The current work presents a study of the tribological properties of composite materials designed based on polyethylene terephthalate (PET), which has an important role in the structures of machines, represented by tribological couplings made of composite polymers. The paper examined the effect of two factors, namely recycled waste heating time (HT) and weight percentage (wt. %), on the improvement of the abrasive wear resistance of micro-filler-reinforced epoxy composites.

The current research aims to develop epoxy composites by improving abrasive wear resistance while ensuring low cost and weight. Improving wear resistance due to the use of epoxy composites to connect joints that operate under conditions without lubrication in various industrial fields will increase their operational life. The signal-to-noise ratio was analyzed to find out the effect of test parameters HT and wt. % on the wear rate of epoxy composites. Using MINITAB 19 software, regression equations were obtained for each variable to compare it with the Artificial Neural Network (ANN) results. Predictive models based on the regression equation and artificial neural network were developed to predict the wear rate of epoxy composites, and to determine which model is more efficient, their results were compared and the most appropriate model with the low error was determined. The results of the current research showed that the wear resistance of epoxy composites reinforced with RCCF improved by 41 % when increasing wt. % and HT, and also showed that the ANN model is more suitable than the regression model for predicting the wear rate of epoxy composites

Keywords: epoxy composites, PET waste, abrasive wear, Taguchi, artificial neural network

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OPTIMUM ABRASIVE WEAR RESISTANCE FOR EPOXY COMPOSITES REINFORCED WITH POLYETHYLENE (PET) WASTE USING TAGUCHI DESIGN AND NEURAL NETWORK

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1. Introduction

Epoxy composites appeared as alternatives to traditional materials used in various industrial fields, being known for their reliability and efficiency in connecting joints under conditions without lubrication. Thus, developing their properties became a goal for all researchers in this field. The current research aims to develop a new series of polymer composites to achieve low cost and weight with high abrasive wear resistance, taking into account the time and effort spent to reach the results, as these results serve different industrial applications, especially the parts of the machine in which they operate. This requires contact and friction.

The solution to the problem of increasing the abrasive wear resistance of epoxy composites will contribute to improving the reliability of connecting joints in machine structures. Moreover, adding fillers from cheap and lightweight sources will help reduce production costs and, on the other hand, preserve the environment [1, 2]. Adopting heating as a method for recycling waste results in a filler with varying specifications depending on the heating period. The importance of the current research procedures is due to the increasing use of epoxy composites in the industrial sector, and polyethylene waste is also increasing and is considered a problem of the present era. Therefore, the research procedures aim to solve two problems at the same time.

2. Literature review and problem statement

The study was conducted to review the effect of fillers as well as the curing method and parameters on the general mechanical performance of a matrix of thermoplastic recycled composites. The study revealed that an increase in filler leads to an increase in the mechanical performance of thermoplastic composites. There are few studies found in the archival literature in the section on composite materials based on a thermosetting resin matrix in chronological order and no significant experimental works on fatigue and creep [3]. One of the objectives of the current study is to evaluate the mechanical behavior of epoxy coatings modified with recycled tire waste products. In this study, epoxy coatings reinforced with ground tire rubber, vulcanized tire rubber, carbon black pyrolysis, and original carbon black particle contents were prepared and applied to a galvanized steel substrate. The performance of the tribological coatings was also evaluated. The experimental results showed that recycled tire products significantly enhanced composite coatings in wear resistance. The most remarkable result was a 77.7 % increase in wear resistance in the coating reinforced with sintered tire rubber [4]. Epoxy resins were reinforced with different fillers of silica, graphite, and coconut shell powder, in order to study the effect of fillers on the tensile strength, stress rate, impact strength, hardness, and wear behavior of epoxy composites. The tensile modulus improved significantly due to the solid filler particles, as well as the friction coefficient and wear rate decreased significantly for the epoxy composites [5]. The most important problem in the twenty-first century is waste management. Waste materials are usually combined with polymer and mineral compounds as a way to recycle waste and strengthen polymer or mineral compounds, thus preserving the environment. Based on this principle, the study used cherry seed filler to strengthen polypropylene composites for tribological applications. The researcher adopted different concentrations and particle sizes. Under dry friction conditions, the friction coefficient of polymer composites was calculated. The results show that a higher content of cherry seed powder filler (manifested both by higher percentage and higher granulation) has a positive effect on frictional behavior and wear resistance [6]. Due to the mechanical/thermal stability of polymer composites, they were used in marine engineering structures under harsh environmental conditions. The research concluded with the preparation and analysis of multi-filler-reinforced epoxy compounds (MFREC) and the study of mechanical and thermal properties as well as tribological properties. The results showed an increase in tensile strength by 98 %, tensile modulus by 22 %, and elongation by 39 %. An increase in loads and temperatures reduced the friction coefficients due to the MFREC wear rate and line roughness due to the change in the contact state (from elastic to plastic) [7]. Due to the use of epoxy composites on a large scale in the field of industry and engineering structures, both studies aimed to improve the mechanical properties by reinforcing epoxy composites with fillers of different origin, including natural and mineral. The first study used accurate fillers of palm pollen and sea shells reinforced with epoxy compounds, while the second study adopted accurate metal fillers of nickel and copper. Both studies showed a clear improvement in the mechanical properties of epoxy composites, and with specific weight ratios, an ideal condition was achieved in both studies [8, 9].

The above literature shows that all efforts related to developing a new series of low-cost polymer composites for various industrial applications remain relatively limited. The choice of matrix or fillers plays a vital role in the development of a new series of low-cost polymer composites. Nevertheless, all this allows us to say that it is appropriate to conduct a dedicated study on how to increase the abrasive wear resistance of epoxy composites by adopting cheap materials that have not been dealt with and in a unique method that guarantees ease of preparation and low cost. The adoption of fillers from plastic waste, in fact, guarantees a solution to two existing problems. The first is the development of epoxy composites by increasing the resistance to abrasive wear, and the second is benefiting from waste recycling in industrial sectors. The research that studies composite materials on the basis of recycling plastic waste with the aim of developing these composites and the consequent reduction of industrial costs and environmental pollution is promising and is receiving great attention from various scientific and industrial sectors.

3. The aim and objectives of the study

The aim of this study is to improve the wear resistance of epoxy composites reinforced with polyurethane waste and determine the optimal result.

To achieve this aim, the following objectives are accomplished:

– to study the abrasive wear rate of epoxy composites by experimental and predictive methods;

– to study the abrasive wear of composites by mathematical modeling;

– to study the abrasive wear of composites using an artificial neural network.

4. Materials and methods

4. 1. Materials

The current research adopted the following steps in preparing samples for tribology tests:

a) recycled waste clamshell container (RCCF): the micro-filler is prepared from waste clamshell by heating it for 2, 4 and 6 minutes (HT), turning into a heavy liquid, then pouring it into molds and letting it cool for 24 hours. The purpose of heating is to induce changes in the RCCF properties. The castings are milled after leaving them to cool and then the granules are sorted using a 75 μm and 150 μm sieve. Just to indicate that the source of clamshell residue collection is the landfill of Shifta village, Baquba city, Diyala, Iraq;

b) adhesive: the resin used in this work is epoxy with sika-dur32 hardener at mixing ratios of 2:1 and a density of 1.1 kg/L, obtained from the chemical warehouse in Baghdad, Iraq;

c) fabrication of composites: epoxy composites were prepared by mixing different weight percentages (wt. %) of 1 %, 2 %, and 4 % of micro-filler with various particle sizes (75 μm and 150 μm) from recycled clamshell waste (RCCF) with epoxy. The stages of preparing composites and samples are presented in Fig. 1. In order to study the effect of the factors HT and wt. % on the wear behavior of epoxy composites, they were taken into consideration during the preparation and formation of castings as shown in Table 1.

For more details about the preparation and recycling of waste, you can refer to our previously published research [10].

Table 1

Detail fabrication of epoxy composites

Composites	Epoxy (wt. %)	RCCF (wt. %)	Particle size (μm)	HT (min)
Unfilled	100	0	0	0
1th 75–2	99	1	75	2
2th 75–2	98	2		
4th 75–2	96	4		
1th 150–2	99	1	150	
2th 150–2	98	2		
4th 150–2	96	4		
1th 75–4	99	1	75	4
2th 75–4	98	2		
4th 75–4	96	4		
1th 150–4	99	1	150	
2th 150–4	98	2		
4th 150–4	96	4		
1th 75–6	99	1	75	6
2th 75–6	98	2		
4th 75–6	96	4		
1th 150–6	99	1	150	
2th 150–6	98	2		
4th 150–6	96	4		

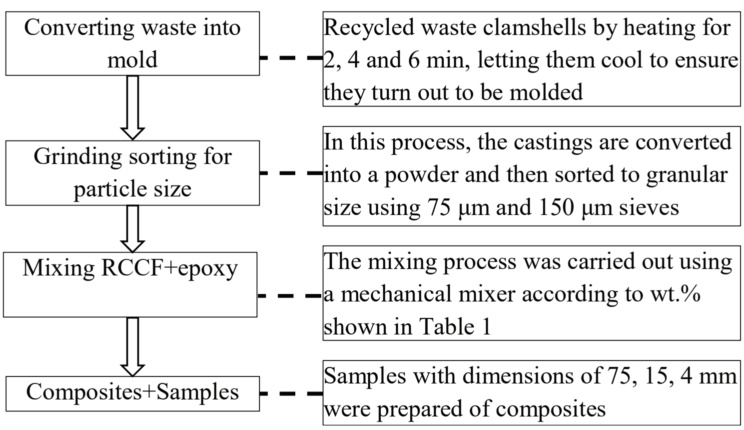

Fig. 1. Steps for preparing epoxy composites

4. 2. Experimental method

4. 2. 1. Abrasive wear rate of composites reinforced with micro-filler

The wear rate behavior of epoxy composites was verified using the pin-on-disc under dry conditions against the counter surface of a steel disc for a normal applied load of 10 N, 16 N and 22 N. All experiments were carried out at 25 °C, relative humidity (RH) of 10 % and constant sliding speed of 149.15 m/s along a circular path. All tests were performed in a circle with a diameter of 13 cm and a fixed sliding distance of 58.17 m. Using a digital electronic scale (KERN PLE) with high accuracy of 0.01 g, all samples of the current research were weighed before and after testing, and the vertical shape of the sample was kept on the surface of the turntable, in order to ensure appropriate wear behavior conditions. Before and after each test, the sample and the surface of the hard disk are wiped with a cloth dampened with acetone. In order to be accurate in obtaining the average values, the tests were repeated three times for each sample. The specimen is pressed against the rotating steel wheel forcefully due to the presence of a dead weight applied to the other end of the lever, as a result, the specimen's surface particles begin to abrade. The tests are performed by rotating the steel wheel at a constant speed. Samples are placed on one side of the lever while the other side of the lever is loaded with different weights. The applied load is normal to the horizontal diameter of the rotating wheel. Mass loss for each composite was recorded after each experiment. The specific wear rate (W_s) in cm^3/N·m unit can be determined using (1) [11, 12]:

$$W_s = \frac{\Delta m}{\rho L P}, \tag{1}$$

where Δm is the abrasion mass loss (g), ρ is the density of the specimen (g/cm^3), L is the abrading distance (m), P is the normal load (N).

4. 3. Experimental design technique

In general, the application of the experimental design technique aims to determine a set of appropriate control variables while reducing the number of experiments required to obtain the optimization of the output. In the current study, the effect of heating time (HT) and RCCF content (wt. %) on the wear behavior of composites was investigated. In Table 2, six levels of each of these two control factors are selected for the wear rate of composites. Using a Taguchi experimental design, data parameters were analyzed to reduce the number of experiments. Taguchi procedures are also used to determine the deviation between the experimental values and the desired data. In this method, the loss function is converted into a signal/noise ratio (S/N). There are three types of quality characteristics in S/N ratio analysis, which are largest, best, smallest and nominal best. For each process parameter level, the S/N ratio is determined based on the S/N analysis. The purpose of S/N analysis is to obtain the minimum wear response for epoxy composites. Based on Taguchi's design, the orthogonal matrix L18 was chosen. The S/N ratio for wear behavior is determined using "the smaller the better" quality characteristics described in (2):

$$\text{smaller} - \text{is} - \text{better}\, S/N = -\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y^2\right), \tag{2}$$

where Y – experimental outcome, n – number of factor level combinations.

4. 3. 1. Artificial neural network predictions

The current study also takes into account the prediction of the wear rate of composites using a three-layer feed-forward network with a backpropagation model. The neural network was developed using MATLAB software. In Fig. 2, the input layer of two neurons corresponds to the heating time (HT) and micro-filler content (wt. %). The output layer consisted of one neuron, representing the wear rate of the epoxy composites. In the hidden layer, twelve neurons were selected (Fig. 2). The percentage of experimental data considered for training, testing and validation was 70 %, 15 % and 15 %. To predict the wear rate of epoxy composites, the entire system must be thoroughly trained based on the data provided by the experimental results of the wear rate test.

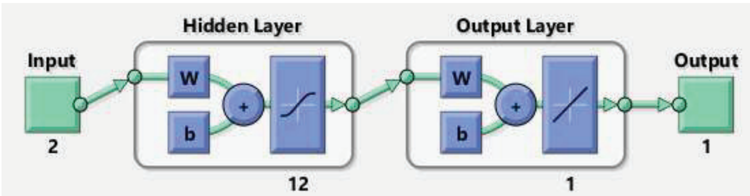

Fig. 2. Artificial neural network (ANN)

When the training phase starts, the neural network captures the defined relationship between the input and output parameters in the different test ranges. The current computational procedures are used to predict the wear rate response during the testing phase, while the remaining data is used for validation. It is noted that the ANN structure is based on the backpropagation algorithm used to predict the wear behavior of RCCF/epoxy composites.

factors, as well as the extent to which they are affected by changing the values of these factors. The response value reflects that the most powerful factor affecting the wear rate of composites is in the first place factor A (HT) and in the second place factor B (wt. %). Under low loads and velocities, a protective triple layer is formed on the sample surface as a result of trapping the wear debris displaced between the sliding surfaces, which in turn protects the sliding surface from additional wear. While high speeds and loads cause a high rate of wear due to the collapse of the protective layer.

The speed and high loads lead to an increase in the temperature of the sliding interface due to the increased friction forces, which in turn leads to the thermal softening of the interface and dismantling of the composites and then an increase in the wear rate of epoxy composites.

5. Results of studying the abrasive wear rate of epoxy composites

5. 1. Results of studying the abrasive wear rate of epoxy composites by experimental and predictive methods

The results of wear experiments performed on three sets of samples along with the wear rate (W_s) are presented in Table 2. Eighteen experiments were performed on three types of samples and two factors identified in the research, according to Taguchi's design. In order for the results to be accurate under constant conditions, each test was repeated three times to obtain the average value. The test procedures were applied to all samples in addition to the unfilled sample to compare the results, where three different loads of 10 N, 16 N and 22 N were applied as mentioned previously. It is noted that columns 5–7 in Table 2 represent the experimental wear data of the samples under the influence of three loads, while the eighth column represents the average wear for the three cases. Fig. 3 shows the relationship between the specific wear rate ($W_{s(av)}$) of the composites and the effect of the factors. Under the current test conditions, the minimum wear rate of composites is 3.081×10^{-4} mm^3/Nm. The results also showed that the maximum wear rate is 3.941×10^{-4} mm^3/Nm. In the same table, we note that the wear rate of the epoxy sample without the filler (unfilled) was recorded at a value of 5.21×10^{-4} mm^3/Nm, which is higher than the highest value among the epoxy composites. Therefore, the use of filler (RCCF) as a reinforcing material in epoxy composites led to an increase in the wear resistance of epoxy composites by 41 %, when the lowest wear rate represented by sample No. 18 was compared with the original sample (unfilled) in the first row, Table 2. Fig. 3 shows the plot of the main effect of the S/N ratio of wear rate. It is possible to determine the ideal state of the factors leading to the least wear rate of epoxy composites, which was achieved at 6 min of A3 and 4 % of B3. The effect of the factors specified in the research on the wear rate is determined by analyzing the response ratio S/N shown in Table 3, and the S/N percentage is clearly shown at each level of the test

Table 2

Wear rate results for RCCF-reinforced epoxy composites

Exp. Run	Com-posite material	*B*, (wt. %)	*A*, (HT) min	Experimental data of W_s*10^{-4} under loading			$W_{s(av)}$ 10^{-4} (mm^3/Nm)	S/N ratio (dB)
				10N	16N	22N		
No. run	Unfilled	0	0	5.78	4.39	5.47	5.21	0
1	1^{th} 75–2	1	2	3.610	4.062	3.741	3.804	–1.664
2	2^{th} 75–2	2	2	2.915	4.148	4.544	3.870	–1.832
3	4^{th} 75–2	4	2	2.821	4.495	4.294	3.870	–1.643
4	1^{th} 150–2	1	2	2.957	4.084	4.527	3.856	–1.664
5	2^{th} 150–2	2	2	3.279	4.001	4.542	3.941	–1.832
6	4^{th} 150–2	4	2	3.9373	3.786	3.579	3.768	–1.643
7	1^{th} 75–4	1	4	3.493	4.540	3.573	3.869	–1.597
8	2^{th} 75–4	2	4	2.199	3.813	3.935	3.316	–0.527
9	4^{th} 75–4	4	4	2.7005	3.109	4.716	3.509	–0.783
10	1^{th} 150–4	1	4	3.1668	4.220	3.795	3.727	–1.597
11	2^{th} 150–4	2	4	2.431	3.397	4.369	3.399	–0.527
12	4^{th} 150–4	4	4	1.442	4.578	4.219	3.414	–0.783
13	1^{th} 75–6	1	6	2.256	2.997	4.743	3.332	–0.413
14	2^{th} 75–6	2	6	3.018	3.112	3.224	3.119	–0.9944
15	4^{th} 75–6	4	6	1.713	3.251	4.3806	3.115	–0.8133
16	1^{th} 150–6	1	6	2.736	3.582	3.582	3.300	–4137
17	2^{th} 150–6	2	6	3.243	2.908	3.462	3.205	–0.9944
18	4^{th} 150–6	4	6	2.948	2.851	3.445	3.081	–0.8133

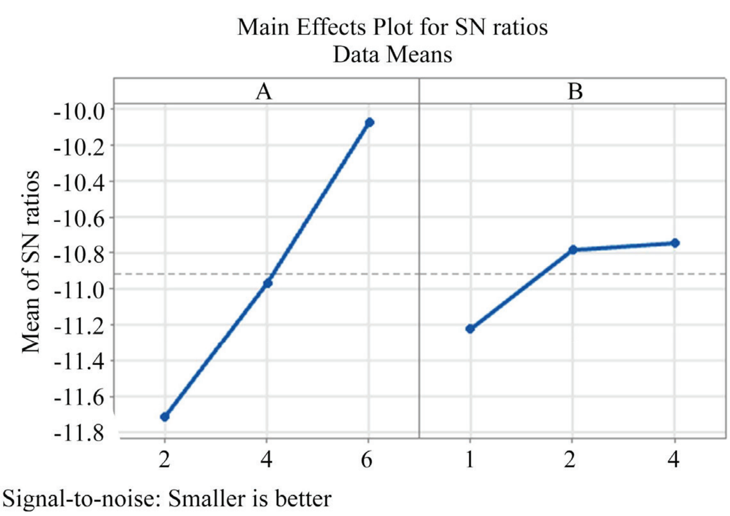

Fig. 3. Effect of control factors on the wear rate of epoxy composites

Table 3

Response table for S/N Smaller is better (wear rate)

Level	*A* (HT) min	*B* (wt. %)
1	–11.71	–11.23
2	–10.97	–10.78
3	–10.07	–10.75
Delta	1.64	0.48
Rank	1	2

5. 2. Results of studying the abrasive wear of composites by mathematical modeling

The wear rate of the composites can be predicted using the linear regression equation. This analysis is based on finding a functional relationship between the control factors and the response to the output represented by the wear rate using experimental data. Through this analysis, it is possible to obtain a mathematical relationship for the output response (wear rate) and control factors as a function of two variables *A* (HT) and *B* (wt. %):

$$W_{s(math)} = 4.3183 - 0.1653A - 0.0555B. \quad (3)$$

Fig. 4 shows the remaining wear rate plots for RCCF/epoxy composites obtained using (3). It is clear from the normal probability curve that the distribution is normal for the residuals as it indicates their proximity to the straight line for all the developed models, which confirms the acceptability of the appropriate models as well as indicates their properties. Also, the random nature of the residual distribution against the fit value indicates that the model is unsymmetrical with a constant variance. This indicates the independent nature of the behavior of each residual. From the histogram, it can be seen that most of the remaining values have frequencies lying within the range of 0–1. Thus, the importance of the experimental design becomes clear, and we note that the remaining values are also above and below the mean line, according to the design prepared for the 18 experiments.

However, it was found that the experimental residuals against the expected wear rates from the studied models are about 26 % as in Table 4. Therefore, another predictive model using ANN is proposed for further study. ANN is considered as an effective tool for interaction and suitable for cases where it is. The relationships are very complex. The analysis indicates that the current prediction model is able to find a relationship between the wear rate of epoxy composites and the control parameters. It is noted that the parameters have a clear effect on improving the wear resistance of epoxy composites, as the increase in the HT of recycled waste and wt. % led to a significant improvement in the wear resistance of epoxy composites.

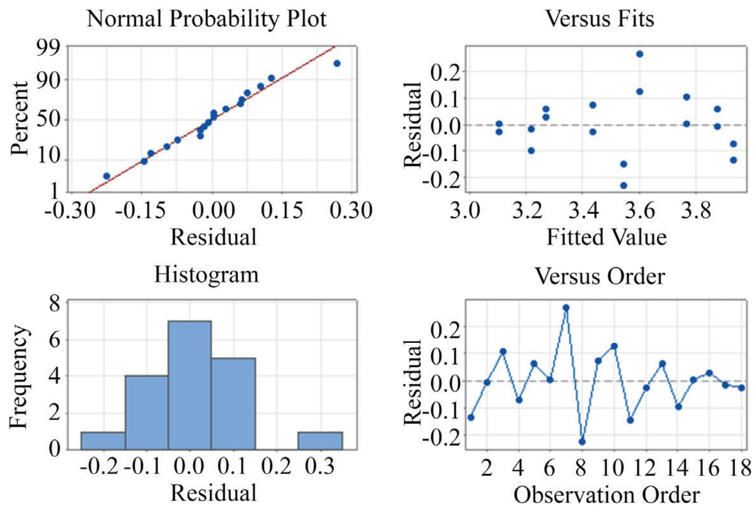

Fig. 4. Residual plots for the wear rate of epoxy composites

5. 3. Results of studying the abrasive wear of composites using an artificial neural network

There are two plots in Fig. 5. Fig. 5, *a* shows the mean square error for the training, validation and testing phases, and Fig. 5, *b* shows the regression plot for the trained network. The R-value of the observations is acceptable for the proposed model, where the results of the experimental data (W_s(exp)) and neural network (W_s(ANN)) are close to each other and this can be inferred as the R-value approaches 1. The current R-value is 0.98248, which reflects the possibility of using the network to predict experimental results. In Table 4, the experimental, mathematical and predicted ANN wear rate values for RCCF/epoxy composites are presented. Fig. 5 shows a comparison of the experimental data, mathematical and ANN models for composite wear rate, where it was observed that the ANN model is more efficient than the proposed mathematical model.

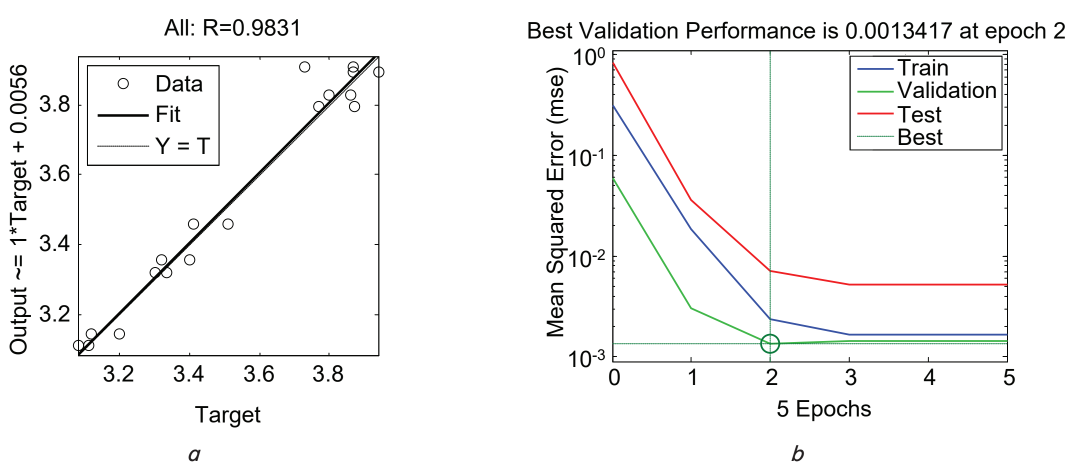

Fig. 5. Efficiency of the neural network model: *a* – mean square error (mse); *b* – regression plot for the trained network

Table 4

Comparison of wear rate of epoxy composites as obtained experimentally (EXP), using a mathematical model (math) and ANN predictions

No. of run	Material composites	W_s(exp)	W_s(theo)	% error	W_s(ANN)	% error
1	1th 75–2	3.800	3.932	–13.22	3.823	–2.299
2	2th 75–2	3.870	3.877	–0.67	3.965	–9.586
3	4th 75–2	3.871	3.766	10.53	3.870	0.092
4	1th 150–2	3.860	3.932	–7.22	3.823	3.700
5	2th 150–2	3.940	3.876	6.33	3.965	–2.586
6	4th 150–2	3.770	3.765	0.43	3.8701	–0.007
7	1th 75–4	3.870	3.601	26.84	3.740	12.957
8	2th 75–4	3.320	3.546	–22.61	3.364	–4.405
9	4th 75–4	3.510	3.435	7.49	3.5044	0.553
10	1th 150–4	3.730	3.601	12.84	3.740	–1.042
11	2th 150–4	3.400	3.546	–14.61	3.364	3.594
12	4th 150–4	3.411	3.435	–2.41	3.504	–9.346
13	1th 75–6	3.333	3.271	6.2	3.326	0.638
14	2th 75–6	3.120	3.215	–9.55	3.123	–0.393
15	4th 75–6	3.110	3.104	0.55	3.128	–1.856
16	1th 150–6	3.300	3.271	2.9	3.32661	–2.661
17	2th 150–6	3.200	3.215	–1.55	3.123	7.606
18	4th 150–6	3.080	3.105	–2.45	3.128	–4.855

The error rate between the expected data (ANN) and the experimental data is within ±12 %, which appears in Table 4 in the sixth and seventh columns. Therefore, the error rate values indicate the acceptability of the neural network model of the current model if it is compared with the resulting error rate between the experimental and mathematical data, which reached ±26 %.

6. Discussion of the results of studying the abrasive wear rate of epoxy composites reinforced with micro-filler

The current study indicates a significant improvement in the wear resistance of epoxy composites reinforced with polyethylene waste. The results also showed that the heating time factor adopted in the preparation of the filler, as well as the factor of weight ratios, have a clear effect in raising the abrasive wear resistance of the epoxy composites. The wear resistance of the composites improved by 41 % compared to epoxy without fillers as shown in Table 4.

By adopting the Taguchi design as shown in Fig. 3, the ideal wear condition is determined, which is achieved when the agents are in the A3 B3 phase, meaning HT=6 min and wt %=4 %, which is the lowest abrasive wear rate of the epoxy composites, represented by the sample with sequence 18, i.e. with a particle size of 150 μm and a load of 16 N. The results of the current research are consistent with [3] through the improvement of the abrasive wear resistance of the epoxy composites by increasing the weight ratios of plastic fillers.

From Table 4, the comparison of the data results of the three models, a good joint correlation was observed between the experimental data and ANN, with an error rate of ±12 % and with the regression model an error rate is 26 %. By comparing the results of the two models as shown in Fig. 5, ANN was found to be more acceptable than the regression model because it achieved the lowest error rate.

The current study developed epoxy composites by increasing their abrasive wear resistance and the composites became more suitable for an industrial abrasive environment, and also provided an easy and low-cost method for preparing the composites.

The current work opens a new method for recycling non-biodegradable and polluting plastic waste by heating to convert it into fillers with new specifications. The research presents a method different from traditional methods of recycling plastic waste to obtain new specifications. The research recommends using procedures in the current research to prepare fillers from different plastic waste with different resins and comparing the results in terms of tribology behavior to choose the best composites.

7. Conclusions

1. The current study found that the factors of heating time (HT) of polyethylene waste and the percentage of filler content (wt. %) have a significant impact on changing the tribology behavior of epoxy composites and improving their wear resistance. The wear resistance of RCCF-reinforced epoxy composites improved by 41 % compared to the unfilled sample, while the highest wear rate among the epoxy composites was recorded in the unfilled sample.

2. The filler additive significantly enhanced the abrasive wear resistance of the epoxy composites compared to the unfilled epoxy samples. Taguchi's design indicated that the ideal state of wear is achieved when the agents are in phase A3 B3 meaning HT=6 min and wt. %=4 %, which is the lowest wear rate of the composites. Under the stability conditions in the current study, it is clear that the sample with sequence 18 showed the lowest abrasive rate among the composite materials, and it has specifications of 4 wt. %, 6 min of HT, and particle size 150 microns under a load of 16 N.

3. A good correlation between the experimental and ANN data was observed, with an error within ±12 % compared to the regression model error within 26 %. From comparing the results of the two models, ANN was found to be more acceptable than the regression model.

Conflict of interest

The authors declare that they have no conflicts of interest in connection with this research, whether financial, personal, authorship, or otherwise, that might affect the research and its findings presented in this paper.

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The study was conducted without financial support.

Data availability

The manuscript has associated data in a data repository.

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