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PREDICTION ON WEAR PROPERTIES OF PTFE AND PVC POLYMERS USING ANFIS

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Abstract: *Superior strength in loading, wear resistance, environmental stability, insulating properties, and low cost are the main distinguishing properties of polymer materials, which encouraged many researchers to analyze the different behavior of these materials. In this work, a comparative study was conducted on the tribological behavior under dry sliding conditions of two pins of Teflon (PTFE) and Polyvinyl Chloride (PVC), both sliding on a steel disc. The study was conducted under different laboratory conditions to investigate the effect of normal load change, sliding time and roughness modulus on the wear rate. Sliding time minutes (10-60 min), three applied loads (5N, 10N and15N), and two discs with different roughness coefficients of 0.611 µm and 2.394 µm were used, and the speed of rotation of the disc was constant (480 rpm) according to the specifications of the test device. These results showed that the wear degree depends on the nature and composition of the polymeric material. The material loss for both polymers increases with the applied load, but the loss of PTFE is greater for the same applied load than for PVC. The material loss for both polymers increases at the start of operation and then stabilizes to a specific value according to the applied loadwith the confirmation that the increase in the applied load decreases the volumetric wear coefficient k for both type specimens. It is a measure of the wear stability level of the composites. The ANFIS technique was used to study the predictability of the wear performances of PTFE and PVC and it was found that the developed ANFIS model showed promising results in predicting the wear coefficient of PTFE and PVC polymers that are subjected to different vertical loads, sliding time and change of the roughness coefficient.*

Keywords:: *wear, normal load, sliding time, roughness coefficient, ANFIS.*

1. INTRODUCTION

Self-lubricating polytetrafluoroethylene composites run dry. Polytetrafluoroethylene composites have low water absorption and chemical resistance [1]. Wang et al. investigate a tribological behavior of a polytetrafluoroethylene (PTFE) disc and an AISI1045 steel screw in a straight line and torsional motion. The friction coefficients for one-directional rotation, linear frequency, and torsional motion were 0.1, 0.118, and 0.12. On PTFE's maximum linear-frequency wear-related mass loss was observed. Turning the object reduced wear. PTFE wore away by mild ploughing, substantial abrasive wear, and adhering together in unidirectional rotating, linear reciprocating, and torsional motion. Friction and wear experiments were completed on ultra-high molecular weight polyethene with Hank's balanced salt solution lubrication using a stainless steel pin-shaped disc. As load grew, friction and wear rates dropped. Dry sliding friction coefficient and wear rate were higher for the measured sliding speeds and loads[2].

Low-dimensional fillers are essential for improving the tribological properties of PTFE-containing composites. Carbon nanotubes (CNT) and graphene-filled composites exhibit substantially greater wear resistance than pure PTFE, and corrosion is reduced by 76.2% and 85.7%, respectively[3].

Soft PVC's tribological properties were tested under typical load and sliding speed. Infrared detected friction heating. PVC wears better under high speed and normal load due to friction heating during sliding[4].

PVC samples reinforced with $CaCO_3$ were tested for visibility. Also, examined are thermal ageing effects on pipe friction and wear. Several samples' wear was measured. Wear on composites and steel pins were studied [5]. The equipment were changed to research spherical-disc charge buildup and tribology. Positive and negative charges were tested using photoelectric nylon and electrostatic PVC. When there's no charge buildup at the friction interface, the friction pair has outstanding friction reduction, anti-wear performance, and stability. COF can be adjusted by altering Coulomb force charge accumulation. This study compares polymeric (PTFE and PVC) and steel wear (the revolving disk). [6].

Prediction of the frictional performances of T-BFRP using artificial neural networks was performed. Large amounts of experimental data were used to train the ANN with varying loads and sliding distances. When the ANN model was trained using the Levenberg-Marquardt function, experimental and numerical findings were accurate[7]. ANFIS has been used to estimate hydraulic jumping in channels with varying bed conditions (that is, channels with different shapes and dependencies). 1700 experimental data were used to model hydraulic jump characteristics. The results showed that the approach accurately models hydraulic jump qualities. Channel expansion models with blocks were more successful than others[8]. The objective of the presented work is to apply the ANFIS method to predict the wear behavior of PTFE and PVC polymeric materials using a pin-on-disc type tribometer,

The main inputs affecting wear are the coefficient of roughness, sliding time and vertical load, and the sliding speed remains constant at 480 rpm.

2. THEORETICAL METHOD

2.1. Loss of material (wear)

Wear is the slow removal of materials or the distortion of those materials that occurs on solid surfaces. The following is what we derive from the wear model, which is also often known as Archard's law of wear:

$$\frac{V}{S} = K \cdot \frac{F_N}{H} \tag{1}$$

where: V is the volume of the material that has been worn away due to wear [m^3], F_N is the radial force operating on the bearing [N], s is the total sliding distance [m], and H is the hardness of the soft surface of the material that is being worn away [Pa].

For figuring out wear performances, it's best to use Archard's general wear law, which can be found by dividing equation (1) by the contact surface A:

$$\frac{V}{s \cdot A} = \frac{K}{H} \cdot \frac{F_N}{A} \xrightarrow{yields} \left\{ h = \frac{V}{A}, k = \frac{K}{H}, p = \frac{F}{A}, s = v \cdot t \right\} \xrightarrow{yields} \quad (1$$

$$h = k \cdot p \cdot v \cdot t \tag{2}$$

or:

$$k = \frac{\Delta m}{F_N \cdot s \cdot \rho}, \; s = v \cdot t \tag{3}$$

where k is the volumetric wear rate [m^3/Nm], p is the specific load [Pa], v is the sliding speed [m/s], t is the sliding time [s], and is the density of the softer material.

2.2. The Foundations of the ANFIS

Adaptive Neural Fuzzy Inference Systems (ANFIS) simulate human brain cells. ANFIS combines the fundamental properties of Fuzzy Logic (FL) and Artificial Neural Networks (ANN). Based on experimental data, ANFIS has been used to predict the tribological behavior of two thermoplastic polymers.

Fuzzification, Rule, Normalization, Defuzzification, and Output summation nodes were created in MATLAB to train and assess ANFIS. A dual-input ANFIS network is shown in Figure (1).

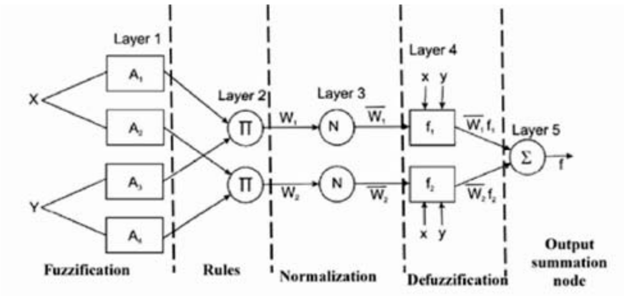

Figure.1. Design of a dual-input adaptive neural fuzzy inference system (ANFIS).

The Gaussian Membership Function (GMFs) was used in this study. GMFs takes the highest value (1.0) and chooses the lowest value (0.0). The model's performance was evaluated using root mean square error (RMSE), which is given in equation 4:

$$RMSE = \sqrt{\sum_{i=1}^{N} \frac{(n_{ex} - n_{pr})^2}{N}} \tag{4}$$

where n_{ex} is the experimental number of the output, n_{pr} is the expected number of the output using the ANFIS model and N is the data numbers.

3. EXPERIMENTAL DESIGN AND PREDICTION METHOD

3.1. Experimental Design

Materials: Tests were done on samples made of PTFE and PVC, both of which are thermoplastics that are widely used in many fields as shown in Figure 2. the mechanical properties of both specimens test and test disc are listed in Table 1.

Test discs are made by heating stainless steel to 440^{o}C. Fig. 3 shows the Surface roughness tester TR220, two discs with different roughness coefficients of 0.611 µm and 2.394 µm are used.

The test device (SHEMADZU/XDR-6000) (Fig. 4a) was used to calculate the material lost due to the vertical load and rotation of the test disc, according to the vertical load (5 N, 10 N and 15N) and the sliding time (10-60 min).

Figure 2. The tested PTFE and PVC specimens

Table 1. The mechanical properties of PTFE, PVC and Disc test

Property	PTFE	PVC	Disc test type grade 440C (440C stainless steel)
Density [kg/m3]	2200	1300–1450	7800
Yield stress [MPa]	/	40.7–44.8	450-1900
Tensile Strength [MPa]	20.7–34.5	40.7–51.7	/
	0.6	/	0.27-0.30
Poisson's ratio	0.5	3.4	190-215
Young's modulus [GPa]	0.4 -0.55	2.4-4.14	200
Elasticity modulus [GPa]	327	400	1483

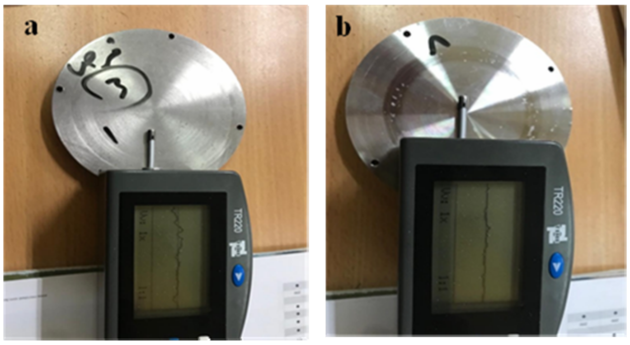

Figure.3 The device used to measure the surface roughness coefficient of the disc, a) the roughness coefficient disc 0.611, (b) the roughness coefficient disc 2.394 µm.

To ensure the accuracy of the results, the tests were repeated three times for each specimen, and the material loss (volumetric wear rate) was calculated by weighing the specimen before and after the test (for 10 minutes) and for 60 minutes using a digital sensitive balance (0.0001 mg) type (satorius-BL210s), (Figure.4b). All of the experiments were performed at ambient temperature.

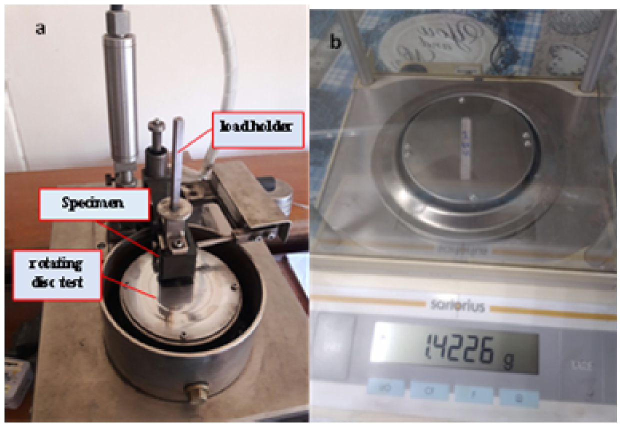

Figure 4: (a) Pin-on-disc tribometer type 'DUCOM's Wear Monitor, and (b) digital sensitive scale type (satorius-BL210s, 0.0001)

3.2. Prediction Method

The ANFIS network model was developed using PTFE and PVC wear rate data. Fig. 5 illustrates neural network predictions. The input layer represents the test disc roughness coefficient, sliding time of test specimens, and vertical load applied to test specimens and the output layer represents wear rate.

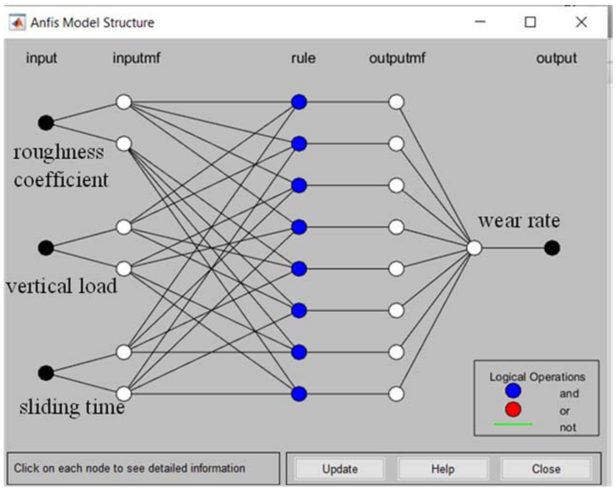

Figure 5. Generate ANFIS Model Predictive Wear Rate

Training error converges with ANFIS model iterations. In this model, 30 adaptive iterations were required to predict the wear rate of PTFE 0.0014 and 0.001 for PVC (Figure.6 a and b). The MF membership function type and options method was linear and mixed respectively.

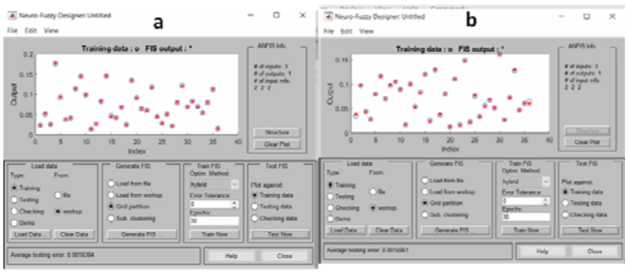

Figure 6. ANFIS model iterations and error rate to predict wear rate, a) PTTFE, b) PVC.

4. RESULTS AND DISCUSSION

4.1. Experimental results

PTFE and PVC specimens were tested, with an average of three specimens tested per material type to ensure reliable results. Therefore, wear test results were calculated as an average over a minimum of three samples.

In this study, the average value of local and total wear, as well as the load, roughness of the test disc, and sliding time were compared for PTFE and PVC materials, and it was found that the behaviour of the two materials is very comparable.

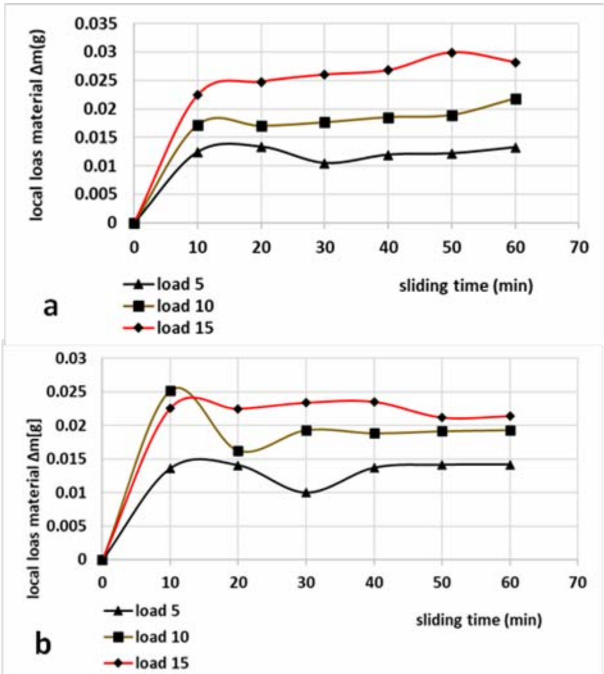

Figure 7. Effect of sliding time on the local lost material of disc roughness coefficient Ra 0.611 [µm], (a) PTFE (b) PVC

PTFE's wear rate was 0.015 g at a 5N load, whereas it reached PVC at the same load, sliding time, and roughness of 0.013 g, showing that as the vertical load increased, the number of lost materials increased, *i.e.* the wear rate. The data suggest that PVC can be used as a self-lubricating material with a lower wear rate than PTFE. This behavior is identical to the two vertical loads (10N and 15 N), however as shown in Figure. 7 a, b, the wear rate is precisely proportional to the increase in load.

Increasing the roughness coefficient (Ra) from 0.611 µm to 2.349 µm leads to an increase in the wear rates of PTFE more than PVC, and this is clear in comparison with the two figures (7 and 8)

The total wear rate is a linear function with the change of sliding time, and the PTFE specimens show a greater total wear rate than the PVC specimens when the sliding time, test disc roughness coefficient, and vertical load are all increased as shown in Figs. 9 and 10.

Due to the high temperature between the surface of the test disc and the selection specimen as a result of the interlocking of the microscopic peaks of both contact surfaces at the beginning of the running, which causes an increase in the ductility of the contact surface of the test specimen, and this, in turn, reduces the shear stress, which leads to abrasion of the specimen layer in contact with the hard surface, *i.e.* test disk.

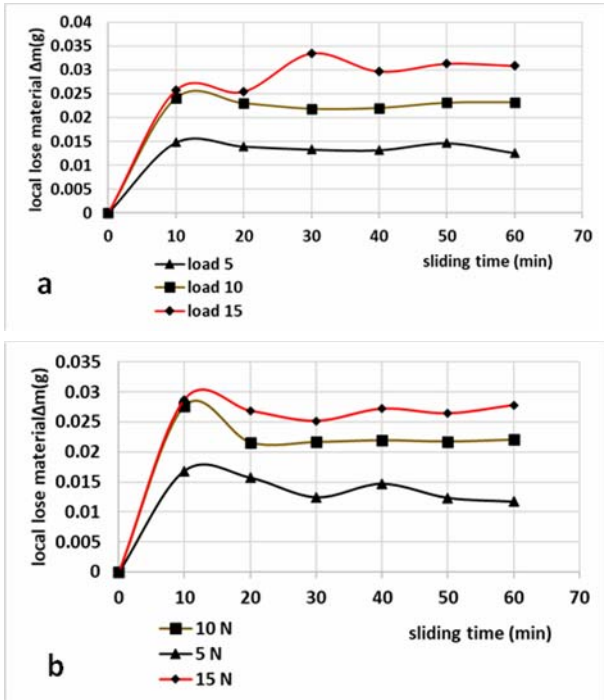

Figure 8. Effect of sliding time on the local lost material of disc roughness coefficient Ra 2.349 µm, (a) PTFE (b) PVC

The relationship between PTFE volumetric wear rate k and sliding time, normal load and coefficient roughness k can be separated into two regimes: transient wear and stable wear. The volumetric wear rate curve as a function of sliding time is depicted in Figure 10. The volumetric wear rate increases over the first 10 minutes of running to achieve the values load (15 N, 10 N and 5 N, respectively), suggesting that the transient wear system has the maximum values. As indicated in Fig. 8, it then declines and the period of steady wear system begins at 39 minutes of sliding time. Increasing the load causes the rate of volumetric wear to go up during the running period. However, as the sliding time goes by, the rate of volumetric wear stays stable, and the value of the wear rate converges during the stable period.

The same thing occurs when determining the relationship between volumetric wear rate k and sliding time of PVC specimens, as shown in Figure 11.

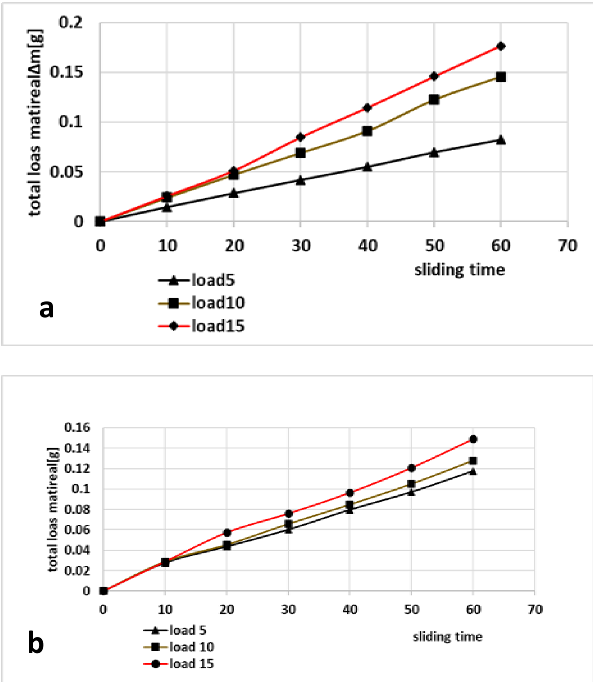

Figure 9. Effect of sliding time and vertical load on the total lost PTFE material of disc roughness coefficient Ra (a) 2.349 µm and (b) 0.611 µm

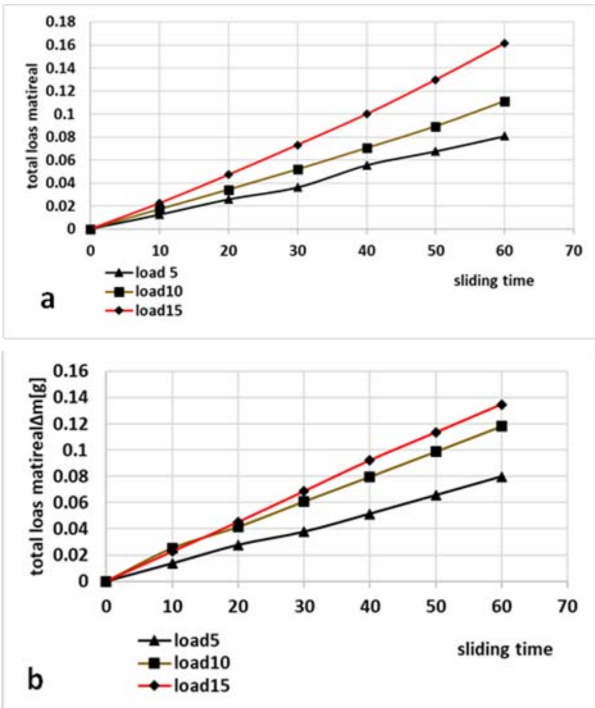

Figure 10. Effect of sliding time on the total lost PVC material of disc roughness coefficient Ra (a) 2.349 µm, (b) 0.611 µm

Figure 8 demonstrates that the change in the volumetric wear coefficient of PVC is more stable when the roughness coefficient of the test disc is less, and it increases with the decrease in the value of the vertical load, which indicates that the loss of the material becomes more stable at high loads. This behavior is similar to the PTFE samples as shown in Figure 11, which confirms that the loss of material PTFE is more stable than the loss of material PVC.

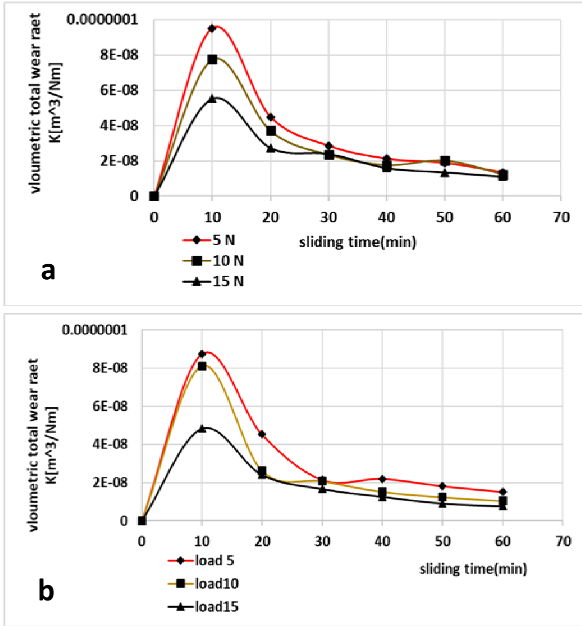

Figure 10. Effect of sliding time and vertical load on the volumetric wear rate k of PTFE material of disc roughness coefficient Ra (a) 2.349 µm, (b) 0.611 µm

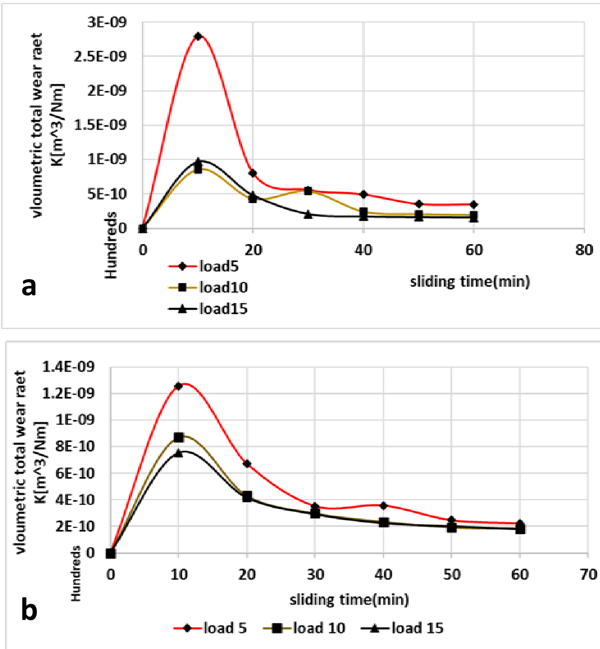

Figure 11. Effect of sliding time and vertical load on the volumetric wear rate k of PTFE material of disc roughness coefficient Ra (a) 2.349 µm, (b) 0.611 µm

4.2. ANFIS essential and exchange effect curves

The base curves and 3D surface complex were predicted by examining the influence of two parameters simultaneously while keeping the third parameter constant to a mean level to determine the interaction of input parameters on output parameters.

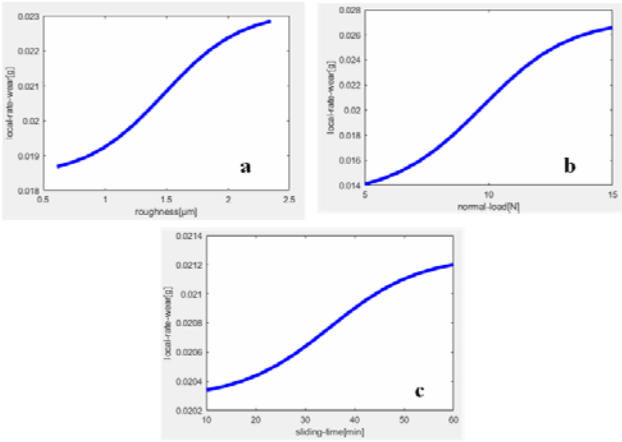

Figure 12. Prediction of the basic curves of wear rate change with: a) roughness coefficient, b) vertical load, and c) sliding time of PTFE specimens.

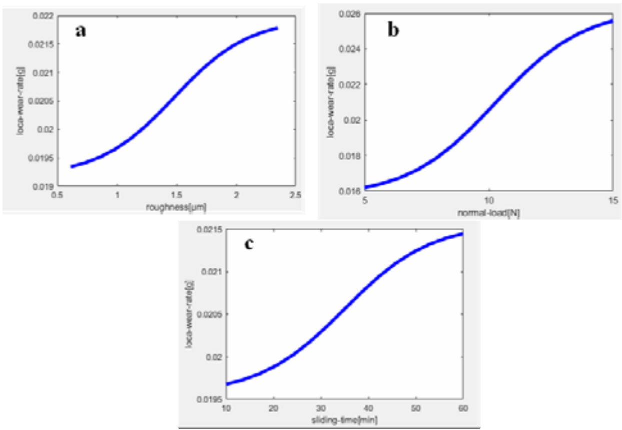

Figure 13. Prediction of the basic curves of wear rate change with: a) roughness coefficient, b) vertical load, and c) sliding time of PVC specimens.

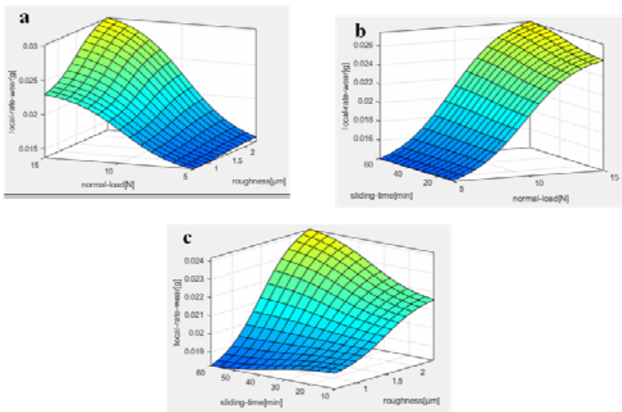

Figure 14. Prediction of the mutual effect of local wear rate for PTFE specimens with a) roughness modulus and vertical load, b) vertical load and slip time, and c) roughness modulus and slip time.

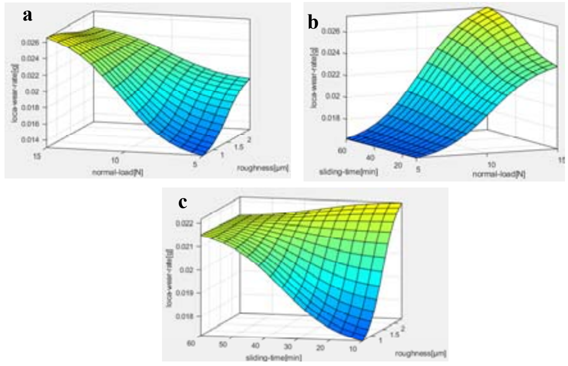

Figure 15. Prediction of the mutual effect of local wear rate for PVC specimens with a) roughness modulus and vertical load, b) vertical load and slip time, and c) roughness modulus and slip time.

Figure 12a shows the predicted increase in the local wear rate with the gradual increase in the roughness coefficient for PTFE specimens. It is evident from the curve that the change and the relationship are non-linear, which is a logical result. Figure.12 b shows the same for the change in the local wear rate with the change in the vertical load and sliding time. Predictive results showed a similar trend for PVC specimens, except that as the roughness coefficient R was raised, the local wear rate was lower for PVC than for PTFE (Figure 13a). Figures (12 b and c) and (11 b and c) respectively, demonstrate that as the vertical load and sliding time changed, the local wear rate of the PVC specimens increased but that of the PTFE specimens did not, confirming the anticipated results.

To explore and assess the influence of test disc roughness coefficient, vertical load, and sliding duration on local wear rate by doubling two parameters while retaining one parameter, as illustrated in Figure 14 for PTFE specimens and Figure 15 for PVC specimens.

4.3. ANFIS model test for local wear rate predictions.

Checking predictive models and estimating error rates were required. Six new tests were conducted from different experiments using the proposed ANFIS model for PTFE and PVC local wear rate. The roughness coefficient of the two test discs was fixed with vertical force and sliding time. As demonstrated in Tables 3 and 4 for PTFE and PVC specimens, the individual error % was validated by the recorded vertical load and sliding time using the statistical standard square error (RMSE).

Tables 2 and 3 show that experimentally determined wear rates and ANFIS predictions accord well. The ANFIS model can forecast local polymer wear well.

Table 2. Testing the Prediction Model for Local wear rate PTFE specimens

roughness Ra[µm]	sliding time [min]	normal load FN[N]	Δmex[g]	manfisΔ	error%
0.611	7.3	12	0.016	0.0152	5
0.611	12.8	8	0.023505	0.0228	3
0.611	6.5	36	0.014796	0.0145	2
2.349	8.5	5	0.019787	0.0186	6
2.349	13.1	18	0.028404	0.0267	6

Table 3. Testing the Prediction Model for Local wear rate PVC specimens

roughness Ra[µm]	sliding time [min]	normal load FN[N]	Δmex[g]	manfisΔ	error%
0.611	6	13	0.013617021	0.0128	6
0.611	9	25	0.017157895	0.0163	5
0.611	12	33	0.023958333	0.023	4
2.349	8.5	37	0.021020408	0.0206	2
2.349	13.1	43	0.025698925	0.0239	7
2.349	7.5	57	0.021304348	0.0196	8

Figure 16a predicts an increase in total wear rate with a rising roughness coefficient for PTFE specimens, as the curve indicates a non-linear change and relationship, which is logical. Figure 16b predicts an increase in total wear rate with changing vertical load and sliding time. Same behaviour for PVC specimens, but with the roughness coefficient, where the prediction findings revealed that the overall wear rate is lower for PVC specimens than PTFE specimens when the roughness coefficient is increased (Figure 17a). As for the vertical load and sliding time, the prediction results were validated by the rise in the overall wear rate of the PVC specimens from the PTFE specimens (Figures 16b and c and 17 b and c).

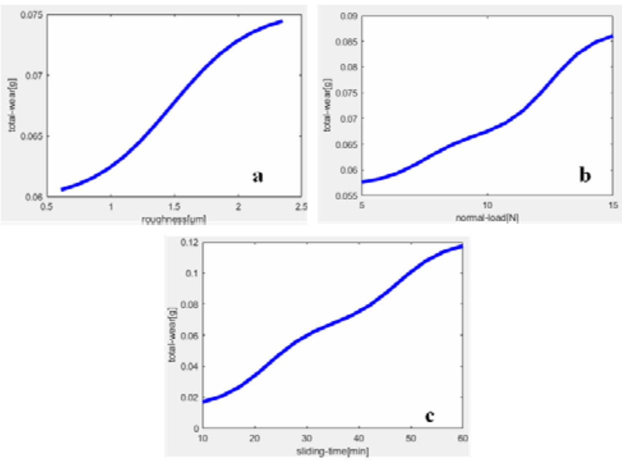

Figure 16. Prediction of the basic curves of total wear rate change with: a) roughness coefficient, b) vertical load, and c) sliding time of PTFE specimens.

To examine and assess the prediction of the total wear rate from the effect of the test disc roughness coefficient, vertical load, and sliding time by doubling two factors with the diaper for PTFE specimens and PVC specimens.

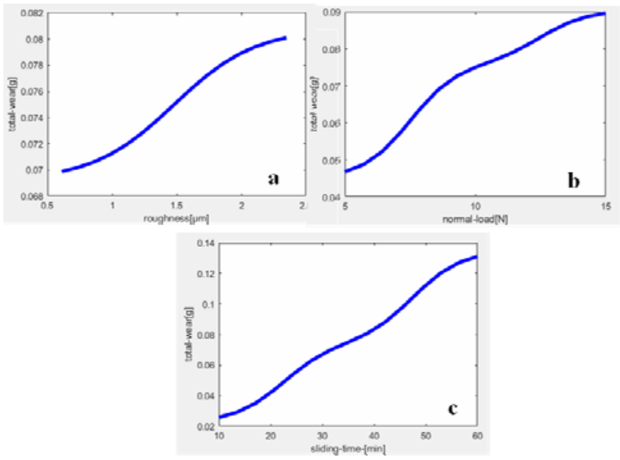

Figure 17. Prediction of the basic curves of total wear rate change with: a) roughness coefficient, b) vertical load, and c) sliding time of PVC specimens.

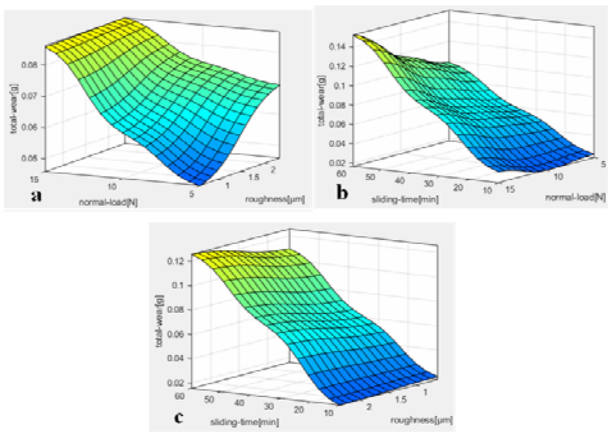

Figure 18. Predicting the interaction of the total wear rate of PTFE samples with a) roughness modulus-vertical load), b) vertical load-slipping time, and c) roughness modulus-slipping time.

The total wear rate increases (Fig. 18a and 19a) with rising roughness coefficient and vertical load for both polymers (PTFE and PVC), but more for PTFE. As the vertical load and sliding duration double, the total wear rate increases slightly, as seen in Figures 16b and 17b. Figures 16c and 17c show that the total wear rate increases gradually with a rise in sliding time and a decrease in the roughness coefficient of the contact surfaces, and it is larger for PTFE.

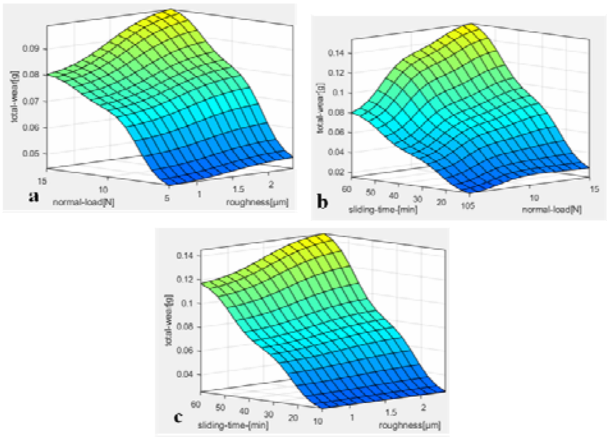

Figure 19. Predicting the interaction of the total wear rate of PTFE samples with a) roughness modulus-vertical load), b) vertical load-slipping time, and c) roughness modulus-slipping time.

4.4. ANFIS total Wear Rate Model Test:

Total wear rate prediction models and error ratio estimates were tested. By employing the suggested ANFIS model for the total wear rate of PTFE and PVC in six new tests, the roughness modulus of the test discs was set with vertical load and sliding time. As indicated in Tables 4 and 5 for PTFE and PVC materials, the individual error % was validated by the recorded vertical load and sliding time using statistical standard square error (RMSE).

Tables 4 and 5 show that experimentally determined wear rates and ANFIS predictions accord well. The ANFIS model predicts polymer wear well generally.

Table 4. Testing the Prediction Model for Total wear rate PTFE specimens

roughness Ra[µm]	sliding time [min]	normal load FN[N]	Δmex[g]	manfisΔ	error%
0.611	7	15	0.0198	0.0187	6
0.611	12	22	0.043	0.0422	2
0.611	6.5	43	0.060	0.059	2
2.349	8.2	17	0.030	0.0288	5
2.349	11.7	28	0.067	0.0646	4

Table 5 Testing the Prediction Model for Total wear rate PVC specimens

roughness Ra[µm]	sliding time [min]	normal load FN[N]	Δmex[g]	manfisΔ	error%
0.611	8	18	0.032	0.0309	4
0.611	11.5	27	0.061	0.0598	2
0.611	13.2	33	0.076	0.0748	2
2.349	7.3	14	0.024	0.0237	5
2.349	12	26	0.069	0.0671	4
2.349	14	56	0.169	0.1657	2

4.5. Volumetric wear rate

To research and assess the prediction of the influence of the test disc roughness coefficient, vertical load, and sliding time of test specimens on the volumetric wear rate by changing one parameter at a time, as illustrated in Fig. 20 for PTFE specimens and Fig. 21 for PVC specimens.

Figure 20 a predicts a rise in volumetric wear rate with increasing roughness coefficient for PTFE specimens, as the change and connection are non-linear. Same behavior for PVC specimens with predictive results, but with roughness modulus, where predictive results showed that volume wear rate of PVC and PTFE when roughness modulus was raised (Fig. 21a). As vertical load and sliding period changed, the predictive results indicated a decrease in the total wear rate of PTFE specimens vs to PVC specimens (Figures 20 b and c), (21 b, and c) respectively.

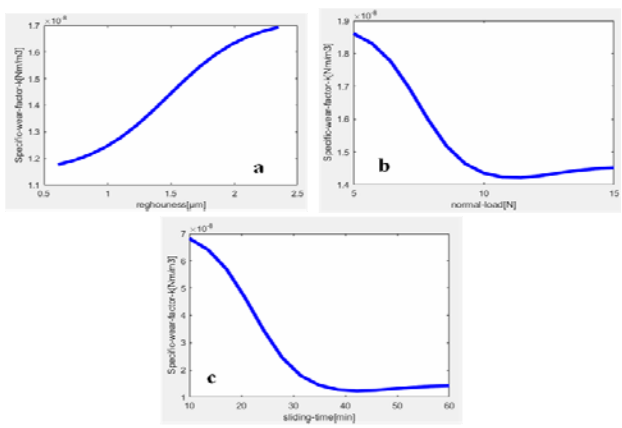

Figure 20. Prediction of the basic curves of volumetric wear rate change with: a) roughness coefficient, b) vertical load, and c) sliding time of PTFE specimens.

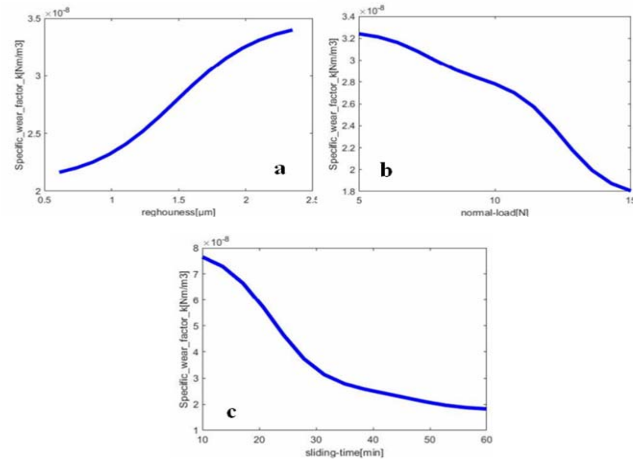

Figure 21. Prediction of the basic curves of volumetric wear rate change with: a) roughness coefficient, b) vertical load, and c) sliding time of PVC specimens.

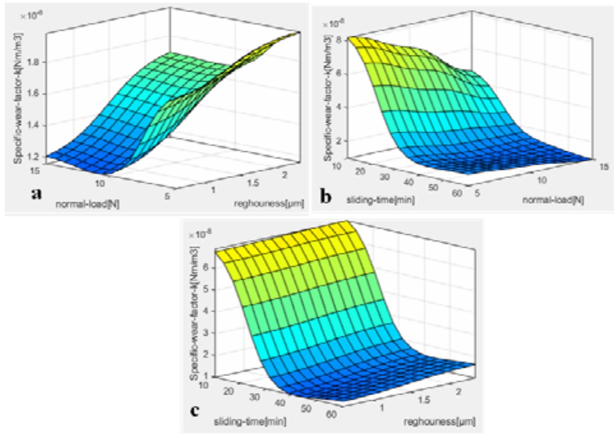

Figure 22. Predicting the mutual effect of volume wear rate K for PTFE specimens with a) Roughness modulus-vertical load), b) Vertical load-sliding time, and c) Roughness modulus-sliding time.

To determine the influence of test disc roughness coefficient, vertical load, and sliding time on volumetric wear rate by changing two parameters while retaining one parameter, as illustrated in Figure 22 for PTFE specimens and Figure 23 for PVC specimens.

Figures 22a 23a show that the volumetric wear rate goes up when the roughness coefficient and vertical load go up. This is true for both PTFE and PVC copolymers, but the PVC rate is lower. As the vertical load and sliding time both go up twice, the volumetric wear rate goes up gradually. This increase is close to what is shown in figures 22b and 23b.

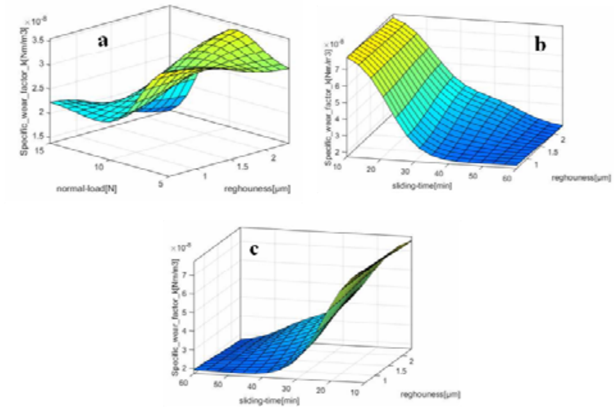

Figure 23. Predicting the mutual effect of volume wear rate K for PVC specimens with a) Roughness modulus-vertical load), b) Vertical load-sliding time, and c) Roughness modulus-sliding time.

Table 6. Testing the Prediction Model for Volumetric wear Rate of PTFE specimens

Ra [μm]	Load [N]	sliding time [min]	K_{ex} [Nm/m^3]*1.0e-07	K_{anfis} [Nm/m^3]*1.0e-07	error%
0.611	6.4	13	0.775789	0.737	5
0.611	12	22	0.367755	0.3604	2
0.611	14.5	44	0.101031	0.098	3
2.349	8	18	0.654086	0.6083	7
2.349	6	38	0.185789	0.1765	5

Table 7. Testing the Prediction Model for Volumetric wear Rate of PVC specimens

Ra [μm]	Load [N]	sliding time [min]	K_{ex} [Nm/m^3]*1.0e-07	K_{anfis} [Nm/m^3]*1.0e-07	error%
0.611	6	12	1.09E-01	1.06E-01	3
0.611	11	27	3.61E-02	3.36E-02	7
0.611	14	55	1.96E-02	1.90E-02	3
2.349	6	14	2.02E-01	1.96E-01	3
2.349	11	29	3.89E-02	3.81E-02	2
2.349	14	54	1.70E-02	1.67E-02	2

Regarding the changes in the volumetric wear rate with the double change of the roughness coefficient and the sliding time, it is clear from Figures 22c and 23c that the volumetric wear rate goes up gradually with increasing sliding time and, to some extent, the roughness coefficient. Six new experiments were performed. While the suggested ANFIS volumetric wear rate model was used for PTFE and PVC test specimens, the roughness coefficient of the test discs was fixed. As indicated in Tables 5 to 7 for PTFE and 5 to 8 for PVC, the individual error percentage was validated by measuring the vertical load and sliding time. The standard is RMSE.

5. CONCLUSIONS

ANFIS was used to predict the wear behavior of PTFE and PVC polymeric materials. The results showed that applying an ANFIS-based model to predict the amount of local and total wear and the volumetric wear coefficient is possible for the independent variables to test disk roughness coefficient, sliding time variance and vertical load variance, producing the best match between the predicted data and the experimental data. The predicted values were compared with the experimental values and their closeness was determined. The ANFIS model can predict the values of local, total, and volumetric wear coefficients with an error rate of less than 10%. The results presented in this paper are expected to be very useful to bearing designers as well as the academic community.

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