

Regression Models for the Prediction of Poplar Particleboard Properties based on Urea Formaldehyde Resin Content and Board Density

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ABSTRACT

The aim of this study was to explore the minimum amount of urea formaldehyde (UF) resin content and optimum particleboard density while maintaining boards' quality to reduce production costs. Board density at three levels (520, 620 and 720 kg m⁻³) and resin content (6, 7 and 8%) were variable parameters. Stepwise multivariate linear regression models were used to evaluate the influence of board density and resin content on board properties and to determine the most effective parameter. In order to obtain the optimum board density and minimum resin content, contour plots were drawn. Regression models indicated that both board density and resin content were included in Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) models based on the degree of their importance. Internal Bond (IB) model only had one step and resin content positively affected it. The results obtained from contour plots revealed that manufacturing poplar particleboards with density ranging from 600 to 650 kg m⁻³ and 6% resin would result in boards with mechanical properties within those required by the corresponding standard. Thickness swelling (TS) values were slightly higher (poorer) than the requirements. The panels required additional treatments such as using adequate amount of water resistant materials to improve thickness swelling after 2 and 24 hours of immersion.

Keywords: Mechanical and physical properties, Multivariate-linear regression, Particleboard, UF resin content.

INTRODUCTION

Successful development of wood-based panels in the last 40 years can be attributed to the economic advantage of low-cost wood and other ligno-cellulosic fibrous materials and inexpensive processing with various types of binders (Anon, 2003). The demand for composite wood products such as plywood, oriented strand board (OSB), hardboard, particleboard, medium density fiberboard and veneer board products has increased substantially throughout the world (Sellers, 2000). Particleboard is a panel product manufactured under pressure from particles of wood or other lingo-cellulosic

materials and an adhesive (Nemli, *et al.*, 2008).

According to Maloney (1977), particleboard properties are strongly influenced by the boards' compaction rate, particle geometry, adhesives type and content, density, press conditions, among other processing variables. Board density is one of the most important factors affecting the properties of particleboards and other wood composites. Studies have indicated that there is a high correlation between board properties and its density (Hiziroglu *et al.*, 2005; Hayashi *et al.*, 2003; Hua *et al.*, 2006; Hecsh, 1993; Zhou, 1990). Increases

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in board density result in improvement in board properties.

Currently, resins used in wood industries are generally heat-cured, among which Urea-formaldehyde (UF) resins are the predominant adhesives for interior class plywood and particleboard (Rowell, 2005). Over 90% of wood-based panel products in the world are manufactured with UF resins (Doosthoseini, 2008). UF resins have several advantages including low cost, non-flammability, very rapid curing rate, and light color. However, the bonds are not water resistant and formaldehyde continues to be emitted from the adhesive (Rowell, 2005). Increase in resin content leads to improvement of physical and mechanical properties of wood-based panels (Ashori and Nourbakhsh, 2008; Nemli *et al.*, 2007). On the other hand, the increase in formaldehyde-based resins content brings about concerns about human health and the environment (Kim, 2009). Resin content has an important effect on final price of products and accounts for about 35% of production cost (Doosthoseini, 2008).

Developing countries, such as Iran, have poor resources for particleboard manufacturing. To satisfy the increasing demand for forest products, fast-growing trees such as poplar are being seriously considered for future supply needs (Balatinecz and Kretschmann, 2001). Poplar wood is considered to be an excellent raw material for manufacturing particleboard. Some characteristics which favor its use in particleboard are: relatively small springwood to summerwood density gradient which permits quality flaking and uniform drying; lack of resinous substances which enhances good adhesive bonding; and the light color which is aesthetically pleasing to many users (Geimer, 1976; Mohebbi and Hadjihassani, 2008). The aim of this study was to determine the minimum amount of urea-formaldehyde resin content and optimum poplar particleboard density while maintaining boards' quality and consequently reducing production costs. Also, regression models were used to

evaluate the balance between board density and resin content.

MATERIAL AND METHODS

Material

The logs of poplar wood (*Populus alba*) with diameters at breast height ranging from 20 to 25 cm came from Taleghan region of Iran. The logs were cut into small pieces with dimensions about 6 cm×6 cm×1 cm. These were then chipped using a laboratory-scale drum-chipper in two steps. The particles were dried down to 3% moisture content and were classified to eliminate over-and under-sized (> 20mm and < 4mm) particles. The average length and thickness of core particles were measured to be 15 and 1.2 mm, respectively. Urea-formaldehyde (UF) resin was supplied by Tiran Shimi Tehran Co. The properties of UF resin presented in Table 1.

Panel Manufacturing

Single-layer panels were manufactured. The particles were blended with UF resin in a rotating drum-type mixer fitted with a pneumatic spray gun. Resin content varied. Based on oven dry particles weight, 6, 7 and 8% resin contents were applied. No wax emulsion or any other additives were used for panel manufacturing. Ammonium chloride (NH₄Cl) was applied at 2 wt% as a hardener.

The materials were placed in a mat forming box and manually formed. The mats

Table 1. Properties of the UF resin used in the present study.

| | |
|-----------------------|--------------------------------|
| Solid content (%) | 60±2 |
| Density (at 20°C) | 1.26 - 1.28 g cm ⁻³ |
| Viscosity (at 20°C) | 200- 400 cps |
| pH (at 20°C) | 7.5 -7.7 |
| Free formaldehyde (%) | Max. 0.20 |

were pre-pressed at a pressure of approximately 10 bars and were then compressed in a hot press at 170°C using a pressure of 30 bars for 5 min. The final dimensions of the boards were 40 cm×40 cm×1.6 cm. Board density at three levels (520, 620 and 720 kg m⁻³) and resin content (6, 7 and 8%) were compared. Three replicate boards were fabricated for each treatment.

Mechanical and Physical Testing

The panels were conditioned at a temperature of 20±2°C and 65±5% relative humidity for about three weeks and then cut into test specimens according to EN 326 (1993) standard. Three specimens were prepared from each sample board to determine each mechanical and physical property. The mechanical and physical properties were determined in accordance with European Union (EN) standards: Modulus of rupture (MOR) and modulus of elasticity (MOE) (EN 310, 1993), internal bond (IB) strength (EN 319, 1993), thickness swelling (TS) after 2 and 24 hours of immersion (EN 317, 1993) and density (EN 323, 1999).

Statistical Analysis

The effects of resin content and board density on physical and mechanical properties of the particleboards were evaluated based on multivariate linear regression. The multivariate linear regression is presented in Equation (1) (Draper and Smith, 1998) as:

$$Y_i = a_0 + a_1 X_{1i} + a_2 X_{2i} + \dots + a_k X_{ki} + e_i \quad (1)$$

Where, a_0, a_1, \dots, a_k are the parameters of the model, given by Equation 1, also called coefficients of regression, and e_i is the random error. In fact, errors are amounts of dependent variables not explained by independent variables.

In this study, resin content and board density were considered as independent variables whereas board properties (*MOR*,

MOE, *IB*, *TS* 2 h and *TS* 24 h) were dependent variables. A stepwise regression procedure using SPSS 15 software was performed to determine which variables could be included in the model. Stepwise regression started with no variables in the model and first added the most significant.

The coefficients of determination (R^2) of these models and the mean average error value (*MAE*) (Kalogiro *et al.*, 2003; Fernández *et al.*, 2008) were used to assess this testing process, taking into account that, for particleboard manufacturing process, the prediction of board properties values with an *MAE* of 15% is regarded as acceptable, while an *MAE* of 20-30% is not (Cook and Chiu, 1997; Malinove *et al.*, 2001). *MAE* was calculated according to Equation (2):

$$MAE = \frac{1}{n} \sum_{i=1}^n \left| \frac{z^*(x_i) - z(x_i)}{z(x_i)} \right| \times 100 \quad (2)$$

Where, *MAE*= Mean square error value; $Z^*(X_i)$ = Predicted value by regression models, $Z(X_i)$ = Observed value by testing.

In order to determine optimum levels of board density and minimum use of resin while maintaining particleboard quality, contour plots were drawn by Minitab 15 software and the values of each property were compared with EN 312 (2003) and ANSI 208.1 (2009) standard values for particleboard.

RESULTS AND DISCUSSION

The average values of *MOR*, *MOE*, *IB*, and *TS* of the sample panels are presented in Table 2. Also, multivariate regression models are shown in Table 3.

Modulus of Rupture

The complete predictive equation for *MOR* was built at the 2nd step. Both board density (*D*) and resin content (*R*) were found to affect *MOR* positively.

The coefficient of determination ($R^2=0.79$) for this model indicates that the proposed model is capable of explaining 79% of observed values. The model with standardized coefficients [Table 3, Equation



Table 2. Mechanical and physical properties of experimental panels.

| Target density (kg m ⁻³) | Resin content (%) | Panel code | MOR (MPa) | MOE (MPa) | IB (MPa) | TS (%) | | Actual density (kg m ⁻³) |
|--------------------------------------|-------------------|------------|-----------|-----------|----------|--------|------|--------------------------------------|
| | | | | | | 2 h | 24 h | |
| 520 | 6 | A1 | 10.2 | 1143 | 0.42 | 16.8 | 21.6 | 521 |
| | 7 | A2 | 10.8 | 1196 | 0.48 | 12.7 | 19.7 | 523 |
| | 8 | A3 | 11.8 | 1484 | 0.54 | 15.6 | 17.6 | 522 |
| 620 | 6 | B1 | 15.6 | 1619 | 0.49 | 13.6 | 20.3 | 622 |
| | 7 | B2 | 15.7 | 1630 | 0.48 | 14.8 | 21 | 622 |
| | 8 | B3 | 16.9 | 1735 | 0.57 | 9.6 | 17.3 | 623 |
| 720 | 6 | C1 | 17.9 | 2122 | 0.49 | 23.2 | 30.9 | 723 |
| | 7 | C2 | 19.5 | 1810 | 0.52 | 17.3 | 29.7 | 724 |
| | 8 | C3 | 23.6 | 2153 | 0.49 | 14.8 | 23.1 | 721 |

Table 3. Multivariate regression models with Unstandardized (US) and standardized (S) coefficients.

| Number | Equation | F | Sig |
|--------|-------------------------------------------------------------|---------|---------|
| | (99% confidence interval) | | |
| [3] | $MOR = -23.498 + 4.704 \times 10^{-2} D + 1.444R$ (US) | 146.799 | 0.000** |
| [4] | $MOR = 0.85D + 0.261R$ (S) | | |
| [5] | $MOE = -1251.679 + 3.770D + 1.444R$ (US) | 87.093 | 0.000** |
| [6] | $MOE = 0.812D + 0.175R$ (S) | | |
| [7] | $IB = 0.263 + 3.333 \times 10^{-2} R$ (US) | 7.151 | 0.009** |
| [8] | $IB = 0.288R$ (S) | | |
| [9] | $TS\ 2\ h = 20.640 - 2.257R - 1.698 \times 10^{-2} D$ (US) | 17.663 | 0.000** |
| [10] | $TS\ 2\ h = -0.448R - 0.337 D$ (S) | | |
| [11] | $TS\ 24\ h = 13.948 + 4.144 \times 10^{-2} D - 2.468R$ (US) | 46.958 | 0.000** |
| [12] | $TS\ 24\ h = 0.635D - 0.378R$ (S) | | |

** Significant difference at the 1% level.

(4)], shows that the effect of board density (0.85) on MOR is about 3.3 times greater than that of resin content (0.261). In terms of Equation (2), MAE obtained for MOR (4.8%), is much lower than 15%, which means that this regression model can be regarded as appropriate for obtaining information on MOR.

Increase in board density causes an increase in compression rate and contact between wood particles and results in MOR improvement. Moreover, with the increase in resin content, surface contact between the resin and wood particles increases which can

lead to bonding quality improvement. Rijo (1988) showed that the adhesive effect was significant for MOR only over a 600 kg m⁻³ board density level and with a resin level over 8%. Hiziroglu et al. (2005) reported that board density is the most important factor affecting all physical and mechanical properties of particleboard.

Evaluating the contour plot presented in Figure 1, it is possible to determine optimum amounts of board density and resin content while maintaining MOR above minimum requirements set by standard values related to these boards.

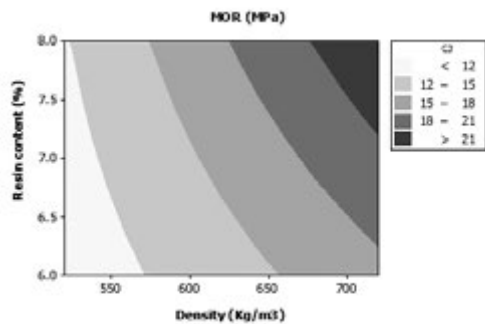


Figure 1. Contour plot for MOR.

Figure 1 shows that the highest MOR values (above 21 MPa) were reached at about 670-720 kg m⁻³ board density and resin content of 7.2–8%. The minimum requirements for MOR of particleboard panels for general uses and interior fitments (including furniture application) are 12.5 and 14 MPa, respectively (EN 312, 2003). Also, the MOR of particleboards can meet ANSI A 208. 1 (2009) standard for wood particleboard of class M-O, M-1, M-2, M-S, M-3 (Table 4). Therefore, particleboards with density of 570-670 kg m⁻³ and 6% resin content met these standard requirements.

Modulus of Elasticity

The complete equation for MOE was built at the 2nd step. The effects of board density (D) and resin content (R) on MOE were positive. Models with unstandardized and standardized coefficients for MOE are presented in Table 3, Equations (5) and (6).

The coefficient of determination for this model (R²= 0.691) indicates that the proposed model is able to explain 69.1% of

Table 4. The MOR, MOE and IB values required to meet ANSI 208.1.

| Class | MOR (MPa) | MOE (MPa) | IB (MPa) |
|-------|-----------|-----------|----------|
| M-0 | 7.6 | 1380 | 0.31 |
| M-1 | 10 | 1550 | 0.36 |
| M-S | 11 | 1700 | 0.36 |
| M-2 | 13 | 2000 | 0.4 |
| M-3 | 15 | 2500 | 0.5 |

the observed values. Based on coefficients of standardized model, the effect of board density (0.812) on MOE is ~4.6 times greater than that of resin content (0.175). The MAE obtained for MOE is about 15%. Therefore, MOE regression model is regarded as acceptable.

The results obtained are similar to those described by others (Nemli *et al.*, 2007; Hayashi *et al.*, 2003; Zhou, 1990; Ashori and Nourbakhsh, 2008). Rijo (1988) reported a high correlation between MOR and MOE and board density found by linear regression model analysis.

As shown in Figure 2, the highest amount of MOE (2100 MPa) was reached at about 680-720 kg m⁻³ board density and resin content of 7.7 – 8%. The minimum requirement for MOE of panels for general uses and interior fitments (including furniture application) is 1,800 MPa (EN 312, 2003). Moreover, the MOE of particleboards can meet ANSI A 208. 1 (2009) standard for wood particleboard of class M-O, M-1, M-2, M-S, and M-3 (Table 4). Thus, panels with density of 640-720 kg m⁻³ and 6% resin content met the standard requirements.

Internal Bonding Strength

The complete model for IB was built at the first step. Only resin content positively affected IB. In fact, with the increase in resin content, increase of bonding between the resin and wood particles led to the improvement of internal bond strength.

The coefficient of determination (R²=

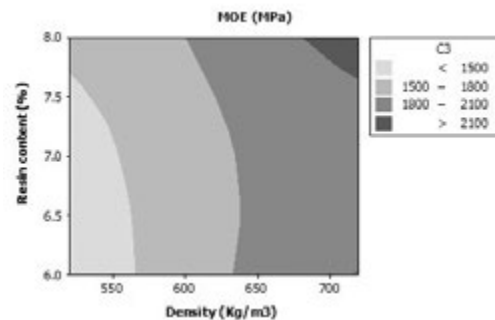


Figure 2. Contour plot for MOE.



0.083) for this equation indicates that the model explains only 8.3% of observed values. Also, *MAE* of *IB* (15.3%) is slightly higher than 15%. Considering R^2 and *MAE* values, *IB* model was not appropriate for predicting this property.

Considering the *IB* contour plot, it is possible to determine optimum levels of board density and resin content while keeping this property within the range set in the corresponding standards (Figure 3).

The minimum requirements for *IB* of panels for general uses and interior fitments (including furniture application) are 0.28 and 0.4 MPa, respectively (EN 312, 2003). The *IB* of particleboards can meet ANSI A 208. 1 (2009) standard for wood particleboard of class M-O, M-1, M-2, M-S and M-3 (Table 4). Based on Figure 3, panels with minimum density and resin content (520 kg/m^3 and 6% resin) are within these standard requirements.

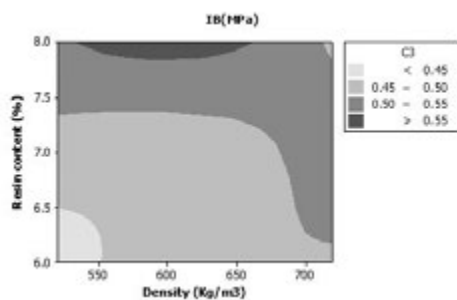


Figure 3. Contour plot for *IB*.

Thickness swelling

The complete equations for *TS* 2 h and *TS* 24 h were built in two steps. Models with unstandardized and standardized coefficients are presented in Table 3.

The coefficients of determination ($R^2=0.560$ and 0.546 for *TS* 2 h and *TS* 24 h, respectively) indicate that the above equations are capable of explaining about 56.0% and 54.6% of *TS* values observed after 2 and 24 hours of immersion, respectively. The model with standardized coefficients [Equations (10) and (12)] shows that the effect of resin content

(0.448) on *TS* 2 h is about 1.3 times greater than that of board density (0.337). Also, the effect of board density (0.635) on *TS* 24 h is 1.7 times greater than that of resin content (0.378). *MAE* values obtained for *TS* 2 h and *TS* 24 h are lower than 15% (14.23 and 14.81, respectively), which means that regression models can be regarded as appropriate for obtaining information on *TS* 2 h and *TS* 24 h.

The maximum values allowed for the *TS* of panels after 2 and 24 hours of immersion are 8% and 15%, respectively (EN 312, 2003). The average *TS* value for the test specimens ranged from 9.6 to 23.2% and 17.3 to 30.9% after soaking for 2 and 24 hours, respectively (Table 2). As shown in Figure 5, with the increase in board density up to 720 kg m^{-3} and resin content to 6-7%, *TS* values are considerably increased. Springback of the panels as they are soaked in water manifests itself in the form of lower dimensional stability which is a common behavior of any wood composite (Kalaycioglu et al., 2005). However, thickness swellings after 2 and 24 hours of immersion reached their lowest values at board density of approximately $550\text{-}640 \text{ kg m}^{-3}$ and resin content of 6-6.8% (Figures 4 and 5). These values (~ 10 and 20% after 2 and 24 hours) were slightly higher

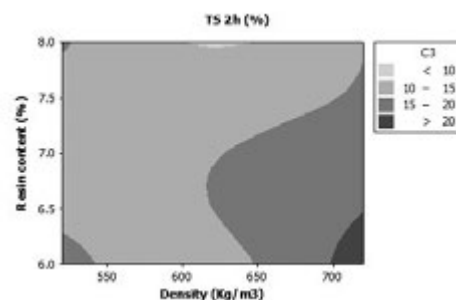


Figure 4. Contour plot for *TS* 2 h.

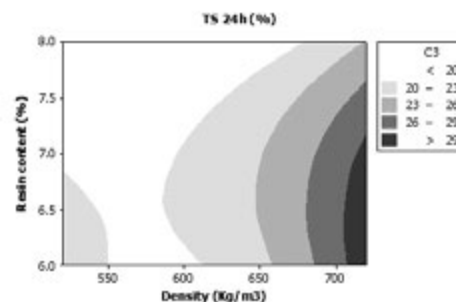


Figure 5. Contour plot for *TS* 24 h.

(poorer) than the required level of thickness swelling of panels for general uses. In general, panels did not meet thickness swelling requirement for general uses. This may be mainly attributed to the lack of wax emulsion and presence of hydrophobic substances in particleboard manufacturing. As a consequence, the panels require additional treatments such as coating of particleboard surface with melamine-impregnated paper or laminates or high press temperature usage to become a more stable product (Nemli, 2002).

CONCLUSIONS

Our results suggest that it is possible to manufacture poplar particleboards using 6% urea formaldehyde resin and density ranging from 600 to 650 kg m⁻³ with mechanical properties within those required by corresponding standards. To improve dimensional stability, the panels would require additional treatments such as using adequate amount of water resistant materials. Regression models proved to be an appropriate approach to evaluate the balance between board density and resin content for *MOE* and *MOR*. For thickness swelling the model was not as good and for *IB* it was contradictory to reality. Models built in this study can only be implemented in situations similar to this research and may not be used in other industrial conditions.

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مدل های رگرسیونی پیش بینی ویژگی های تخته خرده چوب صنوبر بر اساس دانسیتته تخته و مقدار رزین اوره فرم آلدهید

ف. اصلاح، ع. ا. عنایتی، م. تجویدی، و م. م. فائزی پور

چکیده

هدف این تحقیق پیدا کردن حداقل مقدار رزین اوره فرم آلدهید مصرفی و مقدار بهینه دانسیته تخته خرده چوب با حفظ کیفیت تخته برای کاهش هزینه های تولید بوده است. عوامل متغیر شامل دانسیته

تخته‌ها در سه سطح (۵۲۰، ۶۲۰ و ۷۲۰ کیلوگرم بر متر مکعب) و درصد رزین مصرفی (۶، ۷ و ۸ درصد) بودند. به منظور نشان دادن اثر دانسیته تخته و مقدار رزین مصرفی بر خواص تخته خرده چوب و تعیین متغیر اثرگذارتر، از مدل‌های رگرسیون چندگانه خطی به روش گام به گام استفاده شد. همچنین برای مشخص کردن حد بهینه دانسیته تخته و حداقل میزان رزین با حفظ کیفیت تخته‌ها، از نقشه‌های اثرات متقابل استفاده شد. مدل‌های رگرسیونی بیانگر آن بودند که هر دو عامل دانسیته تخته و مقدار رزین بر اساس میزان اثرگذاری در مدل‌های MOR، MOE، TS₂ و TS₂₄ وارد شدند. مدل IB فقط دارای یک گام بود و میزان رزین مصرفی اثر مثبتی بر این ویژگی داشت. نتایج حاصل از نقشه‌های اثرات متقابل حاکی از این بود که با ساخت تخته خرده چوب‌های گونه صنوبر با دانسیته ۶۰۰-۶۵۰ کیلوگرم بر متر مکعب و استفاده از ۶٪ رزین اوره فرم آلدهید، کلیه خواص مکانیکی تخته‌ها دارای حد نصاب مقادیر تعیین شده توسط استاندارد مربوطه هستند، هر چند مقادیر واکنشیدگی ضخامت، کمی بیشتر (ضعیف تر) از مقدار استاندارد مورد نیاز بود. برای بهبود واکنشیدگی ضخامت بعد از ۲ و ۲۴ ساعت غوطه وری، پانل‌ها به تیمارهای اضافی مانند استفاده از مواد مقاوم به آب نیاز داشتند.