A wear rate model incorporating inflationary cost of agro-waste filled composites for brake pad applications to lower composite cost

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Abstract

Wear rate appraisals are currently indispensable on agro-waste filled composites for brake pads as they predict the expected lifespan of the materials. However, existing wear rate models are inaccurate as predictions omit the inflationary cost of the materials. In this paper, the idea is to account for the inflationary cost of the materials and adjust that into a pseudo wear rate model. The wear rate of agro-waste fillers in an organic matrix to create brake pads under dry sliding wear experiments was considered. Five composite specimens were fabricated in cylindrical specimen height of 14.5 mm and varying diameters of 8, 10, 12 and 15.5 mm and the material wear loss was measured. The 8, 10 and 12 mm diameter specimens revealed that the composite with the best and worst wear resistance were the wear rates of 0.6, 1.4, 1.73 mm³/Nm, and 3.07, 3.54, 4.19 mm³/Nm, respectively. The 15.5 mm diameter specimen showed lower wear rates of 2.13 and 2.14 and 1.56 mm³/Nm than commercial brake pad's 2.58 mm³/Nm. The pseudo wear rate model predicts the impact of the independent variable i.e. inflationary cost, opportunity cost, time, and sample size. The utility of this effort is to assist the composite manufacturers to take cost-effective decisions and design optimisation can be accomplished to lower the cost of composite products.

Keywords Wear rate · Wear · Economics of wear · Agricultural wastes · Composites

Abbreviations

SD	Sliding distance
IF	Inflationary factor
WR	Wear rate
COF	Coefficient of friction
OC	Opportunity cost
SWR	Specific wear rate
AL	Applied load

1 Introduction

The dominant practice of appraising the wear rate of composite materials concerns hardness, particle agglomeration, volume of reinforcement particles and the fracture toughness of composites [1–3]. Unfortunately, the

prevailing wear rate model of composite materials fails to account for the inflationary cost of composite materials [4]. But this propels cost-effective decisions and design optimization and consequently, to lower the cost of composite products [5]. This leads to an underestimation of real cost and may lead to gross inadequacy in wear rate estimations of composite materials [6–8]. But incorporating inflationary costs will offer superior and more practical picture [6]. Nowadays, this concern is more compelling than before to implement in the industry [9–11] because of the incredibly impressive accuracy expected from initiating inflationary costs into wear rate estimations in composite material. In this paper, a new wear rate model is proposed to account for the inflationary cost of composite materials and adjust that in a pseudo wear rate model.

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Consequently, this research applies the theory of inflation [6–8] to appraise and update the current knowledge on wear rate. The theory of inflation is a theoretical base which offers a method to appraise the inflationary cost of composite materials and adjust to a wear rate model by incorporating price changes. This research is substantial as it offers a structure to establish the important deficiency of inflationary costs in wear rate estimations of composite materials. Furthermore, it offers substantial details to composite researchers concerning the basic constituents of an inflationary based wear rate model and the necessary appraisal measures. Moreover, by exploiting and identifying the problem that is unattended to and weakness within the inflationary-based wear rate model domain stimulates future investigations,

This research contributes to the wear rate assessment literature by:

- highlighting assessment parameters and characteristics unclear in earlier wear rate research that could associate with enlarging the comprehension of researchers on the assessment parameters and scheme of appraisal;
- implementing the theory of inflation that can offer new reasoning and enhancement to the present ideas in appraising wear rate
- establishing research flaws of wear rate to properly position novel research pursuits

The next section details the literature survey, which widely scanned related references in the field. The methodology adopted for modelling the wear rate is discussed in Sect. 3. Section 4 highlights the results and the inferences from the study. Section 5 offers concluding remarks and ends the paper.

2 Literature review

In this section, a review is presented on brake pads in composites reinforced with agro-waste [12–14], single [15, 16], dual/multiple fillers [17]. First, an introduction to the brake pad is made [18, 19]. Brake pads are heat and energy-absorbing media attached to the discs calipers, triggered to action by a hydraulic scheme in a squeezing action on the brake pads to a rotor, thus converting kinetic into heat energy in an automobile [20, 21]. The brake pad medium, a most significant part of the automobiles braking scheme, consists of materials originally developed from organic basis (asbestos and carbon, for instance), tightly held by an effective resin [22–24]. In many brake pads, braking is instigated after a pedal is slowed down within the automobile. The squeezing action produces friction which is

connected into heat that attacks the brake pads as well as the rotor [25–27]. The friction generated finally compels the automobile to stop [28, 29].

2.1 Brake pads with agro-fillers

Fu et al. [30] prepared brake pad composite from natural materials and metals to study the influence of both compositions of treated flax fibres and frictional temperature on frictional parameters (wear rate, frictional coefficient). Maleque et al. [15] reinforced aluminium matrix with different degrees of coconut fibre contents (0, 5, 10, and 15 volume ratios) using the powder metallurgy method. Elevated density, higher compressive strength, and lower porosity of the 5 and 10% coconut fibre reinforced composite specimens were obtained. Sugözü et al. [31] experimented with ulexite and combined it with cashew to make brake pads. The results revealed that the composite exerts substantial influences on its functional strength and fade resistance. Öktem et al. [32] produced composites with 3.5 and 7% contents of hazenut and walnut dust and noted that competing friction-wear test results with the commercial-grade brake pad. Rajmohan et al. [33] formed coconut shells, sugarcane and SiC powder brake pad composite and obtained the wear rate that ranged from 3.11×10^{-6} to 4.13×10^{-6} mg/m. Akıncioğlu et al. [34] produced two groups of brake pads: one originating from boron oxide powder (6%) and the other arising from hazenut shell powder (7%) and confirmed that the wear test yielded results comparable with commercial brake pads.

2.2 Brake pads with single-fillers

Aigbodion et al. [14] studied the bagasse reinforced composite for brake pads. The average wear of 4.20 mg/m for the composite was obtained. Olumodeji [35] established the wear resistance of powdered coconut shells and palm kernel shells reinforced latex composites with cement binder. The wear volume for an hour was 1.17 gm and 2 gm for the palm kernel pad and coconut pad, respectively. Ademoh and Olabisi [36] produced maize husk filled epoxy composited and declared that the optimum abrasion resistance of 4.47×10^{-6} g/m was obtained. Idris et al. [18] developed banana peel waste composite while using phenolic resin binder. The outcome reveals that wear rate reduced with the growth in wt% of the resin. Olabisi et al. [37] analysed the wear rate for the pulverized cocoa beans shell epoxy composite and obtained the wear rate of 3.934 mg/m. Yawas et al. [38] studied the wear rate of periwinkle shell filled composite and concluded that the wear rate reduced as the corresponding powder size reduced. Ahmed et al. [39] produced brake pads using watermelon peels and revealed that 25 wt% preparation

(resin) matched the commercial counterpart. Achebe et al. [40] produced palm kernel filled epoxy composite and reported the abrasion resistance of 1.67 mg/m. The wear resistance enhanced as the palm kernel filler content increased. Akıncıoğlu et al. [41] studied the influence of braking performance on walnut shell powder composite using two classes of samples (3.5 and 7% walnut shell dust). A positive influence of the walnut shell dust composite on the frictional coefficient was established.

2.3 Brake pads with dual/multiple-fillers

Adeyemi et al. [42] intermixed three fillers (cocoa beans shell, palm kernel shells and maize husks) with an epoxy binder to obtain a composite subjected to the test of abrasion resistance. It was found that abrasion resistance reduced when the epoxy wt% increased in the preparation. Masturi et al. [43] produced organic brake canvas from two organic materials (durian fruit skin and teak leaves) reduced to powder with polyester resin and magnesium oxide additive. The wear resistance result obtained was close to the national standard by the Indonesian government. Uzochukwu et al. [44] developed brake pads with intermixed particles of cow-horn and periwinkle shells in epoxy resin and reported on their tribological characteristics. They revealed wear rates of 3.56×10^{-4} g/m and 3.7×10^{-4} g/m for composites containing 26% cow-horn/periwinkle shells, 60% epoxy resin plus hardener and the other containing 32% cow-horn/periwinkle shells and 54% epoxy resin plus hardener, respectively.

2.4 Wear mechanisms and testing machines

The scientific literature framework on the types of wear mechanisms of composite materials and the testing machines used to obtain wear results are briefly mentioned. The wear mechanism phenomenon is best understood by analysing the complicated transformation during friction. The wear mechanisms discussed in the composite literature are mainly corrosive [45], abrasive [46, 47], fatigue [48], impact, adhesive and erosive [49]. Since the focus of this paper is on brake pads which fit into the automobile sector, alternatives to the DIN abrasion tester used in this work are briefly mentioned. Kumar [50] presented a wear testing machine capable to evaluate composites subjected to rolling and sliding wear. The design presented by Allebert et al. [51] tackles drum-like objects.

The review of the literature concluded in this paper exposes interesting research gaps as follows:

1. Attaining robust appraisal concerning wear rate of composites has been the key element of discussions in modelling and experimental reports. Quantified parameters of frictional coefficient, volume fractions of reinforcements and the effects of lubricants are very crucial in wear rate estimations. However, the economic aspects that echo an understanding of the real values of wear rate were not considered in the literature.
2. The mathematical models using the regression analysis and the Archard model are broadly elaborated in the literature. Neither the earlier nor the later model has sought the incorporation of the cost elements. But the real values of wear rate may be challenging to obtain in a practical sense without this perspective. Moreso, the regulatory environment on manufacturing industries call for sustainability, which may be cost-driven. The inflationary cost viewpoint is henceforth a promising research aspect of wear rate modeling, experimentation and analysis.
3. A wide range of research on wear rate has been conducted, from polymer composites to aluminium metal matrix composites.
4. Studies have been experimental in nature as well as mathematical modelling of parameters as regression functions. The experiments include thermo-mechanical loading. Scanning electron microscopy was also used.
5. The production method has been mainly the stir casting method.
6. Interests of researchers were in hybridizing materials for enhanced wear rate but the metal matrix composites have been the major aspect of that attention.
7. Active research has been in the area of material coating where resistance to wear is highly desirable.
8. Studies have extensively exploited reinforcing metals with TiB and TiC, and TiB₂.
9. The theme of brake pads with agro-waste and single fillers have been extensively studied. However, extremely less research has been conducted on the theme of brake pads with dual/multiple fillers

From the research gaps indicated previously, it is implicit that incomplete attempts were made concerning the wear rate evaluation of agro-waste filled organic composites in brake pad applications. Furthermore, exceedingly negligible research was conducted in particular formulations involving the mixtures of particulate orange peels, coconut shells, eggshells, palm kernel shells and periwinkle shells. Subjected to some chosen parameters. Moreover, studies have been conducted with restrictions to the technical tribological parameters of hardness, wear volume, normal load and sliding distance to obtain enhanced wear rate. However, negligible research efforts were invested in the economic dimensions, viz. inflationary cost of composite materials. Consequently, in this

paper, the researchers made an effort to account for the inflationary cost of agro-waste filler organic composites and adjusted that into a pseudo wear rate model. The material used finds great utility in brake pad development.

3 Methodology

3.1 Materials

The primary matrix used in this investigation is Epoxy resin of LY 556 type and it was cured at room temperature by the addition of amine hardener HY 951 which served as a secondary matrix. Orange peels, coconut, periwinkle, palm kernel shells were collected from local retailers in Oyingbo and Akoka market areas of Lagos, Nigeria while eggshells were obtained majorly from local fast-food chains in the aforementioned areas. The orange peels were sun-dried to remove moisture, while all the materials were cleaned to remove dirt and other impurities. The different materials were pulverized before milling into particulate forms. Each of the sieved particles was passed through a British Standard test sieve (Wykeham Farrance) with the use of an electric auto shaker for a minimum of 15 min to obtain 75 µm particle size.

3.2 Specimen preparation

A 75 µm particle size of dried orange peels, coconut, periwinkle, palm kernel and eggshells were combined according to different formulations in steps of 5 to obtain 25 weight percentage of total epoxy. Epoxy resin and amine hardener were combined in a ratio 1:0.5 by weight into a homogenous whole by careful mixing. Each of the reinforcement formulations was added to the epoxy resin and the mixture was stirred continuously for 5 min until homogeneity was attained. The composite material was poured into a prepared mould and coated with a PVC release agent to ensure ease of removal of the composite. The mould was held securely with the use of G-clamps. The composites were allowed to cure at room temperature for 24 h. They were further post-cured in an electric oven at 100 °C for 4 h to improve the mechanical properties of the composites. Figure 1a shows the research scheme outlining the remaining part of the work.

In the present work, five different formulations and a control formulation, which is examples from the open market, for commercial usage is embarked upon and employed in our experimentation. From the family of formulations, only one sample is used based on directions from previous experimentation that specifically singled out the best samples according to the highest tensile values, and the corresponding specifications of samples are

chosen. The samples chosen based on maximum tensile values are as follows (Table 1): The formulations in Table 1 represent the best among the variant formulations that combine particulates from the related organic materials. Before the commencement of the experiment, a literature study was made to discover the common weight percentages by the composition of organic materials in the domain of research. It was found out that several authors have different choices for the weight composition percentages. While some authors used 25wt% for the organic materials others used 30wt% and extremely less number of authors used 40wt%. However, to avoid fabricating a brittle composite it was thought that making the composition of the fillers above 25wt% may not offer the best result. So the upper boundary of any two mixed organic materials used in the work was limited to 25wt%. So extensive tests were conducted to vary the percentages of any two combinations, which sums up to 25wt%. For instance, in formulation 1, the wt% of OP and CSP must be 25wt%. This means that we have the options of 5wt% of OP and 20wt% of CSP, 10wt% of OP and 15wt% of CSP, 5wt% of CSP and 20wt% of OP, 10wt% of CSP and 15wt% of OP, 20wt% of CSP and 5wt% of OP. All these options were tested for hardness and the option with the highest hardness was obtained as 10wt% of OP and 15wt% of CSP and chosen as the representative for formulation 1 in Table 1. Other formulations 2 to 5 were combined and similarly tested for hardness and the final results are displayed in Table 1.

The samples' specifications are known by mass (g), height (cm), radius (cm), volume (cm³) and density (g/cm³) and the ranges are specified in Table 2.

3.3 Measurement of wear and coefficient of friction (COF)

Tests on dry sliding wear were conducted using a DIN abrasion tester as per ASTM G 99 standard for polymeric materials. The tip of the specimen was held securely in a sample holder against an abrasive paper of size P 60 commercial grade attached with the aid of an adhesive to a cylindrical disc of 150 mm diameter. Other parameters like applied load, time of rotation were fixed manually in the course of the experiment. The quantities used in the measurement of the wear process were obtained as follows:

$$S_s(m/s) = \frac{\pi DN}{60,000} \quad (1a)$$

where D is the diameter of wear track in mm, N is the speed in rpm, and T is the duration of the test in seconds, s

Fig. 1 a Research scheme for wear studies on epoxy composites and brake pad Cylindrical shaped specimens of varying diameters, notably four: 8, 10, 12 and 15.5 mm, were used for the experiments under three varied loads of 5, 7.5 and 15 N while each of the samples run for four different timings: 60, 120, 180 and 240 secs. **b** Rep-

resentative SEM/EDS micrograph of (10OPp/15CSp)% composite. **c** Representative SEM/EDS micrograph of (10PKSp/15CSp)% composite. **d** Representative SEM/EDS micrograph of (10PSP/15ESp)% composite. **e** Representative SEM/EDS micrograph of commercial grade brake pad

Fig. 1 (continued)

Table 1 Formulations and descriptions

Formulation	Acronym	Description
1	10% OP + 15% CSP	10% particulate orange peels + 15% particulate coconut shell + epoxy resin
2	10% PKSP + 15% CSP	10% particulate palm kernel shells + 15% particulate coconut shell + epoxy resin
3	10% PSP + 15% ESP	10% particulate periwinkle shells + 15% particulate eggshells + epoxy resin
4	10% OP + 5% PSP	10% particulate orange peels + 5% particulate eggshells + epoxy resin
5	5%PK + 10% ESP	5% particulate palm kernel shells + 10% particulate eggshells + epoxy resin

Table 2 Parametric ranges of the specimens for experiments

Formula- tions	Mass (g)	Height (cm)	Radius (cm)	Volume (cm ³)	Density (g/cm ³)
1–5	3.11 – 4.16	1.09 – 1.45	0.775	2.71–2.75	1.14 – 1.16

$$\text{The specific wear rate} = \frac{\text{wear volume}}{(\text{Normal load}/\text{sliding distance})} \quad (1b)$$

The sliding speed is the velocity and the coefficient of friction was determined by multiplying the weight of the specimen before each test by the velocity to give the momentum (N). As per Newton's law, where actions and reactions are equivalent and opposed, the frictional force is obtained by subtracting the momentum from the originally applied force.

Therefore,

$$\text{COF} = \frac{\text{Applied force}}{\text{Frictional force}} \quad (2)$$

The wear rate was determined using the following, known as the Archard's model:

$$W_r = \frac{V_L}{F_N S_D} \quad (3)$$

where V_L is the volume loss of the specimen in mm³, F_N is the applied force in Newton, N, and S_D is the sliding distance in meters, m

3.4 Economics based wear rate models

3.4.1 The basis for the selection of Archard model

Many studies on wear behaviour of composites with applications in engineering practices reveal that wear rate increase in composites is a central concern [1–5]. Moreover, a couple of studies in the manufacturing domain emphasize cost as a dominant factor in the progress assessment and determining the sustainability of the system. For instance, Shehab et al. [52] declared that

the application of composites increased considerably in aerospace structures but further usage was threatened by the high material and manufacturing costs. Consequently, they asserted that it is necessary to develop cost estimation instruments to accurately estimate the cost at the initial design phases, and then cost-effective decisions and design optimisation can be accomplished to lower the cost of composite products. But while the research theme promotes cost estimation, there is a prominent research theme that advocates for wear rate analysis. Unfortunately, there has not been any meeting point for these ideas in the composite literature yet though synergy of ideas is flourishing in scientific investigations. There is, therefore, the necessity to integrate these ideas the development of a pseudo wear rate model that capture both the inflationary cost and the wear rate technical parameters.

Besides, a typical wear appraisal problem is to tackle the wear rate concept using a technically sound and economically inclined idea. Thus, a trade-off is required among the technical and economic (inflationary cost) needs to wear rate appraisal to resolve the serious task of finding a feasible strategy for the synergic modelling effort. Furthermore, it is compelling for researchers to consider the possible model development using a method that could assist in practice and still retain a good theoretical framework. This model could assist in practice and still retain a good theoretical framework. This model would help to have an understanding of the elements of the model and the interactions among them, which will entail the important real-life feature for wear rate modelling. However, due to the decision variables and their associations, the complication involved in such modelling emerges and should be resolved. Therefore, the Archard model of wear appraisal would be the best fit analytical tool to aid the wear rate decisions for the wear rate appraisal problem of concern in this work. The Archard model is straightforward with no computational complexity for practical usage in the industry. So, the Archard model is a method useful for wear rate problem in brake pad applications in automobiles. Archard method is deployed in this work with the introduction of inflationary cost into the model.

3.4.2 Inflationary factor-based wear rate model

The monthly inflationary factor was applied to the wear parameters of the composites as a means of predicting the wear rates of the composites using the parameters as the working conditions in a month. The incorporation of the monthly inflationary factor into the wear rate model correctly reveals the wear performance of the considered samples in a practical economically-influenced environment in which the products are to be used in reality. Therefore, we have

$$W_{r.\text{inf}} = \left(\frac{V_L}{F_N S_D} \cdot \left(1 + \frac{\theta}{12} \right)^n \right) \quad (4)$$

where θ is the inflationary factor, obtained from the National Bureau of Statistics as 17.24 n is the period of analysis taken as 1 year, while 12 represents the number of months in a year.

During the service life of organic-based composites, materials are removed from their surfaces, damaging their strengths and compromising the integrity of the composites. The rate of material removal is an important element to establish the possible lifespan of the composite, maintenance and replacement costs. However, a general rise in cost with associated enhancement in the quality of the composites exists, which impacts on cost decisions of the composite engineer. This, cost, referred to as inflation, is important and very frequently associates with decisions to replace the composites and maintenance cost over time. It may have a multiplier effect as the cost of composite inputs such as resins, moulds, spaced for fabrication and labour cost for composite manufacturing may trigger a rise in the cost of producing composites. Consequently, inflation becomes a substantial parameter when deciding on modelling the wear rate for the organic-based composites.

3.4.3 Opportunity cost-based wear rate model

The opportunity cost was applied in this investigation as the alternative cost of carrying out all production and analysis leading to the wear rate of each sample. In this work, the cost of materials, transportation and wear experiment was estimated per sample. These costs represent the benefit, profit or values that were forgone to determine the wear rate of each sample. Each of the five formulations considered in this investigation has four samples making a total of twenty samples. Therefore, the opportunity cost for each of the twenty samples will be estimated by dividing the total estimated cost by the total number of samples as follows:

$$kt = 1/n(\text{cost of materials} + \text{cost of transportation} + \text{cost of wear experiment}) \quad (5)$$

where k is the opportunity cost relating to the determination of the wear rate of each sample, t is the time frame considered and n is the total number of samples involved in the process.

During the fabrication of organic-based composites, a choice must be made on which filler to use or the matrix to select in the fabrication process. As these options are selected, an opportunity cost exists, which is the cost of not benefiting from others while enjoying the best option. But opportunity cost is often associated with cost decisions while fabricating composites. This parameter is very necessary to be incorporated into the analysis of wear rate for organic-based composites during composite development.

The opportunity cost based wear rate model is introduced into the wear rate model, described mathematically as follows:

$$W_{r+kt} = \left(\left(\frac{V_L}{F_N S_D} \right) + kt \right) \quad (6)$$

3.4.4 Joint inflationary factor and opportunity cost model based wear rate model

The inflationary factor and opportunity cost indices were further incorporated into the wear rate model to factor in the cost of inflation and alternative forgone in the wear rate of each sample. Thus, we have:

$$W_{r.\text{inf}+kt} = \left(\frac{V_L}{F_N S_D} \left(1 + \frac{\theta}{12} + kt \right)^n \right) \quad (7)$$

For Eqs. (4), (6) and (7), the wear rate will be measured in mm^3/Nm , because other quantities in the model are dimensionless and are subject to peculiar changes in the region or country where they are being applied.

In composite development, inflation factor and opportunity cost impacts on the cost-effectiveness of the development endeavour. Nonetheless, it is essential to include these parameters when contemplating on developing organic-based composites.

4 Results and discussion

The five different composites: (10OPp, 15CSp), (10PKSp, 15CSp), (10PSp, 15ESp), (10OPp, 15PSp) and (5PKSp, 20ESp)% which exhibited the best mechanical properties from each composite group, were selected for the wear test alongside the commercial grade brake pad (Table 3). The result of the wear test was obtained in terms of wear rate from 2 scenarios. The first scenario was by

Table 3 Wear rate results for the developed composites and commercial grade brake pad

Applied load (N)	(OPp/CSp) (mm ³ /N.m)	(PKSp/CSp) (mm ³ /N.m)	(PSP/ESp) (mm ³ /N.m)	(OPp/PSp) (mm ³ /N.m)	(PKSp/ESp) (mm ³ /N.m)	Commercial grade (mm ³ /N.m)
Scenario 1						
Agarwal et al. [54] wear rate model						
5	3	1.5	0.64	3.01	2.76	3.64
7.5	1.1	0.77	0.38	2.06	2.84	1.96
10	1.11	0.72	0.3	0.8	2.23	1.06
15	0.75	0.9	0.19	0.43	1.99	0.65
Scenario 2						
Newly developed wear rate model						
5	5.23	3.65	1.55	7.34	6.74	8.88
7.5	2.69	1.88	0.93	5.03	6.93	4.78
10	2.71	1.76	0.72	1.95	5.44	2.61
15	1.82	2.2	0.46	1.04	4.84	1.58

Agarwal et al. [54] which is the Archard wear model and the second scenario is the developed wear rate model from this work (Table 3).

4.1 Scanning electron microscopy (SEM)/energy dispersive spectroscopy (EDS) tests on the samples

The scanning electron microscopy (SEM) is a characterisation technique that is used to produce images from a material after its surface has been examined with the concentration of a beam of electrons. The samples were carbon coated and held steadily in a sample holder with a double sized carbon tape before they were placed in a sample chamber. The acceleration voltage used in the imaging of the samples was 20 kV. The energy dispersive spectroscopy (EDS) is carried out alongside the SEM for elemental composition of the microstructure of a given sample. The representative SEM/EDS micrographs in Figs. 1(b–e) have been used to identify the dominant phase in the microstructure of each of the composite blends as well as that of the commercial grade brake pad.

1. Orange peel/coconut shell blend: (10OPp/15CSp)% epoxy composite
2. Palm kernel/coconut shell blend: (10PKSp/15CSp)% epoxy composite
3. Periwinkle/egg shell blend: (10PSP/15ESp)% epoxy composite
4. Commercial grade brake pad

In this paper, only figures explaining the 8 mm and 15 mm samples are shown for coinciseness. However, discussion of results is extended to all categories of samples i.e. the 8, 10, 12 and 15.5 mm samples.

4.2 Effect of AL (applied load) and SD (sliding distance) on the SWR (specific wear rate) of (10OP,15CSP)% epoxy composite

For the 8 mm sample, the specific wear rate decreased with increasing sliding distance and increased with higher applied loads. However, it was highest with the 7.5 N load. In the 10 mm specimen, the wear rate decreased under higher sliding distance and reduced with higher loads except under 5 N where it increased with greater sliding distance. The 12 mm specimen experienced higher wear rate as the sliding distance increased but the wear rate declined with increase in applied loads. The 15 mm sample recorded the highest wear rates with increasing sliding distance as the applied load reduced with the highest wear rate obtained under the application of 5 N.

4.3 Effect of AL and SD on the SWR of (10PK, 15CSP)% epoxy composite

The wear rate of the 8 mm specimen decreased with higher sliding distance but increased from 56.52 to 75.36 m under 5 and 7.5 applied loads. For the 10 mm and 12 mm specimens, higher wear rates with increasing sliding distance and reduced loads were noticed due to the increase in surface area of the sample used. The wear rates of the 15.5 mm specimen were the highest due to a larger cross-sectional area but it reduced with increasing sliding distance and reduced significantly with higher loads.

4.4 Effect of AL and SD on the SWR of (10PSP, 15ESP)% epoxy composite

The highest wear rate experienced by the 8 mm sample was under an applied load of 7.5 N but the wear rate dropped with the increase in sliding distance. The wear behaviour of the 10 mm sample shows significantly reduced values with higher load application but reduced with a higher sliding distance. The 12 mm sample showed a similar behaviour to that of the 10 mm sample. For the 15 mm sample, wear rates declined as the sliding distance increased.

4.5 Effect of AL and SD on the SWR of (100P,15PSP)% epoxy composite

For the 8 mm sample, wear rates reduced with increasing sliding distance and reduced with higher sliding distance. For the 12 mm sample, the increase in the surface area resulted in higher wear rate. With the 5 N load, the wear rate began at $2.66 \text{ mm}^3/\text{Nm}$ before dropping to $1.03 \text{ mm}^3/\text{Nm}$. The wear rate of the 12 mm sample under 7.5 N began at $2.2 \text{ mm}^3/\text{Nm}$ and reduced continuously with increasing sliding distance to $0.73 \text{ mm}^3/\text{Nm}$. Further increase of load to 15 N resulted in a lower wear rate of $1.25 \text{ mm}^3/\text{Nm}$ which dropped to $0.4 \text{ mm}^3/\text{Nm}$ after the sliding distance reached 75.36 m. For the 15.5 mm sample, higher wear rates existed under loads. The 15.5 mm sample exhibited the highest wear rates under 5 N load with a magnitude of $3.02 \text{ mm}^3/\text{Nm}$. The sample experienced lower wear rates under higher wear loads. For all loads, the wear rates reduced with increasing sliding distance.

4.6 Effect of AL and SD on the SWR of (5 PK,20PSP)% epoxy composite

The 8 mm sample, exhibited the highest wear rates under 5 N load while lower wear rates were displayed under the application of the 15 N load. The wear rates reduced with increasing sliding distance, similar to 10 and 12 mm samples. The wear rates also declined with an increased load and higher sliding distance. The 15.5 mm sample exhibited wear rates higher than other samples. However, the highest wear rates was for 7.5 N then 5 N. For 15 N, the wear rate increased to $2.9 \text{ mm}^3/\text{Nm}$ after a sliding distance of 37.68 m (highest). The wear rate declined for all loads with an increased sliding distance.

4.7 Effect of AL and SD on the SWR of automobile brake pad

For the brake pad, only the 15.5 mm specimen was considered. Under the application of 5 N load, the brake pad sample exhibited a wear rate of $2.58 \text{ mm}^3/\text{Nm}$ which reduced gradually to $1.57 \text{ mm}^3/\text{Nm}$ while under the 15 N load its wear rate reduced gradually from 1.63 to $1.19 \text{ mm}^3/\text{Nm}$ with increasing sliding distance. However, under the 7.5 N load, the wear rate of the specimen increased from $1.53 \text{ mm}^3/\text{Nm}$ to a peak value of $3.05 \text{ mm}^3/\text{Nm}$.

4.8 Effect of IF (inflationary factor) on the SWR of epoxy composites

The wear rate increased significantly as shown by Fig. 2 by an average of 225.36, 143.2, 143.9 and 143.46%, for the 8, 10, 12 and 15.5 mm samples respectively. The highest

Fig. 2 Effect of an inflationary factor on the specific wear rate of (100P, 15 CSP)% epoxy composite. **a** Effect of an inflationary factor on the wear rates of 8 mm (100P,15 CSP)% epoxy compos-

ite. **b** Effect of an inflationary factor on the wear rates of 15.5 mm (100P,15 CSP)% epoxy composite

percentage increase in wear rate was obtained as 5.18 mm^3/Nm by the 15.5 mm sample under an applied load of 5 N at a sliding distance of 18.8 mm.

After the introduction of the wear rate inflationary factor model to the (10PK,15CSP)% epoxy composite, the percentage increase in wear rate of the 8, 10, 12 and 15.5 mm samples were 143.76, 141.99, 143.43 and 142.94% respectively. Figure 3 describes the increase in the wear rates of the composite with the highest wear rate of 5.22 mm^3/Nm was obtained by the 15.5 mm sample by the under the application of 5 N.

For the (10PSP,15ESP)% composite, the wear rate increased by 140.45, 144.66, 142.07 and 142.85% for the 8, 10, 12 and 15.5 mm samples, respectively, with the introduction of the inflationary factor into the wear rate equation described by Eq. (4). The effect of the new wear rate model on the composites is shown in Fig. 4, with the highest wear rate recorded by the 3.79 mm^3/Nm by the 15.5 mm sample with a load of 5 N.

The wear rate inflationary factor model increased the wear rate of the (10OP, 15PSP)% epoxy composite by 142.8, 110.84, 298.34 and 143.69% for the 8, 10, 12 and 15.5 mm samples, respectively. Figure 5 shows the

Fig. 3 Effect of an inflationary factor on the specific wear rate of (10 PK, 15CSP)% epoxy composite. **a** Effect of an inflationary factor on the wear rate of 8 mm (10 PK,15CSP)% epoxy composite. **b** Effect of

an inflationary factor on the wear rate of 15.5 mm (10 PK,15CSP)% epoxy composite

Fig. 4 Effect of an inflationary factor on the specific wear rate of (10 PSP, 15ESP)% epoxy composite. **a** Effect of IF on the WR of 8 mm (10PSP,15ESP)% epoxy composite. **b** Effect of IF on the WR of 15.5 mm (10PSP,15ESP)% epoxy composite

Fig. 5 Effect of an inflationary factor on the specific wear rate of (100P, 15PSP)% epoxy composite. **a** Effect of an inflationary factor on the wear rates of 8 mm (100P,15PSP)% epoxy compos-

ite. **b** Effect of an inflationary factor on the wear rates of 15.5 mm (100P,15PSP)% epoxy composite

influence of the model on the wear rates of the composites, with the 15.5 mm sample exhibiting the highest wear rate of $7.36 \text{ mm}^3/\text{Nm}$ with a load application of 5 N at a distance of 18.36 m.

The introduction of the inflationary factor into the wear rate model increased the wear rates of the (5PK, 20ESP)% composite as described by Fig. 6. This represents an increase of 144.72, 143.55, 235.39 and 143.46% in the average wear rate of the 8, 10, 12 and 15.5 mm samples after introducing the monthly inflationary factor to the wear rate model. The highest wear rate of 11.18

mm^3/Nm obtained in this category is by the 15.5 mm sample under a load of 7.5 N.

Lastly, the brake pad sample exhibited an increase in wear rate of 143.44% with the introduction of the inflationary factor into the wear rate model (Fig. 7). This highest wear rate was obtained by the brake pad sample was $7.44 \text{ mm}^3/\text{Nm}$ with an applied force of 7.5 N.

4.9 Opportunity cost

$$kt = 1/20(N \ 15,000 + N \ 5,000 + N \ 48,000) = N \ 3,400 \text{ or } 0.034/N1,000.$$

Fig. 6 Effect of an inflationary factor on the specific wear rate of (100P, 15PSP)% epoxy composite. **a** Effect of an inflationary factor on the wear rates of 8 mm (5PK,20ESP)% epoxy composite. **b** Effect

of an inflationary factor on the wear rates of 15.5 mm (5PK,20ESP)% epoxy composite

Fig. 7 Effect of applied loads and sliding distance on the wear rates of brake pad sample

4.10 Effect of OC (opportunity cost) on WR of epoxy composites

The addition of the opportunity cost factor into the wear rate model resulted in a percentage increase in the wear rate of the (10OP,15CSP)% composite by an average of 4.59%. Figure 8 shows the influence of the opportunity cost factor on the wear rate. The 8 mm sample exhibited the highest percentage increase in wear rate with 5.03%, followed by the 12, 10 and 15 mm samples with increase in wear rate of 4.79, 4.64 and 3.9%, respectively.

The effect of the opportunity cost factor on the wear rate model is described by Fig. 9. the (10PK,15CSP)% composite exhibited a higher percentage increase in wear rate due to the inclusion of the opportunity cost in the wear rate model. The percentage increases in wear rate

were recorded as 9.71, 7, 4.98 and 3.97% for the 8, 10, 12 and 15.5 mm samples, respectively.

The influence of the opportunity cost on the wear rate of the (10PSP, 15ESP)% composite is described in Fig. 10. The (10PSP, 15ESP)% composite experienced a percentage increase in wear rate by 5.24%. The 10 mm sample experienced the highest increase of 5.82%, while the 8, 12 and 15.5% samples exhibited 5.62, 5.04 and 4.48% increase, respectively.

For the (10OP, 15PSP)% composite, the wear rate increased by 3.87% due to the influence of the opportunity cost in the wear rate model (Fig. 11). The percentage increase reduced gradually as the sample diameter increases with 4.54, 3.98, 3.65 and 3.32% for the 8, 10, 12 and 15.5 mm samples, respectively.

The effect of the opportunity cost on the wear rate of the (5PK, 20ESP)% composite resulted in a percentage increase in wear rate of 2.56% (Fig. 12). This effect was obtained as 3.57, 2.76, 2.66 and 1.25% for the 8, 10, 12 and 15.5 mm samples, respectively.

The brake pad sample experienced a percentage increase of 1.91% in its wear rate due to the influence of the opportunity cost in the wear rate model (Fig. 13).

4.10.1 Combined effects of IF and OC on the WR (wear rate) of composites

The effect of the wear rate, inflationary factor and opportunity cost model as described by Eq. (7) on the (10OP, 15CSP)% composite is shown by Fig. 14. The composite recorded 149.08, 148.44, 148.54 and 147.43% percentage increase in wear rate by the 8, 10, 12 and 15.5 mm samples, respectively. The highest wear rate was recorded as 5.21

Fig. 8 Effect of opportunity cost on the specific wear rate of (10OP, 15CSP)% epoxy composite. **a** Effect of OC on the WR of 8 mm (10OP,15CSP)% epoxy composite. **b** Effect of OC on the WR of 12 mm (10OP,15CSP)% epoxy composite

Fig. 9 Effect of opportunity cost on the specific wear rate of (10OP, 15CSP)% epoxy composite. **a** Effect of opportunity cost on the wear rates of 8 mm (10PK,15CSP)% epoxy composite. **b** Effect of OC on the WR of 15.5 mm (10PK,15CSP)% epoxy composite

Fig. 10 Effect of opportunity cost on the specific wear rate of (10PSP, 15ESP)% epoxy composite. **a** Effect of OC on the WR of 8 mm (10PSP,15ESP)% epoxy composite. **b** Effect of OC on the WR of 15.5 mm (10PSP,15ESP)% epoxy composite

mm³/Nm by the 15.5 mm sample under a load of 5 N and 18.84 m sliding distance.

Figure 15 shows the influence of the wear rate, inflationary factor and opportunity cost model on the wear behaviour of the (10PK, 15CSP)% composite. The composite experienced a 154.19, 150.89, 148.84 and 147.7% percentage increase in wear rates for the 8, 10, 12 and 15.5 mm samples. Despite the huge percentage increase,

the highest wear rate recorded was 5.25 mm³/Nm by the 15.5 mm sample with an applied load of 5 N and 18.84 m sliding distance.

The application of the wear rate, inflationary factor and opportunity cost model on the (10PSP, 15ESP)% composite wear behaviour is shown in Fig. 16. The composite exhibited a percentage increase of 149.22, 150.02, 148.64 and 148.05% by the 8, 10, 12 and 15.5 mm samples,

Fig. 11 Effect of OC on the SWR of (10PSP,15ESP)% epoxy composite. **a** Effect of OC on the WR of 8 mm (10OP,15PSP)% epoxy composite. **b** Effect of OC on the WR of 15.5 mm (10PSP,15PSP)% epoxy composite

Fig. 12 Effect of OC on the SWR of (5PK,20ESP)% epoxy composite. **a** Effect of opportunity cost on the wear rates of 8 mm (5PK,20ESP)% epoxy composite. **b** Effect of opportunity cost on the wear rates of 15.5 mm (5PK,20ESP)% epoxy composite

respectively. The 15.5 mm sample experienced the largest wear rate of $3.83 \text{ mm}^3/\text{Nm}$ under the application of 5 N load and 18.84 m sliding distance.

The combined effects of the wear rate, inflationary factor and opportunity cost on the wear behaviour of the (10OP, 15PSP)% composite are described in Fig. 17. The 8, 10, 12 and 15.5 mm samples had a percentage increase of 148.04, 147.97, 147.24 and 147.14% percentage increases in wear rate, respectively. The highest wear rate was

obtained as $7.4 \text{ mm}^3/\text{Nm}$ with the 15.5 mm sample under an applied load of 5 N.

Figure 18 describes the influence of the wear rate, inflationary factor and opportunity cost model on the (5PK, 20ESP)% composite. The percentage increases were recorded as 151.15, 146.75, 226.45 and 144.91% for the 8, 10, 12 and 15.5 mm samples, respectively. The 15.5 mm produced the highest wear rate of $11.22 \text{ mm}^3/\text{Nm}$. However with a higher applied of 7.5 N.

Fig. 13 Effect of OC on the SWR of brake pad sample

The influence of the wear rate, inflationary factor and opportunity cost model on the brake pad sample is described in Fig. 19. The highest wear rate was obtained by the brake pad sample as $7.22 \text{ mm}^3/\text{Nm}$ under a load application of 7.5 N.

4.10.2 Comparison with existing reports from the literature

In an investigation carried out by Srinivas and Bhagyasheka [53], where graphite and silicon carbide were used as reinforcement in 10, 20, 30 and 40% filled epoxy composites. The highest wear rates from their work were by the 10, 20, 30 and 40% filled composites were 6.82, 6.24, 3.91 and $3.16 \times 10^{-5} \text{ mm}^3/\text{Nm}$ under the application of 10 N. This is comparatively higher than the highest wear rates from

the (10OP,15CSP)%, (10PK,15 CSP)%, (10PSP,15 ESP)%, (10OP,15PSP)% and (5PK,20ESP)% epoxy composites in this work obtained as 1.76, 2.14, 1.37, 3.02, $3.07 \text{ mm}^3/\text{Nm}$, respectively, under the application of 5 N. The same composites also obtained the highest wear rates of 1.05, 1.13, 1.01, 1.4 and $2.36 \text{ mm}^3/\text{Nm}$ under an applied load of 15 N, which could still be considered better than the composites used by Srinivas and Bhagyasheka [53] in terms of wear resistance.

Although Srinivas and Bhagyasheka [53] used silicon carbide and graphite up to 40 wt. % as reinforcement over longer sliding distances, the current work was restricted to 25 wt. % of selected agro-wastes fillers. Further, the behaviour of the composites in the current investigation showed that wear rates decreased with increasing sliding distance and higher applied loads which correlate with Srinivas and Bhagyasheka [53]'s work. In another work, Agarwal et al. [54] used silicon carbide and chopped glass fibre to reinforce epoxy composites. The specific wear rates increased with higher applied loads up to 80 N. They also discovered that the specific wear rate decrease with higher sliding velocity. This was attributed to the fact that at the higher sliding velocity the frequency of surface contact between the abrasive rubber wheel and the specimen reduces, hence the decrease in the value of the wear rates. Although the highest wear rates reported by Agarwal et al.'s [54] was around $0.04 \text{ mm}^3/\text{Nm}$, the high sliding speed range of 40–160 cm/s which is about 4–16 m/s can be said to be responsible. Comparatively, this investigation used a uniform sliding velocity of 0.314 m/s to enable

Fig. 14 The combined effect of IF and OC on the WR of (10OP,15CSP)% epoxy composite. **a** Effect of IF and OC on the WR of 8 mm (10OP,15CSP)% epoxy composite. **b** Effect of IF and OC on the WR of 15.5 mm (10OP,15CSP)% epoxy composite

Fig. 15 The combined effect of IF and OC on the WR of (10PK, 15CSP)% epoxy composite. **a** Effect of inflationary factor and opportunity cost on the wear rates of 8 mm (10PK,15CSP)% epoxy

composite. **b** Effect of inflationary factor and opportunity cost on the wear rates of 15.5 mm (10PK,15CSP)% epoxy composite

Fig. 16 The combined effect of IF and OC on the WR of (10PSP, 15ESP)% epoxy composite. **a** Effect of inflationary factor and opportunity cost on the wear rates of 8 mm (10PSP,15ESP)%

epoxy composite. **b** Effect of IF and OC on the WR of 15.5 mm (10PSP,15ESP)% epoxy composite

frequent surface contact between the abrasive cylindrical disk and the wear specimens.

The application of the inflationary factor, the opportunity cost on the wear rate of the composites and brake pads is a novel attempt to predict the expected wear rates of composites on a real-life basis. Although reports on this application are scarce in the literature, the obtained results are within acceptable limits when

compared with the work of Srinivas and Bhagyashoka [46]. In making the work relevant to the literature on composites, density was compared with literature values. As was found out in the literature, in the wide application area of brake pads, the notable research conducted by Keskin [20] where rice straw was used as single filler for composites could be compared with the current work. For the obtained composite in Keskin

Fig. 17 The combined effect of inflationary factor and opportunity cost on the wear rate of (10OP,15PSP)% epoxy composite. **a** Effect of inflationary factor and opportunity cost on the wear rates of

8 mm (10OP,15PSP)% epoxy composite. **b** Effect of IF and OC on the WR of 15.5 mm (10OP,15PSP)% epoxy composite

Fig. 18 The combined effect of IF and OC on the WR of (10PK,15ESP)% epoxy composite. **a** Effect of IF and OC on the WR of 8 mm (5PK,15ESP)% epoxy composite. **b** Effect of IF and OC on the WR of 15.5 mm (5PK,15ESP)% epoxy composite

[20], the range of density obtained was 1.135–1.746 g/cm³, resulting in an average of 1.4405 g/cm³. In the current research, the range of the five formulations was 1.141–1.288 g/cm³, having an average of 1.2145 g/cm³. In comparison, the results from the current work obtain less dense sets of specimens, aligning with the lightweight drive desirable in composite fabrication. It has a 15.69% less dense advantage, and this strengthens our intention of producing better composite outputs using mixtures of two reinforcements at a time instead of one. Consequently, it could be concluded that our

agricultural based composites are better than rice straw-based composites performance.

5 Conclusions

In this paper, the wear rate is modelled to account for the inflationary cost of materials for cost-effective decisions, design optimization and to reduce the cost of producing composites. The following conclusions were drawn from the study:

Fig. 19 The combined effect of OC on the SWR of brake pad sample

1. The obtained wear rate model accurately predicts the wear rate of the brake pad based on inflationary cost and opportunity cost. Moreover, the pseudo wear rate model predicts the impact of the independent variable i.e. inflationary cost, opportunity cost, time, and sample size.
2. The new wear rate model is very efficient and capable of estimating the wear response of the brake pad without underestimating the values. Therefore, the model is feasible for use in the design of brake pads. Moreover, this study can be a reference point for other products of the automobile such as the brake shoe.
3. The validation of the model was tested with practical results from laboratory experiments, which confirmed the workability of the model.
4. The model aid in reducing the cost of producing composites as it builds in inflationary cost thus bring in cost-consciousness into every worker in the production of composites
5. The use of dual agro-filler is better than single filler as the complementary properties of the constituent fillers are taken advantage of in a combined form as dual fillers than single filler.

The main advantage of dual filler is that the properties of the fillers complement each other. The orange peel particulate is one of the fillers used in this work and has lubricating advantages. It permits enhancement of the lubricating potentials and the tribological properties of the composite. This has a complementary advantage together with the properties of the second filler.

For future work, the following may be pursued. First, effort should be invested to enhance the model to incorporate mode details such as the interest rate for more accurate predictions of the wear rate of composites. Second, binding materials may be introduced between the filler to know their possible effects on wear rates of composites. Future efforts should consider adding a binder such as the pure water sachet [8] and cement [35]. This may improve the wear response of the developed composite.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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