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ORIGINAL PAPER

Improve regression-based models for prediction of internal-bond strength of particleboard using Buckingham's pi-theorem

Akbar Rostampour Haftkhani • Mohammad Arabi

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Abstract: Internal bond (IB) strength is one of the most important mechanical properties that indicate particleboard quality. The aim of this study was to find a simple regression model that considers the most important parameters that can influence on IB strength. In this study, IB strength was predicted by three kinds of equations (linear, quadratic, and exponential) that were based on the percentage of adhesive (8%, 9.5%, and 11%), particle size (+5, -5 +8, -8 12, and -12 mesh), and density (0.65, 0.7, and 0.75 g/cm^3). Our analysis of the results (using SHAZAM 9 software) showed that the exponential function best fitted the experimental data and predicted the IB strength with 18% error. In order decrease the error percentage, the Buckingham Pi theorem was used to build regression models for predicting IB strength based on particle size, density, percentage of adhesive, face-screw withdrawal resistance (SWR_f), and edge-screw withdrawal resistance (SWR_e). From there, three dimensionless groups were created by Buckingham's Pi theorem and IB strength was predicted based on multiple regression models. The results showed these models can predict IB strength with 10.68% and 18.17% error, based on face-screw withdrawal resistance and edge-screw withdrawal resistance, respectively.

Keywords: Buckingham's Pi theorem; internal bond strength; particleboard; screw withdrawal resistance.

Introduction

Particleboard is one of the most important wood-based building materials used in building construction. Nowadays it goes into secondary products such as cabinetry, wall and floor panels, doors, furniture, and other applications. Internal-bond (IB) strength is a critical mechanical property that indicates particleboard's bond quality.

Several models have been developed to quickly estimate the IB strength of particleboard. In some regression based-models, IB strength is predicted based on other physical properties of particleboard. Arabi et al (2011) developed three kinds of equations (linear, quadratic, and exponential) for each mechanical property of particleboard based on slenderness ratio, resin content, and density. The results indicated that an exponential function can better describe the simultaneous effect of slenderness and resin content than a linear equation on mechanical properties of particleboard.

Sun and Airma (1999) examined the relationship between ultrasonic propagation and internal bonding of particleboard, finding that ultrasonic waves could be used to evaluate the internal bonding of particleboard with a density less than about 0.75 g/cm^3. Lin and Huang (2004) estimated IB strength by photographing the particleboard's edge surface and applying single-image multiprocessing analysis. They made single-layer particleboards with various resin contents, densities and particle sizes and found a significant correlation between the percent resin coverage and IB strength. IB strength has also been predicted as a function of physical properties of particleboard (Fernandez et al. 2008). Mechanical properties also are used for predicting IB strength of particleboard. Previous studies have found a correlation between SWR and density of particle board (Johnson 1967; Eckelman 1975). But Barnes and Lyon (1978) investigated the accuracy of Eckelman's models on weathered and unweathered particleboard samples and they found only SWR from unweathered boards was well estimated by Eckelman's models.

One of the major challenges associated with wood-based particleboard is the bond quality of wood material deteriorates when it is exposed to heat and moisture, which reduces screw-holding capacity. Fujimoto and Mori (1983) suggested IB and face and edge-screw withdrawal resistance (SWRf&e) are highly correlated with bond quality. Finally, Zaini and Eckelman (1993) developed a model for face SWR of medium-density fiberboard based on the screw diameter, pilot-hole diameter, and IB strength.

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Akbar Rostampour Haftkhani (✉)• Mohammad Arabi
Department of Wood & Paper Science and Technology, Faculty of Natural Resources, University of Tehran, P.O. Box 4111, Karaj 31587-77871, Iran. Tell: +98 263 222 4496, Fax: +98 263 224 9311
E-mail address: arostampour@ut.ac.ir ,akbar.rostampour@gmail.com

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In previous studies, IB was not predicted based on SWR. Only Semple and Smith (2006) studied the internal-bond prediction of particleboard based on SWR models and reported that there is little or no correlation between the face or edge SWR of particleboards and their density, but that there is a significant correlation with IB strength ($r^2 > 0.7$). Regression based models are simple, cheap and Also software for regression based models is readily available. But they can't predict IB strength with acceptable accuracy (Arabi et al. 2011).

In some researches, artificial neural networks (ANN) and radial-basis function (RBF) have been applied to predict the IB strength of particleboard (Esteban et al. 2009; Cook & Whittaker 1993; Cook and Chiu 1997). These methods showed a smaller degree of error than regression-based models, but the manufacturers do not prefer to use the ANN and RBF modeling techniques. Because they are rapidly changing, need commercial software, are harder to interpret, contain more parameters to estimate, expensive and require more computer time. The manufacturer believed that there needs to be a balance between cost production, modeling process and percentage of error. Therefore, it seems a semi-empirical model has less error percent than simple regression models and has less cost production than artificial cost production (Arabi et al. 2011).

Buckingham's theorem is a semi-empirical method based on dimensional analysis (DA) that is widely used in mathematics, physics, engineering, and economics. Using Buckingham's Pi theorem to build a regression model is an effective way to overcome the limitations of ANN and RBF models and to simplify and reduce the errors of regression models (Vignaux and Scott, 2001, Arabi et al. 2010). Buckingham's Pi theorem focuses on dimensionless groups of variables and, unlike in standard regression analysis, prevents form formation of chance relationships. So, the objective of this study is to improve regression-based models for prediction of IB strength of particleboard using Buckingham's pi-theorem.

Materials and methods

Board fabrication

Small-diameter logs derived from poplar (*Populous alba*) were cut into blocks measuring 50 mm × 50 mm × 10 mm. These blocks were ground with a laboratory Hammer-mill. Particles were dried to a moisture content of less than 3%. After drying, the particles were sifted through three hand-held screens with 5, 8, and 12 mesh respectively (Fig.1). The length, width, and thickness of 5g screened particles for each particle size (+5, -5 +8, -8 +12 and -12) were measured with a micrometer caliper. Table 1 shows the average dimensions of classified particles. Then, the adhesive urea formaldehyde (55% solid content) was sprayed on the particles, and mats were formed and pressed with 35 kg/cm^2 pressure at 180ºC for 5 minutes. Finally, 108 single-layer particleboards with three levels of density (0.65, 0.7 and 0.75 g/cm^3), three levels of percentage of adhesive (8%, 9.5% and 11%) and four levels of particle size (+5, -5 +8, -8 +12, and -12 mesh) were manufactured in the laboratory. The boards were moisture-conditioned at 65 ± 5% relative humidity and 20 ± 2 ^{o}C for two weeks.

Experimental test

The internal bond and screw withdrawal resistance specimens were cut according to European Standards EN 319 (1993) and EN 320 (1993), respectively. Overall, a total of 324 specimens (three specimens from each board) for IB strength and 216 specimens (two specimens from each board) were examined for SWR. Then the specimens were tested using an INSTRON 4489. The screws used in this study were zinc-coated sheet metal (38 mm×4.2mm).

Dimensional analysis is a method for reducing complex physical problems to their simplest forms. This method is widely used in mathematics, physics, engineering, and economics.

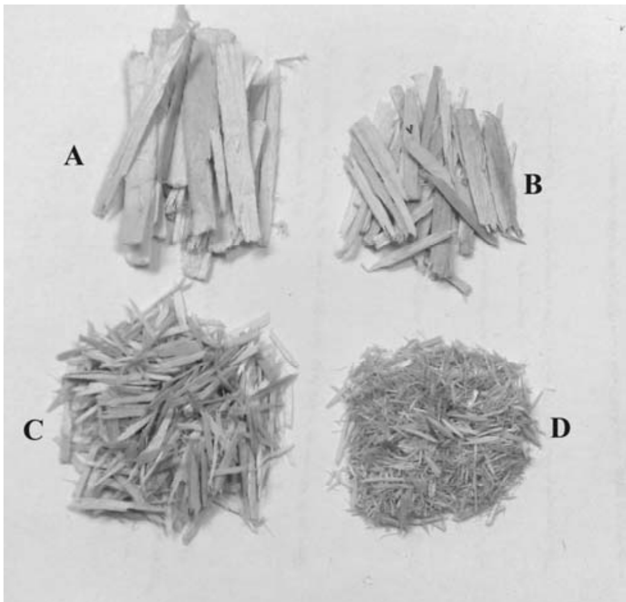

Fig. 1 Four types of particles: A: +5 mesh; B: -5 + 8 mesh; C: -8 +12; and D: -12 mesh.

Table 1 The features of particles for each mesh

Mesh	Length (mm)	Width (mm)	Thickness (mm)	L/W	L/T	W/T
A (+5)	55.1 (7.7) *	7.9 (3.5)	1.19 (0.3)	6.97	46.30	5.85
B (-5 +8)	28.4 (3.1)	4.7 (1.3)	0.84 (0.1)	6.05	33.70	5.57
C (-8 +12)	13.98 (3.8)	2.18 (0.4)	0.65 (0.2)	6.41	21.51	3.35
D (+12)	3.98 (2.3)	0.82 (0.2)	0.31 (0.1)	4.85	12.84	2.65

* The value in the parenthesis represents the standard deviation.

Buckingham's pi theorem

Buckingham's pi theorem, one of the most important theorems based on dimension analysis, gives the number of dimensionless parameters obtained from (n-m), where n and m are the number of variables and fundamental quantities respectively. The variables (n–m) can be expressed as a dimensionless parameter or as π groups.

Results

Resin content–particle size interaction was significantly affected on accuracy of mechanical properties predictions of wood-composite (Arabi et al. 2011; Sun and Arima 1999; Cook and Chiu 1997; Malonay 1977; Post PW 1958).

The purpose of the first stage of this study was to investigate which function (linear, quadratic, or exponential) can best describe this interaction. According to the results from the SHAZAM 9 software (P-value), the quadratic function was not significant. Consequently, the linear and exponential functions were considered for predicting the IB data (Eq.1 and Eq. 2).

$$IB = 0.6924\,D + 0.034079\,G - 0.0022851\,L/t - 0.31083 \tag{1}$$

$$IB = (D)^{1.1843}.(G)^{0.75245}.(\frac{L}{t})^{-0.12489}.e^{-1.7228} \tag{2}$$

Based on the Eq. 3, exponential and linear function can predict the IB strength with 18% and 35% errors, respectively (Table 2).

$$\%MAE = \frac{1}{n}\sum_{i=1}^{n} \left| \frac{z(x_i) - z(x_j)}{z(x_i)} \right| \times 100 \tag{3}$$

Table 2. Average error percent of mechanical properties

Mechanical properties	Average error percent	
	Exponential function	Linear function
IB	18	35

where MAE, z(xi), z(xj) and n are the average absolute error, experimental value, predicted value, and the number of treatments, respectively.

These values may not be satisfactory for manufacturers. Then dimensional analysis (DA) used to build a regression model in order to decrease the prediction error. Six variables (L, t, W, D, IB and SWR) were selected that were based on three fundamental quantities (M, L, and t); from there, three π groups (Eqs.4-6) were created.

$$\pi_1 = (SWR_{f\&e})^a * (D)^b * (W)^c * (IB) \tag{4}$$

$$\pi_2 = \left(SWR_{f\&e}\right)^a * \left(D\right)^b * \left(W\right)^c * \left(t\right) \tag{5}$$

$$\pi_3 = \left(SWR_{f\&e}\right)^a * \left(D\right)^b * \left(W\right)^c * \left(L\right) \tag{6}$$

where L, W and t are length, width, and thickness of particles respectively; and D, IB and $SWR_{f\&e}$ are density, internal bond, and face and edge screw withdrawal resistance.

After determining the dimensionless groups, we rewrote these variables based on their fundamental quantity. For example, the fundamental quantities for π_1 are:

$$\pi_1 = (M.T^{-2})^a * (M.L^{-3})^b * (L)^c (M.L^{-1} * T^{-2}) \tag{7}$$

π_1 is dimensionless, and $L^0 M^0 T^0$ can be substituted for it:

$$L^0 M^0 t^0 = (M * T^{-2})^a * (M.L^{-3})^b * (L)^C (M.L^{-1} * T^{-2}) \tag{8}$$

$$T^0 = T^{-2a-2} \Rightarrow 0 = -2a - 2 = 0 \Rightarrow a = -1 \tag{9}$$

$$M^0 = M^{a+b+1} \Rightarrow 0 = a + b + 1, a = 1 \Rightarrow b = 0 \tag{10}$$

$$L^0 = L^{-3b+c-1} = 0 = -3b + c - 1 = 0\ ,\ b = 0 \Rightarrow c = 1 \tag{11}$$

$$\pi_1 = \frac{IB.W}{SWR_{f\&e}} \tag{12}$$

Similarly, we can find other groups (π_2 and π_3):

$$\pi_2 = (t / W) \tag{13}$$

$$\pi_3 = (L / W) \tag{14}$$

Slenderness ratio (π_4) is obtained from $\pi_3 \times \frac{1}{\pi_2}$:

$$\pi_4 = (\pi_3) \times \left(\frac{1}{\pi_2}\right) = \frac{L}{W} \times \frac{W}{t} = \frac{L}{t} \tag{15}$$

Percentage of adhesive is a dimensionless group:

$$\pi_5 = g\% \tag{16}$$

Dimensionless groups can come together to create the main equation:

$$\pi_1 = \phi(\pi_4)(\pi_5) \text{ Or } \frac{IB.W}{SW\,R_{e\,orf}} = \phi(\frac{L}{T}) * (g\%) \tag{17}$$

Two equations were created using SHAZAM 9 software. The Eq. (18) estimates the IB of particleboard based on face SWR, slenderness ratio, width of particles; and percentage of adhesive.

In Eq. (19), the IB strength is estimated based on slenderness ratio, width of particles, percentage of adhesive, and edge SWR.

$$IB = \frac{SWR_f}{W}\left[(\frac{L}{t})^{1.3365} * g^{0.52564} * e^{-9.7246} \right] \quad (18)$$

$$IB = \frac{SWR_e}{W}\left[(\frac{L}{t})^{1.5833} * g^{0.28351} * e^{-9.7657} \right] \quad (19)$$

The values obtained from the experiment were compared with those obtained from equations 18 and 19 (predicted) based on Eq. 3.

Where MAE, $z(x_i)$, $z(xj)$ and n are the average absolute error, experimental value, predicted value, and the number of treatments, respectively. The results showed that Eq. 18 and Eq. 19 can predict IB strength in densities (0.6, 0.7 and 0.75 g/cm^3) with 2.3 and 4.55% error, respectively (Tables 3 and 4).

Table 3 Average percent errors between experimental and prediction IB data in different densities based on SWRf (Eq. 18)

Variables			Errors%
Density	Experimental IB	Predicted IB	
0.65	0.4	0.39	2.50
0.7	0.43	0.44	2.33
0.75	0.48	0.47	2.08

Table 4 Average percent errors between experimental and predicted IB data in different densities based on SWRe (Eq. 19)

Variables			Errors%
Density	Experimental IB	Predicted IB	
0.65	0.39	0.41	5.13
0.7	0.44	0.43	2.27
0.75	0.48	0.45	6.25

Discussion

Previous studies had indicated that there is little correlation between density and the other factors that influence bond quality, such as IB strength and face and edge SWR (Semple and Smith 2006 ; Zaini and Eckelman 1993).

Finally, IB strength could be predicted with 18.17% and 10.68% error, based on face SWR and edge SWR, respectively (Table 5). IB strength was predicted by regression models, based on processing parameters and physical properties, with 36% and 14.65% error, respectively (Cook and Chiu 1997; Fernandez et al. 2008).

In the DA method, the number of variables were reduced from the original (n) to dimensionless groups (n-m). Certainly, there are fewer dimensionless groups than original variables, which helps simplify the regression models.

Table 5 Experimental and predicted values of IB based on $SWR_{e\&f}$

Number of treatments	Experimental IB	Predicted based on (SWR_e)	Predicted based on (SWR_f)	%Errors* based on (SWR_e)	%Errors* based on (SWR_f)
1	0.23	0.28	0.34	21.74	47.83
2	0.37	0.33	0.33	10.81	10.81
3	0.4	0.36	0.32	10.00	20.00
4	0.36	0.41	0.38	13.89	5.56
5	0.3	0.36	0.31	20.00	3.33
6	0.42	0.47	0.37	11.90	11.90
7	0.51	0.41	0.39	19.61	23.53
8	0.47	0.53	0.48	12.77	2.13
9	0.32	0.37	0.49	15.63	53.13
10	0.49	0.47	0.41	4.08	16.33
11	0.45	0.4	0.36	11.11	20.00
12	0.47	0.54	0.52	14.89	10.64
13	0.33	0.34	0.44	3.03	33.33
14	0.4	0.37	0.33	7.50	17.50
15	0.4	0.38	0.33	5.00	17.50
16	0.37	0.45	0.46	21.62	24.32
17	0.41	0.4	0.41	2.44	0.00
18	0.48	0.5	0.46	4.17	4.17
19	0.45	0.45	0.42	0.00	6.67
20	0.41	0.49	0.53	19.51	29.27
21	0.31	0.37	0.41	19.35	32.26
22	0.53	0.46	0.46	13.21	13.21
23	0.52	0.45	0.40	13.46	23.08
24	0.5	0.53	0.56	6.00	12.00
25	0.32	0.34	0.44	6.25	37.50
26	0.41	0.43	0.38	4.88	7.32
27	0.4	0.37	0.36	7.50	10.00
28	0.53	0.47	0.49	11.32	7.55
29	0.37	0.34	0.54	8.11	45.95
30	0.47	0.48	0.50	2.13	6.38
31	0.48	0.56	0.47	16.67	2.08
32	0.44	0.45	0.58	2.27	31.82
33	0.4	0.34	0.47	15.00	17.50
34	0.45	0.47	0.54	4.44	20.00
35	0.57	0.49	0.45	14.04	21.05
36	0.6	0.54	0.65	10.00	8.33
The average of error percent				**10.68**	**18.17**

$$* \left| \frac{SWR_{\exp} - SWR_{pred}}{SWR_{\exp}} \times 100 \right|$$

RBF was successful at predicting IB strength within ±12.5% (Cook and Chiu 1997).

Dimensionless groups are obtained based on a mathematical method; therefore, they decrease the formation of chance relationships (Vignaux and Scott, 2001). So the Eq. 18 and 19 can best fit observed and predicted values of internal bond than other regression models (Fig. 2 and 3). Generally, in particleboard manufacturing, the ability to predict the IB strength of the final boards with 15% error would provide valuable information for process control (Cook and Chiu 1997).

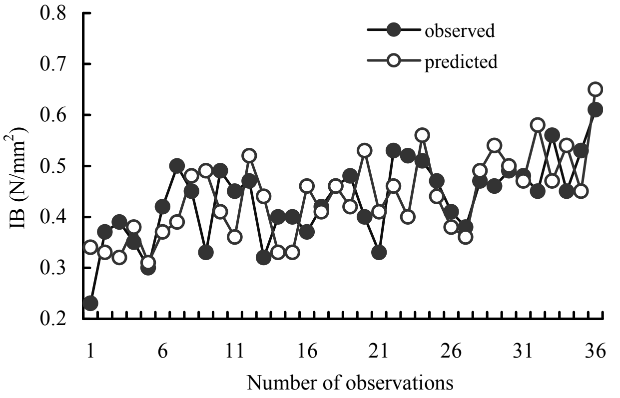

Fig. 2 Observed and predicted values for IB strength based on SWR_f.

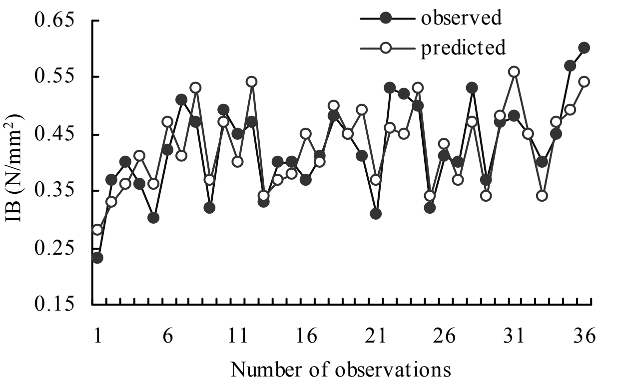

Fig. 3 Observed and predicted values for IB strength based on SWR_e

Regression models are statistical tools for the investigation of relationships between variables. They are extremely flexible and commonly used in estimating the properties of wood composite. Often, the problem is these models cannot predict the properties of wood composite with high accuracy. In addition, previous studies have not considered the effect of particle size on estimating IB strength. Cook and Chiu (1997) attribute this value of error to the size and geometry of the particles, as these factors were not considered in their model. In this study, first IB strength was predicted based on particle size, density, and percentage of adhesive. The results showed 35% and 18% error based on linear and exponential function, respectively. Average percentage error depended on the characteristics of the process, final product, numbers, and type of parameters used for modeling.

Finally, the Buckingham Pi theorem was used to build regression models for predicting IB strength based on $SWR_{f\&e}$ particle size, density, and percentage of adhesive. The lowest errors in predicting IB strength based on regression-based models and RBF were 14.65% and 12.5% respectively. However, the value of errors for Eq. (18) and (19) were 18.17 and 10.68, respectively. Therefore, the accuracy of Eq. (18) is favorable and the use of SWR could be a realistic approach to predicting IB strength. Clearly, the regression model presented here is efficient for the variables used in these models.

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