J. Agr. Sci. Tech. (2013) Vol. 15: 1405-1413

Evaluation of Particleboard Properties Using Multivariate Regression Equations Based on Structural Factors

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ABSTRACT

The application of stepwise multivariate-linear regression models for determination of particleboard properties based on structural factors was studied. Poplar (*Populus alba*), Beech *(Fagus orientaleis)* and Hornbeam wood *(Carpinus betulus)* with dry density of 460, 630 and 790 kg/m^3, respectively, were used as raw materials. Three levels of boards target density (520, 620 and 720 kg m^{-3}) and urea formaldehyde (UF) resin (6, 7, and 8%) were compared. The variables were included in the regression equations of modulus of rupture (MOR), modulus of elasticity (MOE), shear strength, and thickness swell (TS) after 24 hours immersion based on the degree of importance. In order to obtain the optimum board density and resin content for each species, contour plots were drawn by Minitab 13 software. Regarding the results from contour plots, particleboards with density ranging from 520 to 620 kg m^{-3} and 6% resin had most of their mechanical properties within those required by the corresponding standards. Thickness swell values were higher than requirements. We suggest additional treatments such as using adequate amount of water resistant materials to improve TS after 24 hours immersion.

Keywords: Board density, Particleboard, Regression models, Resin content, Wood density.

INTRODUCTION

Particleboard is a panel product manufactured under pressure from particles of wood or other ligno-cellulosic materials and an adhesive (Nemli *et al.*, 2008). It is widely used for construction, furniture, and interior decoration. Particleboard properties are strongly influenced by structural factors such as: wood type density, particle geometry, the boards' compression ratio, board density, adhesives type and content, and others (Maloney, 1977).

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 their density (Eslah *et al.*, 2012; Hiziroglu *et al.*, 2005; Zhou, 1990). Increases in board density result in improvement in board properties. Wood density is a determining factor in particleboard density. A low density wood provides a high density compression ratio and, therefore, a higher contact surface between the particles than high density wood. This leads to a more uniform product with a greater capacity to transmit loads between the particles, resulting in higher flexural and internal bonding properties (Dias *et al*., 2005).

Urea-formaldehyde (UF) resins are the predominant adhesives for interior use plywood and particleboard (Rowell, 2005). Increase in UF resin content leads to improvement of physical-mechanical properties of wood-based panels (Ashori and Nourbakhsh, 2008). On the other hand, the increase in formaldehyde-based resins content is of concern for human health and the environment (Kim, 2009).

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The prediction of wood composites properties using models provides valuable information to improve process control and reduce production cost (Cook and Chiu, 1997). Bending properties of oriented strand board (OSB) panels were investigated as a function of shape, size, and distribution of wood strand (Takuya *et al.,* 2004). Dai *et al.* (2008) showed that internal bond strength (IB) was increased by increase in product density, resin content, and particle thickness.

The present work investigated the possibility of predicting particleboard properties based on structural parameters. Stepwise multivariate-linear regression models were used to evaluate the influence of wood density, board density, and UF resin content on board properties and to determine the most effective parameter.

MATERIALS AND METHODS

Material

Logs of Poplar (*Populus alba*), Beech (*Fagus orientalis*) and Hornbeam wood (*Carpinus betulus*) were cut into small pieces. The dimensions of the elements were about 6cm×6cm×1cm. The specimens were chipped using a laboratory-scale drum-chipper. Particles were dried down until 3% moisture content and were classified to eliminate the over-and under-sized ones. Urea-formaldehyde (UF) resin with 60% solid content was supplied by Tiran Shimi Tehran Co.

Panel Manufacturing

Single-layer panels were manufactured. The particles were blended with UF resin. Hand formed mats were pressed at a temperature of 170°C and a pressure of 30 kg cm^{-2} for 5 minutes. The dimension of each panel after pressing was about 40 cm long by 40 cm wide by 1.6 cm thick. Poplar, Beech, and Hornbeam woods with dry density of 460, 630 and 790 kg m^{-3}, respectively, were used as alternative raw materials. Three levels of board density (520, 620 and 720 kg m^{-3}) and resin content (6, 7, and 8%) were compared. Three replicates were prepared for each treatment.

Mechanical and Physical Tests

The panels were conditioned at 20±2°C and with 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 test board for determination of each mechanical and physical property. The mechanical and physical properties were determined in accordance with the following standards: Modulus of rupture (MOR) and modulus of elasticity (MOE) (EN 310, 1993), Shear strength (ASTM D 1037, 1996), thickness swell (TS) after 24 hours of immersion (EN 317, 1993) and density of boards (EN 323, 1999).

Statistical Analysis

Wood density, resin content and board density were considered as independent variables, whereas board properties (MOR, MOE, shear strength, and TS 24 hours) were dependent variables. A stepwise regression procedure using SPSS 18 software was performed to determine which variables could be included in the model. Stepwise regression started with no variables in the model and initially the most significant ones were added. Afterwards, other variables were added, which could possibly be removed in case they were not significant. Stepwise regression was continuously performed in order to assure the inclusion of only significant variables and removal of non-significant variables in the model (Hood, 2004). 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 property values with a MAE of 15% is regarded as acceptable, while a MAE of 20-30% is not (Malinov *et al.,* 2001). *MAE* was calculated according to Equation (1):

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{z_*(xi) - z(xi)}{z(xi)}\right| \times 100 \qquad (1)$$

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

In order to determine the effect of board density and resin content on particleboard properties in each species, contour plots were drawn by Minitab 13 software and the values of each property were compared with American National Standard (ANSI A208.1, 2009) and European Standard (EN 312, 2003) required values for particleboards.

RESULTS AND DISCUSSION

The average values of *MOR*, *MOE*, shear strength, and *TS* of the sample panels are presented in Table 1. Moreover, multivariate regression models are shown in Table 2.

Modulus of Rupture

Complete equation for *MOR* was built in two steps. Board density (D) and wood density (W) were found to affect *MOR* property (Table 2). The coefficient of determination (R^2= 0.814) indicate that the above equation is capable of explaining about 81.4% of the observed values. The model with standardized coefficients shows that the effect of board density (0.852) on *MOR* is about 2.5 times greater than wood density. *MAE* value (10.5%) obtained for *MOR* is lower than 15%, which means that the regression model can be regarded as appropriate for obtaining information on *MOR*. Increase in board density causes an increase in compression ratio and, hence, the contact between wood particles, which results in *MOR* improvement. Hiziroglu *et al.* (2005) reported that board density was the most important factor affecting all physical and mechanical properties of particleboard. The results of Barboutis and Philippou (2007) indicated that increase in wood density reduced the bending strength of particleboard.

By the evaluation of contour plots, it is possible to determine the optimum amounts of board density and resin content while maintaining particleboard properties above minimum requirements set by standard values.

The highest values of *MOR* (more than 23.5 MPa for poplar particleboard, ~15.5 MPa for beech particleboard, and ~19 MPa for hornbeam particleboard) were reached at 650-720 kg m^{-3} board density and 6.5–8% resin content Figures 1(a, b and c). Based on ANSI A208.1 (2009) and EN 312 (2003) standards for general-purpose particleboard, the minimum requirements for bending strength of particleboard panels for general uses are 11 MPa and 12.5 MPa, respectively. Therefore, particleboards of each of the three species with density of 520-570 kg m^{-3} and 6% resin content met these standard requirements.

Modulus of Elasticity

The complete equation for *MOE* was built in three steps. The effects of wood density (W), board density (D), and resin content (R) on *MOE* were positive. Regarding the coefficients of unstandardized model, wood density is the most important factor included in the *MOE* model. The coefficient of determination for this model (R^2= 0.784) indicates that the proposed model is able to explain 78.4% of the observed values. *MAE* obtained for *MOE* is about 10.3%. Therefore, *MOE* regression model is regarded as acceptable. The results obtained are similar to those described by other authors (Nemli *et al*., 2008; Zhou, 1990; Ashori and Nourbakhsh, 2008; Hayashi *et al*., 2003).

The highest values of *MOE* (~2280 MPa for Poplar particleboard, ~3200MPa for Beech and hornbeam particleboard) were reached at about 620-720 kg m^{-3} board

Table1. Mechanical and physical properties of experimental panels.

Wood species	Board target density (kg m^{-3})	Resin content (%)	Panel cod	*MOR* [a] (MPa)	*MOE* [b] (MPa)	Shear strength (MPa)	*TS* [c] 24 h (%)	Measured density (kg m^{-3})
Poplar	520	6	A1	10.2	1143	4.2	21.6	521
		7	A2	10.8	1196	4.8	19.7	523
		8	A3	11.8	1484	5.4	17.6	522
	620	6	A4	15.6	1619	4.9	20.3	622
		7	A5	15.7	1630	4.8	21	622
		8	A6	16.9	1735	5.7	17.3	623
	720	6	A7	17.9	2122	4.9	30.9	723
		7	A8	19.5	1810	5.2	29.7	724
		8	A9	23.6	2153	4.9	23.1	721
Beech	520	6	B1	7.3	1853	4.5	15.4	522
		7	B2	8.6	2009	4.8	12.8	521
		8	B3	7.4	2279	5.1	10.4	521
	620	6	B4	12.3	2369	6.9	14	621
		7	B5	11.6	2298	6.4	13.5	621
		8	B6	11.4	2862	8.1	10.6	623
	720	6	B7	14.4	2628	6.9	23.9	722
		7	B8	16.3	2769	8.1	22.2	720
		8	B9	14.3	3261	8.8	18.2	721
Hornbeam	520	6	C1	7.4	1973	4.5	19.9	520
		7	C2	7.3	1964	4.3	18.2	521
		8	C3	7.8	2758	5.2	14.8	522
	620	6	C4	12.8	2516	6.9	25.2	621
		7	C5	12.4	2458	7.5	22	622
		8	C6	12.7	3437	7.1	22.6	621
	720	6	C7	14.5	2758	7.7	29.4	723
		7	C8	19.8	2546	8.5	25.6	722
		8	C9	19.3	2934	9.7	22.4	722

[a] Modulus of rupture, [b] modulus of elasticity, [c] Thickness swell after 24h immersion.

Table 2. Multivariate regression models with Unstandardized (US) and standardized (S) coefficients.

No.	*Equation (99% confidence interval)*	R^2 [a]	*F* [b]	*MAE* [c]
2	*MOR* [d] *=7.430+4.500D-1.556W (US)*	0.814	52.357**	10.5
3	*MOR= 0.852D-3.343W (S)*			
4	*MOE* [c]*=165.778+469.556W+351.222D+217.889R(US)*	0.784	27.831**	10.3
5	*MOE=0.665W+0.497D+0.249R (S)*			
6	*Shear strength=.907+1.207D+0.922W+0.478R (US)*	0.697	17.602**	12.1
7	*Shear strength= 0.635D+0.481W+0.249R (S)*			
8	*TS* [e] *24 h= 16.596+4.167D-2.432R (US)*	0.531	13.574**	18.2
9	*TS 24 h= 0.630D-0.366R (S)*			

** Significant difference at the 1% level.

[a] Modulus of rupture, [b] modulus of elasticity, [c] mean average error value, [d] Modulus of rupture, [e] Thickness swell after 24h immersion.

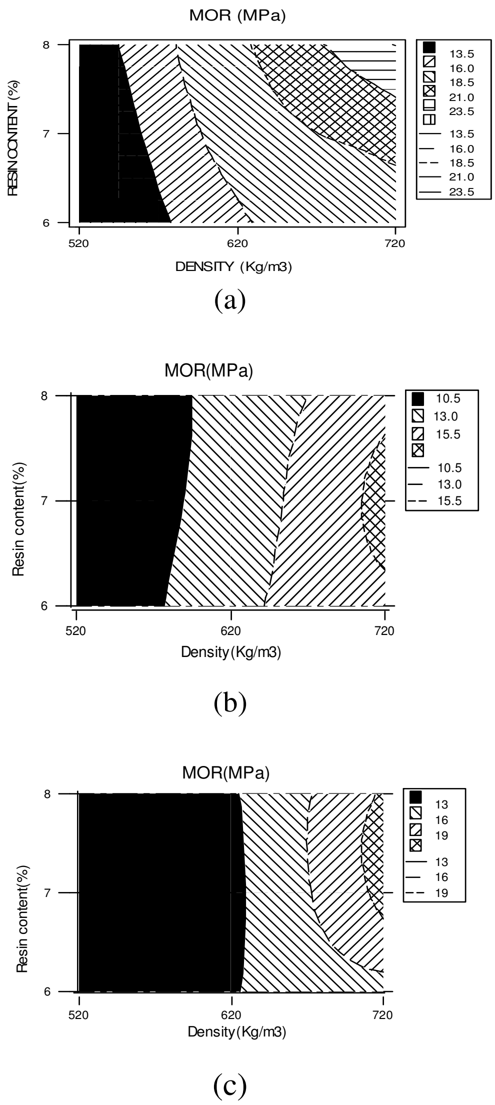


Figure 1. Modulus of rupture (*MOR*) counter plot for (a) poplar panels, (b) Beech panels (c) Hornbeam panels.

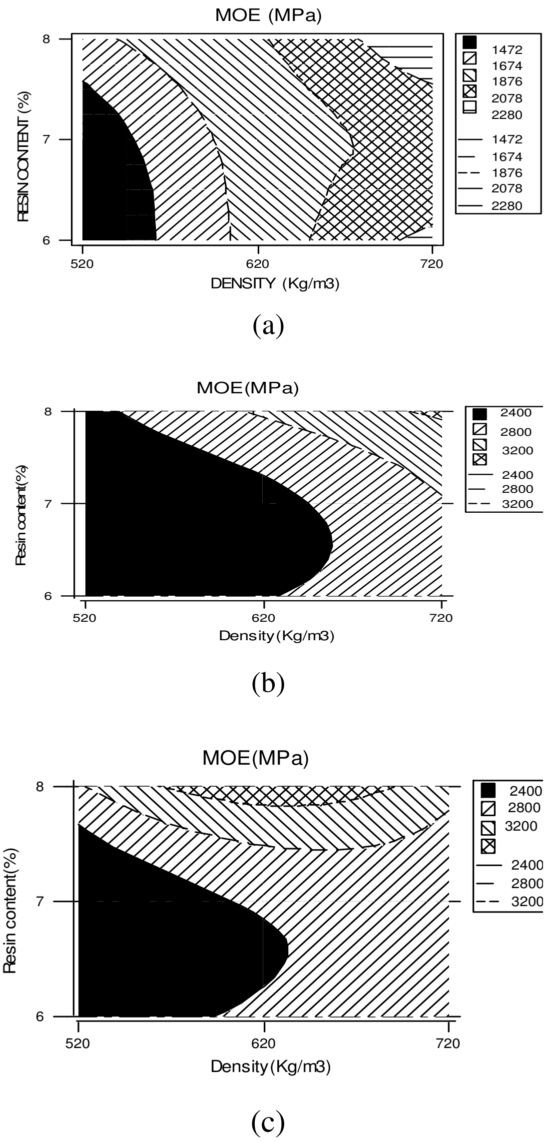


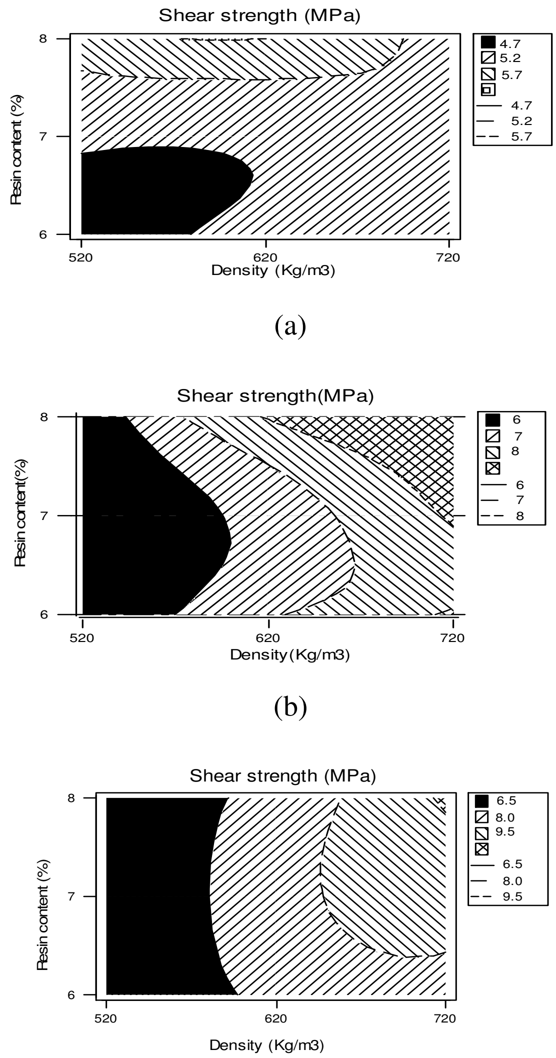
Figure 2. Modulus of elasticity (*MOE*) counter plot for (a) poplar panels, (b) Beech panels (c) Hornbeam panels.

density and resin content of 7.7–8% Figure2 (a, b and c). Based on ANSI A208.1 (2009) and EN 312 (2003) standards for general-purpose particleboard, the *MOE* requirements are 1,700 and 1,800 MPa, respectively. Thus, panels made of Poplar, Beech, and Hornbeam wood with density of 550-650 kg m^{-3} and 6% resin content met the standard requirements.

Shear Strength

Board density (D), wood density (W) and resin content (R) positively affected this property (Table 2, Equations (6) and (7)). The coefficient of determination (R^2= 0.697) indicates that the equation is capable of explaining about 69.7% of the observed values. Board density is the main variable affecting shear strength. Considering *MAE* (12.1%), shear strength model is regarded as acceptable. Barboutis and Philippou (2007) showed that internal bond (IB) of all particleboard increase with board density and wood density. Eslah *et al.* (2012) reported that the increase in UF resin content led to improvement of IB of particleboard.

The highest value of shear strength (~5.7 MPa for Poplar particleboard, ~8 MPa for Beech, and ~ 9.5 MPa for hornbeam particleboard) were reached at about 650-720 kg m^{-3} board density and 7–8% resin content Figure 3 (a,b and c) . For particleboard, the shear strength is closely related to the IB strength (Wang *et al.*, 1999). Based on ANSI A208.1 (2009) and EN 312 (2003) standards for general-purpose particleboard, the IB strength requirements are 0.36 MPa and 0.28 MPa, respectively. From linear regression formula suggested by Wang *et al.* (1999) the minimum requirement for shear strength of particleboard for general uses is in the range of 1.22-2 MPa. Panels with minimum density and resin content (520 kg m^{-3} and 6% resin content) are within these standard requirements Figure 3 (a,b and c).



(c)

Figure 3. Shear strength counter plot for (a) poplar panels, (b) Beech panels (c) Hornbeam panels.

Thickness Swell

Considering the coefficient of determination (R^2= 0.531), the equation is capable of explaining about 53.1% of *TS* values observed after 24 hours immersion in water. The model with standardized coefficients (Table 2, Equation (9)) shows that the effect of board density (0.630) on TS 24 h is about 1.7 times greater than resin content (0.366). *MAE* values obtained for TS 24 h are higher than 15%, which means that the model for this property is not precise.

According to EN 312 (2003) and ANSI A208.1 (2009) standards, maximum thickness swell values for home decking and load bearing particleboards are 15 and 8%, respectively. TS 24 h values reached their lowest amount at board density of approximately 520-640 kg m^{-3} and 6-8% resin content Figure 4 (a,b and c). The TS of the panels were poor. Spring back of the panels as they are soaked in water manifests itself in the form of lower dimensional stability, which is a common behavior of many wood composite (Kalaycioglu *et al.*, 2005). Additional treatments such as coating of particleboard surface with melamine-impregnated paper or laminates or high press temperature could be employed in order to produce more stable products (Nemli, 2002). The panels required

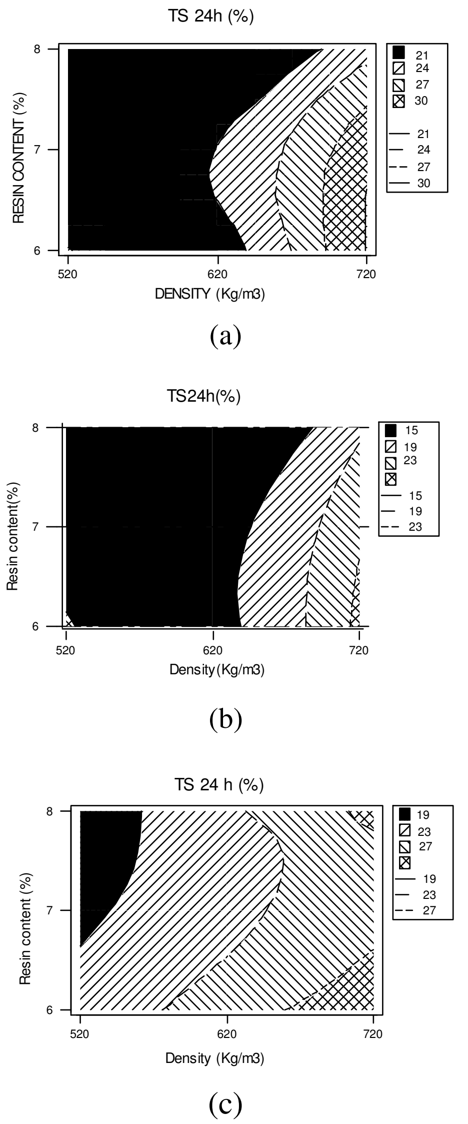


Figure 4. TS 24 h counter plot for (a) poplar panels, (b) Beech panels (c) Hornbeam panels.

additional treatments such as using adequate amount of water resistant materials.

CONCLUSIONS

Regression models proved to be an appropriate approach to evaluate the balance within wood density, board density, and UF resin content for *MOE*, *MOR*, and shear strength. For thickness swell the model was not precise. Models built in our study can only be implemented in situations similar to this research and may not be used for industrial conditions. The results from counter plots suggested that it is possible to manufacture particleboards from the above species using 6% UF resin and board density ranging from 520 to 620 kg m^{-3} with mechanical properties within the range of those required by corresponding standards. To improve dimensional stability, additional treatments such as the use of water resistant materials could be employed.

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ارزیابی ویژگی های تخته خرده چوب با استفاده از معادلات رگرسیونی چندگانه بر اساس فاکتورهای ساختاری

ع. ا. عنایتی، ف. اصلاح، ا. فرهید

چکیده

در این تحقیق کاربرد مدل های رگرسیونی چند گانه خطی به روش گام به گام برای تعیین ویژگی های تخته خرده چوب بر اساس فاکتورهای ساختاری بررسی شد. چوب صنوبر، راش و ممرز به عنوان مواد اولیه متغیر در ساخت تخته ها مورد استفاده قرار گرفتند. دانسیته تخته ها در سه سطح (۵۲۰، ۶۲۰ و ۷۲۰ کیلوگرم بر متر مکعب) و درصد رزین اوره فرم آلدهید مصرفی (۶ ، ۷ و ۸ درصد) انتخاب شدند. مدل های رگرسیونی بیان گر آن بودند که متغیر ها بر اساس میزان اثرگذاری در مدل های MOR، MOE ، مقاومت برشی و TS_{24} وارد شدند. برای دستیابی به مقدار بهینه دانسیته تخته و رزین با حفظ کیفیت تخته ها در هر گونه، از نقشه های اثرات متقابل استفاده شد. با توجه به نتایج نقشه ها تخته های با دانسیته ۵۲۰ تا ۶۲۰ کیلو گرم بر متر مکعب و ۶٪ رزین اوره فرم آلدهید عموما دارای خواص مکانیکی در حد نصاب مقادیر تعیین شده توسط استاندارد های مربوطه بودند. مقادیر واکشیدگی ضخامت بیشتر (ضعیف تر) از استاندارد بود. برای بهبود ثبات ابعادی، پانل ها به تیمارهای اضافی مانند استفاده از مواد مقاوم به آب نیاز داشتند.