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ORIGINAL ARTICLE

The effect of particle size on the prediction accuracy of screw withdrawal resistance (SWR) models

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Abstract Density and internal bond extremely used for prediction face and edge screw withdrawal resistance (SWR). Structural parameters (particle size and density) can strongly affect the mechanical properties of particleboard, but up to date the effect of particle size on SWR were not investigated. In the current study, firstly face and edge SWR were predicted by an exponential function based on density and IB strength. In continue, aspect ratio was added to the earlier models to investigate the effect of particle size on accuracy of these models. The results showed that the particle size strongly affect prediction errors. The effect of aspect ratio on face SWR and edge SWR models changed based on dependent variable (face SWR and edge SWR) and main independent variables (density and internal bond strength). Prediction of screw face withdrawal strength as function of density and aspect ratio showed the lowest error percent. The most error percent obtained for face withdrawal strength based on internal bond strength and aspect ratio.

Keywords Screw withdrawal strength · Internal bond · Density · Aspect ratio · Exponential function

Introduction

Wood-based panels, such as particleboard (PB), are used widely in the manufacture of furniture, flooring, housing and other industrial products. In these industries, Screws provide an excellent method for fastening many of wood composite components. Previous studies have found strong correlations between density or specific gravity and screw withdrawal resistance (SWR). Firstly, Johnson (1967) presented a model for prediction SWR based on density but this model did not match well with experimental data. Eckelman (1975) developed models for prediction the face and edge SWR based on density, screw dimensions and embedment depth. Barnes and Lyon (1978) investigated the accuracy of Eckelman's models on the weathered and unweathered samples of PB and they indicated that only SWR from unweathered boards well estimated by Eckelman's models. This is one of the major challenges associated with wood-based PB that the bond quality of wood materials deteriorates when they expose to the heat and moisture which cause to reduce screw holding capacity. The SWR has shown a good correlation on bond quality of wood composite. Fujimoto and Mori (1983) suggested, internal bond (IB) and face and edge SWR ($SWR_{f\&e}$) are highly correlated with bond quality of boards. 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. There are many factories that can influence on bond quality of PB including: density, particle size and resin content. The geometry of the wood element plays a crucial role in the manufacturing process of wood composite. There are many studies into the effect of particle geometry on physical and mechanical properties of PB (Lehmann 1965; Barnes 2001; Sackey et al. 2008; Arabi et al. 2010; Sackey 2010). Arabi et al. (2011a, b) investigated the effect of particle size on mechanical property of PB and suggested that an exponential function can better describe the simultaneous effect of slenderness and resin content than a linear equation on mechanical properties of PB. The influence of particle

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geometry on SWRe, which is one of the most important properties for furniture applications, was rarely investigated. Earlier studies on PB have suggested that with increasing the length of thick flakes, slenderness ratio, particle thickness, aspect ratio (length to width ratio SWR increases (Post 1961; Haselein et al. 2002; Sackey 2010). The effect of particle size on IB strength and density were investigated in previous studies (Malonay 1977; Lin and Huang 2004). Arabi et al. (2011a, b) explored options for difference particle size to reduce board density without adversely influencing the board's mechanical properties. For example they showed that for a constant value of MOE 14 MPa, a decrease in density from 0.75 to 0.7 g cm^{-3} could be compensated for by adding 6.88 U of slenderness ratio. With increasing particle size, the percentage of void areas and resin distribution on particle surface increased irregularly (Lin and Huang 2004). The percentage of void area has a negative effect on IB strength and edge SWR. Fins particle can fill the voids and increase the IB strength and produce tighter edges (Nemli 2003; Sackey et al. 2008). There are many researches that have been presented a lot of models to predict SWR as function of panel density, IB strength. Screw dimensions and depth of penetration (Eckelman 1975; Zaini and Eckelman 1993; Semple and Smith 2006), but in these models, the effect of the wood particles size on the screw holding performance has been not considered. So the objective of this study was to investigate the effect of particle size on the accuracy of SWR prediction models that presented based on density and IB.

Materials and methods

Small-diameter logs derived from poplar (*Populous alba*) were cut into blocks with dimensions of 50 × 50 × 10 mm. These blocks were ground with a laboratory Hammer-mill. Particles were dried to a moisture content of <3 %. After drying, the particles were sifted by passing through three hand-held screens including 5, 8 and 12 mesh. The length, width and the thickness of 5 g screened particles for each particle size (+5; −5 +8; −8 +12 and −12) were measured with a micrometer caliper. Average dimensions of classified particles are shown in Table 1. Then, urea formaldehyde (55 % solid content) as an adhesive were sprayed on particles and mats were formed and pressed with 35 kg/cm^2 pressure at 180 °C for 5 min. Finally, 36 Single-layer PBs with three levels of density (0.65, 0.7 and 0.75 g/cm^3) and four levels of particle size (+5; −5 +8; −8 +12 and −12) were manufactured in the laboratory and then for moisture conditioning of the boards they kept at 65 ± 5 % relative humidity at 20 ± 2 °C for 2 weeks. Both IB and SWR samples have been cut according to the EN 319 (1993) and EN 320 (1999) standard, respectively. Overall, a total of 108 samples (3 samples from each board) were examined for both IB and SWR. Then the samples were tested by INSTRON 4489.

Results and discussion

PB is one of the most important wood composite panels that used in furniture industries. Difference in particle size can affect the board properties such as Surface quality, edge smoothness, SWR and IB strength. These factors are the most important board properties that consider in furniture industries. But in previous studies, the effect of particle size on SWR has investigated rarely. The previous studies, showed among dimensionless groups of particles (slenderness ratio, aspect ratio and flat ratio), aspect ratio has more effect on SWR than others.

Prediction SWR based on density

An exponential was obtained using SHAZAM software (version 9) and SWR_f and SWR_e were predicted based on density (Eqs. 1, 2).

$$SWR_f = D^{1.5525} \times E^{4.9910} \quad (1)$$

$$SWR_e = D^{1.3020} \times E^{4.6960} \quad (2)$$

where SWR_f and SWR_e are face and edge SWR, respectively and D is board density (g/cm^3). The correctness of equations were investigated based on the average percent error between experimental and predicated data (Eq. 3).

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 into parenthesis represents Standard deviation

Table 2 Average error percent of face and edge SWR based on density and IB strength

	Percentage of error based on (SWR_f)	Percentage error based on (SWR_e)
Density	16.28	17.3
IB	17.66	15.3

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

where MAE, $z(x_i)$, $z(xj)$ and N are the average absolute error, experimental value, predicted value, and the number of treatment, respectively. Results indicated that an exponential function can estimate the SWR_f and SWR_e with 16.28 and 17.30 % error, respectively (Table 2). In the several past researches, it has been suggested that there is a meaningful correlation between density and SWR (Semple and Smith 2006; Eckelman 1975). Denser boards showed higher screw holding strength which results in better inter-particle contact during pressing and present a better grip for screws and higher resistance during withdrawal (Malonay 1977; Sackey et al. 2008). But prediction SWR just based on density showed a significant percentage of error.

Prediction SWR based on density and aspect ratio

Equations 1 and 2 were developed and SWR were predicted based on density and aspect ratio, (Eqs. 4, 5).

$$SWR_f = A^{0.263395} \cdot D^{1.5744} \cdot E^{4.1564} \quad (4)$$

$$SWR_e = A^{0.06}.\ D^{1.3213}.\ E^{4.5056} \quad (5)$$

where SWR_f and SWR_e are SWR respectively, A is aspect ratio (length/width) and D is board density (g/cm^3). Results showed density–particle size interaction was significantly affected on accuracy of Eqs. 1 and 2. Adding aspect ratio to the Eq. 1 decreased the value of error percent for SWR_f and increased error percent for SWR_e (Table 3). Previous studies have found a high correlation between SWR and aspect ratio of particle (Post 1961; Haselein et al. 2002; Sackey 2010). Particles with higher aspect ratio provide higher surface area for resin coverage, smoothness surface, more ability to transfer stress and as results indicate a better grip for screws, (Malonay 1977; Lin and Huang 2004; Sackey 2010). Therefore, Eq. 4 could better predict SWR_f than Eq. 2. Unlike the face SWR, edge SWR_e did not show a good correlation with adding aspect ratio. Bond qualify of particle board strongly affects SWR_e. Aspect ratio causes that resin irregularly distribute on particle surfaces and void areas increase in panel that these factors have negative effect on bond quality (Lin and Huang 2004; Sackey 2010). As a result, with adding the aspect ratio to Eq. 5, the prediction error increased.

Table 3 Average of error percent of SWR based on density in different aspect ratio

Aspect ratio	Percentage of error based on (SWR_f)	Percentage of error based on (SWR_e)
5.85	15.58	19.9
5.57	14.23	18.8
3.35	12.08	17.42
2.65	13.15	17.08
The average of error percent	13.76	18.3

Prediction SWR based on IB

Equations 6 and 7 estimate face and edge SWR based on IB strength. Results indicated 17.66 and 15.30 % error percent for face SWR and edge SWR, respectively (Table 2).

$$SWR_f = IB^{0.0344} \cdot E^{4/4616} \quad (6)$$

$$SWR_e = IB^{0.29555/0} \cdot\ E^{4.4807} \quad (7)$$

Earlier studies, have found strong correlations between SWR and IB of PB. Semple and Smith (2006) studied the IB prediction of PBs based on SWR models and reported that there is a significant correlation between IB strength and edge SWR.

Prediction SWR based on IB and aspect ratio

The Eqs. 8 and 9 were developed with adding aspect ratio to Eqs. 6 and 7. The average error percentage based on Eq. 3 showed that adding aspect ratio increase average error percent, especially for face SWR (Table 4). There is a little coloration between IB strength and face SWR (Semple and Smith 2006). In addition, in earlier studies, IB strength did not show a direct correlation with increasing

Table 4 Average of error percent of SWR based on IB strength in different aspect ratio

Aspect ratio	Percentage of error based on (SWR_f)	Percentage of error based on (SWR_e)
5.85	24.94	18.42
5.57	19.81	16.1
3.35	16.94	13.49
2.65	16.95	14.54
The average of error percent	19.66	16.38

aspect ratio. Therefore, with increasing aspect ratio, the values of error percent increased (Table 4).

$$SWR_f = A^{0.57119} \cdot IB^{0.4288} \cdot E^{3.539} \quad (8)$$

$$SWR_e = A^{0.10124} \cdot IB^{0.3381} \cdot E^{4.1887} \quad (9)$$

Void areas in PB and irregularly resin distribution (resin distributes irregularly with increasing length and width on particle surfaces) have negative effects on bond quality of PB (Lin and Huang 2004). Instead fins fill the voids and increase the IB strength and edge SWR (Nemli 2003; Sackey et al. 2008). Results of this study showed, that difference in particle size can significantly affect prediction accuracy of SWR models. The effect of particle size on face SWR and edge SWR changed based on dependent variable (face SWR and edge SWR) and main independent variable (density and IB). Some researchers suggested that it is better to SWR were predicted based on IB strength as a main factor (Fujimoto and Mori 1983; Eckelman 1975; Zaini and Eckelman 1993). But under the condition of this study, face SWR showed the lowest error percent as function of density and aspect ratio. Therefore, it seems, particle size could be considered as one of main factors such as screw dimensions and embedment depth in prediction SWR. However, the efficiency of the particle size on the prediction accuracy SWR models has been demonstrated only for the specific variables that used in this study. Therefore, for more information and make better decision it needs to be considered in different conditions.

Conclusion

Nowadays, most of PB plants use from wood or lignocelluloses waste particles. These waste particles are very different in their size. Particle size is one of the most parameters that can influence on the accuracy of SWR models but it has been not considered in previous models. Today for the reason of increasing in cost production, manufacturers try to control more and more their cost production and their process. Therefore, in this study, three levels of density including 0.65, 0.7, and 0.75 g/cm^3 and also, four levels of particles size including +5, −5 +8, −8 +12, and −12 mesh were investigated. In previous studies, it has been suggested that the SWR can be predicted as a function of IB, screw dimensions and embedment depth without considering particle size. But in this study results indicated, difference in particle size can affect the accuracy of SWR prediction models. Results of this study can be summarized in 2 points:

(1) Face SWR can be predicted as a function of density and aspect ratio.
(2) Edge SWR can be estimated based on IB strength and aspect ratio.

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