The Effects of Continuous Press Speed and Conditioning Time on the Particleboard Properties at Industrial Scale

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Effects of continuous press speed (580 and 600 mm/s) and conditioning time (0 and 72 h) on some physical and mechanical properties and formaldehyde content of particleboards were investigated. The 18 mm thick boards were manufactured using urea-formaldehyde, with a 50% pine, 40% oak wood, and 10% poplar biomass mixture of the wood materials. According to the results of the unconditioned samples, the density, modulus of rupture (MOR), moisture content (MC), thickness swelling (TS), and water absorption (WA) were increased 0.8%, 4.4%, 0.4%, 4.4%, and 5.5% when press speed increased from 580 to 600 mm/s, while thickness, modulus of elasticity (MOE), internal bond (IB), surface soundness (SS), and free formaldehyde (FF) were decreased 0.3%, 4.9%, 2.4%, 10.6%, and 21.1%, respectively. On the contrary to the results of unconditioned samples, MOE and SS were increased 1% and 1.4%, respectively, and WA was decreased 3.5% with the increase in press speed when samples were conditioned for 72 h. Free formaldehyde content was the most prominent parameter influenced by the increase in press speed both for the unconditioned and 72 h conditioned samples.

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Keywords: Continuous press speed; Conditioning time; Particleboard; Physical and mechanical properties; Formaldehyde content

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INTRODUCTION

Particleboards (PBs) are engineered wood-based panel materials that are widely used in construction concerning painting, veneering, or other surface coatings. Due to its competitive price and remarkable physical and strength properties, PB is one of the most commonly used panel materials in the furniture or construction industry. On the other hand, formaldehyde release with the lapse of time in use is a safety burden even if they are produced in compliance with the standards.

Literature Background

When literature is reviewed, it becomes apparent that the essential investigation variables are pressing parameters (type, time, pressure, speed, *etc*.), material (standalone or a mixture of wood species, resin type and ratio in the core and surface layers, agricultural materials or wastes, cotton stalks, *etc*.), and modification agents (minerals, nano-wollastonite, nanosilver, *etc*.). Changes in physical (density, thickness, moisture content-MC, thickness swelling-TS, water absorption-WA, surface roughness-SR, *etc*.) and mechanical (modulus of elasticity-MOE, modulus of rupture-MOR, internal bond-IB, surface soundness-SS, screw holding resistance-SHR, *etc.*) properties, and formaldehyde emission (FE) are commonly evaluated dependent variables in the studies concern with particleboard production.

Effects of press type and parameters, wood species, and resin

The performance of the pressing process depends on time, pressure, temperature, resin type, *etc.* for discontinuous systems such as hydraulic plate press. In addition to these parameters, speed is one of the essential factors that have influences on the press time, temperature, pressure, resin curing, *etc.* for continuous press systems. Such combined influences for continuous press were evaluated in the following limited studies: Candan *et al.* (2012) evaluated the effect of continuous press speed (CPS) (6.9 and 7.4 m/min^1 speed, and 220°C temperature) on layer TS of 18 mm thick medium-density fiberboard (MDF) produced using a chip mixture (70:30 beech and birch wood, respectively). It was stated that TS (2 and 24 h) values decreased when CPS increased, and resin content (RC) and moisture content (MC) and CPS could be effectively used to obtain the desired performance. Çamlıbel (2020a) evaluated the effect of UF utilization percentages on the properties of 18 mm thick 725 kg/m^3 density fiberboard produced using the birch and continuous press. However, no production parameters for pressing were reported. Çamlıbel (2020b) evaluated the effect of speed (200, 230, 240, and 250 mm/s), temperature (185, 210, 220, and 230°C), and time (150, 160, 170 and 200 s) of press application on the density, WA, TS, and free formaldehyde (FF) of the PB produced using continuous press and 40:30:20:10 mixture of Scots pine (*Pinus sylvestris* L.), sessile oak (*Quercus petraea* (Matt.) Liebl.), poplar (*Populus alba* L.), and sawdust. The author stated that further increases than optimum set-up values in press time and temperature were responsible for adverse effects on the PB properties. Ciobanu *et al.* (2014) evaluated the effects of CPS (500 to 1190 mm/s), temperature (190 to 250 °C), and pressure (1.5 to 5 MPa) on the properties of oriented strand boards (OSB type 3) produced using melamine-urea-formaldehyde (MUF) and polymeric diphenylmethane diisocyanate (PMDI) adhesives, and the mixture of soft- and hardwood species. The authors stated that physical and mechanical properties are strictly related to speed and press factor, and low speed increased all the mechanic properties.

Onuorah (2001) evaluated the effect of pressure and time for fast (4.83 and 3.79 MPa for 1.5 min) and slow (3.45 and 2.76 MPa for 3 min) closing application in hot pressing (350 °C) on the properties of 13 mm thick PBs produced using pine and maple furnishes. Miyamoto *et al.* (2002) evaluated the effect of press closing time (PCT) (4, 10 to 900 s correspond to 115, 117 to 105 °C temperature) on MOR, MOE, and IB of 10 mm thick PB produced using Hinoki (*Chamaecyparis obtusa* Endl.). The authors stated that "The bending properties decreased with increasing PCT because of the low density and the pre-cured layer in the surface regions of the board," and "TS seemed to increase with increasing PCT."

Warmbier *et al.* (2014) evaluated the effects of temperature (180 and 200°C), press time (4 and 6 min), and shelling ratio (0.3 and 0.4) on the MOE, MOR, IB, and SHR of 16 mm thick PB produced using willow *Salix viminalis* and pine particles for the core and face layers, respectively. The authors stated that 180 °C and 4 min press application was not enough for the adequate cure of adhesive. Iswanto *et al.* (2014) evaluated the effects of pressing temperature (110, 120, and 130 °C) and time (8 and 10 min) on the quality of the PB treated by immersing in 1% acetic acid solution, and stated that higher pressing temperature and time provided the highest physical and mechanical properties. Nitu *et al.* (2020) evaluated the effect of press temperature and time (160 to 240 °C and 4 to 10 min), varying mixtures (0, 30, 40, 50, 100%) of fine and coarse particles on the properties of 6 mm thick 900 kg/m^3 density jute stick binderless PB. The authors reported that 220 °C and 6 min were the optimum pressing conditions. Saad *et al.* (2019) evaluated the utilization of empty fruit bunches (EFB) and the Merkusii pine bark for 10 mm thick PB production by optimizing the composition (90:10, 85:15, 80:20, 75:25, and 70:30), temperature (150, 160, 170, 180 and 190 °C), and time (10, 15, 20, 25, and 30 min) variables. However, the authors stated that PB did not meet the requirements of density, MC, and MOR. Widyorini (2020) evaluated the effect of pressing temperature (160, 180, and 200 °C) and time (5 min + 1 min breathe + 5 min) on the properties of PB produced using bamboo petung particles, and the mixture of sucrose and ammonium dihydrogen phosphate (100:0, 95:5, 90:10, 85:15, and 80:20 wt%) as adhesive. The author stated that the combined effect of temperature and the adhesive ratio was found to be significant for TS, WA, SR, MOR, MOE, IB, and SHR properties.

Nemli (2002) evaluated the effect of press temperature (180 and 200 °C), time (135 and 150 s), pressure (3.19 and 3.4 MPa), and adhesive ratio in outer and core layers (9.5:8.5, 11:9, and 9:7 dry wt) on TS, MOR, IB, and FE of PB produced using 50:40:10 mixture of beech, pine and poplar chips, and E1 class UF adhesive. The author stated that an increase in the temperature, time, and pressure in the pressing process improves the technological properties of PBs. Heebink *et al.* (1972) evaluated the effect of press temperature (163, 191, 218, and 246 °C), time (15, 30, 60, and 120 s), species (Douglas fir, aspen, and southern pine), thickness (6.35, 12.7, 19 and 25.4 mm), density (481, 641, 801, and 961 kg/m^3), MC (8, 10, 12, and 14%), and resin type (urea-formaldehyde (UF), phenol-formaldehyde (PF), and melamine-formaldehyde (MF)) on the properties of PB to provide maximum values at minimum pressing time. The authors stated that optimum time-temperature combination provides a proper cure of binder and loss of sufficient moisture to prevent steam blisters. However, reduction in pressing time caused proportional decreases in board strength. Li *et al.* (2010) stated that for the exact cure of the resin, extended press time (350 s; 40 s closing, 260 s at the target thickness, and 50 s opening) was used for the production of PB using different geometries of rice straws. Ramezanpoor Maraghi *et al.* (2018) evaluated the effect of pressing temperature (160 and 170°C), density (650, 700, and 750 kg/m^3), and RC (9 and 11%) on the properties of 16 mm thick PB produced using poplar wood slab, citrus branches and twigs of beech, and UF adhesive. The authors stated that temperature increases provided slight increases in WA and MOE, while there were decreases in IB and TS. Barragàn-Lucas *et al.* (2019) determined the effects of pressing temperature (150 and 170 °C) and RC (15 and 35%, and 25 and 45% coarse and fine fibers, respectively) on the properties of the PB made of banana pseudo-stem. The authors stated that temperature negatively affected the density and TS, and positively affected the FF, WA, MOE, and MOR. Yel *et al.* (2020) evaluated the effect of press temperature (20, 30, 40, 50, 60, 70, and 80 °C) on cement-bonded PB produced with spruce and poplar wood species, and stated that exceeding the 60 °C causes reverse effects on the properties. Ferrandez-Villena *et al.* (2020) evaluated the effects of pressing time (7, 7+7, 15, 15+15 min), pressing cycle (two cycles of 7+7 and 15+15 min), and particle size on the the properties of PB produced using *Arundo donax* L. The authors stated that mechanical properties are increased with the increase in time. On the contrary, a shorter pressing time caused better TS and WA values. The 0.25 to 1 mm particle sizes provided better mechanical properties.

Nemli *et al.* (2004) evaluated the effect of press type (continuous and discontinuous hydraulic plate) on MOE, MOR, SHR, Tensile Strength (TS), 18 mm thick 680 kg/m^3 density PB produced using 50:40:10 mixture of beech, pine, and poplar species, respectively. According to results, MOR, MOE, SHR (perpendicular to the plane), and TS were found to be lower than the values obtained using discontinues press. On the contrary, TS (perpendicular to the plane) and SHR (perpendicular to the edge) were found to be higher than the values obtained using a discontinuous press. Differences in core layer furnishing, and press temperature, and pressure were assumed as factors that caused value deviations between continuous and discontinue presses. Nemli and Demirel (2006) determined MOR, MOE, IB, TS, and SR of 18 mm thick PB produced using continuous (220 °C and 155 s) and one-opening presses, and beech (*Fagus orientalis* Lipsky.), poplar (*Populus tremula* L.), pine (*Pinus sylvestris* L.), and oak (*Quercus cerris* L.) species. The authors stated that TS of the PB was influenced by press type, and continuous press application provided lower TS values than on-opening. On the other hand, MOR and MOE of PB produced using a one-opening press provided higher values. Significant IB values for the PB were obtained when the continuous press was used. Güler and Sancar (2016) stated that boards produced using discontinuous (one-layer) press provided higher MOR and IB, and lower TS (2 h) values than continuous press. Furthermore, one-layer discontinuous press can be chosen to produce the better quality board, but when production capacity is taken into consideration continuous presses come to forefront.

Effects of modification agents

Mantanis *et al.* (2018) reported that fire retardant agents for PB are used in solid form and mixed with the chips in the blending phase. Up to 30% slower press speed is needed in this type of production. Lehmann *et al.* (1973) evaluated the effect of variables (catalysts used in gluing, and non-catalyzed resin binders) on the physical and mechanical properties of PB for the determination of minimum pressing time for production. The authors stated that heat transfer is the primary issue that varies with thickness, press temperature, closing rate, and mat moisture distribution. The nano-wollastonite addition to improve thermal conductivity, physicals and mechanical properties of the boards was evaluated by Taghiyari and Nouri (2016), and the authors reported that 15% utilization can be recommended to advance the properties. Taghiyari and Norton (2014) reported that hot press duration and nano-silver addition have significant effects on the hardness, WA, and TS properties of fiberboard. Yıldırım and Candan (2021) stated that nanocellulose and boric acid have significant influences on physical and mechanical properties of PB. Leng *et al.* (2017) stated that density and cellulose nanofibrils addition (10, 15, and 20% dry wt) have significant positive influences on MOE and MOR, while particle size has slight influence. İstek *et al.* (2018) reported the formaldehyde-related problems and reduction methods for the FF or FE of wood-based boards. Çamlıbel and Yılmaz Aydın (2020) reported that zeolite utilization reduces the ability of making bonds between fibers that is assumed as one of the reasons for higher TS and WA values. However, the 1.5% zeolite addition provided decreases in FE. Çolak *et al.* (2015) stated that addition of tannin and chitosan (2%) decreased and increased the FE of PB, respectively. Furthermore, maximum FE was observed when both tannin and chitosan added. Nemli and Çolakoğlu (2005) reported that using mimosa bark on PB production caused the lowest mechanical properties, and FE and TS of PB were significantly decreased with bark usage. Lum *et al.* (2014) reported that FE of PB was reduced when amino compounds were applied in production. Buyuksari *et al.* (2010) determined FE, and some physical and mechanical properties of 10 mm thick PB produced using mixture of *Pinus nigra* Arnold var. *pallasiana* and *Fagus orientalis* Lipsky woods and cone particles. The authors stated that PB can be produced using cone in a mixture with wood particles and UF adhesive.

Numeric modeling and analysis

Continuous hot presses (CHP) are one of the main equipment types for fiberboard production (Zhu *et al*. 2018). Besides the cited study, the following studies present numerical analyses of CHP for fiberboard or PB production. Godbille (2002) provided a two-dimensional numeric model for CHP of PB and determined the effects of parameters on the process. Pereira *et al.* (2006) developed a three-dimensional model for CHP of MDF and simulated predictions of the model. Thoemen and Humphrey (2003) provided a numerical model that is directly applicable to CHP, due to the provided specific properties for CHP such as “changing mat thickness and steel belt temperatures in the feed direction, and the escape of vapor and air through the horizontal surfaces immediately in front of and behind the press, and the possibility to vary the mat thickness across the width of the press”. Lv *et al.* (2020) suggested a fuzzy failure mode and effects analysis technique combined with defect and failure analysis technique for the quality control of MDF production using CHP.

Apart from the categories already considered, the following studies also dealt with PB. Mirski *et al.* (2019) evaluated the effects of the three different chipboard structures (microchips, chip-sawdust, and chipboards) on the physical and mechanical properties. Taş and Sevinçli (2015) evaluated the utilization of different mixtures of waste lavender stems and red pine chips, and UF resin. An intensive literature review for the processing parameters and physical, strength, and moisture-related dimensional properties of PB was reported by Kelly (1977). Jasmani *et al.* (2020) reviewed nano-technology applications for the property (ultraviolet absorption, fire retardancy, mechanical properties, durability, biocide enhancement, *etc.*) improvements of wood or wood-based products.

As can be seen in the extensive literature review provided above, many studies have reported on the effects of different factors on the properties of PB. However, the effects of CPS and conditioning time (CT) on some physical and mechanical properties and FF of the PB have not been reported before. Also, PBs evaluated in this study were not produced using laboratory-type machines. On the contrary, they were produced using the actual production line of a factory to provide advances on the production process with fulfilling the commercial product requirements. Therefore, this study tried to figure out this issue using two different press speeds and conditioning periods under real production conditions.

EXPERIMENTAL

Materials

Wood

Scots pine (*Pinus sylvestris* L), sessile oak (*Quercus petraea* (Matt.) Liebl) woods, and waste poplar (*Populus alba* L.) woods (biomass) were used in this study due to the ease provided in these naturally grown species and physical, mechanical, and chemical properties as well. Scots pine, oak, and poplar raw materials were provided from Bolu, Zonguldak, and Sakarya province of Turkey, respectively. The mixture of 50, 40, and 10% of the species was prepared for panel production. Invaluable poplar wastes were used to reduce the cost of the boards.

Adhesive

Urea-formaldehyde adhesive, which was produced by the Kastamonu Glue Plant (Kasatamonu, Turkey) was used in this study, and the properties of the adhesive are presented in Table 1.

Table 1. Properties of the UF Adhesive Used for Panel Production

Properties	Values
Solids content (%)	62 ± 1
Molar ratio	Surface Layer (SL):0.98 and Core Layer (CL):1.07
Density (g/cm³ @ 20 °C)	1.227
Viscosity (250 cP)	20 to 35 s
Gel time (100 °C) (20% (NH_4Cl)	20 to 45 s
pH	7 to 8.5
Free formaldehyde (% max.)	0.20
Methylol groups (%)	12 to 15
Shelf life (day)	75

Hardener

Ammonium chloride (NH_4Cl), an organic compound, was used as the hardener agent provided by a private company in Gezbe, Turkey. The 20% NH_4Cl solution was used for the catalyst process. The density and pH of the solution were 0.95 g/cm³ and 6.5, respectively.

Paraffin

Paraffin, in liquid form and dirty white color, was provided by a commercial company (Mercan Chem. Co., Denizli, Turkey). The solid content, pH, viscosity, and density of the paraffin were 60%, 9 to 10, 13 to 23 s, and 0.96 g/cm³, respectively.

Methods

Board production

Raw wood materials were roughly chipped (Fig. 1-A) using a chipping machine, and chips were separately ensilaged using a band-type conveyor in terms of wood species. Chip mixtures were arranged according to production parameters. Chips for the surface layer (SL) and center layer (CL) were dried up to 2.5% and 1.5 to 1.75% MC level using a rotary cylinder dryer. Chips were screened using a three-leveled mechanic vibrating sieve. Pallman type mills were used for sizing the SL and CL, using the standardized chips. The sizes of the SL and CL chips were around 0.12 to 0.26 and 0.3 to 0.47 mm, respectively. Chips were ensilaged in the CL and SL silos according to their dimensions. The 10.8% and 6% adhesive solid contents were used for the SL and CL. The volumetric content of the boards for the CL and SL was 65% and 35%, respectively. Mats were obtained using the adhesive, hardener, and paraffin added chips in the layering station. Mats were pre-pressed for making them ready for the hot press process.

Particleboards were produced using the actual production line of the plant instead of laboratory-type machines. Production parameters of the PBs are presented in Table 2. Two different speeds (580 and 600 mm/s) were used to determine the CPS effect on the board properties. However, there are five different sequential sections of the CP, and the pressure and temperature of these sections were as shown in Table 2. Boards were cooled for around 60 min to obtain 20 to 25 °C temperature using a Star cooler. The PBs were sized in the dimension of 18 x 2100 x 2800 mm and sanded using 40, 80, and 100 grit sandpapers. Prepared PBs are presented in Fig. 1-B. To determine the effect of the CT on the properties, one of the speed groups was immediately tested and the other one was conditioned for 72 h in the acclimatization room at the end of all the production processes.

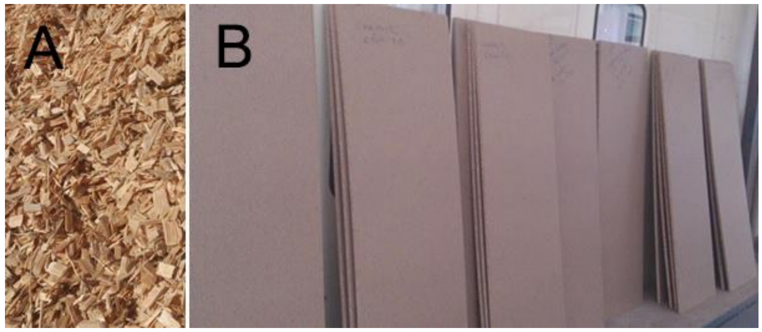

Fig. 1. A) Raw wood material, B) produced PBs

Table 2. Panel Production Parameters

Press Speed (mm/s)	580 and 600
Press Temperature (°C)	210 (1st and 2nd sections), 200 (3rd section), 185 (4th section), and 180 (5th section)
Press Pressure (MPa)	24 (1st section), 16 (2nd section), 11 (3rd section), 6 (4th section), and 1.5 (5th section)
Molar Ratio of UF (molar)	SL:0.98 and CL:1.07
Wood Mixture	50% Scot pine + 40% Sessile oak + 10% Poplar
Adhesive (L/Min) (%)	10.80 to 6.00
Hardener (L/Min) (%)	1.6 to 2.8
Paraffın (L/Min) (%)	0.30 to 25
Adhesive CL pH	8.14
Adhesive SL pH	8.19
Adhesive Solid Content CL	65
Adhesive Solid Content SL	50
Adhesive Molar Ratio UF CL	1.07
Adhesive Molar Ratio UF SL	0.98
Mixed Chips Moisture CL (%)	5.4
Mixed Chips Moisture SL (%)	14

Physical tests

Thickness, density, MC, TS, and WA of the samples were determined in compliance with the EN 324-1 (1993), EN 323 (1993), EN 322 (1993), EN 317 (1993), and EN 317 (1993) standards, respectively. Physical and mechanical properties and FF of the panels were determined in two different periods (immediately after the production and following the 72 h of conditioning) to determine the effects of CT.

Mechanical tests

The modulus of rupture and MOE, IB, and SS of the samples were determined in compliance with the EN 310 (1993), EN 319 (1993), and EN 311 (2002) standards, respectively. The Board Property Tester IB700 (IMAL Srl, San Damaso, Italy) was used to determine both physical and mechanical properties in compliance with the aforementioned standards.

Free formaldehyde content measurements

The free formaldehyde content of the boards was determined in compliance with the EN 120 (1992) standard. The perforator method was used for the determination of the content as described in the standard.

Statistical analysis

Analysis of Variance (ANOVA) was performed to reveal the influences of the CPS and CT on the PB properties. Furthermore, differences between the average values of the groups were presented by Duncan's multiple range tests (DMRT). A scatterplot matrix was created and coefficients of determination between all the variables were presented.

RESULTS AND DISCUSSION

Mean values for the thickness, density, MC, TS, and WA of the samples, and differences within and between the groups are presented in Table 3. According to the table, the maximum decrease with the increase in CT and increase in CPS were calculated for WA (-9.8%) within the 600 mm/s groups and TS (7.75%) between the 72 h groups, respectively. When CPS and CT increased, thickness and density values were slightly changed and the percentage changes ranged from -0.3 to 0.4% and -0.6 to 0.8%, respectively. According to the results, only TS and WA presented remarkable decreases with the increase in CT within the speed groups. The moisture content of the samples was steadily increased (6.69 to 6.89%) with the increase in CPS and CT. Lower MC values were obtained for the T_1P_{580} group and the maximum increase in MC was 2.8% for the $T_{72}P_{600}$ group.

Table 3. Means of the Physical Properties and Differences Within and Between the Groups

PB Groups*	N	Thickness (mm)	Density (Kg/m³)	MC (%)	TS 24 h (%)	WA 24 h (%)
T_1P_{580}	5	17.97	619	6.69	17.70	73.36
$T_{72}P_{580}$	5	17.984 (0.07)**	619 (0)	6.698 (0.06)	16.104 (-9.02)	72.38 (-1.34)
T_1P_{600}	5	17.922 (-0.28)**	624 (0.81)	6.72 (0.39)	18.478 (4.4)	77.428 (5.54)
$T_{72}P_{600}$	5	17.988 (0.37)*** (0.02)****	620 (-0.64) (0.16)	6.888 (2.5) (2.84)	17.352 (-6.09) (7.75)	69.87 (-9.76) (-3.47)

* T_x is the conditioning time and P_y is the press speed, ** % differences between T1P580, *** % differences between T_1P_{600}, and **** % differences between $T_{72}P_{580}$

Statistics and Duncan's homogeneity groups (DHG) for the thickness, density, MC, TS, and WA are presented in Table 4. CT and CPS had significant effects on the TS and WA within and between the groups. Mean values of the density and MC presented significant differences only for $T_{72}P_{600}$ and T_1P_{600}, respectively. Furthermore, mean values of the thickness were significant within the speed groups while they were not within the CT.

Table 4. Physical Properties of the Panels and Statistics

Physical Properties	Groups	N	Mean	DHG*	Std. Dev.	Std. Error	95% CI for Mean		Min.	Max.
							Lower	Upper		
Thickness (mm)	T_1P_{580}	5	17.922	A	.02683	.01200	17.8887	17.9553	17.90	17.96
	$T_{72}P_{580}$	5	17.984	B	.02074	.00927	17.9583	18.0097	17.96	18.01
	T_1P_{600}	5	17.922	A	.02683	.01200	17.8887	17.9553	17.90	17.96
	$T_{72}P_{600}$	5	17.988	B	.01483	.00663	17.9696	18.0064	17.97	18.01
Density (g/cm^3)	T_1P_{580}	5	619	A	1.87	0.84	616.68	621.32	617.0	621.0
	$T_{72}P_{580}$	5	619	A	1.58	0.71	617.04	620.96	617.0	621.0
	T_1P_{600}	5	624	B	2.35	1.05	621.09	626.91	621.0	626.0
	$T_{72}P_{600}$	5	620	A	2.35	1.05	617.09	622.91	617.0	622.0
M.C. (%)	T_1P_{580}	5	6.694	A	0.03	0.01	6.65	6.73	6.65	6.74
	$T_{72}P_{580}$	5	6.698	A	0.15	0.07	6.51	6.89	6.50	6.85
	T_1P_{600}	5	6.72	A	0.06	0.03	6.65	6.79	6.64	6.77
	$T_{72}P_{600}$	5	6.888	B	0.04	0.02	6.83	6.94	6.84	6.94
TS 24 h (%)	T_1P_{580}	5	17.7	C	.02739	.01225	17.6660	17.7340	17.67	17.74
	$T_{72}P_{580}$	5	16.104	A	.07503	.03356	16.0108	16.1972	16.02	16.21
	T_1P_{600}	5	18.478	D	.03194	.01428	18.4383	18.5177	18.44	18.52
	$T_{72}P_{600}$	5	17.352	B	.05119	.02289	17.2884	17.4156	17.29	17.41
WA 24 h (%)	T_1P_{580}	5	73.362	C	0.03	0.01	73.32	73.40	73.32	73.40
	$T_{72}P_{580}$	5	72.38	B	0.07	0.03	72.30	72.46	72.30	72.45
	T_1P_{600}	5	77.428	D	0.04	0.02	77.38	77.47	77.38	77.47
	$T_{72}P_{600}$	5	69.87	A	0.06	0.03	69.79	69.95	69.81	69.94

* DHG, Duncan homogeneity groups

Mean values for MOR, MOE, IB, SS, and FF, and differences within and between the groups are presented in Table 5. As can be seen in the table, there were remarkable differences within and between the groups. The maximum increase and decrease in the mechanical properties were observed for MOR (4.4%) and SS (-10.6%) in the T_1P_{600}, respectively. The modulus of rupture steadily increased (11.19 to 11.69 MPa) with the increase in CPS and CT. On the contrary to 600 mm/s CPS, MOE decreased with the increase in CT in 580 mm/s. Furthermore, around a 1.3% increase in MOE was observed when CT increased within the 600 mm/s CPS groups. Internal bond values were increased (3.1%) with the increase in CT; however, increasing speed between the immediate CT groups caused around 2.4% decrease. The same behavior with the MOE was observed for SS. Surface soundness values were decreased with the increase in CT and CPS except for $T_{72}P_{600}$. The maximum decrease (10.6%) in SS values was observed between T_1P_{580} and T_1P_{600}. As can be seen in Table 5, the FF was the most prominent parameter influenced by the increase in CPS for unconditioned PB, and a 21.1% decrease in FF was observed. However, this percentage was decreased to -8.8% when the samples were conditioned for 72 h. The 72 h conditioning caused a 12.8% reduction in FF in 580 mm/s speed groups while it was only 0.8% in 600 mm/s.

Table 5. Mechanical Properties and FF of the Groups

PB Group	N	MOR (MPa)	MOE (MPa)	IB (MPa)	SS (MPa)	Formaldehyde (mg/100 g)
T_1P_{580}	5	11.192	2372	0.332	1.428	5.146
$T_{72}P_{580}$	5	11.206 (0.13)*	2263 (-4.6%)	0.338 (1.81)	1.292 (-9.52)	4.486 (-12.83)
T_1P_{600}	5	11.682 (4.38)*	2256 (-4.89)	0.324 (-2.41)	1.276 (-10.64)	4.058 (-21.14)
$T_{72}P_{600}$	5	11.686 (0.03)** (4.28)***	2285 (1.29) (0.97)	0.334 (3.09) (-1.18)	1.310 (2.66) (1.39)	4.090 (0.79) (-8.83)

* % diff. between T1P580, ** % diff. between T1P600, and *** % diff. between T72P580

Table 6. Mechanical Properties of the Panels and Statistics

Mechanical Properties	Groups	N	Mean	DHG*	Std. Dev.	Std. Error	95% CI for Mean		Min.	Max.
							Lower	Upper		
MOR (MPa)	T_1P_{580}	5	11.192	A	0.03	0.01	11.16	11.22	11.16	11.22
	$T_{72}P_{580}$	5	11.206	A	0.01	0.01	11.19	11.22	11.19	11.22
	T_1P_{600}	5	11.682	B	0.04	0.02	11.63	11.73	11.64	11.74
	$T_{72}P_{600}$	5	11.686	B	0.05	0.02	11.63	11.74	11.63	11.74
MOE (MPa)	T_1P_{580}	5	2372	D	5.15	2.30	2365.61	2378.39	2367	2378
	$T_{72}P_{580}$	5	2263	B	3.87	1.73	2258.19	2267.81	2258	2267
	T_1P_{600}	5	2256	A	0.00	0.00	2256.00	2256.00	2256	2256
	$T_{72}P_{600}$	5	2285	C	3.61	1.61	2280.52	2289.48	2280	2289
IB (MPa)	T_1P_{580}	5	0.332	A	0.03	0.01	0.30	0.36	0.30	0.36
	$T_{72}P_{580}$	5	0.338	A	0.02	0.01	0.32	0.36	0.32	0.36
	T_1P_{600}	5	0.324	A	0.02	0.01	0.31	0.34	0.30	0.34
	$T_{72}P_{600}$	5	0.334	A	0.02	0.01	0.31	0.36	0.31	0.37
SS (MPa)	T_1P_{580}	5	1.428	B	0.04	0.02	1.38	1.47	1.38	1.46
	$T_{72}P_{580}$	5	1.292	A	0.03	0.01	1.25	1.33	1.25	1.33
	T_1P_{600}	5	1.276	A	0.03	0.01	1.24	1.32	1.22	1.30
	$T_{72}P_{600}$	5	1.31	A	0.03	0.01	1.27	1.35	1.28	1.35

* DHG, Duncan homogeneity groups

Statistics and DHG for the MOR, MOE, IB, and SS are presented in Table 6. CPS had statistically significant influences on the MOR. The influence of CT on the MOR was insignificant. All the MOE values differed significantly from each other in terms of CPS and CT. Contrary to MOE, neither CPS nor CT had statistically significant influences on the IB values of the boards. Only T_1P_{580} values of the SS presented statistically significant differences. Statistics and DHG for the FF of the samples are presented in Table 7.

Table 7. Free Formaldehyde Content of the Panels and Statistics

	Groups	N	Mean	DHG*	Std. Dev.	Std. Error	95% CI for Mean		Min.	Max.
							Lower	Upper		
Free Formaldehyde Content (mg/100 g)	T_1P_{580}	5	5.146	C	0.05	0.02	5.08	5.21	5.10	5.21
	$T_{72}P_{580}$	5	4.486	B	0.25	0.11	4.17	4.80	4.14	4.70
	T_1P_{600}	5	4.058	A	0.04	0.02	4.01	4.10	4.02	4.10
	$T_{72}P_{600}$	5	4.09	A	0.06	0.03	4.02	4.16	4.02	4.16

* Duncan homogeneity groups

According to DMRT, CPS and CT had statistically significant influences on the FF of the boards. However, no statistically significant difference was observed for the CT within the 600 mm/s groups. According to Nemli and Öztürk (2006) an increase in specific gravity, shelling ratio, and pressure caused an increase in FF of the PB. In the current study, a slight increase (0.8%) in density was observed when CPS was increased from 580 to 600 mm/s. Plus and minus error bars representing uncertainty or variation of the physical and mechanical properties and FF in terms of panel groups are presented in Figs. 3 through 5.

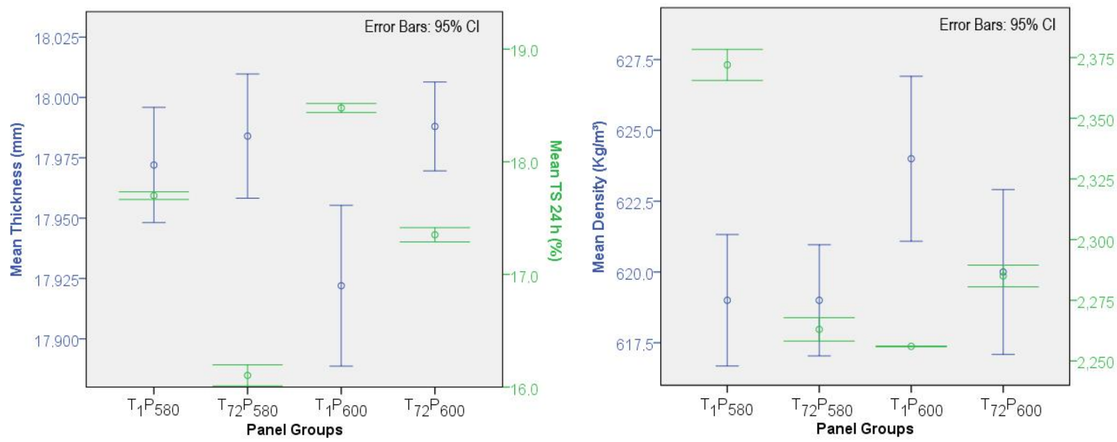

Fig. 3. Thickness, thickness swelling, density, and MOE properties of the panels

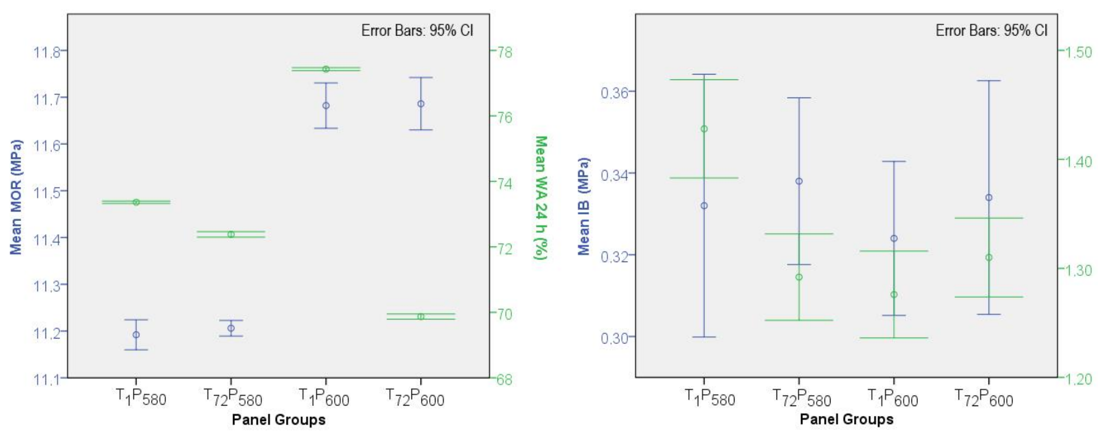

Fig. 4. MOR, WA, IB, and SS properties of the panels

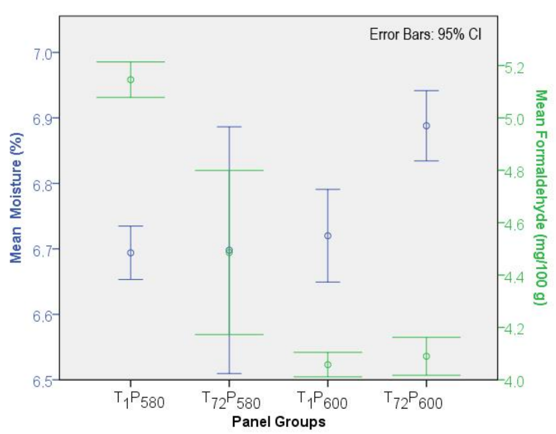

Fig. 5. Moisture and FF of the panels

Strength properties strongly depend on the density gradients of the panels. This means that decreasing the press time by setting the manufacturing parameters may cause proportional decreases in the strength of the boards (Heebink *et al.* 1972). In the current study, CPS was increased around 3.5%, and therefore a decrease in press time was obvious. However, the MOR of the PBs was increased (around 4.3%) with the increase in CPS. Also, slight increases (0.97% and 1.39%) in MOE and SS of the PBs were calculated when CPS increased. These increases were obtained after 72 h of conditioning. On the contrary, the increase in CPS caused reductions in MOE, IB, and SS of the PB that were tested immediately.

The temperature in the pressing also has influences on the quality of produced PB. The characteristics of PB are advanced due to the increased adhesive bonding rate because of the increased pressing temperature (Malanit *et al.* 2009; Ramezanpoor Maraghi *et al.* 2018). Increasing the CPS without changing the press temperature may decrease the heat transfer period. Therefore, the effective temperature on the continuous pressing may alter the results of this study. To identify this issue, the temperature should be taken into consideration in future studies as a crucial factor that has influences on the process.

According to EN 312 (2010), minimum MOR and IB values of PB (13 mm < thickness ≤ 20 mm) for general-purpose dry use (Type P1) are 11.5 and 0.25 MPa, respectively. Furthermore, minimum MOR, MOE, IB, and SS values of Type P2 PB (interior use including furniture, dry conditions) are 13, 1600, 0.35, and 0.8 MPa, respectively. The minimum value for the TS 24 h of PB is 14% (Type P3, interior use, wet conditions). Modulus of rupture for general and furniture manufacturing, and MOE for general purposes of the PBs are also reported as 11.5 and 13 MPa, and 1600 MPa, respectively (Nemli and Çolakoğlu 2005).

In this study, the MOE values of all the groups were considerably higher than the minimum requirements for both interior and general purposes. On the other side, only T_1P_{580} fulfilled the requirement of the dry condition for the structural purpose. Furthermore, none of the groups fulfilled the minimum requirements for heavy-duty structural utilization.

As can be seen in Table 5, the MOR of PBs that were produced using 580 mm/s CPS was slightly lower (2.68%) than the general-purpose reference values. On the contrary to 580 mm/s speed groups, MOR of the 600 mm/s groups was slightly higher (1.6%) than the general-purpose reference values reported by EN 312 (2010) and Nemli and Çolakoğlu (2005). According to standard, these PBs were neither suitable for interior nor structural because of the low MOR values, and only PBs that were produced using 600 mm/s CPS can be utilized just for general purposes.

The IB values of all the groups were considerably higher (40.8% for $T_{72}P_{580}$) than the minimum values for general purpose (P1), and slightly lower (3.4%) than the minimum values for interior purposes (P2 and P4). However, IB values of this study were significantly lower (24.9 to 51.7%) than the minimum values of P3, P5-7 type PBs.

The lower and higher TS 24 h values ($T_{72}P_{580}$ and T_1P_{600}) of this study were 15 to 32% and 7.4 to 23.2% higher than the reference values of P3 and P4 or P6 types PBs, respectively. However, TS 24 h values of P5 and P7 type PBs were significantly lower than the results of this study, and the differences between lower and higher values of this study. The P5 and P7 values ranged from 61 to 84.8% and 101 to 131%, respectively. Therefore, it's seen that produced PBs were able to meet neither interior nor structural requirements in terms of TS 24 h.

According to EN 312 (2010), SS of the P2 type PB (13 mm < thickness ≤ 20 mm) is 0.8 MPa. The SS values of this study ranged from 1.267 (T_1P_{600}) to 1.428 (T_1P_{580}), and these values were 58.4 and 78.5% higher than the minimum value of the reference. Therefore, all the produced PBs conform to the standard in terms of SS.

As mentioned in the introduction, studies have evaluated the effects of different types of variables on the physical and mechanical properties and FE of the PBs. However, the effect of CPS in PB production was evaluated in limited studies, while CT had not yet been studied. Ciobanu *et al.* (2014) stated that low speed and corresponding high press values cause increases in mechanical properties. Internal bond, TS, and WA slightly varied between the groups. In this study, only MOE (T_1P_{580}) and IB ($T_{72}P_{580}$) values were the maxima at low CPS as mentioned for OSB. On the contrary to OSB, MOR was considerably increased with the increase in CPS in this study.

Candan *et al.* (2012) stated that TS (2 and 24 h) values were decreased with the increase in CPS. However, an opposing behavior was observed for TS 24 h in this study. Çamlıbel (2020b) stated that further increases other than optimum set-up values in press time and temperature cause adverse effects on the PB properties. Press closing time has an adverse relation with density and an increase in PCT causes density reduction and pre-cured layer, which are responsible for the decreases in bending properties (Miyamoto *et al.* 2002). Porosity, water diffusion, and absorption are related to the density, and low density in the core layer cause increases in these properties. Furthermore, high density in the surface layers positively influences the bending properties. Moreover, IB has an adverse relationship with core layer density. Also, SR of the PB produced using a continuous press was higher than a one-opening press due to surface density differences (Nemli and Demirel 2006). Time and temperature combinations should be optimized to obtain a proper cure of binder and loss of enough moisture to avoid steam blisters, but it should be taken into consideration that reducing the time in pressing can cause a proportional reduction in strength of board (Heebink *et al.* 1972). An increase in pressing time provides advances in mechanical properties but for better TS and WA performance press time can be shorter (Ferrandez-Villena *et al.* 2020).

Addition of wollastonite nanofibers (10% dry wt.) in the UF resin used in MDF production using the mixture of beech, alder, maple, hornbeam, and poplar species provided around 11.5% improvement in thermal conductivity (Taghiyari *et al.* 2013), which is one of the essential factors for heat distribution. Furthermore, pressing time can be significantly reduced when the accelerated homogenous heat distribution is achieved by applying such modification agents, and proper resin curing and target MC levels can be achieved. Therefore, such minerals can be used for increasing the CPS.

As can be seen in the results of this study, CPS and CT have different influences on the PB properties instead of overall improvement or reduction. Therefore, CPS corresponding to press time should be in accordance with temperature and pressure to provide achievements. Due to the lack of comparative data in the literature, the discussion section of this study is limited. Furthermore, it is expected that this study may provide such data for future studies.

CONCLUSIONS

1. The influence of the continuous press speed (CPS) and conditioning time (CT) on the physical and mechanical properties and free formaldehyde (FF) of the particleboard

(PB) were evaluated in this study. When the temperature and pressure are constant in pressing, press speed defines the pressing time. Therefore, when the CPS increases, press time decreases. As a result of the duration decrease, the polymerization of resin would be affected. This circumstance influences the physical and mechanical properties of PB but in a different manner, as seen in the results.

2. Only moisture content (MC) and modulus of rupture (MOR) were increased with the increase in both CPS and CT. These increases within the CPS groups were not statistically significant for MOR. However, a significant difference within or between the MC groups was observed only for 72 h CT and 600 mm/s CPS. It's expected that statistically significant differences would be observed between the CPS groups instead of CT groups. This is reasonable because when the CP parameters are constant such as temperature and pressure, pressing time is shortened with the increasing of speed, and evaporation of moisture inside the mat decreases. In these circumstances, it's thought that PBs interacted with surrounding conditions while in storage.
3. Continuous press speed has no influence on thickness, while CT provided some slight but statistically significant increases. A saw tooth behavior was observed. As mentioned above, interaction with the surrounding at conditioning is assumed as one of the reasons for the differences.
4. Modulus of elasticity and surface soundness (SS) were decreased with the increase in CPS. However, CT had an adverse effect on MOE and SS in CPS groups. These values were decreased and increased with the increase in CT when the CPS was 580 mm/s and 600 mm/s, respectively. Furthermore, means of MOE within and between groups presented statistical differences. On the contrary, only SS values of T_1P_{580} presented statistically significant differences.
5. As in the MOE and SS, FF presented the same behavior relative to CPS and CT. An adverse effect of CT was observed when CPS increased. Formaldehyde emission was decreased when CPS increased. However, FF deceased and increased with the increase in CT when CPS was 580 mm/s and 600 mm/s, respectively. Furthermore, no statistically significant differences were observed for CT at 600 mm/s CPS.
6. Continuous press speed and CT had adverse effects on WA and TS. Water absorption and TS were increased and decreased with the increase in CPS and CT, respectively. Statistical significant differences were observed within and between the groups. This phenomenon was related to the issue mentioned in the first conclusion.
7. Conditioning time had no influence on density when CPS was 580 mm/s. On the contrary, CT adversely influenced the density when CPS was 600 mm/s, and density was increased with the increase in CPS.
8. Both CPS and CT had no statistically significant influences on internal bond (IB), but they oppositely affected IB. Internal bonding was increased and decreased with the increase in CT and CPS, respectively. Press time is one of the essential pressing parameters for the exact cure of the resin. Pressing time decreases as a natural consequence of the increase in press speed. Decreases in time, while other parameters are constant, may cause improper polymerization and reduction in bonding. Therefore, time, temperature, pressure, and speed should be optimized to obtain better physical and mechanical properties.

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