Hasan Ozturk¹, Aydin Demir², Cenk Demirkir²

Prediction of Optimum Expanded Polystyrene Densities for Best Thermal Insulation Performances of Polystyrene Composite Particleboards by Using Artificial Neural Network

ABSTRACT • The objective of this study is to predict the optimum expanded polystyrene (EPS) densities for the best insulation properties of the particleboards manufactured with waste EPS instead of formaldehyde-based adhesives used in particleboard production with artificial neural network (ANN). For this purpose, the waste EPS particles of five different densities were used in the production of composite particleboards. The experimental data used in the study were obtained from the previous study. Half of the beech, poplar, alder, pine and spruce chips were dried in a drying oven and the other half were naturally conditioned at room temperature, and then 18 mm thick three-layer composite particleboards were produced. The thermal conductivity of panels was determined according to ASTM C 518. The prediction model with the best performance and acceptable deviations was determined by using statistical and graphical comparisons between the experimental data and the prediction values obtained as a result of ANN analysis. Then, using this prediction model, the thermal conductivity coefficient values were estimated for the intermediate EPS densities that were not experimentally tested. According to the analysis findings, the thermal insulation performance for both beech and spruce polystyrene composite particleboards (PCP) panels increased with using of waste EPS foams with a density of 30 kg/m³. The lowest thermal conductivity values were obtained from the EPS waste foams with the density of 18, 13 and 22 kg/m³ for the PCP panels produced with poplar, alder and pine in the natural drying, respectively. In the technical drying, these values were found to be 15, 14 and 11-13 kg/m³, respectively. Technical drying showed much better thermal performance than natural drying while poplar indicated the best performance among the wood species.

KEYWORDS: polystyrene composite particleboard; thermal insulation; thermal conductivity; EPS; ANN

¹ Author is lecturer at Karadeniz Technical University, Arsin Vocational School, Materials and Material Processing Technologies, Trabzon, Turkey. https://orcid.org/0000-0002-5422-7556
² Authors are research assistant and associate professor at Karadeniz Technical University, Faculty of Forestry, Department of Forest Industry Engineering, Trabzon, Turkey. https://orcid.org/0000-0003-4060-2578, https://orcid.org/0000-0003-2503-8470
SAŽETAK • Cilj je ove studije primjenom umjetne neuronske mreže (ANN) predvidjeti optimalne gustoće ekspandiranog polistirena (EPS) radi postizanja najboljih izolacijskih svojstava ivrice proizvedene s otpadnim EPS-om unistu s lepilom na bazi formaldehida, kako se rabi u proizvodnji ivrice. Stoga je za proizvodnju ivrice upotrijebljeni otpadni EPS pet različitih gustoća. Eksperimentalni podatci primijenjeni u studiji dobiveni su prijašnjim istraživanjem. Jedna je polovica ivrja bukovine, topolovine, johovine, borovine i smrekovine osušena u sušniku, a druga je polovica ivrja kondicionirana na sobnoj temperaturi. Od osušenoga i kondicioniranog ivrja proizvedene su troslojne kompozitne ivrice debljine 18 mm. Toplinska vodljivost ploča određena je metodom ASTM C 518. Predikcijski model najboljih svojstava i prihvatljivih devijacija određen je statističkom i grafičkom usporedbom eksperimentalnih podataka sa vrijednostima predviđenima ANN analizom. Potom su primjenom predikcijskog modela procijenjeni koeficijenti toplinske vodljivosti za one gustoće ekspandiranog polistirena koje nisu eksperimentalno ispitane. Prema toj analizi, termoizolacijska svojstva polistirenske kompozitne ivrice (PCP) od bukovine i smrekovine poboljšana su pjenom od otpadnog ESP-a gustoće 30 kg/m³. Najniže vrijednosti toplinske vodljivosti za polistirensku kompozitnu ivricu od prirodnice osušene topolovine, johovine i borovine dobivene su uz uporabu pjeone otpadnog ESP-a gustoće 18, 13 i 22 kg/m³. Za polistirensku kompozitnu ivricu od tehnički osušenog ivrja te su vrijednosti bile 15, 14 i 11-13 kg/m³. Tehničkim sušenjem ivrja postignuta su znatno bolja toplinska svojstva polistirenske kompozitne ivrice nego prirodnim sušenjem, a topolovina je pokazala najbolja svojstva od svih ispitivanih vrsta drva.

KLJUČNE RIJEČI: polistirenska kompozitna ivrica; termoizolacija; toplinska vodljivost; ESP; ANN

1  INTRODUCTION

1. UVOD

Thermal insulation is one of the most effective measures to increase energy efficiency by improving the thermal properties of building envelopes (Cetiner and Shea, 2018). At first, it was tried to provide thermal insulation in buildings by using natural materials such as rice straw, rice husk, sawdust, animal fur and wood (Wei et al., 2015). After the industrialization process, chemicals were used in the production of insulation materials to improve their performance (Khoukhi, 2018), and foam insulation materials based on polymer compounds such as polyurethane, polystyrene, and polyethylene have been recently developed (Wi et al., 2021). Expanded polystyrene (EPS) foam, usually called Styrofoam, is widely used in packaging, appliances, building insulations, and decorations because of its outstanding properties, such as superior thermal insulation, excellent dimensional stability, low cost, low density, and low sensitivity to moisture, and it occupies the largest market share in building insulation materials (Li et al., 2020). However, one of the most abundant plastics waste sources comes from various products of EPS foam (Rajak et al., 2020). Global plastic production has exponentially increased in the past decades, and reached 359 million tons in 2018 (Plastics Europe, 2019). Although the amount of plastic waste sent to recycling has doubled in Europe and major industrial countries since 2006, plastic pollution is still a major environmental concern (Geyer et al., 2017; Plastics Europe, 2019; Tokiwa et al., 2009; Xu et al., 2020; Song et al., 2020). The most of EPS wastes come from food packaging and storage, and therefore studies on the recycling of EPS waste have increased recently in more than 30 countries (Koksal et al., 2020). The toxic gases such as carcinogenic polycyclic aromatic hydrocarbons (PAHs) and dioxin, which are released by burning waste EPS foams, cause serious environmental problems (Chaukura et al., 2016; Uttaravalli et al., 2020). In addition, the low density of EPS can rapidly consume the loading capacity of waste storage areas (Chaukura et al., 2016). Due to these problems, recycling methods of EPS wastes need to be both eco-friendly and economical. Demirkir et al. (2013a) stated that the production of wood and polystyrene materials as a composite could be an effective solution both in reducing the environmental pollution caused by polystyrene waste and in reducing the emission of formaldehyde released from wood-based panels.

In the previous study, it was determined that the thermal insulation properties of the particleboard panels bonded with different densities of EPS foam wastes were much better than those of the control groups produced with urea formaldehyde (Demirkir et al., 2019). It was observed that the densities of EPS foams used in the production of these panels influenced the thermal conductivity values. Based on this, it is crucial to determine the optimum EPS densities to get the best thermal insulation performance for the building industry. Therefore, it is very important to use the right methods that do not require further experimentation, labour, time, energy and high costs (Demirkir et al., 2013b). Researchers used artificial neural networks (ANN), which are more adaptable than traditional methods, for optimization of wood and wood-based materials because they were faster and more economical (Esteban et al., 2011; Demirkir et al., 2013b; Ozsahin and Aydin, 2014; Tiryaki et al., 2017; Ozsahin and Murat, 2018). Even if the relationships between the experimentally obtained input and output data were complex and meaningless, ANN modelling could be successfully
performed to obtain the desired optimum values (Fernandez et al., 2008).

The objective of this study is to predict the optimum EPS density values for the best thermal insulation properties of the particleboards produced with EPS waste instead of formaldehyde-based adhesives via artificial neural network (ANN). For this purpose, the thermal conductivity values of intermediate EPS density values, which were not used in experimental studies, were also predicted by ANN model and the effects of EPS densities for each polystyrene composite particleboard (PCP) group were revealed.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Data collection
2.1. Prikupljanje podataka

The experimental data used in this study were obtained from the previous study by Demirkir et al. (2019). Beech (Fagus orientalis Lipsky), poplar (Populus deltoides 1-77/51), alder (Alnus glutinosa subsp. barbata), pine (Pinus Sylvestris) and spruce (Picea orientalis L.) woods, widely preferred in the particleboard industry, were used in the production of composites by chipping. Half of these chips were dried in a drying machine at 90 °C until reaching 3 % moisture content (technical drying). The other half were conditioned at room temperature until reaching 12 % moisture content (natural drying). The waste EPS particles of five different densities (10, 16, 20, 24 and 30 kg/m$^3$) were used as bonding material in the production of composite particleboards. The waste EPS particles, crushed in a polystyrene crusher with a size of 1.5 - 3 mm, were used in the production of polystyrene composite particleboards (PCP). The EPS particles were homogeneously mixed at a rate of 10 % for the surface layer and 8 % for the core layer based on the particle weight (dry weight for technical drying and wet weight for natural drying).

The panel drafts with dimensions of 55 cm × 55 cm × 1.8 cm were pressed for 10 minutes at 150 °C at a pressure of 23-25 kg/cm$^2$. The ratio of the face thickness to the total thickness of a panel, known as the shelling ratio, was 0.35 for all samples, while the target density was 0.68 g/cm$^3$. After the panels were conditioned for three weeks, the thermal conductivity test measurements were carried out to determine the thermal properties of the panels. The thermal conductivity coefficients of the panels were determined according to the ASTM C 518 (2004) standard using the Lasercomp Fox-314 thermal conductivity device (Figure 2). Moreover, the thermal conductivity values of waste EPS foams of 10 cm thickness, with a cell content of 98 %

![Figure 1 Polystyrene composite particleboards (PCP) production process](image1)

![Figure 2 Lasercomp Fox-314 thermal conductivity device](image2)
air and 2% polystyrene, were calculated as 0.040, 0.039, 0.036, 0.035 and 0.034 W/mK according to their density, respectively.

2.2 Artificial neural network (ANN) analysis

ANN analysis, which is one of the algorithms used in nonlinear input and output variables modelling, has started to be preferred in recent years instead of logistic regression analysis, which is one of the most widely used methods in the development of predictive models. ANN, which can successfully model the complex relationships of input and output variables without the need for further statistical training, easily reveals all possible interactions between these variables and enables multiple training algorithms (Tu, 1996; Dumitru and Maria, 2013). ANN was used to predict thermal conductivity values of the EPS densities not used in experimental studies and to predict the optimum EPS densities that gave the best thermal insulating performance for each PCP group. Drying types, wood species and EPS densities were the main variables in ANN modelling of this study. The data obtained from experimental studies were modelled with the MATLAB Neural Network Toolbox. The experimental data were grouped as training data and testing data to determine

Table 1 Training data set used for thermal conductivity prediction model results

<table>
<thead>
<tr>
<th>Drying type</th>
<th>Wood species</th>
<th>EPS density, kg/m³</th>
<th>Thermal conductivity, W/mK</th>
</tr>
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<tr>
<td></td>
<td></td>
<td>Gustoća EPS-a, kg/m³</td>
<td>Actual</td>
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<tr>
<td>Natural drying</td>
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</table>

Mean absolute percent error (MAPE) training: 0.70870
Root Mean Square Error (RMSE) Training: 0.00110
the effects of drying types, wood species and EPS densities on the thermal insulating performance. In order to successfully obtain the ANN prediction model from the experimentally determined thermal conductivity coefficient values, 35 data containing 70% of the total experimental data were separated for the training set, while the remaining 15 data containing 30% of the whole data were separated for the test set by considering the homogeneity of the groups. The thermal conductivity coefficient values obtained from both experiments and ANN analyses and the error percentages are shown in Tables 1 and 2 as training and test data sets.

The reliability of a predictive model whose training process has been completed successfully is determined by commonly used performance functions. The root mean square error (RMSE), mean absolute percent error (MAPE) and coefficient of determination ($R^2$), which are the most important of these functions, were preferred in this study. The equations formed depending on differences between the actual values obtained from the experimental data ($t_i$) and the predicted values obtained from the ANN model ($\hat{t}_i$) in the testing data set are given in Eqs. 1, 2 and 3, respectively ($N$ is the number of objects).

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (t_i - \hat{t}_i)^2} \quad (1)$$

$$MAPE = \frac{1}{N} \left( \sum_{i=1}^{N} \left| \frac{t_i - \hat{t}_i}{t_i} \right| \right) \times 100 \quad (2)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N} (t_i - \hat{t}_i)^2}{\sum_{i=1}^{N} (t_i - \bar{t})^2} \quad (3)$$

The network structure of the most reliable prediction model determined using performance functions after numerous trials is shown in Figure 3. This model consists
of an input layer containing drying types, wood species and EPS densities, a hidden layer containing 6 neurons, and an output layer containing thermal conductivity coefficients. The connection weights and biases of the thermal conductivity prediction model are given in Table 3.

The feed forward and backpropagation multilayer ANN were used to determine the prediction model. In ANN analysis trials, the transfer (activation) function used the hyperbolic tangent sigmoid function (tansig) in the hidden layer, while the linear transfer function (purelin) was used in the output layer. The Levenberg marquardt algorithm (trainlm) and the momentum gradient reduction backpropagation algorithm (traingdm) were chosen as the training algorithm and the learning rule. The mean square error (MSE) was used for stopping the training phase. The MSE equation, which can be calculated based on the difference between the actual values obtained from the experimental data \( t_i \) and the predicted values obtained from the ANN model \( td_i \) in the training data sets, is given in Eq. 4 \( (N \) is the total number of training patterns).

\[
MSE = \frac{1}{N} \sum_{i=1}^{N} (t_i - td_i)^2
\]  

\[ (4) \]

The data in the training and testing set were normalized \((-1, 1\) range) since the hyperbolic tangent sigmoid \((\text{tansig})\) function was used to contribute equally to the model for each parameter in the prediction model and then the data were transformed to their original values by reverse normalization so that the results could be evaluated. The processing of normalization was performed by using Eq. 5.

\[
X_{\text{norm}} = 2 \cdot \frac{X - X_{\text{min}}}{X_{\text{max}} - X_{\text{min}}} - 1
\]  

\[ (5) \]

Where, \( X_{\text{norm}} \) is the normalized value of a variable \( X \) (real value of the variable), and \( X_{\text{max}} \) and \( X_{\text{min}} \) are the maximum and minimum values of \( X \), respectively.

### 3 RESULTS AND DISCUSSION

3. REZULTATI I RASPRAVA

Figure 4 presents the MSE value that gives the best training performance of 0.0099939 in the 500th iteration when the MSE changes based on iteration of the prediction model determined as a result of ANN analysis.
The regression analysis results of the thermal conductivity prediction model are given in Figure 5. The correlation coefficient values for training and testing data sets were calculated as 0.98073 and 0.97381, respectively. These values proved the accuracy and validity of the prediction model obtained. Since the reliability of prediction models increases as the correlation coefficients approach 1, a perfect fit between the actual and predicted values can be achieved (Ozsahin, 2012).

The comparison of the thermal conductivity coefficient values obtained from the experiments and the predicted values obtained from the ANN analysis is given graphically in Figure 6. It is seen that the actual values and the predicted values are quite close to each other, and this proves that the predictive ability of the model is quite high.

The MAPE values in the training data sets and testing data sets were calculated as 0.71 % and 1.51 %, respectively (Table 1 and 2). The MAPE value, which is frequently used by researchers to evaluate ANN model performance, is expected to be below 10 % (Antanasijević et al., 2013; Tiryaki et al., 2016). It is proved that the prediction performance of ANN models is high with these values lower than 10 % (Yadav and Nath, 2017). It is stated in the literature that it is extremely important to calculate RMSE values as well as MAPE values in order to determine the performance of prediction models (Kucukonder et al., 2016). In this study, the RMSE values of the thermal conductivity prediction model for training and testing phase were calculated as 0.0011 and 0.0018, respectively (Table 1 and 2). Taspınar and Bozkurt (2014) stated that the low RMSE values obtained from the ANN analyses are an indicator of the successful performance of the prediction model. The MAPE and RMSE values obtained from the study proved that the ANN model used for prediction and optimization are reliable and can give satisfactory accurate results.
Thanks to ANN models with low error values (MAPE and RMSE) and high performance, output values can be predicted with high accuracy for intermediate input values that are not used in experiments (Varol et al., 2018). In this study, the thermal conductivity coefficient values were determined by the ANN prediction model for different EPS densities; they are shown in Figure 7 according to the wood species and drying types.

Figure 7 shows the differences in thermal conductivity values among wood species according to the drying type, depending on the density of EPS waste. In the literature, it was stated that the thermal conductivity coefficient values of wooden materials might differ depending on the wood species (Kol and Sefil, 2011; Rice and Shepard, 2004). Furthermore, thermal conductivity values in wood-based panels changed depending on the types and amounts of various binders, fillers and additives (Demir et al., 2016). The lowest thermal conductivity coefficient values of the beech and spruce PCP panels produced by both natural and technical drying were obtained from EPS waste foams with a density of 30 kg/m³. In the natural drying, the thermal conductivity values of PCP panels produced with poplar, alder and pine gave the lowest values by using EPS waste foams with the density of 18, 13 and 22 kg/m³, respectively. In the technical drying, the lowest thermal conductivity values were found in EPS waste boards with the density of 15, 14 and 11-13 kg/m³ for PCP panels produced with poplar, alder and pine, respectively. Density, moisture content, the ratio of early and late wood zones, temperature and heat flow direction of composite materials are some factors that significantly affect the thermal conductivity of the wood-based panels (Suleiman et al., 1999; Bader et al., 2007; Sondergger and Niemz, 2009; Demirkir et al., 2013a).

While the PCP panels produced with poplar for both types of drying were the group that gave the lowest thermal conductivity values among wood species,
spruce and beech PCP panels generally gave the highest values. It has been stated in many studies in the literature that the thermal conductivity coefficient values of wood and wood-based composites are strongly dependent on the density, and in general, the thermal conductivity values increase with the increase in density (Kamke and Zylkowski, 1989; Kol and Altun, 2009; Aydin et al., 2015). Furthermore, the extractive contents in the spruce wood could be shown as a reason for the increase in the thermal conductivity of spruce composite panels. As stated in the literature, the extractive content and a number of checks and knots were other important factors affecting the thermal conductivity (Simpson and Tenwalde, 2007).

The thermal conductivity coefficient values of the composite panels produced with technically dried chips were found to be lower than the boards produced with naturally dried chips. It was known in the literature that the thermal conductivity of the panels varied depending on the temperature changes. Zhou et al. (2013) investigated the effect of temperature changes on the thermal conductivity of MDF panels and stated that the thermal conductivity increased with temperature up to 50 °C and then decreased with increasing temperature between 50 °C and 100 °C. The density of the air in the cavities of the wood decreases depending on the increase in temperature, and therefore the heat conduction decreases (Suleiman et al., 1999; Aydin et al., 2015). Moreover, the thermal conductivity values also increased with increasing the moisture content of wood-based panels (Sonderegger and Niemz, 2009). Consequently, it was expected that PCP panels produced from particles dried at 90 °C to 3 % moisture content gave lower thermal conductivity values than naturally air-conditioned PCP panels at 12 % moisture content.

4 CONCLUSIONS

4. ZAKLJUČAK

In this study, the optimum EPS densities giving the best thermal insulation performances of PCP panels produced with EPS waste foams were determined with ANN analysis. As a result of the ANN analysis, the MAPE and RMSE values of thermal conductivity prediction model in the testing data sets were determined as 1.51 % and 0.0018, respectively. The coefficient of determination (R²) value was calculated as 0.9483 in the testing data sets. Although there was a complex and non-linear relationship between the input and output variables in the study, the performance of the model was proven with diagnostic tools and accurate, encouraging, and satisfactory results were obtained.

According to the ANN analysis results of the study, the use of EPS waste foams with a density of 30 kg/m³ increased the thermal insulation performance for both beech and spruce PCP panels. Furthermore, the lowest thermal conductivity values were obtained from the EPS waste foams with the density of 18, 13 and 22 kg/m³ for the PCP panels produced with poplar, alder and pine in the natural drying, respectively. In the technical drying, these values were found to be 15, 14 and 11-13 kg/m³, respectively. Poplar species is the wood species that gave the best thermal insulation performance. Technical drying performed much better than natural drying in terms of thermal conductivity. By utilizing the results of this study, PCP panels with the best thermal insulation performance will be produced quickly at low costs, and this will contribute to the recycling of waste EPS foams.

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Corresponding address:

Lecturer Dr. HASAN OZTURK
Karadeniz Technical University, Arsin Vocational School, Materials and Material Processing Technologies, 61080 Trabzon, TURKEY, e-mail: hasanozturk@ktu.edu.tr