Kufa Journal of Engineering
Vol. 10, No. 1, January 2019, P.P. 140-159
Received 14 December 2018, accepted 13 January 2019

PARAMETRIC RATIO OPTIMIZATION AND STATISTICAL MODELLLNG OF WEAR PERFORMANCE IN DUAL-FILLER PARTICLE REINFORCED EPOXY COMPOSITES

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http://dx.doi.org/10.30572/2018/kje/100111

ABSTRACT

Despite the potentials of dual reinforced particulate polymer composites to produce outstanding composite with enhanced wear properties, scholars have devoted insignificant attention to them. This paper introduces five diverse epoxy composites prepared in dual reinforcement blends. Using a mixed design L16 orthogonal array, Taguchi's parametric optimization was conducted with some ratios between the wear parameters as a novel way of revealing the influence of their interrelatedness in the optimization process while the statistical modelling of the wear responses was pursued. Analysis of variance was also conducted as well as regression analysis. With experimental tests on the DIN abrasion tester, the (10OPP,15CSP)% composite obtained an optimal parametric setting of A1B2-3C3D1E4. The (10PKSP,15CSP), (10PSp,15ESP), (10OPP,15PSP) and (5PKSP,20ESP)% composites obtained optimal parameter settings of A3B2C3D3E2, A3B1-3,C3D1E4, A3B2C2D1E4 and A3B2C4D3E3, respectively. The correlation plots between the experimental and predicted values of the wear process and determination coefficient indicate a high level of accuracy of the models in predicting the wear behaviour of the composites.

KEYWORDS: Epoxy composites, wear, Taguchi, ANOVA, regression.

1. INTRODUCTION

A most fascinating part of the extant literature on polymers fortifiers and polymer composites is that blending two reinforcements in polymer composite development often yields outstanding mechanical and physical properties in engineering structural and component design and development (Ajibade et al., 2018; Benyahia et al., 2018; Senthilkumar et al., 2018; Yang et al., 2018; Liu et al., 2019). This outcome has created an array of substantial understanding into the composite development area, and an easy insight into the prediction of the life-cycle cost of composites at the development stage (Ahmed and Tsavdaridis, 2018; Rodríguez et al., 2018; Bernardo et al., 2016; Ilg et al., 2018). Still an essential aspect, this literature till date has offered merely a partial documentation of a selected few particulate fortifiers for polymer composites; it neglects a broad array of useful polymer particulate fortifiers such as coconut shells, orange shells, palm kernel shells, among others. The literature has also almost completely neglected the performance of such mixed fortifiers under wear conditions. The current paper is motivated to tackle this literature gap.

In this research, the concept of dual blending of particulate fortifiers for use in polymer composites in conceived by first mixing the particulates of the following fortifiers in pairs for a volume ratio ranging from 0 to 25%: coconut shells, periwinkle shells, palm kernel shells, egg shell and orange peels. The outcome of this experiment is then used as an input in conducting wear experiments. Taguchi's method is then proposed to optimise the process. Furthermore, the wear rate and co-efficient of friction are modelled from the perspective of multiple regression in terms of influential parameters.

Blending of composite fortifiers could be defined as actions taken to mix at least two fortifiers of different properties to obtain a mixture that contains the properties of the individual substance. Existing studies have converged predominantly on the inquiry related to the manner in which single reinforcements in polymer composites could be enhanced (Panchal et al., 2017, 2018; Panchal et al., 2017; Prakash et al, 2017; Gulhane et al., 2017). The composite community understands less concerning how dual mixed particulate polymer composites of orange peels, coconut shell, periwinkle shells, palm kernel shells and egg shells behave under wear conditions. A few researchers have tackled the blends of coconut shells and orange peels only for water absorption process and also in the absence of epoxy resins to form composites (Ajibade et al., 2017). Research on metal matrix composites reveal that dual mixing of fortifiers has enhanced the mechanical and wear properties of composites in the metallic group (Dwivedi et al., 2016). Arising from the review of the literature is also the gap that optimisation of the blends of reinforcements in polymer composites has not been done. As this study will show, nevertheless, that the dual blending of a selected group of reinforced polymer composites needs to be seriously pursued for competitive composite manufacturing cost, avoidance of wasteful health costs and meeting up with the ever-changing needs of the customer.

To achieve this paper's objective, there is a requirement for a production method, which is defined as the top down approach for the current experiment. There is also a requirement for a wear test rig wherein factors of wear rate, coefficient of friction, sliding speed, load and time will be considered. The third requirement is the need to optimise the wear process through the robust Taguchi method. These are crucial to achieve robust results for the framework presented. Thus, the unique argument made in this report are: (1) the top-down production method provides a cheap and easy to understand approach to the development of dual blended reinforced polymer composites and its economic advantage needs to be appreciated for the most profibable production method for the current blending of reinforcements and polymer composite development. Secondly since wastes concerning the reinforcements used are abundant at sources, it is envisaged that using these material for frictional applications is promising. The literature supports this argument as existing studies have been carried out on some of these reinforcements for frictional applications in brake pads (e.g., periwinkle-rooted brakepads). By developing this idea of brakepad manufacture with the proposed new materials. More profitable and customer friendly brake pad could be made. Third, sub-optimal results need to be abandoned while the most advantageous values of parameters should be embraced. This is achievable with the use of Taguchi method deployed in the current research.

By positing the above arguments, this paper makes a number of interesting contributions to the composite reinforcement literature and the polymer composite literature. First, the paper offers a production method (top-down) that utilises blends of particulates in pairs, concerning particulate orange peels, coconut shells, periwinkle shells, egg shells and palm kernel shells. The method extends beyond the existing production method of single reinforcement applications in composite development. Second, given that there is a huge array of applications of this composite in the automotive sector, the paper focuses on brakepad as the potential application for the work. Based on this, wear process, which is the most crucial procedure for brake pad testing is explored and documented for the first time concerning the paired reinforcements concerning the aforementioned particulates. This draws the attention of the composite community to the important wear parameters for the sliding distance, time, and sliding speed with the corresponding volume fraction of reinforcements in composites. Third, this research contributes a predictive approach to the evaluation of the wear rate and the coefficient of friction for the new composites. An interactive multiple regression models in which certain independent variables are regressed upon by the dependent variables of wear rates and coefficient of friction is proposed. Fourth, a new way of optimising the dual reinforced polymer composite is presented through the robust Taguchi methodical route for the attainment of the most advantageous parametric values may be you should write it in full.

2. METHODOLOGY

2.1. Materials

Epoxy resin (LY 556) and amine hardener (HY 951) were used as the primary and secondary matrices respectively, in the composite being developed. Both materials were procured from Tony Nigeria Enterprises Ltd, a chemical marketing company in Ojota, Lagos, Nigeria. The reinforcement used in this investigation are agro-waste materials namely, coconut shells, periwinkle shells, palm kernel shells, egg shell and orange peels were sourced from retailers in Akoka, Bariga and Oyingbo market areas of Lagos. The agro-waste materials were cleaned and dried carefully to remove dirt and impurities. Both materials were allowed to dry completely to remove moisture. Each material was pulverized to smaller particles before they were grinded in a diesel powered grinding mill (SWSST, Germany) for 12 passes until fine particulate form was achieved. Sieve analysis was carried out with a British standard test sieve (ELE International laboratory test sieve) through an electric power shaker (Impact Auto Sieve Shaker) for an average time of 20 minutes. The 75 µm (0.075 mm) particles were retained for use in the current investigation.

2.2. Composite preparation

Epoxy resin and amine hardener were combined in the ratio 1:0.4. The mixture was stirred continuously until uniformity was attained. The reinforcement particles combined according to formulations described in Table 1 to give 25 wt. % of a measured mass of epoxy resin system. The matrix and reinforcement particles were added and stirred carefully to avoid the entrapment of air bubbles which leads to formation of pores and gaps until homogeneity was achieved. The gelatinous mixture was poured into a prepared aluminium mould coated with engine oil for ease of removal of the composite specimen. The composite was allowed to cure at room temperature conditions for a period of 24 hours before removal. They were post cured in an electric oven at 100^{o}C for a holding time of 4 hours.

2.3. Wear test

The ($10OP_P$, $15CS_P$), ($10PK_P$, $15CS_P$), ($10PS_P$, $15ES_P$), ($10OP_P$, $15PS_P$), (5PK, $20ES_P$) % composites were selected from each composite formulation based on their optimal performance in different mechanical tests. Dry sliding wear tests were performed according to ASTM G-99 standards for polymer samples using the pin-on-ring set up (Halling, 1976; Ameen et al., 2011). The pin-on-ring set up is described schematically in Fig. 1. The cylindrical disc of the machine was smoothed adequately before attaching an abrasive paper of P-60 grit size with the aid of an adhesive.

Table 1. Details of the composite samples.

Composite designation	Epoxy (wt%)	OPp (wt%)	CSp (wt%)	PSp (wt%)	PKSp (wt%)	ESp (wt%)	Density (g/cm^3)	Hardness (HV)
(10OPP,15CSP)	75	10	15	-	-	-	1.15	20.7
(10PK,15CSP)	75	-	15	-	10	-	1.29	24.87

Table 1 (cont'd). Details of the composite samples

Composite designation	Epoxy (wt%)	OPp (wt%)	CSp (wt%)	PSp (wt%)	PKSp (wt%)	ESp (wt%)	Density (g/cm3)	Hardness (HV)
(10PSP,15ESP)	75	-	-	10	-	15	1.16	21.4
(10OPP,15PSP)	75	10	-	15	-	-	1.16	21.87
(5PK,20ESP)	75	-	-	-	5	20	1.14	23.03

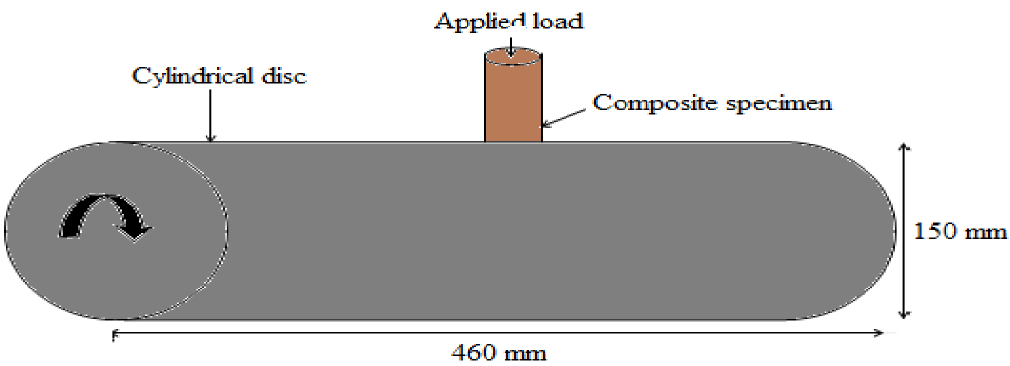


Fig. 1. Schematic diagram of pin-on-ring set up.

Wear of the composites were measured in terms of weight loss with the aid of a high precision weighing device (LN Tuning-fork balances, .01mg accuracy). Weight loss of the wear specimen was converted into volume loss using the calculated densities of the composites. The specific wear rate (W_r) of the specimen is obtained mathematically as

$$W_R = \frac{\Delta V}{A_L \times S_D} \quad 1$$

where ΔV is the volume loss in mm^3, A_L is the applied load in Newton, N and S_D is the sliding distance in metres, *m*. During the wear test, the momentum of each wear specimen was calculated according to Newton's 2nd law while the tangential frictional force was obtained as per Newton's 3rd law. Thus, the coefficient of friction (COF) was calculated by dividing tangential frictional by the applied load as follows

$$\text{COF } (\mu) = \text{Tangential frictional force/ Applied force} \quad 2$$

2.4. Taguchi method

The optimisation process of the current investigation is carried out using the Taguchi method. The main advantage of the Taguchi method is in its ability to test more than one factor at a time with their respective levels in a single experiment. The parameters of the experiment are known as factors while the conditions or measurements describing the factors are termed as levels. The Taguchi method uses a statistical measurement called the signal-to-noise ratio, which is described as the ratio between the average (signal) to the standard deviation (noise) (Zareh et al., 2013). This serves as the objective function of the desired output. The S/N ratio is computed based on the desired quality characteristics of the optimisation process. These quality characteristics are known as "the smaller-the-better" (SB), "the larger-the-better" (LB), and "the nominal-the-best" (NB). In the current investigation, minimum wear rate of the composites is desired in the parametric optimisation of the dual-filler composites. Therefore, the S/N ratio of the SB is chosen for the optimisation as defined in Eq. 1.

$$S/N = -10\text{Log } {}^{1}/n \left(\sum y_j^{\,2} \right) \quad 3$$

where y_j is the value of the smaller-the-better quality characteristic and n is the number of tests in each experimental trial. Multiple regression analysis was used to develop models describing the relationship between the wear rate, COF and parameters for each of the composites. Table 2 shows the parameters with details of their levels while Table 3 reveals the parametric ratios and their levels.

Table 2. Parameters and their levels.

Levels	(10OP,15CSP)% Epoxy composite				
	A: Time (s)	**B: Sliding distance (m)**	**C: Load (N)**	**D: Mass (m)**	**E: Diameter (m)**
1	60	18.84	5	1.98	8
2	120	37.68	7.5	2.51	10
3	180	56.52	10	2.54	12
4	240	75.36	15	3.14	15.5
(10PK,15CSP)% Epoxy composite					
1	60	18.84	5	2.01	8
2	120	37.68	7.5	2.2	10
3	180	56.52	10	2.46	12
4	240	75.36	15	2.8	15.5
(10PSP,15ESP)% Epoxy composite					
1	60	18.84	5	1.98	8
2	120	37.68	7.5	2.51	10
3	180	56.52	10	2.54	12
4	240	75.36	15	3.11	15.5
(10PP,15PSP)% Epoxy composite					
1	60	18.84	5	1.95	8
2	120	37.68	7.5	2.28	10
3	180	56.52	10	2.45	12
4	240	75.36	15	3.11	15.5
(5PK,20ESP)% Epoxy composite					
1	60	18.84	5	2.09	8
2	120	37.68	7.5	2.47	10
3	180	56.52	10	2.85	12
4	240	75.36	15	3.16	15.5

The use of the interaction plots has been used effectively in Taguchi optimization to understand how parameters interrelate as they influence the target quality characteristic (Sudheer, *et al.*, 2013; Sahoo, *et al.*, 2013). This investigation introduces a novel parametric ratio relationship between the parameters of the wear process. The ratio establishes an unconventional mathematical relationship between the different parametric quantities while the combination that would contribute optimally to minimal wear process is determined using the Taguchi method. In Table 4, the mixed orthogonal array is shown. Fig. 3 shows the research scheme for this investigation.

Table 3. Parametric ratios and their levels.

Levels	A: Load/speed	B: Time/speed	C: Dist/speed	D: Load/mass	E: Mass/Dia
	Parametric ratios for (10OPp,15CSp)% Epoxy composite				
1	0.0833	0.0052	0.0167	2.5253	0.2475
2	0.0625	0.0026	0.0083	2.9880	0.2510
3	0.0556	0.0017	0.0056	3.9370	0.2117
4	0.0625	0.0013	0.0042	4.7771	0.2026
Parametric ratios for (10PKSp,15CSp)% Epoxy composite					
1	0.0833	0.0052	0.0167	2.4876	0.2513
2	0.0625	0.0026	0.0083	3.4091	0.2200
3	0.0556	0.0017	0.0056	4.0650	0.2050
4	0.0625	0.0013	0.0042	5.3571	0.1806

Table 3. (cont'd). Parameric ratios and their levels.

Levels	A: Load/speed	B: Time/speed	C: Dist/speed	D: Load/mass	E: Mass/Dia
	Parametric ratios for (10PSp,15ESp)% Epoxy composite				
1	0.0833	0.0052	0.0167	2.5253	0.2475
2	0.0625	0.0026	0.0083	2.9880	0.2510
3	0.0556	0.0017	0.0056	3.9370	0.2117
4	0.0625	0.0013	0.0042	4.8232	0.2006
	Parametric ratios for (10OPp,15PSp)% Epoxy composite				
1	0.0833	0.0052	0.0167	2.5641	0.2438
2	0.0625	0.0026	0.0083	3.2895	0.2280
3	0.0556	0.0017	0.0056	4.0816	0.2042
4	0.0625	0.0013	0.0042	4.8232	0.2006
	Parametric ratios for (5PKSp,20ESp)% Epoxy composite				
1	0.0833	0.0052	0.0167	2.3923	0.2613
2	0.0625	0.0026	0.0083	3.0364	0.2470
3	0.0556	0.0017	0.0056	3.5088	0.2375
4	0.0625	0.0013	0.0042	4.7468	0.2039

Table 4. L1645 Orthogonal array experimental design lay out

S/No	A	B	C	D	E	S/No	A	B	C	D	E
1	1	1	1	1	1	9	3	1	3	4	2
2	1	2	2	2	2	10	3	2	4	3	1
3	1	3	3	3	3	11	3	3	1	2	4
4	1	4	4	4	4	12	3	4	2	1	3
5	2	1	2	3	4	13	4	1	4	2	3
6	2	2	1	4	3	14	4	2	3	1	4
7	2	3	4	1	2	15	4	3	2	4	1
8	2	4	3	2	1	16	4	4	1	3	2

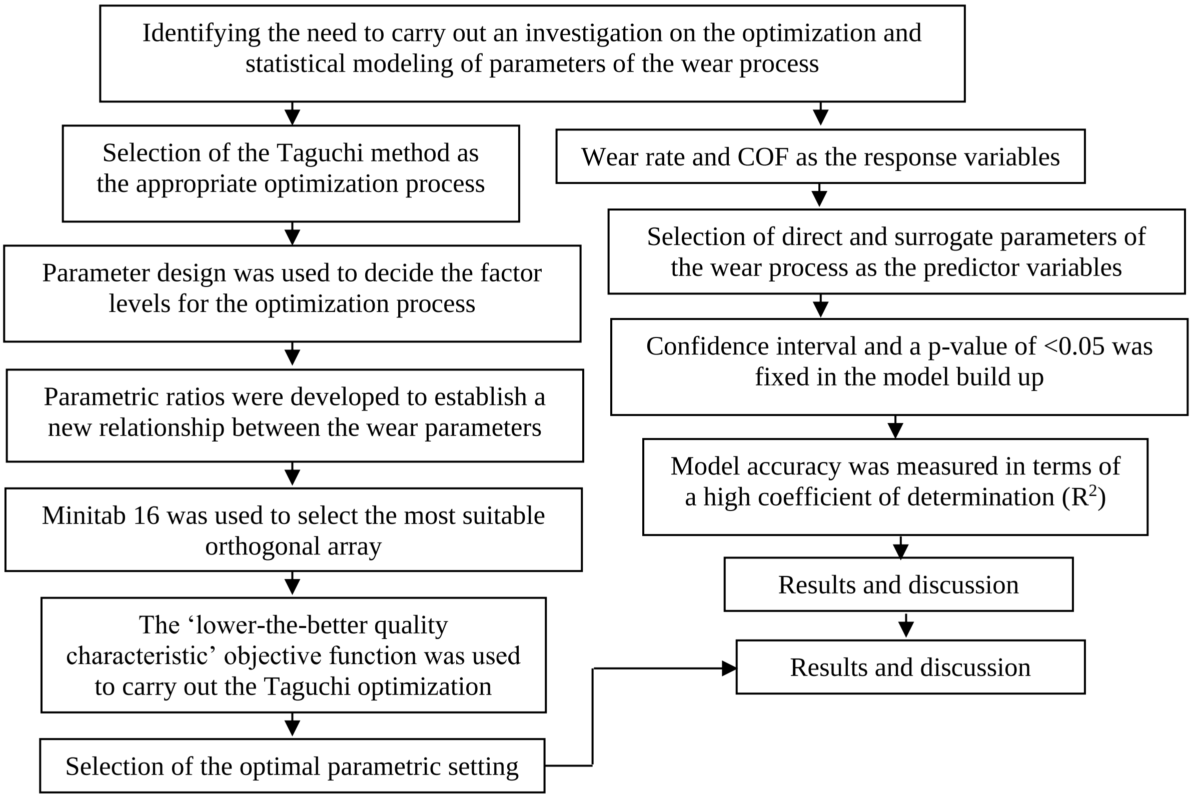


Fig. 2. Research scheme for the investigation.

3. RESULTS AND DISCUSSION

3.1. The Optimal parametric ratio setting

The experimental design for the (10OPp,15CSp)% composite with the use of L16 orthogonal array is shown in Table 5. The optimal parametric ratio setting that gives the minimum wear rate in each of the (10OPp,15CSp)% composite is obtained from the S/N ratios response as described in Table 6, while the main effect plots which shows the impact on each parameter on the wear rate measured in terms of the mean S/N ratio is described in Fig. 3. A parameter which has a steep slope can be said to have a larger influence on the wear rate while a parameter with a gentle slope can be said to exert lesser influence on the wear rate of the composite (Sudheer et al., 2013; Ghosh et al., 2013). In other words, the variability of the wear rate as it is being influenced by the parametric ratios is described in Fig. 3.

Table 5. Experimental design for (10OPp,15CSp)% composite using L16 Orthogonal array.

S/No	Load: speed	Time: Speed	Dist: speed	Load: mass	Mass: Dia	Wear rate (mm^3/Nm)	S/N Ratio
1	0.0833	0.0052	0.0167	2.5253	0.2475	0.74	-1.1030
2	0.0833	0.0026	0.0083	2.988	0.2510	0.55	-2.5518
3	0.0833	0.0017	0.0056	5.9055	0.2117	0.49	-8.4419
4	0.0833	0.0013	0.0042	4.7771	0.2026	0.58	-6.6027
5	0.0625	0.0052	0.0083	5.9055	0.2026	1.65	-1.1041
6	0.0625	0.0026	0.0167	4.7771	0.2117	1.22	-2.5510
7	0.0625	0.0017	0.0042	2.5253	0.2510	0.82	-8.4414
8	0.0625	0.0013	0.0056	2.988	0.2475	0.73	-6.6034
9	0.0556	0.0052	0.0056	4.7771	0.2510	1.05	-2.5432
10	0.0556	0.0026	0.0042	5.9055	0.2475	0.69	-1.0892
11	0.0556	0.0017	0.0167	2.988	0.2026	0.53	-6.6066
12	0.0556	0.0013	0.0083	2.5253	0.2117	0.48	-8.4441
13	0.0625	0.0052	0.0042	2.988	0.2117	1.02	-2.5413
14	0.0625	0.0026	0.0056	2.5253	0.2026	1.06	-1.0917
15	0.0625	0.0017	0.0083	4.7771	0.2475	0.99	-6.6069
16	0.0625	0.0013	0.0167	5.9055	0.2510	1.25	-8.4439

Table 6. S/N ratios response for (10OP,15CSP)% composite.

Level	Load: speed	Time: speed	Dist: speed	Load: mass	Mass: Dia
1	-4.6748	-4.6729	-4.6723	-1.0953	-4.6755
2	-4.6738	-4.6713	-4.6720	-2.5456	-4.6759
3	-4.6695	-4.6723	-4.6712	-8.4425	-4.6689
4	-4.6696	-4.6713	-4.6724	-3.3022	-4.6676
Delta	0.0053	0.0016	0.0012	7.347272	0.0083
Rank	3	4	5	1	2

The optimal parametric setting for the (10OPp,15CSp)% was obtained as $A_1B_{2\text{-}3}C_3D_1E_4$, which can be read as load:speed of 0.0833, time:speed of 0.0026-0.0017, distance:speed of 0.0056, load:mass of 2.5253 and a mass:diameter of 0.2026.

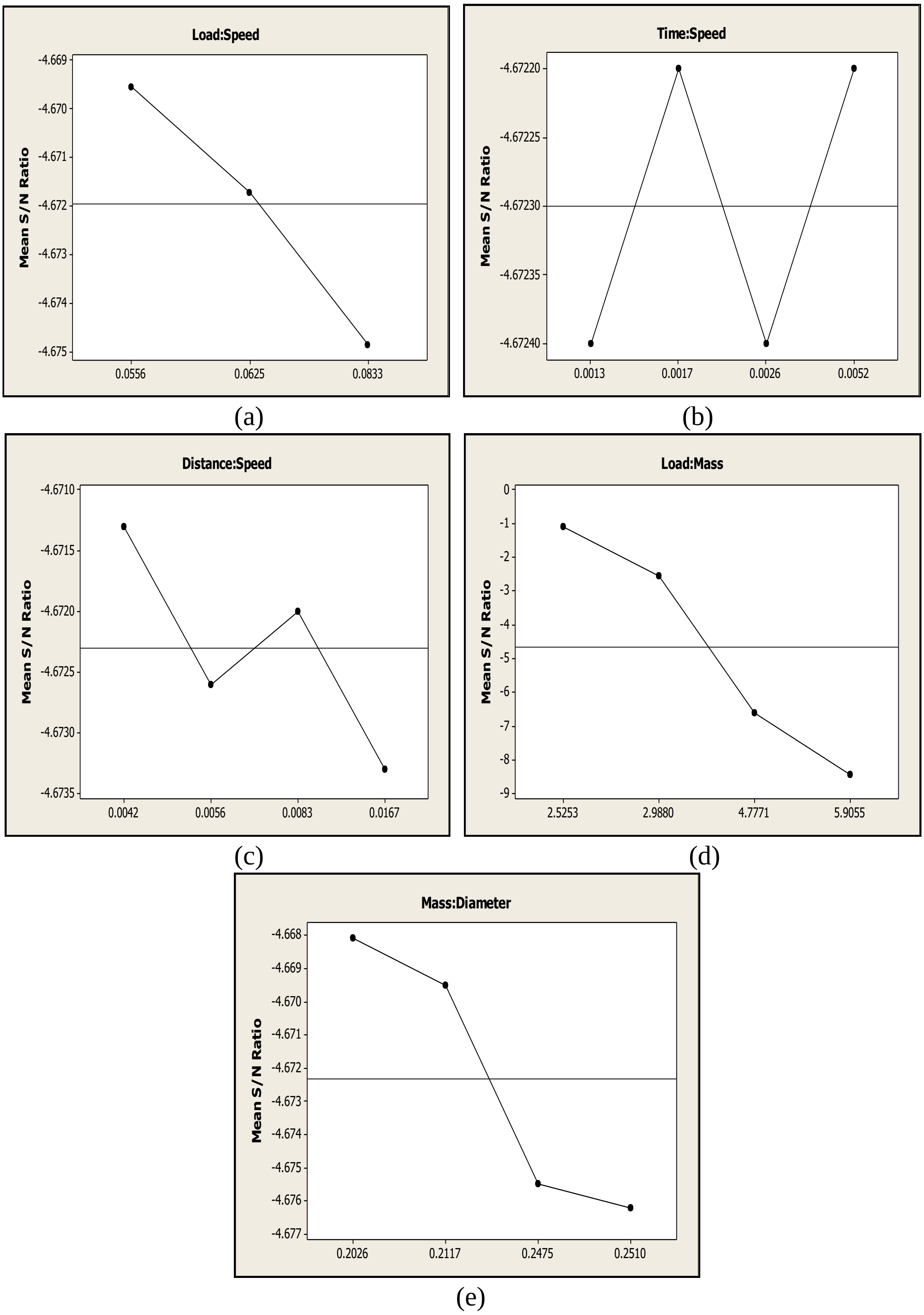


Fig. 3. Main effect plots for (10OPp,15CSp)% composite parametric ratios (a) load:speed, (b) time:speed, (c) distance:speed, (d) load:mass, (e) mass:diameter.

By following the same mathematical procedure observed for the (10OP,15CSP)% composite using L_{16} orthogonal array (Table 5) and the computation performed for the S/N ratios response for (10OP,15CSP)% composite, the results for the next four combinations are summarized as follows:

- For the (10PKSp,15CSp)% composite, the optimal parameter setting was found as $A_3B_2C_3D_3E_2$. This translates to a load:speed of 0.0556, time:speed of 0.0026, distance:speed of 0.0056, load:mass of 4.065 and a mass:diameter of 0.22
- The (10PSp,15ESp)% composite has an optimal parametric setting of ($A_3B_{1\text{-}3}$,$C_3D_1E_4$) which can be interpreted as load:speed of 0.0556, time:speed of 0.0052-0.0017, distance:speed of 0.0056, load:mass of 2.5253 and mass:diameter of 0.2006.
- The (10OPp,15PSp)% composite has an optimal parametric setting of $A_3B_2C_2D_1E_4$ which can be described as load:speed of 0.0556, time:speed 0f 0.0026, distance:speed of 0.0083, load:mass of 2.5641 and a mass:diameter of 0.2006.
- Lastly, the (5PKSp,20ESp)% composite was also found to have an optimal parameter setting of $A_3B_2C_4D_3E_3$ which reads as load:speed of 0.0556, time:speed of 0.0026, distance:speed of 0.0042, load:mass of 3.5088 and mass:diameter of 0.2375.

3.2. Multiple regression models

Multiple regression analysis was used to establish the relationship between the direct parameters in close association with the wear process: (time (T); sliding distance (SD); load (L); mass of sample (M) and diameter (D) as well as the surrogate parameters which are involved in the cause of the wear process: volume loss (VL), momentum (MM), frictional force (FF) with each of the output responses of wear rate and coefficient of friction (COF) of the composites, respectively. Consequently, each of the regression models was fitted to the wear rate and coefficient of friction of the composites. The accuracy of the models has been checked using the coefficient of determination (R^2) which showed good acceptance due to the high level of R^2 (Neseli et al., 2011; Sahoo et al., 2013). The high coefficient of determination indicates goodness of fit and significance of the model.

(1a) Specific wear rate (mm3/N-m) of (10OPp,15CSp)% composite, we have:

$$WR = 1.71 - 0.12M + 0.00274VL - 0.18WL + 0.0042FF - 0.026MM - 0.0068T + 0.0038D - 0.082L \quad 4$$

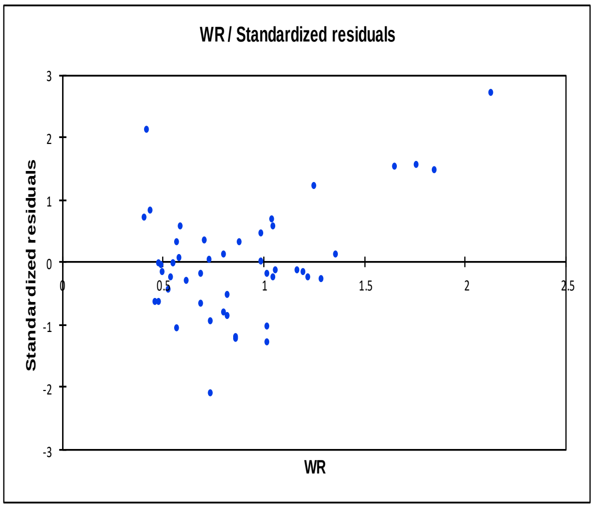
$$R^2 = 80.6\ \%$$

A mathematical model describing the relationship between the wear rate and wear parameters of the (10OPp,15CSp)% composite is described in Eq. 4. Wear rate was fitted as the response/dependent variable while the identified parameters were adjusted as the predictor/independent variable. A confidence level and P value of < 0.05 was fixed in the model development. This produced an F value of 20.21 shows that the possibility of noise occurring in the response variable is negligible, which is in accordance with the literature (Atuanya, et al., a,b; Agunsoye et al., 2017). The p-value (0.0001) <0.05 indicates that the variables used in developing the model were significant to the prediction of the wear rate. The eight degrees of freedom (DF) recognized by the ANOVA table (Table 7) shows that eight matrices were resolved to predict the response variable. The accuracy of the model in predicting the wear rate of the composite was understood in terms of a high coefficient of determination (R^2) which was obtained as 0.806. The R^2 value of 0.806 indicates that 80.6 % of the response variable can be adequately explained by the model, while the remaining 19.4 % represents the residuals between the observed and predicted responses of the wear rate in Fig. 4a and b. The experimental and predicted values of the wear rate exhibited very good correlation as seen in Fig. 4c From Eq. 4, the frictional force was found to have the highest effect on the wear rate of the composite, followed by the diameter of the specimen, and volume loss. Weight loss was discovered to have the lowest effect on the wear rate followed by mass, momentum, time and applied load. The positive coefficient of the wear rate model indicates that the wear rate of the (10OPp,15CSp)% composite rises with increase in the associated variables.

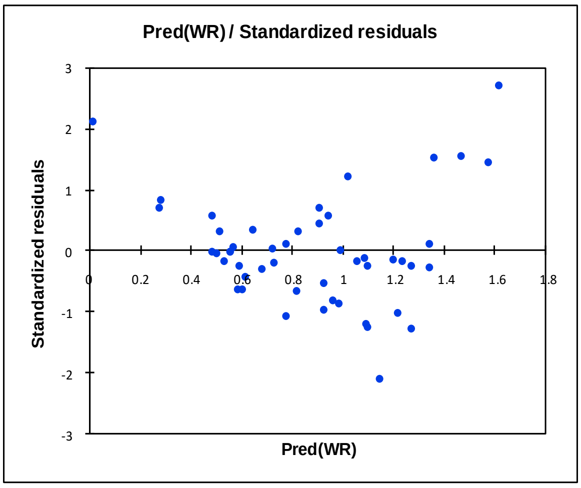
Table 7. Analysis of variance (WR).

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	8	5.873	0.734	20.211	< 0.0001
Error	39	1.417	0.036		
Corrected Total	47	7.289			

Computed against model Y=Mean(Y)



(a)



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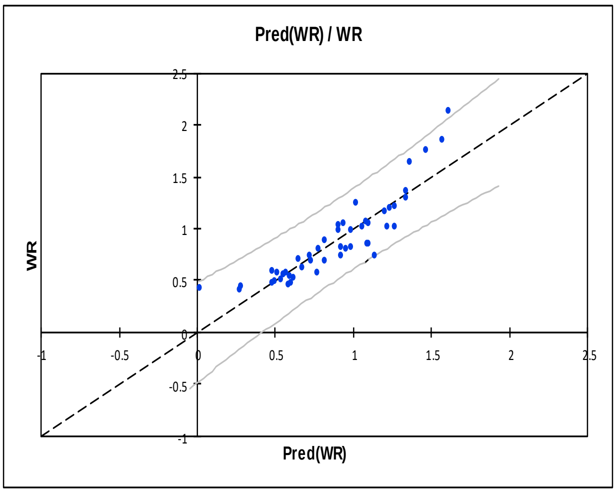

(c)

Fig. 4. (a) Experimental, (b) predicted and (c) correlation plots between experimental and predicted plots for wear rate of (10OPp,15CSp)% composite.

(1b) COF of (10OPp,15CSp)% composite, we have:

$$COF = 0.93 - 0.014M + 0.000044VL - 0.0021WL + 0.000073FF - 0.096MM - 0.000066T - 0.00019D + 0.0083L \tag{5}$$

$$R^2 = 92.6\ \%$$

The relationship describing the relationship between the COF and wear parameters of the (10OPp,15CSp)% composite is modelled in Eq. 4. The COF was adjusted as the response/dependent variable while the identified parameters were fixed as the predictor/independent variable. The model was developed based on a confidence level and P value of < 0.05 which resulted in an F value of 61.3. This signifies a higher probability of noise occurring in the response variable of the COF model over that of the wear rate model which was observed as 20.21. The *p*-value (0.0001) <0.05 indicates that the variables used in developing the model were meaningful and relevant to the prediction of the COF. The eight degrees of freedom (DF) recognized by the ANOVA table in Table 8 reveals that eight matrices were answered to predict the response variable. The correctness of the model in predicting the COF of the composite was understood in terms of a high coefficient of determination (R^2) which was obtained as 0.926. The R^2 value of 0.926 indicates that 92.6 % of the response variable can be adequately explained by the model, while the difference of 7.4 % represents the residuals between the observed and predicted responses of the wear rate in Fig. 5a and b. A high level of accuracy was achieved by the model in predicting the wear rate of the composite with a large number of observations clustering around the true regression line as observed in Fig. 5c. From Eq. 5, load was observed to give the highest contribution to the COF model, followed by the diameter of the specimen, frictional force and volume loss, while mass, momentum, time had the lowest significance on the COF model respectively. Again, the positive coefficient of the model shows the COF of the composite improves with increase in the associated variables. The correlation between the experimental and predicted results is explained graphically in Fig. 5c. this figure shows the higher effectiveness of the COF regression model over the wear rate model of the (10OPp,15CSp)% with a greater percentage of the observations revolving around the true regression line. This agrees with the fact the COF have a higher R^2 value over the wear rate.

Table 8. Analysis of variance (COF).

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	8	0.097	0.012	61.304	< 0.0001
Error	39	0.008	0.000		
Corrected Total	47	0.105			

Computed against model Y=Mean(Y)

A similar procedure used for computation of the wear rate and COF models of the (10OPp,15CSp)% composite was replicated in analyzing the other composites, namely (10PKSp,15CSp), (10PSp,15ESp)%,, (10OPp,15PSp) and (5PKSp,20ESp)%. The results are shown as follows:

1. (10PKSp,15CSp)% composite outcome:

The specific wear rate (mm3/N-m) and COF of (10PK,15CSP)% composite:

$$WR = 0.12 - 0.61M + 0.0027VL - 0.0095FF + 3.67MM - 0.0028T + 0.0067D - 0.057L \quad 6$$
$$R^2 = 82.9\ \%$$

$$COF = 0.93 + 0.092M + 0.00017VL - 0.00083FF - 0.36MM - 0.000036T - 0.006D + 0.0074L \quad 7$$

$R^2 = 92.1$ %

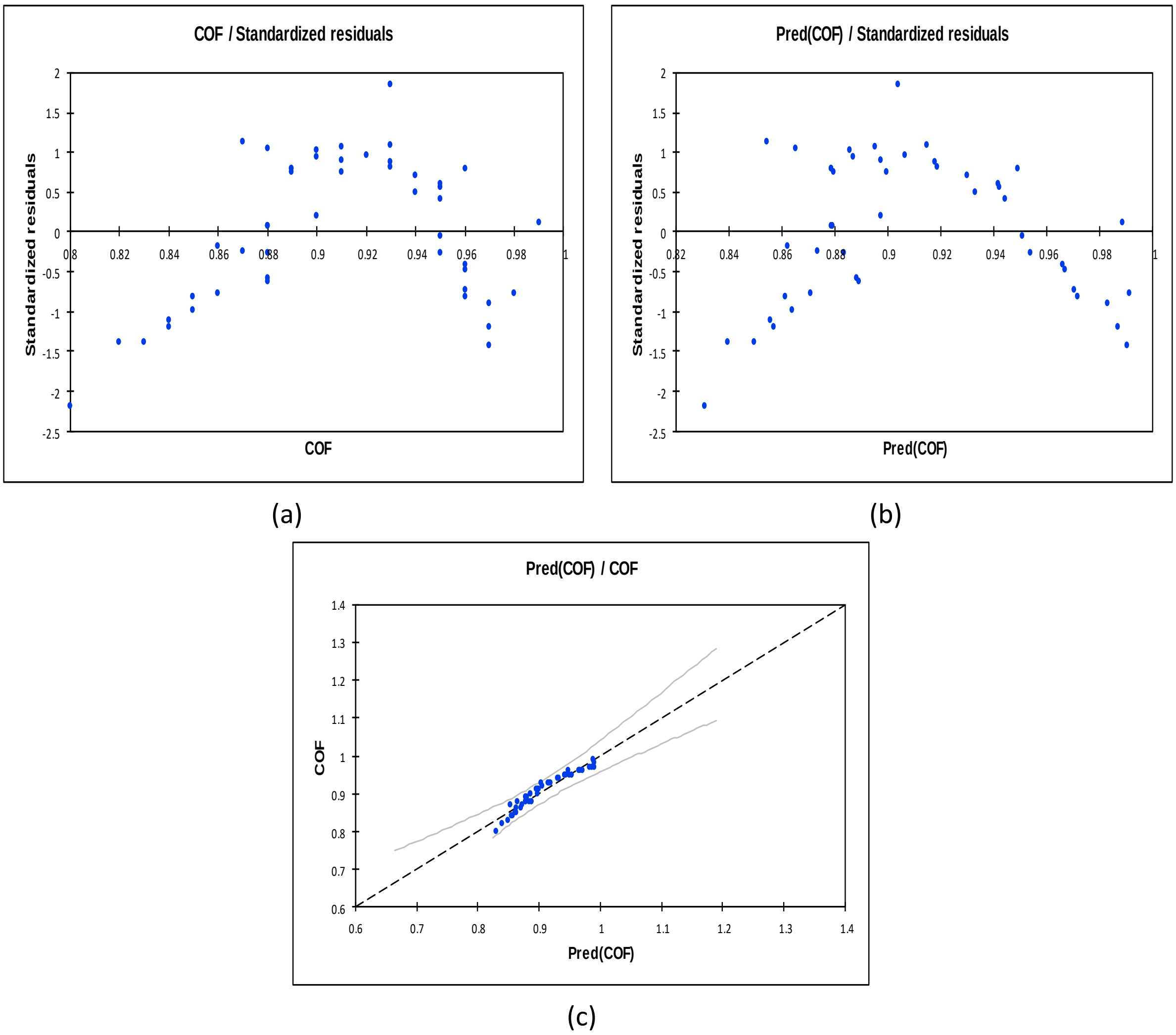

Fig. 5. (a) Experimental, (b) predicted and (c) correlation plots between experimental and predicted plots for COF of (10OPp,15CSp)% composite.

2. (10PSp, 15ESp) % composite outcome:

The specific wear rate (mm3/N-m) and COF of (10PSP, 15ESP) % composite:

$$WR = 1.64 - 4.68M + 0.0023VL - 0.0075FF + 14.44MM - 0.006T + 0.03D \quad 8$$

$$R^2 = 66.5 \%$$

$$COF = 0.94 + 0.17M + 0.00014VL + 0.0075FF - 0.71MM - 0.00019T - 0.000071D \quad 9$$

$$R^2 = 92 \%$$

3. (10OPp, 15PSp) % composite outcome:

The specific wear rate (mm3/N-m) and COF of (10OPP, 15PSP) % composite:

$$WR = 2.9 - 5.19M + 0.0012VL - 0.0078FF + 14.98MM - 0.0088T + 0.14D \quad 10$$

$$R^2 = 85.5\ \%$$

$$COF = 0.9 + 0.08M + 0.00037VL + 0.0044FF – 0.31MM – 0.00012T – 0.0095D \quad 11$$

$$R^2 = 92.7\ \%$$

4. (5PKSp,20CSp)% composite outcome:

The specific wear rate (mm3/N-m) and COF of (5PK,20CSP)% composite, we have:

$$WR = 2.92 – 7.25M + 0.00086VL – 0.13FF – 23.45MM – 0.01T + 0.11D \quad 12$$

$$R^2 = 87.7\ \%$$

$$COF = 0.94 – 0.23M + 0.000021VL + 0.007FF + 0.63MM + 0.0000026T – 0.0024D \quad 13$$

$$R^2 = 89.1\ \%$$

4. CONCLUSION

In this work, a systematic investigation was carried out into the development of new ratios from wear parameters as factors in the Taguchi optimisation scheme. The parametric optimisation of the wear performance of five dual-filler particulate epoxy composites was made. Statistical modelling was performed on the wear rate and COF for predictive purposes. The conclusions from the study are highlighted as follows:

1. The parametric wear ratio relationships exist and they influence the optimisation of the wear behaviour of the composites differently using the parameters of Taguchi method.
2. Direct and surrogate parameters offered holistic and adequate information for predictive purposes.
3. Multiple regression models revealed good relationship between the output responses of wear process and direct parameters.
4. The multiple regression models showed high goodness of fit, high coefficient of determination (R^2) and strong relationship between the experimental and predicted values.

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