

INFLUENCE OF DENSITY ON MEDIUM-DENSITY FIBERBOARD PROPERTIES AT INDUSTRIAL SCALE EXPERIMENTAL

Osman ÇAMLİBEL

Assoc. Prof. Dr. Eng. - Kırıkkale University

Address: Department of Interior Design, Kırıkkale Vocational School, Kırıkkale University, Kırıkkale, Turkey

E-mail: osmancamilibel@kku.edu.tr

Murat AYDIN*

Assoc. Prof. Dr. Eng. - Isparta University of Applied Sciences

Address: Department of Machine, Keçiborlu Vocational School, Isparta University of Applied Sciences, Isparta, Turkey

E-mail: murataydin@isparta.edu.tr

Abstract:

The influence of density on the fiberboard was evaluated by producing 18 mm thick medium-density fiberboards with 568, 683, and 727kgm⁻³ densities. The 35:35:15:15 mixture of oak, beech, Scots pine, and fir woods was used for fiber production. The urea-formaldehyde resin, ammonium sulfate, and liquid paraffin were used as chemicals. Boards were produced on an industrial scale instead of a laboratory scale. The density, thickness swelling (2 and 24 hours), modulus of rupture, modulus of elasticity in bending, and internal bonding strength were determined. According to the results, considerable increases in mechanical properties were observed but internal bonding strength was the most advanced one. When density was increased from 568kgm⁻³ to 683kgm⁻³ and 727kgm⁻³, 1kgm⁻³ increase in density provided 0.0022MPa and 0.002MPa increases for the internal bonding strength, 0.074MPa and 0.08MPa increases for modulus of rupture, and 7.46MPa and 7.13MPa increases for modulus of elasticity, respectively. The thickness swelling (2h) percentages remarkably increased (104.4%) with the increase in density. However, the opposite behavior was observed for thickness swelling (24h) by around 18.5% decrease. Statistical analysis figured out that density has statistically significant influences ($P < 0.05$) on all determined properties.

Key words: industrial production; wood-based bio-composite; fiber composition; density.

INTRODUCTION

Even if the wood material can be supplied by sustainable resources, there are some challenging issues with the utilization of wood as solid material such as the increase in demand, physical and mechanical instability due to interaction with environmental factors etc. Engineered wood-based products came to the forefront to overcome these matters, and fiberboard is one of them. Fiberboards are classified into three levels in terms of density: low (<400kgm⁻³), medium, and high (>800kgm⁻³) (Suchsland and Woodson 1986). Due to its higher tolerance of raw materials, uniform features, excellent secondary processability, precise machining, and finishing ability, medium-density fiberboard (MDF) is a superior alternative for solid wood (Hong *et al.* 2017).

Lots of factors influence the MDF properties. These factors can be categorized into three classes; wood-related factors (species, density, fiber length, fiber moisture content (MC), the strength of the fiber tissue, wetting ability of fiber surface, and surface free energy) (Cai *et al.* 2006), resin-related factors (type, reactivity, chemical structure and composition, condensation degree, molar mass distribution, formaldehyde/urea (F/U) mole ratio, viscosity, level of adhesive spread, and rate of resin curing) (Chow and Zhao 1992), and production-related factors (hot-pressing temperature, pressing pressure and duration, mat MC, and assembly time) (Déneši *et al.* 2012). Particularly, density and resin content (RC) may be the most influential parameters that have effects on MDF properties (Hong *et al.* 2017), and the following are some of the studies that dealt with the impact of density on the physical and mechanical properties of MDF.

Hong *et al.* (2017) evaluated the effect of density (650, 700, 750, and 800kgm⁻³) on thickness swelling (TS), water absorption (WA), formaldehyde emission (FE), internal bonding (IB), modulus of rupture (MOR), modulus of elasticity (MOE), and screw withdrawal resistance (SWR) of 12mm thick fiberboards produced using UF resin (61% solid), *Pinus rigida* Mill., and emulsion wax (40% solid). The authors stated that MOE, MOR, SWR, and IB were increased with the increase in density while TS and WA were decreased.

Ayrılmış (2002) evaluated the influence of fiber types (beech (*Quercus robur* L.), oak (*Fagus orientalis* Lipsky), pine (*Pinus nigra* pallasiana), and 40:40:20 mixture, respectively) on TS and WA for 2 and 24h of 18mm MDF. The 1% wax, 0.8% NH₄Cl as hardener agent, and 11% urea-formaldehyde (UF) resin

* Corresponding author

were included in fiber furnish. Board densities were 758, 763, 763, and 766kgm⁻³, respectively. According to results, TS and WA orders for 2 and 24 h water soaking was oak>beech>mixture>pine.

Wong *et al.* (2000) evaluated the influences of the hot-pressing method and mat MC distribution on forming the density profile (homo and typical U-shaped) and its effects on physical (TS and WA) and mechanical (MOR, MOE, IB, and SWR) of 12mm thick fiberboard manufactured using lauan (*Shorea spp.*) fibers with an isocyanate resin. The authors stated that variation in peak density (PD) was higher than those of core density (CD). The authors reported that MOR, MOE, IB, and SWR, increased with the increase in mean density. Furthermore, for the 0.7gm⁻³ mean density (MD) board, 0.972 and 0.505R² values were reported for MOR vs MD and MOE vs MD, respectively. However, lower R² values (0.765 and 0.286) were reported for the 0.5gm⁻³ MD boards, respectively. On the contrary, 0.866 and 0.940R² values between MOE_{dyn} vs PD were reported for 0.7 and 0.5gcm⁻³ MD boards, respectively. Moreover, it's stated that IB and SWR of the fiberboard are almost completely determined by the CD and MD, respectively.

Minhas *et al.* (2021) evaluated the effect of hot-pressing factors (temperature, pressure, pressing time, and MC) on the IB, MOR, and density profile of the 18mm MDF produced using a 60:20:20 mixture of poplar (*Populus caspia*), ghaz (*Tamarix aphylla*), and lachi (*eucalyptus*) fibers, respectively.

Rockwood *et al.* (2022) produced MDF using *Eucalyptus grandis*, *E. amplifolia*, *Corymbia torelliana*, and *Populus deltoides* with different production parameters (resin type and percentage and fiber screening) and determined the physical and mechanical properties. The authors reported remarkable variation among and within the species, but just minor within tree variation. The authors calculated 0.945R² for the average MOE vs MOR of all boards.

Ganev *et al.* (2005a) evaluated the influences of density (540, 650, and 800kgm⁻³) and MC (50, 65, and 80% relative humidity) on some elastic constants of 12mm MDF produced using *Picea mariana* and UF resin. The authors reported that the influence of nominal density on some elastic constants was significant, and elasticity and shear modulus increased with the increase in density but no significant influences were observed for Poisson's ratios. The authors reported 0.87 (13.1% MC) -0.97 (6.9% and 10% MC) R² and 0.22 (13.1% MC)-0.97 (10% MC) R² values for elasticity and shear moduli, respectively.

OBJECTIVE

A higher volume of materials (fiber, resin, and wax) is required to produce higher-density panels, which is one of the reasons for increased production costs (Hong *et al.* 2017). Certainly, typical features of the material such as microscopic structure, strength properties, chemical composition, etc. could define the fiber production parameters but density is the most significant factor which has effects on the production process (Xu and Suchsland 1998, Ayrılmış 2002). Therefore, the main motivation of this study was to figure out the influence of density on MDF produced using the fiber mixture of four different wood species (70:30 mixture of hardwoods and softwoods), respectively.

MATERIALS AND METHODS

Oak, oriental beech, Scots pine, and fir species were used to obtain fiber. Raw wood materials were obtained from Bolu and Zonguldak Forestry Departments. The urea-formaldehyde (UF) resin, ammonium sulfate ((NH₄)₂SO₄), and liquid paraffin were used as a bonding, hardening, and modification chemicals, respectively. Chemicals were obtained from private companies located in Gebze and Denizli, Turkey.

The MDF with three density groups, 568kgm⁻³, 683kgm⁻³, and 727kgm⁻³, were produced. Boards evaluated in this study were produced on an industrial scale in a commercial board production company instead of a laboratory scale, and the phases of the production are illustrated using Fig. 1. Furthermore, the properties of the chemicals and materials and production parameters to obtain three different density groups of the boards are presented in Tables 1 and 2, respectively.

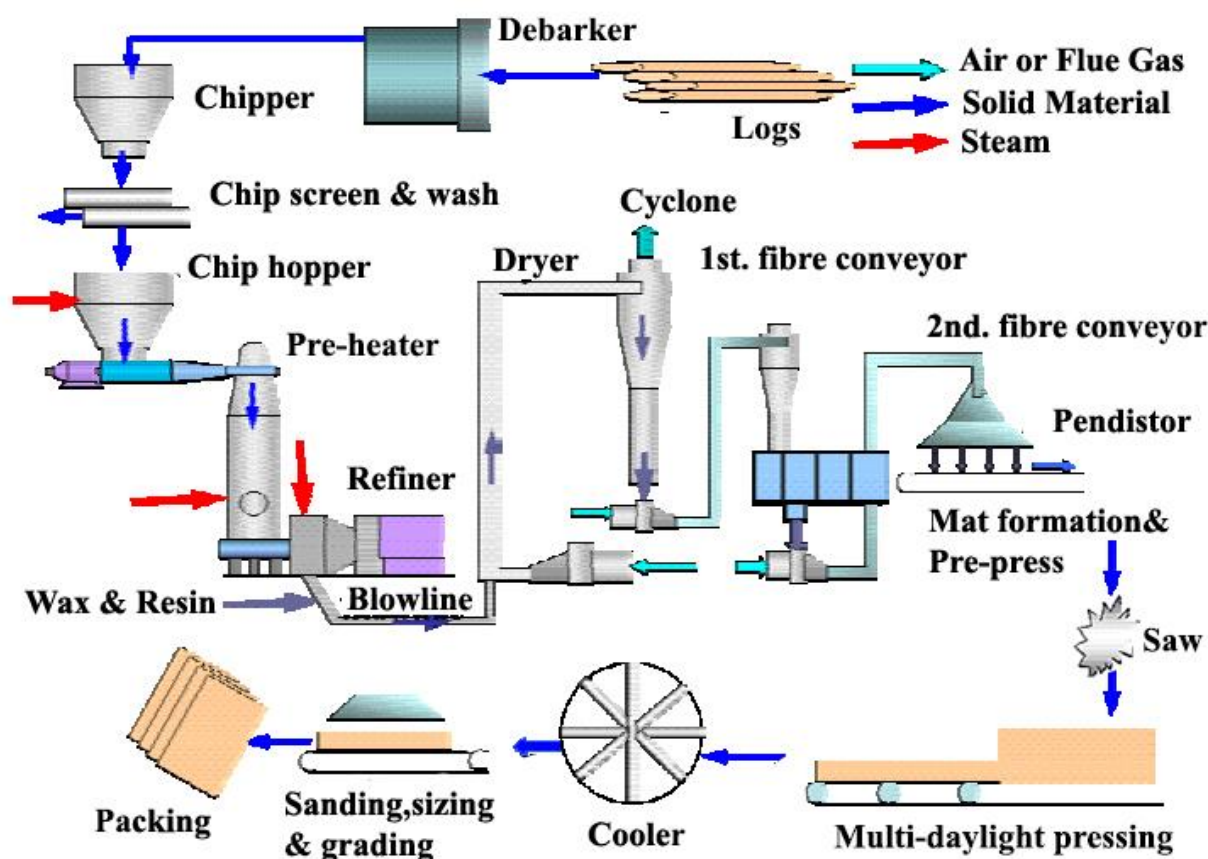


Fig. 1.
Production phases of MDF on an industrial scale, adapted from Li and Pang (2006).

Table 1

Properties of the chemicals

Resin	Appearance	Clear white liquid
	Solid matter (%)	65 ± 1
	Formaldehyde/Urea mole ratio	1.17
	Density (gr cm ⁻³ @ 20°C)	1.265 - 1.275
	Viscosity (cP @ 20°C)	185
	pH	7.5-8.5
	Free formaldehyde (%)	0.5 max
	Metilol groups (%)	12-15
	Shelf time (days @ 20°C)	45
Paraffin	Appearance	Micro crystal
	Fat ratio (% wt.)	1.5 max
	Density (gr cm ⁻³)	0.98
	pH	9-11
Hardener	Appearance	Off-white
	Structure	Crystal grain

Table 2

Raw materials and processing parameters

Properties		Board Densities (kg m ⁻³)		
Chip mixture	Hardwoods (70%)	568	683	727
		Oak (50%)	Oak (50%)	Oak (50%)
	Softwood (30%)	Beech (50%)	Beech (50%)	Beech (50%)
		Scots pine (50%)	Scots pine (50%)	Scots pine (50%)
		Fir (50%)	Fir (50%)	Fir (50%)
Chip processing	Chip size (mm)	25×20×5	25×20×5	25×20×5
	Cooking duration (min)	3.5	3.5	3.5
	Cooking Steam Pressure (bar)	7.0	7.0	7.0
	Cooking Temperature (°C)	180	180	180
	Hardwood Chip Moisture (%)	70	70	70
	Softwood Chip Moisture (%)	95	95	95
	Draft Moisture (%)	12	12	12
	UF Resin (1.17 Moles) (% wt. dry fiber)	8-9	9-10	10-11
	Resin Solid matter (%)	65 ± 1	65 ± 1	65 ± 1
	Hardener Solid (NH ₄) ₂ SO ₄ (% wt. dry fiber)	0.7	0.7	0.7
	Gel Time (s)	100	100	100
	Liquid Paraffin (% wt. dry fiber)	0.55	0.55	0.55
Mat laying and pressing	Pre-pressing Pressure (kg cm ⁻²)	110-90-105	90-90-120	95-15-120
	Pressing Pressure (kg cm ⁻²)	30	32	34
	Mat Moisture (%)	10	10	10
	Pressing Temperature (°C)	174	178	185
	Pressing Time (s)	205	255	270
	Continuous Press Factor (mm s ⁻¹)	12	12	12

As illustrated in Fig. 1, raw materials were transformed into chips and stored in separate silos. Chips were screened using an oscillating/vibrating screener. As can be seen in Table 2, 35:35:15:15 mixture of species was used for board production. Screened chips were pre-steamed at the pre-heating part of the refiner unit using 130°C temperature and 2.4 bar steam pressure. Chips were transferred to Asplund defibrator (digester) (Stockholm, Sweden) using a plug-screw and were cooked for around 3.5 minutes at 130°C temperature and 2.4 bar steam pressure. Cooked chips were transferred to the refiner using a discharge helix, and fibers were produced by the defibrillation process. Paraffin (0.55% kgm⁻³ wt. dry fiber) was applied to fibers at the discharge screw. The 10% solid-state ammonium sulfate (0.7% kgm⁻³ wt. dry fiber) was applied to the fiber at blowline. Three different amounts (Table 2) of the 65% solid-state UF resin were applied to the fiber at blowline. Fibers were dried to 12% MC at the dryer and then dried fiber was equally distributed by pendistor to prepare a uniform mat layout. Uniformly distributed fibers were pre-pressed using three different pressing pressures (Table 2) to obtain mats. Then mats were sized to 2150×2860mm in width and length, respectively. Sized mats were transferred to a multi-daylight hot press using an eight-story loading elevator. As can be seen in Table 2, three different pressing pressures, temperatures, and times were applied for density groups. Following the hot-pressing, boards were cooled using a star cooler and then sized to 2100×2800mm. After five days of conditioning in storage, board surfaces were sequentially sanded using 40, 80, and 120 sand sandpapers to obtain around 18 mm thickness and smooth surfaces. Consequently, 18mm thick 2100×2800mm sized boards were produced and stored in the warehouse.

Boards were acclimatized at 20±2°C and 65%±5 relative humidity (RH) in compliance with TS 642-ISO 554 (1997) standard. Density and thickness swelling (TS) for 2h and 24h of the boards were determined according to TS-EN 323 (1999) and TS-EN 317 (1999) standards, respectively. The modulus of rupture (MOR) and modulus of elasticity (MOE) and internal bonding strength (IB) were determined according to TS EN 310 (1999) and TS EN 319 (1999) standards, respectively. Physical and mechanical properties were determined using Imal IB 200 (Imal s.r.l., San Damaso, Italy) laboratory testing machine.

Descriptive data for physical and mechanical properties are presented. ANOVA test was performed to assess the variances. Duncan's multiple range test (DMRT) was used to figure out the statistically significant subsets for α 0.05. Histograms with interpolation lines and distribution curves were also presented (Fig. 2) in terms of density groups.

RESULTS AND DISCUSSION

The descriptives and statistics for the boards are presented in Table 3. The average densities were 569kgm⁻³, 685kgm⁻³, and 728kgm⁻³, and the coefficients of variation (CoV) were remarkably low (1.38, 2.64, and 2.88, respectively). It's thought that such low CoVs were obtained due to factory production instead of

laboratory production. Furthermore, according to Cai *et al.* (2006), density is linearly correlated with hot-pressing parameters such as core steam pressure and core temperature. As can be seen in Table 2, the pressure, temperature, and time of the 685kgm⁻³ and 728kgm⁻³ density boards are around 6.7% and 13.3%, 2.3% and 6.3%, and 24.4% and 31.7% higher than the 569kgm⁻³ boards, respectively.

Table 3

Descriptive data and statistics for the physical and mechanical properties

Properties	Density Groups (kg m ⁻³)	N	Mean (%) [*]	ANOVA		DHG	Std. Dev.	Std. Error	95% CI for Mean		Min.	Max.
				F	Sig.				Lower Bound	Upper Bound		
Density (kg m ⁻³)	569	20	568.95	489.23	0.000	A	7.84	1.75	565.28	572.61	555	582
	685	20	685.08 (20.41)			B	18.11	4.05	676.60	693.55	657	720
	728	20	727.95 (27.95)			C	21.00	4.69	718.13	737.78	700	766
TS 2h (%)	569	10	0.97	79.58	0.000	A	0.25	0.08	0.79	1.15	0.56	1.29
	685	10	1.08 (11.37)			A	0.15	0.05	0.98	1.19	0.89	1.29
	728	10	1.99 (104.40)			B	0.18	0.06	1.86	2.11	1.73	2.24
TS 24h (%)	569	10	18.00	65.34	0.000	A	0.70	0.22	17.49	18.50	17.01	19.33
	685	10	14.68 (-18.46)			A	0.81	0.25	14.10	15.25	13.25	15.80
	728	10	14.94 (-17)			B	0.65	0.20	14.48	15.40	13.88	16.03
MOR (MPa)	569	10	17.49	44.43	0.000	A	1.40	0.44	16.48	18.49	15.44	19.72
	685	10	26.09 (49.22)			B	2.59	0.82	24.24	27.95	22.25	31.27
	728	10	30.24 (72.96)			C	4.46	1.41	27.05	33.44	24.30	41.03
MOE (MPa)	569	10	1693.81	38.47	0.000	A	192.72	60.94	1555.95	1831.68	1416	1962
	685	10	2560.49 (51.17)			B	248.23	78.50	2382.92	2738.06	2219	2989
	728	10	2827.34 (66.92)			B	418.51	132.34	2527.95	3126.72	2311	3764
IB (MPa)	569	10	0.30	33.29	0.000	A	0.04	0.01	0.27	0.33	0.23	0.36
	685	10	0.56 (84.42)			B	0.05	0.02	0.52	0.59	0.49	0.64
	728	10	0.61 (106)			B	0.15	0.05	0.51	0.72	0.49	0.89

* % difference from 569kgm⁻³ group, DHG; Duncan's homogeneity groups

The mechanical properties of the boards were remarkably increased with the increase in density, but IB was the most influenced property among them. However, according to Ganev *et al.* (2005b), too many researchers did not note a correlation between density and IB strength. As can be seen in Table 3, the IB values of the panels were 0.30MPa, 0.56MPa, and 0.61MPa. Except for 0.7MPa of P7 type board (heavy duty-humid conditions) requirement, boards with 685kgm⁻³ and 728kgm⁻³ densities meet all the requirements (0.24MPa to 0.7MPa) of TS EN 312 (2012). However, as can be seen in Table 4, Levy (2012) reported considerably higher requirements than those of the standard. Moreover, slightly higher 0.62MPa and 0.66MPa values were also reported by Akgül *et al.* (2013) and Camlibel (2020), respectively.

According to Levene's test output ($p < 0.05$), variances for physical and mechanical properties were equal, and as can be seen in (Table 3), there are statistically significant ($P < 0.05$) differences between density vs physical and mechanical properties. Furthermore, Duncan's multiple range test results revealed that only density and MOR subsets are significantly different from each other. Indeed, there are no significant differences between the means of MOE and IB for 685kgm⁻³ and 728kgm⁻³ groups, and TS 2h and 24h for 569kgm⁻³ and 685kgm⁻³ groups.

Table 4

Literature data for comparison

Ref.	Fiber composition (100%)	Density (kg m ⁻³)	MC (%)	Thickness (mm)	TS 2 h (%)	TS 24 h (%)	MOR (MPa)	MOE (MPa)	IB (MPa)
(Çamlıbel and Yılmaz Aydın 2020)	70% (FO and QR) 30% (PS)	713	4.2	14.6	-	27.36	-	-	-
(Camlibel 2020)	70% (FO and QR) 30% (PS)	743	4.2	14	-	28.81	31.92	3384	0.66
(Camlibel and Akgul 2020)	70% (FO and QR) 30% (PS)	715	12	18	3.81	10.55	36.89	3483	0.58
(Akgül <i>et al.</i> 2017)	35% FO, 35% QR, and 30% PN	707	12	18	-	25.76	21.97	4248	0.49
(Ayrılmış 2002)	100% QR	763	-	18	-	-	27.04	2858	-
(Ayrılmış 2002)	40% FO, 40% QR, and 20% PN	-	-	18	-	-	30.8	2952	-
(Akgül <i>et al.</i> 2013)	50% QR and 50% FO	754	12	18	-	9.5	27.9	2628	0.62
(Levy 2012)*	-	640-800	-	≤21	-	-	24	2400	0.6
(Levy 2012)**	-	640-800	-	≤21	-	-	34.5	3450	0.9

FO; *Fagus orientalis* L., QR; *Quercus robur* L., PS; *Pinus sylvestris* L., and PN; *Pinus nigra* P, * for interior and ** for exterior utilization.

To advance the bond strength, an increase in board density and a high rate of compression are essential (Hong *et al.* 2017), and according to Cai *et al.* (2006), increasing compression ratios due to obtaining higher densities may increase the contact area between fibers and decreases the pores of fibers. As can be seen in Table 3, the averages of IB were remarkably increased (86% and 106% for 685kgm⁻³ and 723kgm⁻³, respectively) with the increase in density. Hong *et al.* (2017) reported that around 1kgm⁻³ increase in density causes 0.0004MPa increase in IB. In this study, this ratio is 0.0022MPa and 0.002MPa for 685kgm⁻³ and 728kgm⁻³ boards, respectively. These ratios are around 5.5 and 5.0 times higher than the reported ratios.

The MOR averages of the boards with 685kgm⁻³ and 728kgm⁻³ densities are considerably higher than the maximum value (20MPa) of the TS EN 312 (2012) standard. On the contrary, MOR of the 569kgm⁻³ density is 2.83% and 12.55% lower than P6 type (heavy duty-dry conditions) and P7 type board requirements, respectively while is higher than other board types. When the density increased from 569kgm⁻³ to 685kgm⁻³ and 728kgm⁻³, around 30.46%, and 51.22% improvements were obtained from the highest reference value, respectively. As for IB, Levy (2012) reported 24MPa and 34.5MPa requirements which are 20% and 72.5% higher than the reference value of TS EN 312 (2012) standard, respectively. However, the MOR of this study, particularly for 728kgm⁻³, is comparable with the reported values seen in Table 4. Except for fir, the fiber composition of the boards is comparable to Camlibel (2020) and Camlibel and Akgul (2020) but these are around 5.56% and 21.99% higher than the maximum value of this study.

Following the IB, around 72.96% advancement in MOR was achieved by density increases. However, for the 685kgm⁻³ group, advancement in MOE is slightly higher than those of MOR. According to the results, a 1kgm⁻³ increase in density provided 0.074MPa and 0.08MPa increases in flexural strength for 685kgm⁻³ and 728kgm⁻³ density groups, respectively.

As can be seen in Table 3, the MOE of 569kgm⁻³ density boards meets the minimum requirements of TS EN 312 (2012) for general and interior (including furniture) purposes under dry conditions. Moreover, requirements for nonstructural (humid conditions) and structural (dry and humid conditions) purposes are met by the boards with 685kgm⁻³. However, 2827.34MPa is around 5.76% and 8.8% lower than the TS EN 312 (2012) requirements for heavy-duty utilization in dry and humid conditions, respectively. Except for the 569kgm⁻³ value, MOE values are comparable to Levy (2012)*, Akgül *et al.* (2013), and Ayrılmış (2002), but both are considerably lower than Levy (2012)**, Camlibel (2020), Camlibel and Akgul (2020), and Akgül *et al.* (2017) seen in Table 4. As for MOR, around 51.17% and 66.92% improvements were achieved for MOE by the density increases. According to the results, a 1kgm⁻³ increase in density provided 7.46MPa and 7.13MPa increases in MOE for 685kgm⁻³ and 728kgm⁻³ density groups, respectively.

Density increase has an important impact on the mechanical properties of the boards. The MOE and MOR are positively influenced by panel density, not mat MC while IB is influenced both by mat MC and panel density (Cai *et al.* 2006).

The MDFs are dimensionally stable engineered wood-based products, but particularly when utilized under humid conditions, environmental factors may have influences on the structural integrity. Similarly, Halligan (1970) reported that there is a linear relationship between density (0.4gcm⁻³ to 0.8gcm⁻³) and TS when the particleboard (PB) is exposed to high humidity. According to the results, the TS of the boards was increased with the increase in density for 2 h soaking. Even around 104.4% increase occurred, swelling in thickness percentages (0.97, 1.08, and 1.99 corresponding 569kgm⁻³, 685kgm⁻³, and 728kgm⁻³ groups, respectively) are lower than 3.81% which was reported by Camlibel and Akgul (2020) for 18mm thick 715kgm⁻³ density MDF produced using 70:30 mixture of hardwoods (50:50 of *Fagus orientalis* L. and *Quercus robur*) and softwood (*Pinus sylvestris* L.), respectively. Furthermore, 0.66% to 1.16% and 4.42% to 6.03% TS 2 h and 24h percentages were reported by Candan *et al.* (2012) for commercially manufactured 18mm thick MDF using a 70:30 mixture of beech and birch woods and UF (65% solid content and NH₄Cl) resin to evaluate the influence of RC, MC, and continuous press speed. Wu and Piao (1999) reported that swelling in thickness rate increases with the increase in density for the commercial-oriented strain board. However, for this study, the same is not true for 24h soaking of the commercially produced MDFs, because around 18.46% and 17% decreases were observed for TS when density increased from 569kgm⁻³ to 685kgm⁻³ and 728kgm⁻³, respectively. In this study, the maximum TS was 18%, and the reported percentages seen in Table 4 are 9.5 (Akgül *et al.* 2013), 10.55 (Camlibel and Akgul 2020), 25.76 (Akgül *et al.* 2017), 27.36 (Çamlibel and Yılmaz Aydın 2020), and 28.81 (Camlibel 2020). The TS 24h percentages of this study are in the range of reported values. However, the 14%, 10%, and 10% requirements for P3 type (nonstructural-humid conditions), P5 type (structural-humid conditions), and P7 type (heavy-duty-humid conditions) boards reported by TS EN 312 (2012) could not be met while boards can fulfill the needs for general or interior (including furniture) and structural or heavy-duty purposes at dry conditions.

There are differences between wood-based materials and solid wood in terms of swelling in thickness behavior. Solid wood can go back to its original dimensions after the wetting-drying cycles, but wood-based materials cannot maintain their original dimensions after the cycles which are called non-recoverable TS

(Stamm 1935, Halligan 1970, Böhm *et al.* 2019). Furthermore, it should be noted that non-recoverable TS causes decreases in the strength properties of wood composites, and reduction in IB is directly related to the degree of internal glue bond damage due to excess TS (Wu and Piao 1999). According to Halligan (1970) efficiency of resin utilization can be increased by high density which may decrease TS.

According to the results, a 1kgm^{-3} increase in density caused 0.001% and 0.006% increases in TS 2h for 685kgm^{-3} and 728kgm^{-3} density groups, respectively. Contrary, a 1kgm^{-3} increase in density caused 0.03% and 0.02% decreases in TS 24h for 685kgm^{-3} and 728kgm^{-3} density groups, respectively.

Sarmin *et al.* (2013) evaluated the influence of density (500kgm^{-3} , 600kgm^{-3} , and 700kgm^{-3}) on TS of PB produced using UF resin and *Acacia mangium* and stated that TS performance of the boards have 600kgm^{-3} density was better than others. When compared to the results of this study seen in Table 3, the same is true only for TS 24h while is not for 2h.

Ayrılmış (2007) evaluated the effect of density (720kgm^{-3} , 760kgm^{-3} , and 800kgm^{-3}) on TS of 11mm thick MDF produced using UF resin and fiber mixture of beech and pine. Samples were conditioned at 30%, 65%, and 85% and compared to 65% RH. According to the results, TS ratios for 720, 760, and 800kgm^{-3} densities were 2.05%, 2.31%, and 2.6% for 30% RH, 2.8%, 3.11%, and 3.4% for 85% RH, respectively. Ratios were 2.14%, 2.4%, and 2.71% and 2.85%, 3.14%, and 3.45% for perpendicular to the sanding direction of the panel, respectively. Furthermore, 0.83 and 0.79 R^2 values for density vs TS in adsorption conditions were reported. The author reported that density has an adverse effect on the dimensional stability of MDF. For this study, this is true only for 2h applications because around 17% and 18.5% advances in TS for 24h applications were observed when density increased from 569kgm^{-3} to 685kgm^{-3} and 728kgm^{-3} , respectively.

According to Wu and Suchsland (1997) and Wu (1998), commercial boards provide higher resistance to property changes when they are exposed to high MC levels. From this point of view, when the requirements of the European Standards are taken into consideration, it can be said that both boards are suitable for commercial applications.

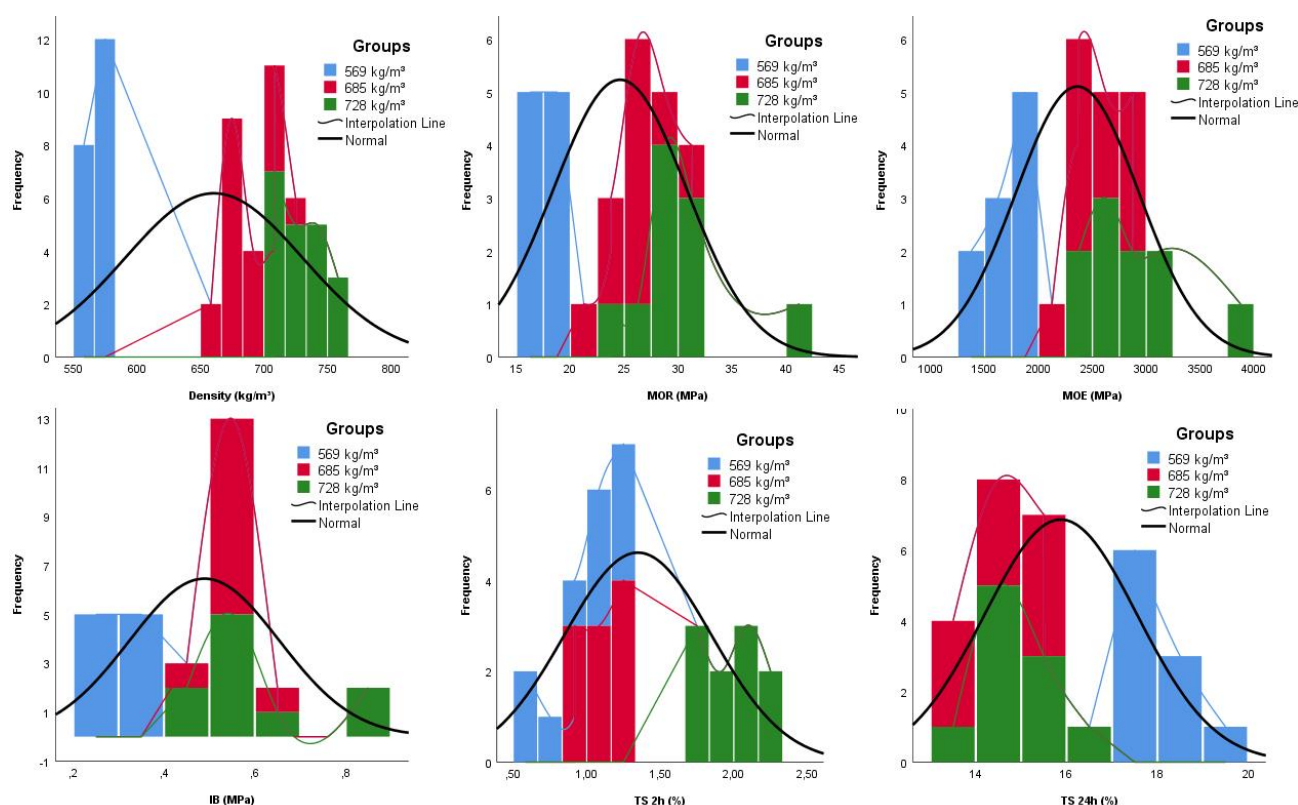


Fig. 2.
Histograms with interpolation line and distribution curve.

Using standalone fiber type may enable production to provide the highest consistency in board properties (Akbulut *et al.* 2000) but, in general, the combination of different species including hardwood and softwood is preferred to make use of wood resources. However, fiber mixture has significant influences on the physical and mechanical properties of the boards along with production parameters. According to Akbulut *et al.* (2000) low-quality oak, beech, and pine are the species generally used for raw materials for

mixture preparation. In this study, four different wood species were utilized for fiber production, and it should be taken into consideration those physical and mechanical properties strictly dependent on the properties of these species. For example, a high degree of homogenous structure of softwoods provides admirable fiber while hardwoods cause mixed fiber types such as Libriform wood fiber, fiber-tracheid, parenchyma cell, etc (Ayrılmış 2002). Therefore, to make an in-depth comparison, boards should be produced using these species as standalone fiber with the same density levels.

According to Ganev *et al.* (2005b) fiber geometry and RC throughout the MDF panel thickness, along and across the forming direction are generally the same. Therefore, the compaction ratio is responsible for the differences among the layers that specify the overall board properties. The quantity of the paraffin and the density profile are some of the parameters that define the interaction of wood-based engineered materials with surroundings. Moisture penetration can be slowed by higher-density surface layers for short-term washing with water. However, the higher density of the surface layers does not appear to be suitable for exposure to high air humidity (Böhm *et al.* 2019). As presented in Table 2, the amount of paraffin utilized was constant for all the density groups, and influences of core and surface layers on the properties were not evaluated.

Due to the wide range of raw material selectivity that can make use of destruction leftovers, plant wastes, logs with small diameters, and low-grade lumber, mat-formed materials like MDF and PB will gain more interest (Sawata *et al.* 2008). The utilization of four different species for board production can be given as an example of this expression.

CONCLUSIONS

Both physical and mechanical properties were statistically significantly influenced by density, but IB was the most positively influenced property among them by around 106% increase and followed by MOR (72.96%) and MOE (66.92%). The TS 2 h is the most negatively influenced property by around 104.4% increase. Furthermore, among the evaluated properties, the oscillation was observed for TS 24h application, and slightly better performance was obtained by 685kgm⁻³ instead of 727kgm⁻³ density. Moreover, opposite behaviors were seen between TS 2h and 24h applications. In general, it's seen that all boards meet the requirements of the EN standards for general or interior (including furniture) and structural purposes under dry conditions.

In-plane density variations may play critical roles in the alteration of properties, and such an investigation should be carried out by performing a future study.

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DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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