ORIGINAL

A study of the influence of press parameters on particleboards' performance

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Abstract

Nowadays, wood-based panel producers intend to lower costs by decreasing the pressing time and reducing resin consumption. Therefore, the aim of this work is to understand the influence of the pressing operating conditions (pressing time and pressing program) on the performance of particleboards (PBs) bonded with a UF resin (alkaline–acid process). For this purpose, several trials were carried out using a computer-controlled laboratory scale hot-press with a press cycle simulating a continuous press and a fixed position laboratory scale hot-press, varying the venting, the total pressing time (< 90 s, 90 s and > 90 s) and the gluing factor (resin content—4, 5 and 6 mg resin solids/g oven dry wood). Analysis of variance (ANOVA) was performed in order to evaluate the significance level of the effects of these parameters on PB's physico-mechanical properties and formaldehyde content. The main results of the study were: to decrease formaldehyde content, resin content (RC) should be increased for pressing times higher or equal to 90 s or decreased for pressing times lower than 90 s; to increase internal bond, RC must be increased for pressing times equal or higher than 90 s, or decreased for pressing times lower than 90 s.

1 Introduction

The manufacture of wood-based panels is an important process, which affects the quality of the final product. The hot-pressing process is the most important and costly operation, with several coupled physical–chemical–mechanical phenomena involved making this operation quite complex. Due to the multiplicity of this process, the development of mathematical models that enable the simulation of the operation is extremely important as it enhances the understanding of both the interactions and the effects of operating parameters on the product properties, whilst saving time and energy.

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Mathematical models are increasingly recognized as important tools for optimization, control and scheduling of this operation, having a potential importance for innovation in processes and products (Carvalho et al. 2003, 2010). In the past, companies changed the gluing factor (resin content— mg resin solids/g oven dry wood). Nowadays, a balance between the gluing factor and the pressing time is crucial.

Several parameters are crucial for the hot-pressing process: moisture content and distribution, steam pressure inside the board, time of pressing closure, press scheduling and density profile (Maloney 1989; Gonçalves et al. 2018). Over the years, a number of researchers have studied the hot-compression process based on empirical data collected on a small-scale laboratory press (Strickler 1959; Maku et al. 1959; Kelley 1977; Dai et al. 2004). Since the eighties, several models have been presented in the literature for the batch process, but they have limitations as they do not include all the phenomena. Humphrey et al. (1989) predicted the variation in temperature and vapor pressure within a particleboard mattress using a theoretical model. The initial mattress moisture content was assumed to be 11%, the press temperature was fixed at 160 °C and the board density at 650 kg m^{-3}. The model basis is a finite difference approximation with the assumption that the steady-state theory can

adequately describe the behavior of the system during each time increment (Humphrey et al. 1989).

In 1998, Carvalho and Costa developed a three-dimensional model for hot-pressing of MDF. The model performance was analyzed using the typical operating conditions for the hot-pressing of MDF. The temperature and moisture effects on the physical properties were included. The predicted results closely followed general temperature and moisture trends during a typical hot-pressing process. The improvement of the model required the accomplishment of an experimental program in a pilot scale press (Carvalho and Costa 1998).

Thoemen and Humphrey (2001) introduced a continuous hot-press numerical model. The heat and mass transfer properties and the rheological characteristics of the mat were determined experimentally. Zombori et al. (2003) developed a two-dimensional mathematical model to describe the internal conditions during the hot-compression of wood-based composite panels. The model is robust enough to simulate industrial pressing situations, including the press closing time and asymmetric boundary conditions. The pressing time was 480 s and the temperature 200 °C (Zombori 2001).

Carvalho et al. (2003) developed a dynamic model to predict the evaluation of the variables related to heat and mass transfer as well as the variables associated with the mechanical behavior including the effect of the chemical reaction. The model performance was analyzed using the typical industrial MDF operating system and the results indicated that the model could predict, in an acceptable way, the behavior of the key variables for the control of the pressing cycle, as well as some physico-mechanical properties of the final product. The initial temperature of pressing was 190 °C, press cycle time 330 s, and the board density 750 kg m^{-3} (Carvalho et al. 2003).

Pereira et al. (2006) presented a three-dimensional model for MDF continuous pressing by integrating all mechanisms involved in panel formation: heat and mass transfer, chemical reaction and mechanical behavior. The model performance was analyzed using the typical operating conditions for the continuous pressing of MDF and the parameters were calculated using empirical and theoretical correlations from the literature obtained for wood, PB or MDF. The authors observed that the obtained results are similar to the literature.

Dai and Yu (2004) presented a three-dimensional heat and mass transfer model as opposed to the two-dimensional model from Zombori (2001) and Zombori et al. (2003) or the cylindrical model of Humphrey et al. (1989). This model uses a more rigorous approach to heat and mass transfer mechanisms and all the main variables were well established. However, further studies were recommended to characterize the basic mat pressing properties such as thermal conductivity and permeability (Dai and Yu 2004).

Thoemen and Humphrey (2006) developed a three-dimensional model based on the fundamental principles to simulate heat and mass transfer and mat densification during batch or continuous hot pressing of wood-based composites. The model can be used as a tool to optimize the manufacture of existing natural fiber composites (Thoemen and Humphrey 2006).

In 2004, the regulation for formaldehyde uses became stricter, so it was needed to change the resin formulations. For these new resins, the mechanisms for resin cure kinetics, bond strength development, mat rheological behavior and heat and mass transfer during the pressing time are still under study. Carvalho et al. (2010) presented the state of the art of the transport phenomena involved in the hot-pressing and of the processes involved in the manufacture of wood-based panels (Carvalho et al. 2010).

Two years later, Martins et al. (2012) proposed a new methodology to predict the optimum pressing time for wood-based panels produced with low formaldehyde content resins. This study focused, in particular, on the additional compression of mat followed by an expansion of the mat, performed during the hot-pressing to promote the heat transfer to the mat core. The particleboards were produced at laboratory level and the pressing cycle was scheduled in order to study the effect of venting. In a first trial, the venting starting time, the total pressing time and the moisture content on the mat face layer were changed. In a second trial, the influence of the more significant pressing parameters on physical–mechanical properties and formaldehyde content were studied. With this work, a new methodology has been developed combining the results of mat internal temperature evolution and bond strength development curves obtained using ABES (automated bonding evaluation system) apparatus to estimate the internal bond strength. The methodology presented allowed for predicting the minimum pressing time needed to obtain a panel that meets the specifications (Martins et al. 2012).

In the present work, using a UF resin (synthetized according to alkaline–acid process), the parameters related to the gluing factor and pressing (time and pressing program) were considered. The impact of different pressing programs on the final properties of the particleboards (PBs) was studied. Using appropriate optimization and statistical tools, it was possible to obtain products that fulfil the desired market specifications, without implying loss of productivity.

2 Materials and methods

2.1 Materials

Formaldehyde (55 wt% solution), urea, ammonium sulphate (30 wt% solution), sodium hydroxide (50 wt% solution) and

acetic acid (25 wt% solution) were provided by Euroresinas-Indústrias Químicas, S.A. (Sines-Portugal). Wood particles (recycled mix) and paraffin (50 wt% solution) for the production of PBs (standard mix of wood particles included 30% maritime pine, 15% eucalypt, 25% pine sawdust and 30% recycled wood) were supplied by Sonae Arauco (Oliveira do Hospital-Portugal).

2.2 Methods

2.2.1 Resins production

The production of the resins was carried out in a 2.5 L round bottom reactor, equipped with mechanical stirrer and thermometer. The reactor was heated using an electrical mantle and the temperature was measured with a thermometer. The pH and viscosity measurements were taken offline on samples taken from the reaction mixture (and re-added after).

The reaction of U and F consists of three steps: a methylolation step under alkaline conditions; a condensation step under acidic conditions and finally the neutralization step and addition of a final amount of U to obtain the desired F/U molar ratio (Dunky 1998; Park et al. 2003; Pizzi and Mittal 2003).

2.2.2 Resins characterization

The resins performance was evaluated using common characterization methods involving the determination of physical and chemical properties, such as viscosity, solid content, gel time and pH. Advanced methods, such as chromatography techniques (gel permeation chromatography/size exclusion—GPC/SEC and high performance liquid chromatography—HPLC), were carried out in order to provide more specific and detailed information on the structure and subsequent performance of the resins.

2.2.3 PBs production and characterization

Wood particles (a standard mix included 30% maritime pine, 15% eucalypt, 25% pine sawdust and 30% recycled wood) were blended with resin, paraffin (1 wt%) and catalyst in a laboratory glue blender. Surface and core layers were blended separately. The catalyst amount in the core layer was 3 wt% and in the surface layers was 1 wt% (dry catalyst per solid resin). Three-layer PBs were hand-formed in a square aluminum deformable container with $210 \times 210 \times 80$ mm^3. Surface and core layer differ in particle size distribution and moisture content (MC). The upper surface layer had a mass of 20% (of the total mass), the core layer 62% and the bottom surface layer 18%. Three different pressing programs were used: one of the programs was carried out using a laboratory batch press equipped with two plates and blocks with

16 mm of height for boards with a final thickness of 16 mm (referred to as P—position control press). The other two programs were performed using a pressing program typical of a continuous industrial press, implemented on a computer-controlled laboratory hot-press equipped with a linear variable displacement transducer (LVDT), a pressure transducer and thermocouples. One of the programs was operated without venting (referred to as S—simulated control press) and another with venting (referred to as V—simulated control press with venting). The differences between the programs are exemplified in Fig. 1. As the time of pressing is adjustable, a percentage of time was considered to show the evaluation of the thickness, when comparing the different pressing programs.

The boards were pressed at 190 °C to produce a panel with a target density between 650 and 670 kg m^{-3} and a thickness of 16 mm. For all resins, three boards were produced using a pressing time shorter than 90 s (< 90), 90 s and longer than 90 s (> 90). For the shortest time, the boards were pressed for 80 s; and for the longest time the boards were pressed for 100 s or 110 s.

After pressing, the boards were stored in a conditioned room (20 °C, 65% relative humidity) and then tested according to the European standards for density (D) (EN 323), MC (EN 322), internal bond strength (IB) (EN 319) and thickness swelling in 24 h (TS) (EN 317). The formaldehyde content (F) of all samples was determined according to the perforator method (EN ISO 12460-5). The detailed procedures can be found in a review article by Gonçalves et al. (2018).

2.2.4 Experimental design

JMP (John's Macintosh Project, http://www.jmp.com) software was used for the design of experiments (DoE). A statistical analysis of variance (ANOVA) was done to determine which pressing parameters are statistically significant.
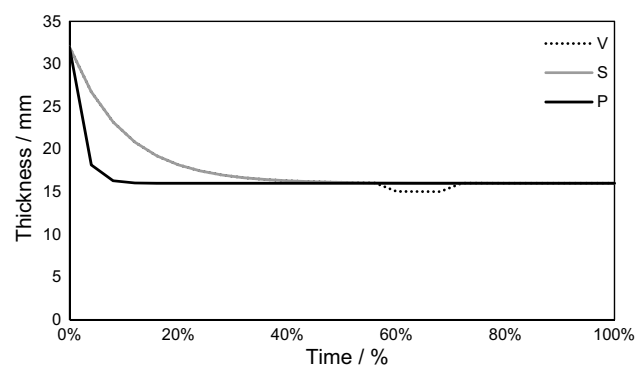

Fig. 1 Pressing program for a batch press (P), without (S) and with venting (V) procedure

Table 1 Factors and levels considered

Factors	Levels		
	1	2	3
Gluing factor (g resin solids/g oven dry wood)—RC	4	5	6
Pressing program	P	S	V
Pressing time (s)	< 90	90	> 90

Table 2 Standard characterization of the UF resin used

Viscosity (mPa s)	pH	Gel time (s)	Density (kg m^{-3})	Solids content (%)
180	8.9	50	1268	63.0

Table 1 summarizes the factors and levels considered for this study.

3 Results and discussion

3.1 Resin characterization

Table 2 summarizes the range of values obtained from the standard characterization of the resin used in this study after 24 h. All the values are within the range of values used by the company for PBs applications (viscosity 150–300 mPa s; pH 7.5–9.0; gel time 45–60 s; density 1265–1270 kg m^{-3} and solids content 62.5–63.0%).

The resin was analyzed by GPC/SEC and HPLC. Figure 2a shows the chromatogram for the UF resin synthesized in this work. The presence of low and high molecular

Table 3 ANOVA p-value and significance level (*5%, **1%, ***0.1%)

	RC	Pressing program	Pressing time (s)
IB (N mm^{-2})	0.0986	0.5338	< 0.0001***
D (kg m^{-3})	0.3215	0.4301	0.0013*
F (mg/100 g oven dry board)	< 0.0001***	0.6400	0.0180*
TS (%)	< 0.0001***	0.5101	0.0050*

weight polymer chains is detected: the peak at higher retention volume corresponds to free U, methylolureas and oligomers, whilst the leftmost portion of the chromatogram is associated with high molecular weight species. Figure 2b presents the results for HPLC. It is important to note that for this resin, the obtained values are within the company specifications.

3.2 Statistical analysis

Table 3 presents the ANOVA p-value and significance level for the studied parameters. According to ANOVA results, IB is significantly affected by pressing time; F and TS are significantly affected by RC.

Figure 3 presents the effect of factor levels (prediction profiler) for internal bond strength (IB), density (D), formaldehyde content (F) and thickness swelling (TS).

As expected, IB increases strongly with pressing time, due to longer resin reaction time. TS decreases with the RC as the entrance of the water is difficult. In addition, the bonds can restrain wood swelling and in this way, the entrance of water is limited. The unexpected result of F increase with
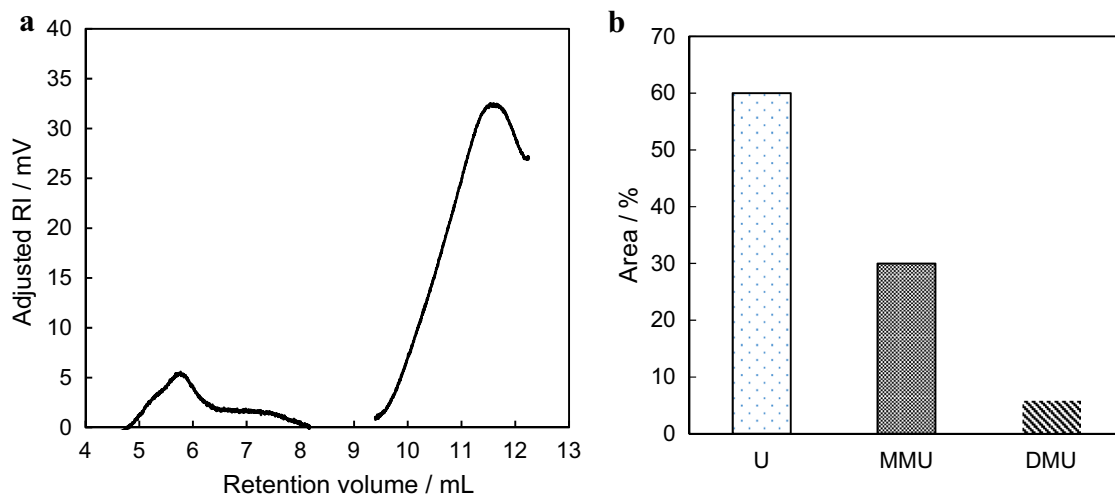

Fig. 2 **a** Adjusted RI (refractive index) for UF resin; **b** peak areas of unreacted U, MMU and DMU for the UF resin
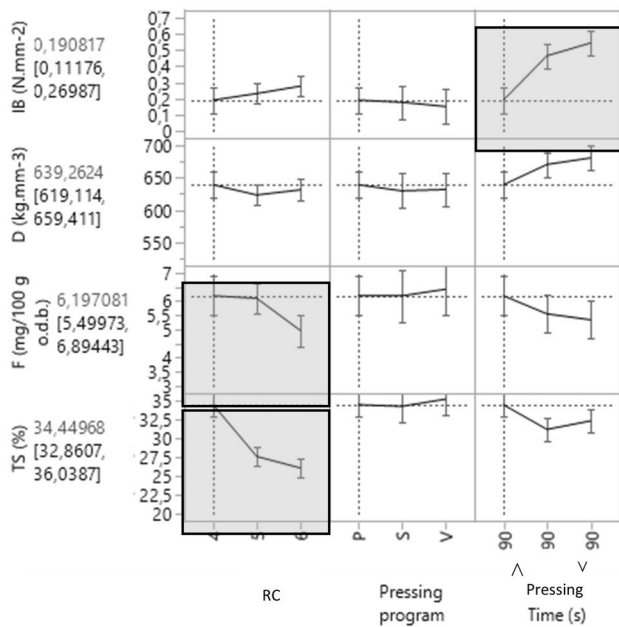
Fig. 3 Prediction profile for internal bond (IB), density (D), formaldehyde content (F) and thickness swelling (TS)
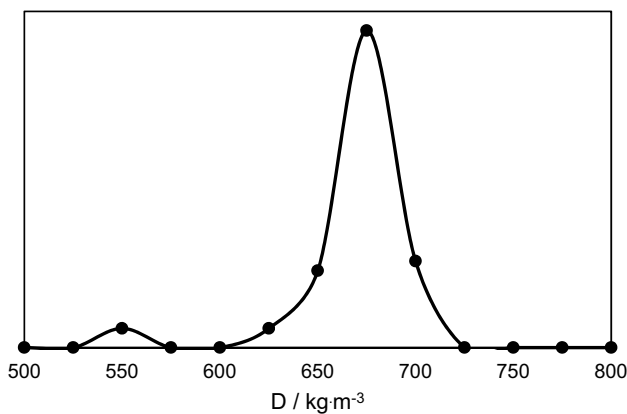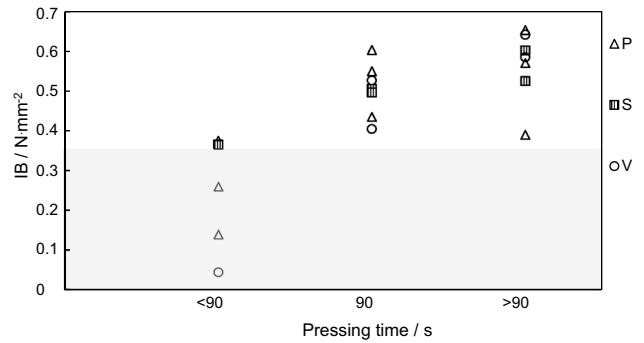

Fig. 5 IB as a function of pressing time for different pressing programs. The grey area represents the minimum acceptable IB specification for boards type P2 (IB ≥ 0.35 N mm^{-2}) according to EN 312
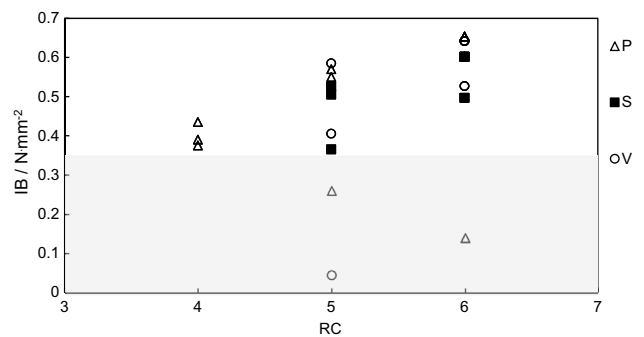

Fig. 6 IB as a function of RC for different pressing program. The grey area represents the minimum acceptable IB value for boards type P2 (IB ≥ 0.35 N mm^{-2}) according to EN 312

Fig. 4 Normal distribution for D

RC is here presented and explained below. The black-framed plots in Fig. 3 represent the main studied factors.

Figure 4 shows the distribution of D values for the studied boards. The results show a normal distribution, which might indicate that this property is almost constant for all boards. The only deviation is associated with the opening of the press during the preparation of that specific board. As D can be assumed constant and its impact on the remaining parameters is not significant, it will not be considered later.

The results obtained for IB as a function of pressing time are presented in Fig. 5 for the different pressing programs. As can be observed for pressing times above 90 s, all the boards are above the minimum acceptable IB specification

for boards type P2 (IB ≥ 0.35 N mm^{-2}), according to EN 312. However, for pressing times shorter than 90 s the minimum acceptable IB value is only achieved for some boards. It is also important to note that the obtained values are independent of the pressing program. Thus, under these conditions the pressing program is much less important than the pressing time.

Although statistically not significant, the evolution of IB as a function of RC is shown in Fig. 6. As expected, the average values of IB increase slightly with RC. However, there are some points that do not follow that pattern. These results can be explained by the different levels of moisture presented in the board and the degree of cure of the resin. If the water present does not have time to be released through the board edges, a pressure build-up occurs. When the press opens and the press pressure is released, the board can delaminate, if the adhesive bond strength is not sufficient. The same can be observed if the resins are not completely cured. When the press opens, and because the temperature at the core is higher than 100 °C, there is always water vaporization, which tends to expand the panel, if the bond strength is not

enough. In the case of program C, when venting begins, water vapor pressure decreases and equalizes through the mat (S), while temperature stays high. The venting gas may move to the edges and toward the surfaces of the mat. In opposition to what was expected, it is observed that the pressing program is not significant to explain differences in IB. It is also important to clarify that the boards are small, so edge effects and vapor loss through the edges make the behavior of the laboratory mat very different from a large industrial one, where vapor/gas is trapped horizontally. To overcome this effect, aluminum deformable containers were used for board forming, which avoids the vapor to escape easily through the board edges, permitting to simulate more closely the heat and mass transfer that occurs inside an industrial board, where the vapor has to travel a long distance for escaping through the edges.

Figure 7 shows the TS values as a function of RC. The triangle marked with a circle corresponds to a board with low IB, which delaminated during the test. The TS values obtained for a laboratory board should not be compared with TS values obtained for the industrial board, because the board forming methodologies are quite different and as consequence, the orientation and distribution of wood
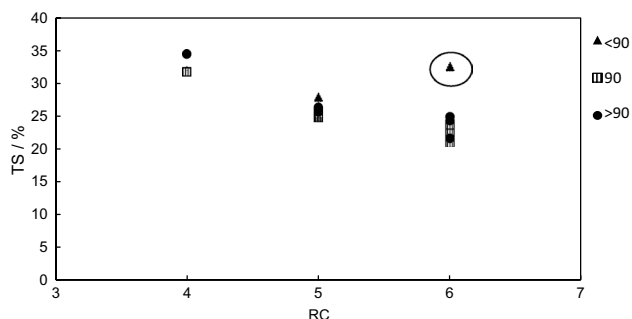
particles are very different. Therefore, it is not correct to establish an acceptance limit for TS, as was done for IB. Analyzing Fig. 7, it is observed that TS decreases as the RC increases. Nevertheless, considering that the error associated with the TS method is $\pm 10\%$, all the values are within the error $(30 \pm 10)\%$. When the effect of the pressing time is analyzed, it is possible to conclude that TS and RC are independent of the pressing time.

Figure 8 shows the dependence of F as a function of RC for different pressing times as well as its relationship to different TS. According to Fig. 8a, it can be concluded that the formaldehyde content decreases as RC increases, but seems to be independent of pressing time. A similar trend is observed when the variation of F as a function of RC is considered for different values of TS (Fig. 8b). The similarity of the trends registered for different pressing times and TS values is thought to be associated with the cohesion of the particles. Lower values of TS indicate that the board structure is tighter, thus it is more difficult for water to enter (causing fiber swelling) and for formaldehyde to be released. It is also important to mention that lower TS values can indicate higher degree of cure and therefore, lower amounts of unreacted formaldehyde are released. It is important to note that all F contents are equal or below the minimum acceptable for E1 class PBs ($F \leq 8$ mg/100 g o.d.b.—oven dry board) according to EN 13986.

An ANOVA was performed once again to verify that only F varies significantly with IB (p-value and significance level < 0.0001) and its variation with TS is only slightly significant (p-value and significance level 0.0013). The predictive profile is presented in Fig. 9, which shows the increase in IB with the decrease in F; and the increase in TS with the increase in F.

In turn, Fig. 10a shows F as a function of IB and, as expected, it is observed that F seems to decrease with the increase in IB. As mentioned before, higher IB values are
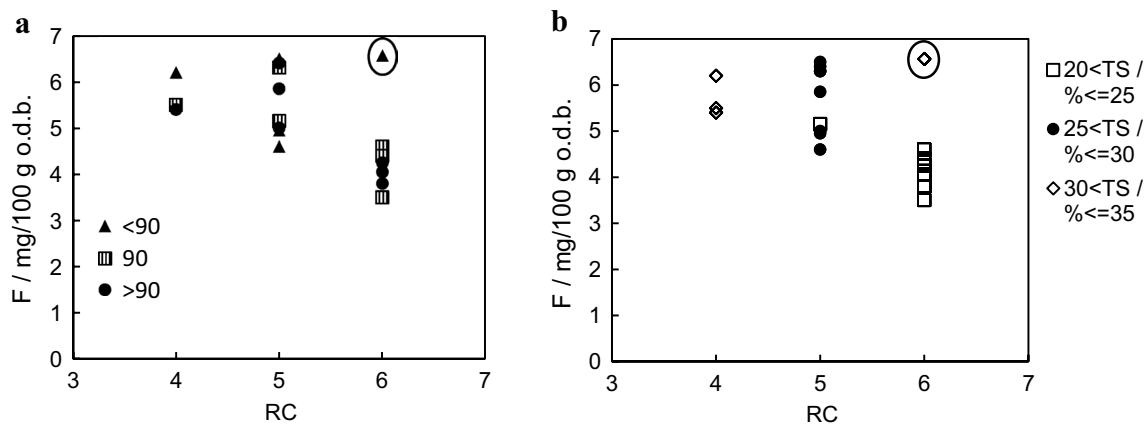

Fig. 7 TS as a function of RC for different pressing times

Fig. 8 F as a function of RC **a** for different pressing times and **b** for different TS values
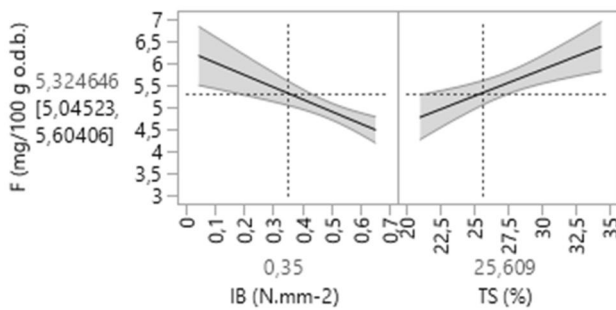
Fig. 9 Prediction profile for F

associated with higher adhesive bond strength and so can indicate higher degree of cure. Indeed, it is also possible to notice that the obtained F values are between 4 and 7 mg/100 g o.d.b., all below the minimum acceptable for E1 class PBs (F ≤ 8 mg/100 g o.d.b.) according to EN 13986. Figure 10b presents the relationship between the F values and those of TS, where it is possible to distinguish three clusters (marked with a dashed circle) associated with different values of RC. In this figure, it is also notorious that higher TS shows higher values of F, and these values increase with RC (circles > squares > triangles).

Figure 11 summarizes the results obtained in this study, showing the evolution of F, TS and IB as a function of RC. According to Fig. 11a, to reduce the values of F, RC should be increased (RC = 6) for pressing times higher or equal to 90 s. However, for pressing times shorter than 90 s, RC should be reduced (RC = 4). Moreover, as shown in Fig. 11b, to decrease TS, RC = 6 for pressing times higher or equal to 90 s is the best choice. Finally, in agreement with Fig. 11c, to improve IB, RC should be increased for pressing times equal or higher than 90 s. On the other hand, for pressing times lower than 90 s, the best option is

to reduce RC (RC = 4). As mentioned above, this result can be explained by the different levels of moisture presented in the board. For RC = 4 and pressing time shorter than 90 s, resin cure is incomplete and the water present does not have time to vaporize. Nevertheless, the IB is above the minimum acceptable value for boards type P2 (IB ≥ 0.35 N mm^{-2}) according to EN 312. For RC higher than 4, there is partial delamination and so the IB is below the specification limit.

4 Conclusion

The impact of different pressing programs on the final properties of the particleboard was studied in order to try to obtain products that fulfill market specifications without losing productivity. To achieve that, ANOVA was carried out to identify the best operating parameters that allow increasing the internal bond whilst reducing the formaldehyde content and thickness swelling. Internal bond is significantly affected by pressing time; formaldehyde content and thickness swelling are significantly affected by resin content. Internal bond increases strongly with the pressing time, due to longer resin reaction time. Thickness swelling decreases with the resin content as the entrance of the water is difficult. Although statistically not significant, the evolution of internal bond as a function of resin content was analyzed. As expected, the average values of internal bond increase slightly with resin content. The formaldehyde content decreases as resin content increases. As regards the resin studied it was possible to conclude the following.

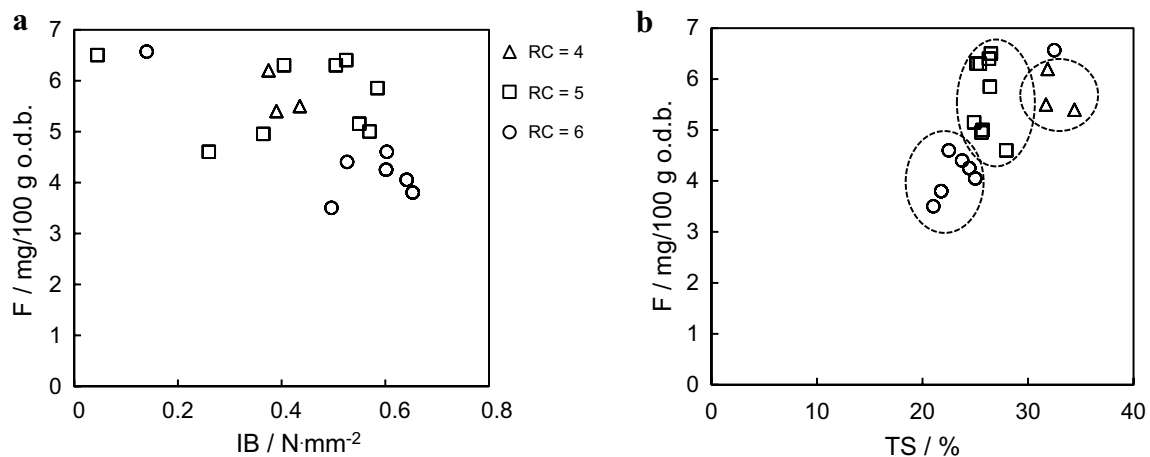To decrease the values of formaldehyde content:

Fig. 10 Study of independent parameters. F as a function of **a** IB and **b** TS for different RC values.
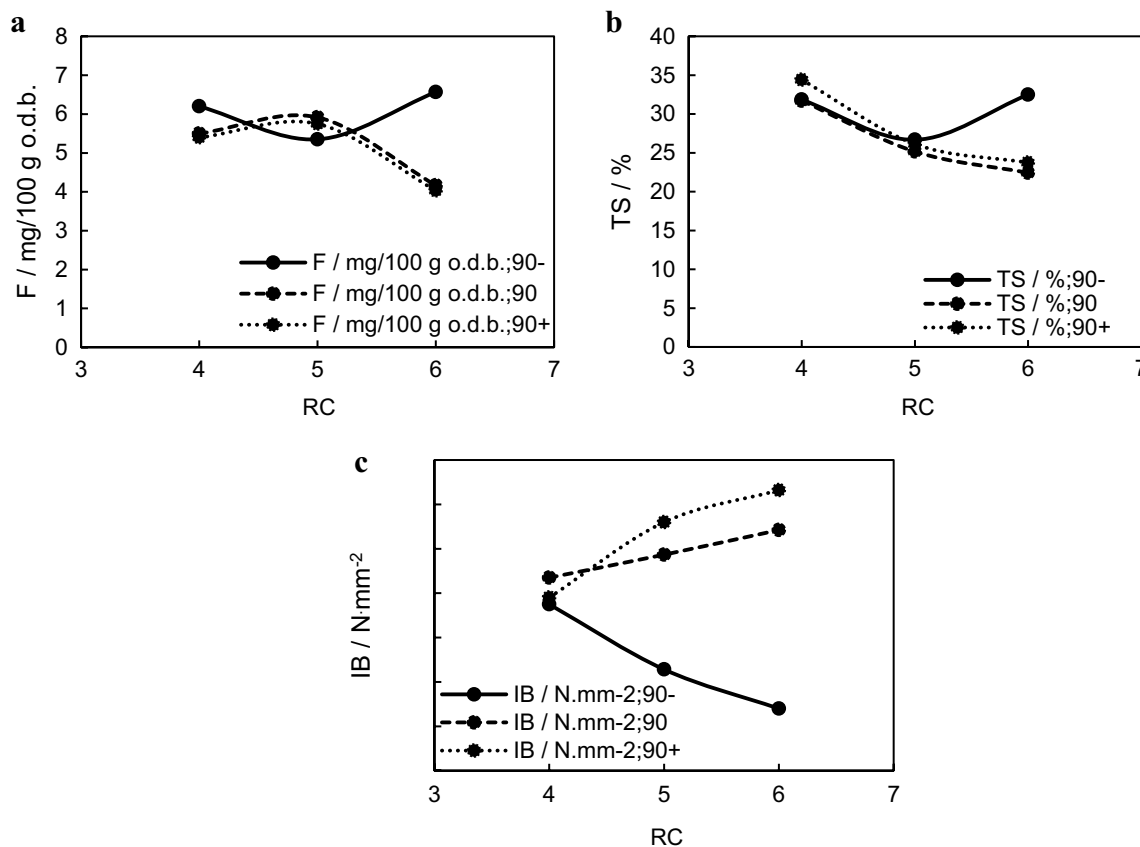
Fig. 11 Dependence on RC of the most important parameters **a** F, **b** TS and **c** IB

- The resin content (RC) should be 6 for pressing times equal to 90 s or longer. RC should be 5 for pressing times shorter than 90 s.
- The values of formaldehyde content seem to be related to the adhesive bond strength (IB). Higher IB value is associated with a higher degree of cure and less percentage of unreacted formaldehyde.

To decrease the values of thickness swelling:

- RC = 6 for pressing times equal to 90 s or longer. The thickness swelling decreases with the increase in resin content, as the water inlet in the board is hindered.

To increase the values of internal bond strength:

- The resin content must be increased for pressing times equal to 90 s or longer. With this pressing time, the water release is sped up and the higher resin content allows higher adhesive bond strength. On the other hand, for pressing times shorter than 90 s, resin content must be reduced. This reduction should be such that the water content does not promote delamination, but the bond strength is enough.

It must be noted that the results obtained are valid only for this specific combination of particles and resin.

Compliance with ethical standards

Conflict of Interest The authors declare that they have no conflict of interest.

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