown that density of panel II changes between 856.24 kg/m³ and 886.09 kg/m³. The density of panel I varies from 851.67 kg/m³ and 885.02 kg/m³. The average density value has been shown to be 871.94 kg/m³ for panel I and 866.05 kg/m³ for panel II. The sheets created in two different tubes also have a density value near the specified standard limits. These measurement results show two reaction panels with TS in 324-1 [1999], TS in 322 [1999], and TS in 323 [1999] in terms of thickness, humidity, and density. These results show that the manufacturing parameters that were used are suitable, and that both panels have the predicted performance (Table 2).

Table 3 presents the results of water absorption tests and 24h thickness for HDF panels with different adhesive ratios. The tests were performed according to TS in 317 [1999], stipulating that the maximum absorption-value of water must be less than 35% and the swelling of the thickness must be less than 18%. In this study, two different adhesive reports were used for HDF sheets: panel I with the adhesion ratio of 81 kg/m³ (10.73% on the dry fiber base) and panel II with the adhesive ratio of 85 kg/m³ (11.30% on dry fibers). According to the test results, water absorption value of panel I varies from 26.92% to 31.06%, with an average of 28.88% while water absorption value for panel II varies from 28.91% to 33.82%, with an average of 31.46%. In the swelling test according to the thickness, the result of panel I has changed from 12.47% to 13.94%, with an average of 13.13%. For panel II, the thickness varies from 12.64% to 13.99%, with an average of 13.27%. These results show that panel II presents slightly higher water absorption values, but both panels have proven that satisfactory water resistance is TS in 317 [1999]. There is no significant difference in thickness that has been observed between the two plates. In addition, these results provide valuable data to assess the effects of adhesion on water absorption and the size stability of HDF panels (Table 3).

Table 4 presents the results of surface tensile and hardness tests conducted on HDF panels with varying adhesive proportions. The tests were performed in accordance with TS EN 319 [1999] and ASTM D 1037-12 [2020]. According to the standard limit values for HDF panels, the vertical tensile strength must exceed 1.22 N/mm², and the surface hardness must be greater than 1 N/mm². In the vertical tensile tests, the results for panel I ranged from 1.30 N/mm² to 1.50 N/mm², while panel II showed values between 1.22 N/mm² and 1.48 N/mm². The average vertical tensile strength was 1.42 N/mm² for panel I and 1.32 N/mm² for panel II. Both panels exceeded the standard limit for vertical tensile strength and yielded satisfactory results. For the surface hardness test, the hardness values for panel I ranged from 1.13 N/mm² to 1.90 N/mm², while those for panel II ranged from

Table 3. Water absorption and swelling results of HDFs after 24 h

Tests	Water Absorption (24 h)		Thickness Swelling (24 h)	
Test Standards	TS EN 317 [1999]		TS EN 317 [1999]	
Standard limit values for HDF boards	Maximum 35%		≤ 18%	
Test Sample Number	Panel - I	Panel - II	Panel - I	Panel - II
1	26.92	29.91	12.72	12.64
2	28.46	32.85	13.08	13.43
3	30.28	32.67	13.64	13.99
4	29.06	31.59	13.06	13.18
5	28.66	30.27	13.17	13.11
6	27.92	28.91	12.52	12.74
7	27.46	33.82	13.48	13.53
8	29.28	31.67	13.94	12.99
9	31.06	32.59	13.26	13.48
10	29.66	30.37	12.47	13.61
Mean	28.88	31.46	13.13	13.27
Standard Deviation	1.27	1.56	0.48	0.42
Minimum Result	26.92	28.91	12.47	12.64
Maximum Result	31.06	33.82	13.94	13.99
Coefficient of Variation	4.40	4.95	3.63	3.16

Table 4. Bending strength and surface hardness results of HDF panels produced with different strain rates

Tests	Surface Perpendicular Tensile		Surface Hardness	
Test Standards	TS EN 319 [1999]		ASTM D 1037-12 [2020]	
Standard limit values for HDF boards	≥ 1.22 N/mm²		≥ 1 N/mm²	
Test Sample Number	Panel - I	Panel - II	Panel - I	Panel - II
1	1.50	1.30	1.90	1.77
2	1.34	1.48	1.49	1.17
3	1.40	1.24	1.23	1.16
4	1.42	1.25	1.37	1.36
5	1.37	1.29	1.76	1.58
6	1.49	1.41	1.40	1.67
7	1.30	1.34	1.29	1.27
8	1.48	1.35	1.13	1.16
9	1.43	1.31	1.37	1.36
10	1.48	1.22	1.76	1.38
Mean	1.42	1.32	1.47	1.39
Standard Deviation	0.07	0.08	0.25	0.22
Minimum Result	1.30	1.22	1.13	1.16
Maximum Result	1.50	1.48	1.90	1.77
Coefficient of Variation	4.92	6.08	17.29	15.64

1.16 N/mm² to 1.77 N/mm². The average surface hardness was 1.47 N/mm² for panel I and 1.39 N/mm² for panel II. Both panels satisfied the standard limit values for surface hardness. In conclusion, both panels met the specified standard limit values for vertical tensile strength and surface hardness, demonstrating that their mechanical properties fulfilled the desired performance requirements (see Table 4).

The results of flexural strength and modulus of elasticity tests conducted on HDF panels with varying adhesive proportions are presented in Table 5. These tests adhered to the TS EN 310 [1999] standards. According to the standard limit values for HDF panels, the flexural strength should exceed 40 N/mm², and the modulus of elasticity should be greater than 2700 N/mm². In the flexural strength test, the results for panel I ranged from 32.17 N/mm² to 38.50 N/mm², while panel II showed results between 31.24 N/mm² and 36.92 N/mm². The average flexural strength was 35.81 N/mm² for panel I and 34.20 N/mm² for panel II. Unfortunately, neither panel met the standard limit values for flexural strength. However, these values are still within acceptable limits, indicating that both panels possess adequate flexural strength. In the elastic modulus test, results for panel I ranged from 3561.00 N/mm² to 3879.82 N/mm², while for panel II – from 3478.46 N/mm² to 3998.53 N/mm². The common elastic modulus becomes 3748 N/mm² for panel I and 3764 N/mm² for panel II. Both panels extensively surpassed the usual restrict for elastic modulus. In conclusion, even though each panel excelled in elastic modulus using a sizable margin, they fell quickly in reaching the desired flexural strength. This shows that whilst the elastic houses of the panels surely meet the standards (as proven in Table 5), a similar assessment is needed concerning the effect of producing parameters on flexural strength.

In a laboratory study conducted by Çamlıbel and Ayata [2020], it was concluded that the results of the thickness, tensile strength, surface durability, surface absorption, modulus of elasticity, board moisture content, and formaldehyde gas emission tests increased with increasing mole ratio in HDF boards. It was also observed that the results of the 2-h and 24-h thickness swelling (%) tests, which are physical properties, decreased with increasing mole ratio from 0.88 to 1.17.

In the research conducted by Çamlıbel and Aydın [2025], HDF were produced using UF resin (0.98 mol) at five different consumption rates (10.10%, 10.65%, 11.12%, 11.55%, and 12.47% dry fiber weight), and the mechanical and physical properties of the boards, as well as their formaldehyde contents, were determined. According to the results, the average values of the physical and mechanical properties showed significant differences except for surface durability (SS). The most improved property was SS, which increased by 25.4% when the UF consumption was 105 kg/m³. Among the physical properties, the greatest improvement was in surface wear (15.7%) at the same consumption rate. For thickness swelling and water absorption, a consumption of 115 kg/m³ provided the greatest improvements (decreases of 15.3%, 6.8%, and 8.7%, respectively). Therefore, considering all the properties evaluated, no single consumption could be determined that provided the greatest improvement. One of the most important characteristics of the panels is their FE value. With

Table 5. Bending strength and flexural modulus test results of HDF panels produced with different fillers

Tests	Bending Strength		Modulus of Elasticity	
Test Standards	TS EN 310 [1999]		TS EN 310 [1999]	
Standard limit values for HDF boards	≥ 40 N/mm²		≥ 2700 N/mm²	
Test Sample Number	Panel - I	Panel - II	Panel - I	Panel - II
1	38.10	36.56	3879.22	3998.53
2	32.17	32.06	3561.00	3564.78
3	35.41	31.24	3739.94	3498.46
4	37.54	36.92	3815.58	3995.82
5	38.50	36.36	3879.82	3981.53
6	32.47	32.26	3563.00	3574.78
7	38.50	36.26	3879.82	3972.53
8	32.37	32.26	3564.00	3591.78
9	35.61	32.34	3839.94	3478.46
10	37.44	35.72	3765.58	3991.82
Mean	35.81	34.20	3748.79	3764.85
Standard Deviation	2.62	2.32	136.80	237.73
Minimum Result	32.17	31.24	3561.00	3478.46
Maximum Result	38.50	36.92	3879.82	3998.53
Coefficient of Variation	7.32	6.78	3.65	6.31

a UF consumption of 115 kg/m^3, the FE decreased by approximately 17.6%.

In the study by Hasanah et al. [2024], HDF were produced from palm leaf fibers and polyester resin. Polyester resin was used as the matrix, and palm leaf fibers with a mesh size of 80 were used as filler. Fiberboard composites were fabricated using a hot press at 70°C for 20 min with varying bulk compositions of polyester resin and palm leaf fibers: S1 (60%:40%), S2 (65%:35%), S3 (70%:30%), S4 (75%:25%), and S5 (80%:20%). Observed parameters included physical properties and mechanical properties. The results show that S5 exhibits optimum properties such as a density value of 1.197 g/mL, a low porosity ratio of 0.232% and impact strength of 271 J/m^2, tensile strength of 23 MPa, and flexural strength of 149 MPa.

Antov et al. [2021] investigated the potential of producing environmentally friendly, formaldehyde-free HDF from hardwood fibers bonded with UF resin and a novel ammonium lignosulfonate (ALS). Consequently, the HDF boards reportedly exhibited highly satisfactory physical and mechanical properties.

Gumowska and Kowaluk [2023] produced HDF at different resignification levels (12%, 15%, and 20%) using natural binders such as polylactic acid (PLA), thermoplastic starch (TPS), and polycaprolactone (PCL). The biopolymer HDF was compared with a reference HDF containing binders such as UF resin and produced using an industrial technology. Various tests on physical and mechanical properties were conducted. The results showed that increasing the binder content significantly improved the mechanical properties of the starch binder layers and deteriorated them for PLA and PCL. The wet starch addition method improved the mechanical properties of the sheets but weakened their response to water.

Conclusions

In this study, several physical and mechanical properties of HDF were investigated. In conclusion, the experimental results confirmed that panels with each trait performed well in many physical and mechanical parameters, with a small difference in flexural strength. This shows that those panels meet the standards required in fashionable databases for distinct product categories.

Conflict of interest

The author(s) declare(s) that there is no conflict of interest concerning the publication of this article.

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