UNIZIK JOURNAL OF ENGINEERING AND APPLIED SCIENCES (UJEAS)

Research Article

Evaluative Analysis of Specific Wear Rate of Glass Fibre Reinforced Epoxy Resin (GFRP) based on Applied Load and Weight Loss while Sliding Under Dry Medium

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Special Issue

A Themed Issue in Honour of Professor Clement Uche Atuanya on His retirement.

This themed issue pays tribute to Professor Clement Uche Atuanya in recognition of his illustrious career in Metallurgical and Materials Engineering as he retires from Nnamdi Azikiwe University, Awka. We celebrate his enduring legacy of dedication to advancing knowledge and his impact on academia and beyond through this collection of writings.

Edited by
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UJEAS

UNIZIK JOURNAL OF ENGINEERING AND APPLIED SCIENCES

UNIZIK Journal of Engineering and Applied Sciences 3(3), September (2024), 945-957
Journal homepage: https://journals.unizik.edu.ng/index.php/ujeas
PRINT ISSN: 2992-4383 || ONLINE ISSN: 2992-4391

Evaluative Analysis of Specific Wear Rate of Glass Fibre Reinforced Epoxy Resin (GFRP) based on Applied Load and Weight Loss while Sliding Under Dry Medium

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Abstract

The specific wear rate of glass fibre reinforced epoxy resin while sliding under dry medium was evaluated based on the weight loss (of the composite while sliding) and applied load. The predictive analysis was carried out using a derived empirical model; $Ⱳ = N(e^{ƀω} + e^{ßƐ}) - Ƙ$, whose validity was rooted on the core model structure; $Ⱳ + Ƙ \approx N(e^{ƀω} + e^{ßƐ})$, considering that both sides of the structure are correspondingly almost equal. The symbols Ⱳ, ω and Ɛ are specific wear rate of the glass fibre-epoxy resin composite (mm^2/Nm), weight loss of the composite while sliding (mg) and applied load on the composite to enable sliding (N), while Ƙ, N, ƀ and ß are equalizing constants respectively. Results generated from experiment, derived model and regression model are characterized by very similar trend, spread of results and corresponding point values. Evaluated correlations from derived model and experimental results, between the specific wear rate and applied load & weight loss are 0.9988 & 0.9270 and 0.9980 and 0.9625 respectively. The overall standard error, associating prediction of specific wear rate of the composite, is 0.11%, for every change in the applied load and composite weight loss. This gives a model confidence level above 99%. The specific wear rate of the composite, per unit applied load and weight loss are 0.0116, 0.0130 & 0.0120 mm^3/N^2m and 0.1377, 0.1543 & 0.1425 $(mm^3/Nm)/mg$ respectively. Overall maximum deviation of the model-predicted specific wear rate from experimental results was 8.04%. The derived model will predict the specific wear rate of the composite, within the experimental results range, on substituting into the model, values of the applied load on the composite and its corresponding weight loss, providing the boundary conditions are considered.

Keywords: Specific wear rate, glass fibre-epoxy resin composite, applied load, weight loss, dry medium

1. Introduction

People have been using composite materials since antiquity; for example, straws were used in bricks to boost their strength and structural properties. Research with superior reinforcing fibers in a base of polymer or epoxy resin materials has emerged as a low-cost, easily shapeable composite material that for several applications may be the best alternative among the materials available due to superior characteristics such as high impact strength and amenability to low-cost manufacturing, having a higher strength-to-weight ratio, and having a lower overall cast, among other things. Thus, different applications of composite materials have emerged in the automotive and aerospace industries, such as cams, seals, shafts, gears, bushes, and so on (El-Tayeb et al. 2005: Edward, 1998)), and some of them necessitate an understanding of their tribological properties as well. Even though epoxy resin polymer reinforcement with fibres increases the tribological properties of epoxy resins, it can also make them inferior (El-Tayeb et al. 2005). Many earlier studies (El-Tayeb et al. 2005; Bahadur et al. 1990; Pihtili, 2002) focused on the wear and friction properties of polymer fibre reinforced composites. Among the operating circumstances, surface temperature may be important in studying the tribological behavior of specific polymer composites [El-Tayeb et al. 2005; Bhawani et al. 1993; Myahkin et al. 2005).

However, very few investigations on these issues have been conducted to date (Myshkin et al. 2005; Kishore et al. 1999). Because composite materials are increasingly being used in applications where sliding wear characteristics are important, it is desirable to have a better understanding of the tribological behaviors of these fibre-reinforced polymers and epoxies under a variety of operating conditions. Furthermore, despite the fact that a large range of materials have been made up to this point, the glass-fibre-reinforced polymer (GFRP) category need more and more research to improve its usage in light of its technical application capabilities. These are more expensive, but they form an excellent material for a wide range of engineering applications (Collyer, 1996; El-Tayep, 1996). Because of their low density and ease of shaping, they can be formed into various stacking sequences to achieve high strength and stiffness for heavy loads (Kukureka et al. 1999). Such composite materials are made up of epoxy resin and reinforcement selected based on the mechanical properties required for the applications (Srivastava and Pathak. 1996). The most prevalent wear mechanisms for FRP composites are fibre-matrix debonding, matrix fracture, and fiber breaking (Kishore et al. 2000; Srivastave et al. 1996). Additional mechanisms highlighted include fibre pullout, resin pealing, matrix wear linked with fibre separation, wear track edge deformation, and fiber shear deformation. Thus, the application of FRP composites in mechanical parts with acceptable wear resistance in actual service settings would necessitate a thorough understanding of and study of friction and wear characteristics.

It is widely known that a gaseous atmosphere can have a significant impact on the friction and wear performance of steels when in contact with other materials. Friction and wear behavior of steel and other metals are governed in part by oxygen (O2) adsorption and the formation of oxide layers, which are more supportive of sliding conditions than pure non-oxidized metal surfaces, where adhesiveness is much higher and cold welding may occur. However, findings show that the effects of gaseous environment on tribological characteristics in polymer composites to steel or metal contact varies and differs between studies, and thus factors such as adhesion, friction of oxidized metal surfaces, etc. causing more wear have already been identified (Findik et al. 2004; Kishore et al. 2001; Lancaster, 1990; Merstallinger et al. 2009). However, due to the complexity and the sensitivity of the gas- lubricated systems, the results from these studies do not apply to every gas-lubricated combination.

The adsorption of gas molecules and the chemical change of the contact surfaces substantially determine the behaviour of each metal differently; therefore, the friction and wear behavior of gas-lubricated systems are highly related to the operating conditions and material combination. Furthermore, findings obtained from different research, using gases as lubricating medium at non-lubricated metal contacts, often show different responses and can even appear contradictory when applying different operating conditions (gas pressure, contact pressure, temperature and other contact dynamics, etc.) or using different material combination. Furthermore, in research using Argon (Ar) and Nitrogen (N_2) atmospheres, friction and wear of different metal alloys and bearing steels higher than in an air atmosphere (Mishina, 1992). Prior research by other investigators has shown that when the polymer resins are reinforced with glass, carbon or other hybrid fibres, the wear rate of polymers sliding against steel is reduced; though, the performance is influenced by parameters such as the matrix composition, amount, shape, size, the type and angle of orientation of the fibres, and the testing parameters such as speed of sliding, load and environment [Chand et al. 1993; Yetgin et al. 2013; Unal and Findik, 2008).

To expand on prior research, the current study seeks to investigate the effects of such testing settings on the wear rate of GFRP composite materials. The majority of earlier findings have been based on fibre composites that are randomly or unidirectionally oriented. Woven fabric-reinforced composites are gaining popularity due to their balanced properties in the fabric plane and ease of manufacture. As a result, the current research article focuses on glass woven fabric reinforced epoxy composite materials and their wear behavior. The wear behavior of GFRP materials is experimentally examined under a variety of normal loads, sliding velocities, sliding circumstances, and lubricating fluids, including dry, oil-lubricated, and inert gas.

Researchers (Agrawal et al. 2016) derived an expression for specific wear rate K_o (mm^3/N^2m) of glass fibre-epoxy resin composite as:

$$K_o = \frac{\Delta m}{\rho L d} \qquad (1)$$

Where Δm, ρ, L, and d are the weight loss (kg), the density of the composite (kg/mm^3), applied load (N), and sliding distance (m) respectively.

The wear rate is computed using the mathematical expression Agrawal et al. 2016)], which considers weight loss, composite density, applied force, and sliding distance. However, no mathematical formula or model has been developed to evaluate the specific wear rate using only two variables: weight loss (of the composite during sliding) and applied load. This necessitated the current endeavor to close the deficit. The current study aims to create an empirical model for predicting the wear rate of a glass fibre-epoxy resin composite using just weight loss and applied force. If the model is generated, it must evaluate the composite's specific wear rate within the experimental result range, provided that the input parameters fall within the boundary requirement.

2. Materials and methods

2.1. Materials

In the experimental work, composite specimens were built as described in (Agrawal et al. 2016) with glass fiber reinforcement in an epoxy resin matrix material. Glass fibre was chosen as reinforcement to epoxy resin to form, GFER because of the need to produce a composite which possesses toughness, good wear resistance, good mechanical resistance & dimensional, resistance to chemicals and low shrinkage at high temperature.

The glass fabric used was woven roving E-glass from Hindustan Fibre Glass Industries in India, which was reasonably priced. The woven glass cloth was 600 GSM. (Continuous fibers do not often require spinning, but in this case, it was necessary). The fabric is created by weaving the fibers in a regular pattern. If fibres are not spun, the fabric becomes denser and has less fibre flexure. Plain weave glass fibre consists of E-glass fibres with diameters ranging from 12 to 24 mm. Woven textiles should be used when higher shear strengths are required along the reinforced sheet's plane. Unidirectional weaving often has a lower shear strength than conventional weaving. GFRP is a good engineering material with high impact strengths, mouldability, and a high strength-to-weight ratio, making it suitable in commercial applications due to its low cost. 2.2. Preparing the specimen The vacuum bagging procedure produced GFRP epoxy resin composite plates with shaving dimensions of 270mm, 320mm, and 4mm. To achieve a nominal thickness of 4mm, eight layers of glass fabric were employed. We utilized the stacking sequence [0°/745°/90°]s. During the wear and friction studies, the surface in contact with the steel disc had a fiber orientation of 0°. All of the layers of fabric were cut and put in the correct order, warp facing down. The entire process was carefully segregated to minimize dust, grease, and other contaminants that could disrupt layer bonding during consolidation. The plates were cured at room temperature for 48 hours. The prepared plates were checked with the naked eye for any abnormal surface imperfections. The plates were free of surface effects and delaminations. The specimen pins were made by gluing GFRP sections measuring 8mm x 8mm x 4mm to 8mm diameter aluminum pins.

2.3. Testing procedure

Prior research (Agrawal et al. 2016) was conducted on a wear tester, a pin-on-disc machine manufactured by DUCOM, Bangalore (India), specifically for high PV conditions at 1000N load and 10m/s speed. Before the experiment, the specimen pin (8mm x 8mm x 4mm) was rubbed on a hardened steel disk with a surface roughness of 0.5-0.6 mm to ensure even contact. This rubbing for even contact was done under the same load at which the experiment was conducted. Later on, this rough disc was exchanged with a steel disc of En31 hardened to 60HRC and having Ra values in between 0.2–0.3 mm. Before starting the experimental study, the initial weight of the pin was taken after cleaning it with acetone and drying. It was rubbed over the steel disc at two different speeds of 2.51m/s (600rpm at 80mm track diameter) and 3.14m/s (600rpm at 100mm track diameter). The complete distance of 1.507km and 2.827km was attained by rubbing the pins for 600s and 900s to attain considerable wear. Later on, the pin was again cleaned by the same method, dried, and weighed with the help of a balance with a least count of 0.01mg.All set of experiments was conducted two times in the same manner and the precise value of weight loss was taken for calculating the specific wear rate.

The experiment was repeated at 40N, 80N and 120Nloads. It was observed during the experiment that some of the parameters such as an increase in coefficient of friction, increase in disc temperature, mark of abrasion on disc, as light color change in disc surface, and noise generation at excessive loads occurred. Experiments for adhesive wear studies were performed by sliding specimens under dry, oil-lubricated, and argon gas atmospheres at 40N, 80N, and 120N loads at room temperature. All sets of these experiments were conducted as explained earlier and weight loss was measured after each experiment. The complete procedure was thus repeated for oil-lubricated and inert gas i.e. argon medium sliding. The oil used for lubricating the disc surface during the experiments was SAE20 engine oil, with a kinematic viscosity of 25–30 cSt at 50 °C. Before start of each experiment, two drops of lubricating oil were placed over the sliding surface. Further, the oil was poured at a flow rate of 0.02ml /min during the experiment. The specimens, cut from the prepared composite plates, and glued to aluminium pins were used.

Before each experiment, the disc surface was cleaned using 600-grade SiC emery paper, then rinsed with acetone and dried. During inert gas sliding, argon gas of better than 99.99% purity was used. The trials employed 0.025 bar of gas overpressure and a flow rate of 1.5l/min. The fabric used in the GFRP examples was parallel to the sliding surface, whereas the warp fibres were parallel to the sliding direction. To determine accurate weight loss, the ultimate weight of all specimens was measured after cleaning with acetone and drying (Agrawal et al. 2016).

3. Model Derivation

Table 1: Variation of specific wear rate of glass fibre-epoxy resin composite with its weight loss and applied load

(Ƴ) $\times 10^{-5}$	(ω)	(Ɛ)
2.1802	2.48	40
2.1975	3.14	50
2.2151	3.80	60
2.2325	4.46	70
2.2501	5.12	80
2.4651	6.15	90
2.6803	7.18	100
2.8951	8.21	110
3.1097	9.23	120

Computational analysis of the experimental results shown in Table 1, resulted to Table 2 which indicate that;

$$Ƴ + Ƙ \approx N(e^{ƀ\omega} + e^{ß Ɛ}) \quad (2)$$

$$Ƴ = N(e^{ƀ\omega} + e^{ß Ɛ}) - Ƙ \quad (3)$$

The expression in (3) a derived empirical model predicts the specific wear rate of glass fibre reinforced epoxy resin, based on applied load and weight loss, while sliding under dry medium. The model is a sum of two exponential functions. Table1 and Table 2 reveal that Ƴ, ω and and Ɛ are specific wear rate of the glass fibre-epoxy resin composite (mm^2/Nm),weight loss of the composite while sliding (mg) and applied load on the composite to enable sliding (N) respectively. The model is referred to as Nwoye`s 1st Model for Glass Fibre Reinforced Epoxy Resin Wear Rate or Nwoye`s 1st GLAFEC-WERT Model. The equalizing constants; Ƙ, N, ƀ and ß are 0.34 x 10^{-5}, 10^{-5}, 0.0556 and 0.0045 respectively. These constant were generated by a software (Nwoye, 2008). The interaction between these constants and variables ensures that the units at both sides of the derived model are equal.

4. Results and Discussion

4.1 Boundary and Initial Conditions

Consider glass fibre (filler), interacting with the matrix (epoxy resin). The specific wear rate of the composite results from weight loss, which in turn is induced by the applied load. During the model derivation, the considered range of these parameters are (2.1802 - 3.1097) x 10^{-5}(mm^2/Nm), 2.48 - 9.23kg and 40 – 120N respectively.

Table 2: Variation of Ꮃ + Ꝁ with N($e^{ƀϖ}$ + $e^{ßε}$)

(Ꮃ + Ꝁ) $x10^{-5}$	N($e^{ƀϖ}$ + $e^{ßε}$) $x10^{-5}$	Differentials $x10^{-5}$
2.5202	2.3450	0.1752
2.5375	2.4431	0.0944
2.5551	2.5453	0.0098
2.5725	2.6517	-0.0792
2.5901	2.7626	-0.1725
2.8051	2.9070	-0.1019
3.0203	3.0589	-0.0386
3.2351	3.2190	0.0161
3.4497	3.3866	0.0631

4.2 Model Validity

The validity of a derived model determines functionality and acceptability of the model. The core model structure in (2), expressed as Ꮃ + Ꝁ ≈ N($e^{ƀϖ}$ + $e^{ßε}$) is the basis for establishment of validity of the derived model in (3). This is because both sides of the structure are correspondingly near-equal. The model structure agrees with Table 2, following proximity of corresponding structure component values, computed from experimental results in Table 1.

Table 1 shows that the specific wear rate increases with increase in the composite weight loss and applied load. The material loss resulted from the interaction between friction on the sliding surface (which opposes the movement) and applied load. Table 2 indicates the differential between both sides of the core model structure. The magnitude of the discrepancy determines the functionality and acceptability of the derived model. Analysis of the table shows that the differentials are very negligible. It is strongly believe that this will translate into a very negligible deviation of model-predicted results from corresponding experimental values.

The derived model was also validated by comparing the predicted results with the experimental, through graphical, statistical and deviational analysis.

4.2.1 Graphical Analysis

Figure 1 shows experimental and model-predicted results, represented by aligned curves of specific wear rate of glass fibre reinforced epoxy resin (relative to applied load), while sliding on a dry medium, at a velocity of 2.51m/s, through a distance of 1508m. These curves significantly indicate very close point-to-point corresponding values, though slightly different in spread and trend of results distribution. Figure 2, show a representation of regression model-predicted specific wear rate of the composite; indicating similar trend and spread of results distribution with derived model-predictions. It is therefore very instructive to state that the regression model (standard model) prediction upheld the derived model-predicted results, which are largely close to that of the experiment. The curves from both figures are positive in nature, prompting positive slopes, as a result of the direct relationship between the specific wear rate of the composite and applied load.

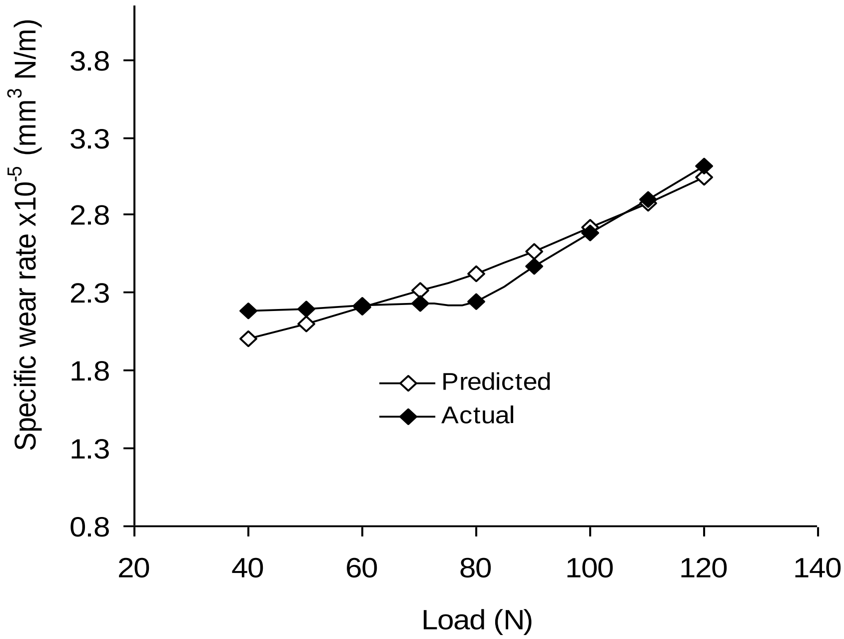

Figure 1: Comparison of specific wear rates of glass fibre-epoxy resin composite (relative to applied load) from actual results and derived model

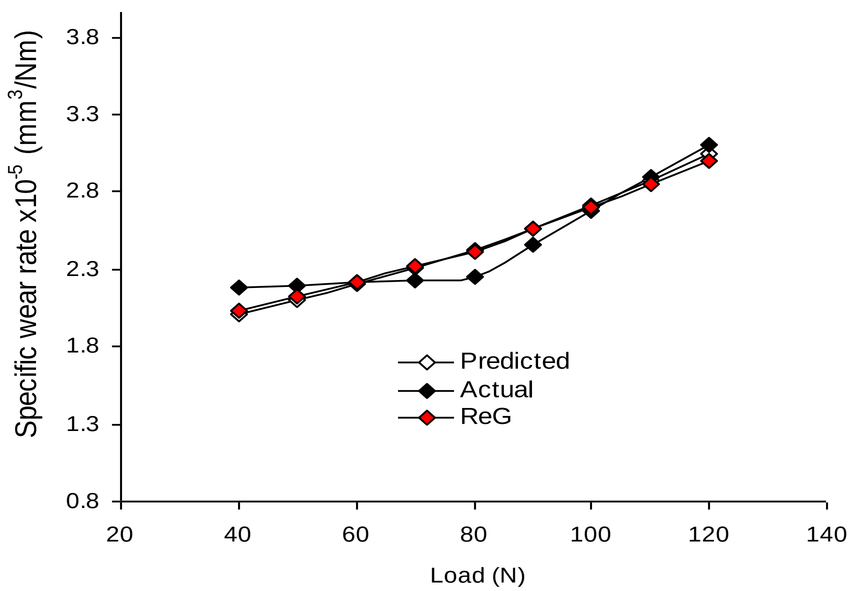

Figure 2: Comparison of specific wear rates of glass fibre-epoxy resin composite (relative to applied load) from actual results, derived model and regression model

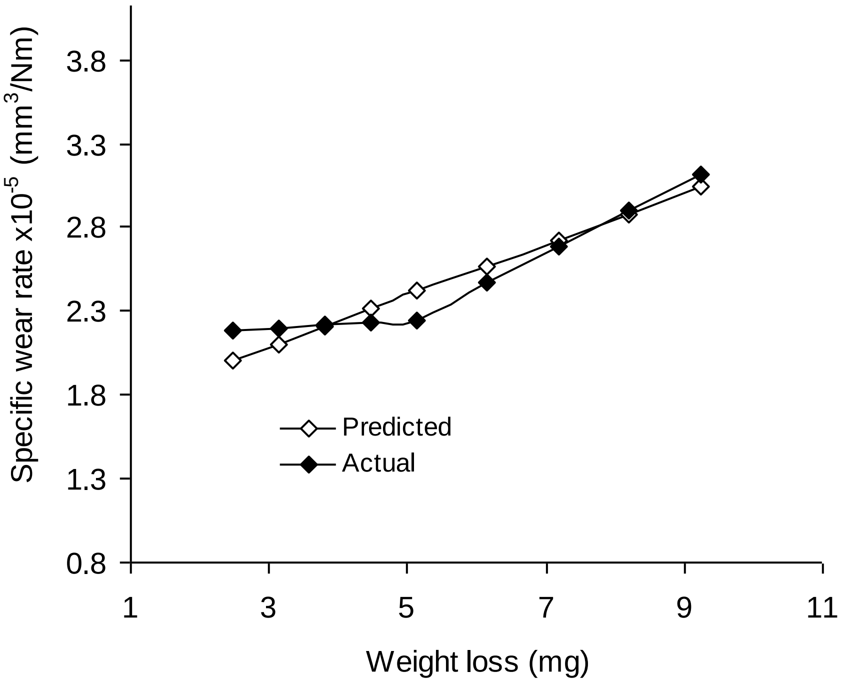

Figure 3: Comparison of specific wear rates of glass fibre-epoxy resin composite (relative to weight loss) from actual results and derived model.

Graphical analysis of Figure 3 and Figure 4 reveals close knitted similarities to result representations in Figure 1 and Figure 2 respectively. The difference is just in the plot on the x-axis; applied load and weight loss respectively. Curves from Figure 3 show specific wear rate of the composite, generated from experimental and derived model-predicted results, while Figure 4 indicates result from experiment, derived model and regression model-prediction. These curves, in line with Figure 1 and Figure 2 respectively, are orientated in the positive plane, being positive in nature. This emphasizes also, a direct variation of specific wear rate of the composite with its weight loss, while sliding on a dry medium, prompting positive slopes.

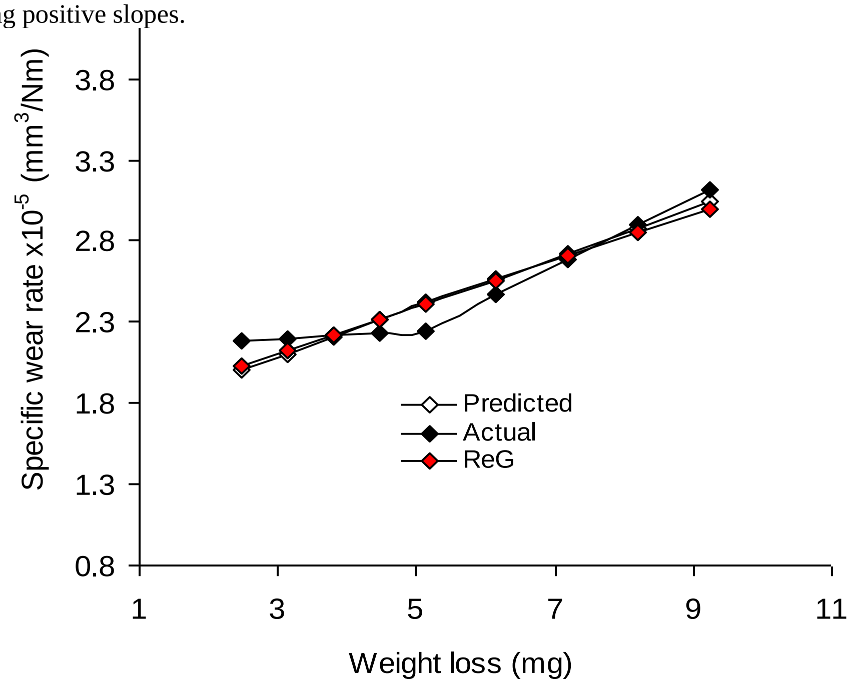

Figure 4: Comparison of specific wear rates of glass fibre-epoxy resin composite (relative to weight loss) from actual results, derived model and regression model.

4.2.2 Statistical Analysis

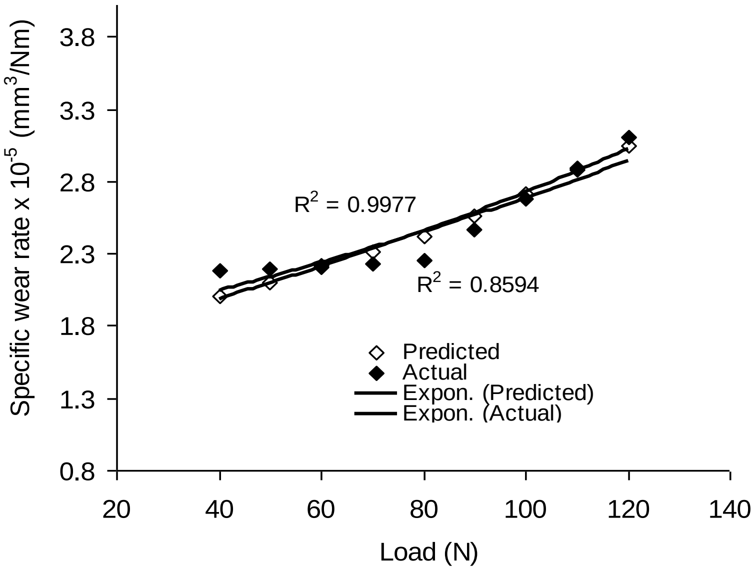

Figure 5: Coefficient of determination between specific wear rate and applied load as evaluated from actual results and derived model

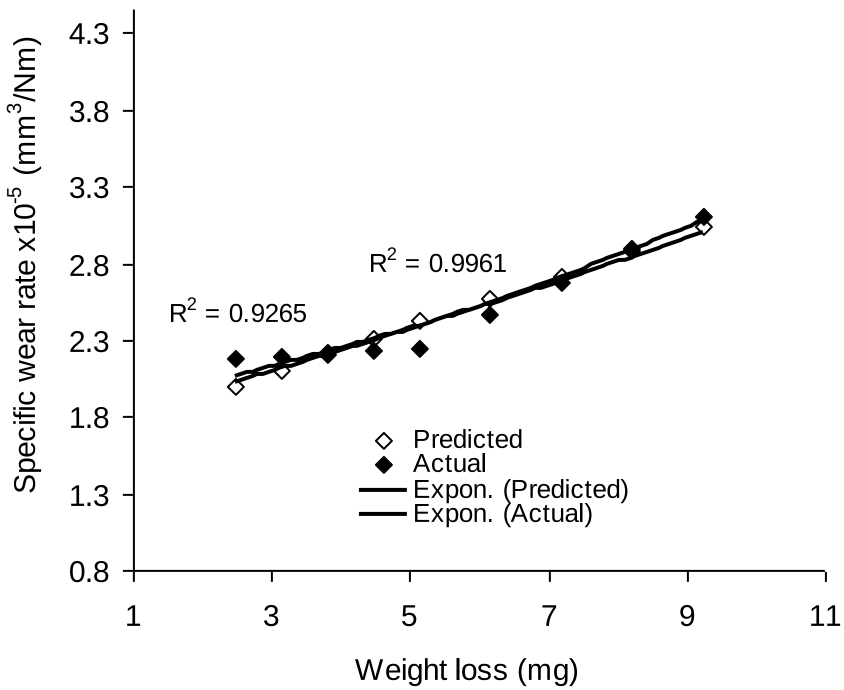

Figure 6: Coefficient of determination between specific wear rate and weight loss as evaluated from actual results and derived model

The evaluated correlations from Figure 5 and Figure 6, between specific wear rate of the composite and applied load & weight loss are 0.9988 & 0.9270 and 0.9980 and 0.9625, using derived model-predicted and experimental results respectively. These values were calculated as the square root of the coefficients of determination R^2 shown in Figures 5 and 6. These correlations are all > 0.92. Results of the investigation indicate that the overall standard error, associating prediction of specific wear rate of the composite, is 0.11%, for every change in the applied load and composite weight loss. This gives a model confidence level above 99%. The standard error was evaluated using Microsoft excel.

4.2.3 Deviation Analysis

Table 3: Differential between experimentally determined and model-predicted specific wear rate of glass fibre-epoxy resin

(W) x10^{-5}	$\Delta W = (W_{M} - W_{\varepsilon})$ x10^{-5}
2.1802	-0.1752
2.1975	-0.0944
2.2151	-0.0098
2.2325	0.0792
2.2501	0.1725
2.4651	0.1019
2.6803	0.0386
2.8951	-0.0161
3.1097	-0.0631

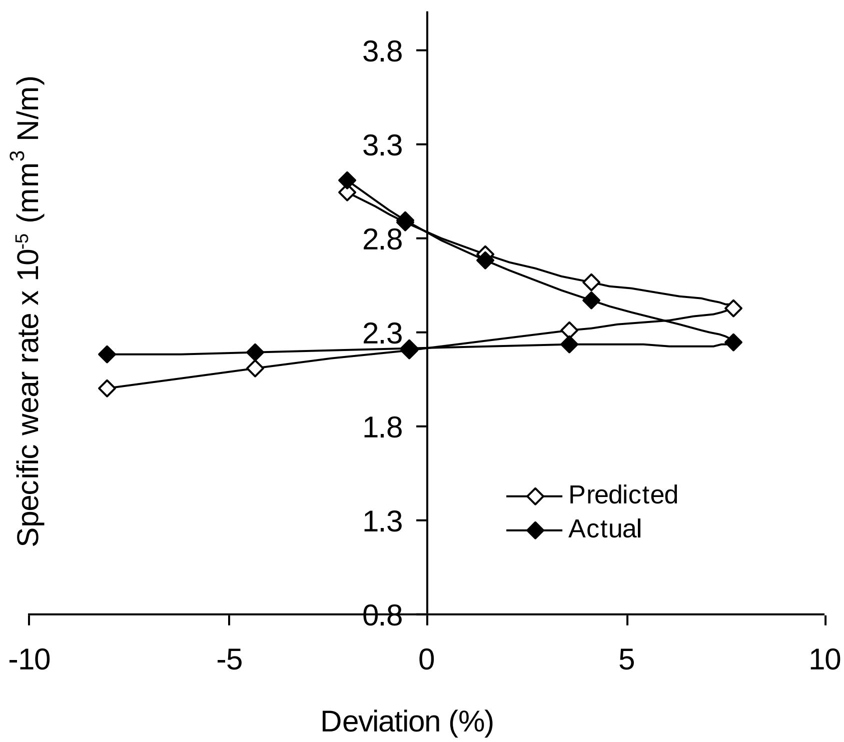

Figure 7: Variation of model-predicted specific wear rate of glass fibre-epoxy resin composite with its corresponding deviation from experimental results

Graphical representation in Figure 7 indicates point-to-point variation of model-predictions with corresponding experimental results. The figure shows the overall maximum deviation of model-predicted specific wear rate of glass fibre-epoxy resin composite, from experimental results, as 8.04%. This translates into over 91% operational model confidence level. The figure indicates that each set of points on the curves, gives the magnitude (in percent) at which the model-predicted results deviated from corresponding experimental values. Figure 7 also shows that the least and highest deviations of model-predicted specific wear rate of composite are - 0.44 and -8.04 %. These deviations correspond to specific wear rates: 2.2053 & 2.005 mm^2/Nm, applied loads: 40 & 60N and composite weight losses: 2.48 and 3.8 mg respectively. Following evaluations from maximum deviation, correlations and standard error, it is instructive and admissible to place the overall model confidence level between 92-99%. The model-predicted results are made up, to experiment results through introduction of correction factors, which are numerically equal, but of opposite sign to the deviation values.

The deviation Dv, of model-predicted specific wear rate from the corresponding experimental result was evaluated from the expression.

$$D_v = \left[\frac{W_m - W_E}{W_E}\right] \text{x } 100 \qquad (4)$$

Where

W_E and W_m are specific wear rates of the composite evaluated from experiment and model-predicted results respectively. Correction factor which overcomes the deviation is calculated as the negative of equation (5)

$$C_f = -\left[\frac{W_m - W_E}{W_E}\right] \text{x } 100 \qquad (5)$$

Specific wear rate of glass fibre-epoxy resin composite per unit load applied W_ε(mm^3/N^2m) was calculated from the expression;

$$W_\varepsilon = W/\varepsilon \qquad (6)$$

Re-written as

$$W_\varepsilon = \Delta W/\Delta\varepsilon \qquad (7)$$

The expression (7), is detailed as

$$W_\varepsilon = W_2 - W_1/\varepsilon_2 - \varepsilon_1 \qquad (8)$$

Where,

ΔW = Change in the specific wear rates W_2, W_1 at two applied loads ε_2, ε_1

On plotting points (40, 2.1802) & (120, 3.1097), (40, 2.005) & (120, 3.0466) and (40,2.0349) & (120, 2.9968) as shown in Figure 2, designating them as (ε_1, W_1) and (ε_2, W_2) for experimental, model and regression-predicted results, and then substituting them into the expression (8), gives the slopes: 0.0116, 0.0130 and 0.0120 mm^3/N^2m as their respective specific wear rate of glass fibre-epoxy resin per unit applied load.

Specific wear rate of glass fibre-epoxy resin composite per unit weight loss W_ω(mm^3/Nm)/mg was calculated from the expression;

$$W_\omega = W/\omega \qquad (9)$$

Re-written as

$$W_\omega = \Delta W/\Delta\omega \qquad (10)$$

The expression (10), is detailed as

$$W_\omega = W_2 - W_1/\omega_2 - \omega_1 \qquad (11)$$

Where

$\Delta\omega$ = Change in the two weight losses ω_2, ω_1

Similarly, a plot of points (2.48, 2.1802) & (9.23, 3.1097), (2.48, 2.005) & (9.23, 3.0466) and (2.48,2.0349) & (9.23, 2.9968) as in Figure 4, designating them as (ε_1, W_1) and (ε_2, W_2) for experimental, model and regression-predicted results, and then substituting them into the expression (11), also gives the slopes: 0.1377, 0.1543 and 0.1425 (mm^3 /Nm)/mg as their respective specific wear rate of glass fibre-epoxy resin composite per unit weight loss.

Conclusion

The specific wear rate of glass fibre reinforced epoxy resin while sliding under dry medium has been evaluated based on the weight loss (of the composite while sliding) and applied load. The predictive analysis was carried out using a derived empirical model; $W = N(e^{b\omega} + e^{\beta\varepsilon}) - K$, whose validity was rooted on the core model structure; $W + K \approx N(e^{b\omega} + e^{\beta\varepsilon})$, considering that both sides of the structure are correspondingly almost equal. Evaluated correlations from derived model and experimental results, between the specific wear rate and applied load & weight loss are 0.9988 & 0.9270 and 0.9980 and 0.9625 respectively. The overall standard error, associating prediction of specific wear rate of the composite, is 0.11%, for every change in the applied load and composite weight loss. This gives a model confidence level above 99%. The specific wear rate of the composite, per unit applied load and weight loss are 0.0116, 0.0130 & 0.0120 mm^3 /N^2m and 0.1377, 0.1543 & 0.1425 (mm^3 /Nm)/mg respectively. Overall maximum deviation of the model-predicted specific wear rate from experimental results was 8.04%. The derived model will predict the specific wear rate of the composite, within the experimental results range, on substituting into the model, values of the applied load on the composite and its corresponding weight loss, providing the boundary conditions are considered.

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