

Tribological Behaviour of Polyethylene and Polypropylene Reinforced with Coconut Shell and Bagasse on Steel Contact

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Abstract- The effect of some functional groups of coconut shell and bagasse fillers on the tribological behaviour of polymeric materials on steel contact have been studied. In the spectroscopic analysis, 30 scans were made on each filler at a frequency range of 650–4000 cm^{-1} with resolutions of 8 cm^{-1} . The polymers were formulated with 0, 30, 50 and 70% of sieved 100 μm sizes of the fillers. The formulations were compounded into a polymeric material in a two-roll milling mixer at a temperature of 150 $^{\circ}\text{C}$, fed into a mould 70mm x 70mm square plate, thickness 5mm, diameter 25mm, and were compressed in a hydraulic press into disc shapes. The spectroscopic analysis of the fillers revealed a high level of carboxylic acid functional group 1722 cm^{-1} , at the transmittance of 98.218 in the coconut shell filler. In the friction and wear simulation, it was inferred that carboxylic acid initiated transfer film formation on the tribo-pairs and the film reduced the transition rate of the friction coefficient of the filled polymeric materials from their transient state at 0-50m, to their lubricity steady-state at 50-150m, compared to the unfilled polymer. The friction coefficient of the coconut shell-filled and bagasse-filled polymeric materials were less than 0.2 and their wear rates were in the order of 10⁻³ $\text{mm}^3\text{N}^{-1}\text{m}^{-1}$. The wear rate of polypropylene-based coconut shell-filled polymeric materials 0.0093, 0.0085, 0.0083, and 0.0078 $\text{mm}^3\text{N}^{-1}\text{m}^{-1}$, decreases with the filler concentration. The wear rates of bagasse-filled polymeric material 0.0093, 0.0065, 0.0089 and 0.0088 $\text{mm}^3\text{N}^{-1}\text{m}^{-1}$, was not linear. That of polyethylene-based coconut shell-filled polymeric material 0.0064, 0.0081, 0.0060, and 0.0085 $\text{mm}^3\text{N}^{-1}\text{m}^{-1}$, increases with filler concentration and that of polyethylene-based bagasse-filled polymeric material were 0.0064, 0.0081, 0.0060 and 0.0085 $\text{mm}^3\text{N}^{-1}\text{m}^{-1}$. It is therefore suggested that a different counterface should be used to ascertain this behaviour.

Keywords- Friction, Wear, Polyethylene, Polypropylene, Bagasse, Coconut Shell, Transfer Film

I. INTRODUCTION

Currently, an area of engineering with a heightening interest in the design of polymeric materials is tribology. In the absence of an external lubricant, polymers have shown low friction coefficient (μ) < 0.2 and low wear rate (k) < 10⁻⁶ $\text{mm}^3\text{N}^{-1}\text{m}^{-1}$ [1] [2]. The low μ and k of polymers are

attributed to their self-lubrication properties [3], [4]. This, in turn, is tied to the formation of a thin and continuous layer of transfer film on the metallic counterface, especially steel, as enunciated by [5], and [6]. Ever since then, [7], have shown evidence of transfer film evolution and its role in promoting low wear on tribo-pairs. Also, attempts have been made by [8], [9] and [10] to quantitatively correlate transfer film with wear rate. Ye et al. [7], measured the uncovered region (free-space) of transfer film on the disc surface between adjacent transfer films, and the result obtained correlated with the wear rate. Thus, transfer film has become the most hypothesized mechanism that initiates low friction coefficient and wear rate in tribo-pairs [11]. This information on transfer film has propelled research in industry, and by academics, on the utilization of polymeric materials for the design of engineering components that move relative to each other [12]. However, no general rule was been successfully established for their design. Rather, their low friction coefficient and wear rate are tied to the favourable effects of filler on the polymer matrix for the promotion of transfer film on the counterface.

Fillers, depending on their nature and properties, when properly controlled, play a vital role in composites [13]. Coconut shell (Cs) filler is hydrophilic, but [14] showed that it makes a good interfacial bond with a hydrophobic polymer matrix and, has improved mechanical properties and glass transition temperature. Also, [15] showed improved transfer film quality by fillers. Thus, this study aims to design polymeric material filled with coconut shells and bagasse fillers. The changes that accompanied the loading of the thermoplastic matrix with varying percentages of these natural fillers is measured, based on friction coefficient and wear rate response, and the role of the fillers' functional groups in transfer film formation are evaluated.

II. MATERIALS AND METHODS

A. Materials

High-density polyethylene (HDPE) and high-density polypropylene (HDPP) were filled with varying percentages of sieved 100 μm sized coconut shell and bagasse fillers. Twelve polymeric materials and two unfilled polymers; namely, HDPE and HDPP, were formulated (see Table 1). The formulations were compounded at a temperature of 150 $^{\circ}\text{C}$ in a two-roll

milling mixer (Model HTR-300). The composites were fed into a mould of 70mm x 70mm square plate, thickness 5mm, diameter 25mm, moulded in a hydraulic press and were cool in air.

TABLE I. FILLED POLYMERIC MATERIALS

HDPE (% wt)	HDPP (% wt)	100 μm Bagasse (%wt)	100 μm Coconut shell (% wt)	Composite (100%wt)
	30	70		A1
	50	50		A2
	70	30		A3
	30		70	A4
	50		50	A5
	70		30	A6
30		70		A7
50		50		A8
70		30		A9
30			70	A10
50			50	A11
70			30	A12

B. Experimental set-up and procedure

An Agilent Cary 630 Fourier Transmission Infrared Spectroscopy (FTIR) was used to characterize the functional groups in the fillers. Fig. 1 presents a schematic diagram of the instrument. During the scanning process, 30 scans were made on each sample at a frequency range of 650–4000cm⁻¹ with resolutions of 8cm⁻¹.

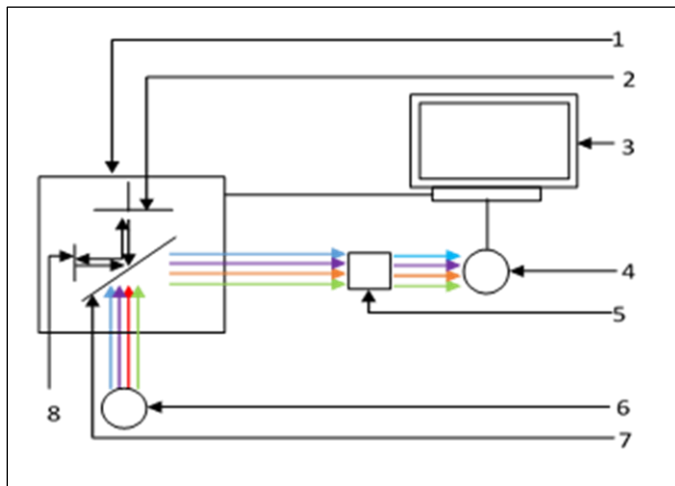


Figure 1. A Schematic Diagram of a Fourier Transmission Infrared spectroscopy. 1. Interferometer, 2. Moving mirror, 3. Computer, 4. Detector, 5. Sample, 6. Source, 7. Beam splitters, 8. Stationary mirrors

At every scan, the light source gets to the sample through a beam splitter. The beam splitter sends radiation from the light source at right angles to a stationary mirror and a moving mirror. The two lights return to the beam splitter and are

recombined, and travel through the sample to a detector. The different samples' spectra absorbed are emitted as wavelengths. For all the wavelengths produced, the detector reports variation in energy with time. Fourier transform, a mathematical function (Equation 1), converts the intensities versus time spectra into intensities versus frequency spectra. Where A(r) present the frequency domain, X(k) represent the time domain points X represent the spectrum points.

$$A(r) = \sum X(k)e^{(-2\pi\frac{irk}{N})} \tag{1}$$

An Anton Paar compact (600mm x 700mm, 550mm height) pin-on-disc tribometer, as shown schematically in Fig. 2, was used for the friction coefficient and wear rate measurements. The pin was a 10mm diameter AISI 420 stainless steel, with a sphere-shaped 6mm diameter indenter tip. The pin was made to contact the sample. As the sample was rotated at a speed of 5cm/sec, 10N load and 150m distance, experimental readings were displayed on a personal computer (PC) screen attached to the tribometer.

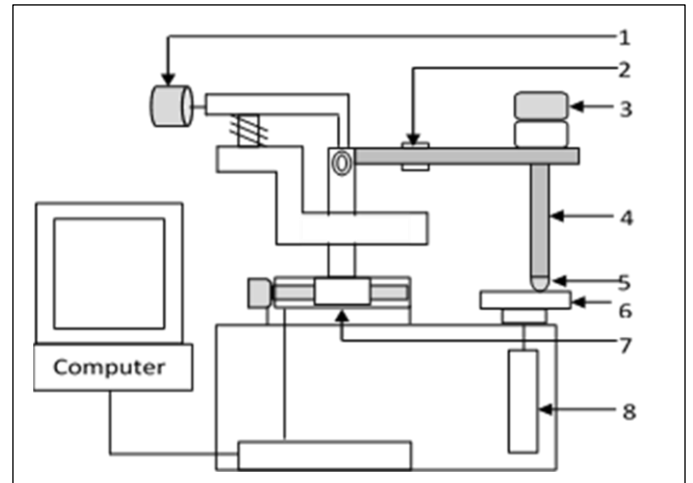


Figure 2. Pictorial and schematic view of the Tribometer. 1. Counterweight, 2. Load cells, 3. Static loads, 4. Static pin holder, 5. Stainless steel ball, 6. Circular discs, 7. Radius measurement assembly, 8. DC Motor

Applying the classical theory of Bowden and Tabor, friction force (F) is a product of the real contact area (A_r) and shear strength (τ) of materials. Thus, the friction coefficient can be expressed as Equations (2) and (3). Where τ₀ is interfacial shear strength, α is a constant and L is the applied load.

$$\mu = \frac{A_r \tau}{L} + \alpha \tag{2}$$

$$\mu = \frac{\tau_0}{P_H} + \alpha \tag{3}$$

For sufficiently thin coatings, the constant in Equations 2 and 3 can be ignored. Application of the Hertzian elastic contact model Equation 4, shows that an increase in load will result in a slight increase in the frictional force and a corresponding increase in the friction coefficient.

$$\mu = \tau_0 \cdot \pi \left(\frac{3R}{4E^*}\right)^{2/3} L^{-1/3} + \alpha \tag{4}$$

where R is the sphere radius, E^* is the young modulus of elasticity of the material. This was verified by [16], who investigated the tribological behaviour of carbon steels, using a pin-on-disc apparatus. The Archard constant k for wear rate measurement is expressed as Equation (5), where Δm is mass loss, ρ is density, F_N is applied load, and S is sliding distance.

$$k = \frac{\Delta m}{\rho \times F_N \times S} \left(\frac{mm^3}{N \times m} \right) \quad (5)$$

III. RESULTS AND DISCUSSION

The spectroscopic analysis showed that hydroxyl (-OH), and carboxylic acid (C=O) spectra are contained in a coconut shell and bagasse fillers. In Fig. 3, the spectra of the OH band in the fillers is between 3000 to 3500 cm^{-1} . It measured the hydrophilic nature of the two fillers. The carboxylic acid band is between 1900 to 1600 cm^{-1} at the 1722 cm^{-1} wavenumber and transmittance of 95.954. The transmittance for the two fillers coconut shell and bagasse are similar. But bagasse filler at 1900 to 1300 cm^{-1} presented a higher value of the transmittance than the coconut shell filler. It shows that there is a higher content of carboxylic acid in coconut shell filler than the bagasse filler.

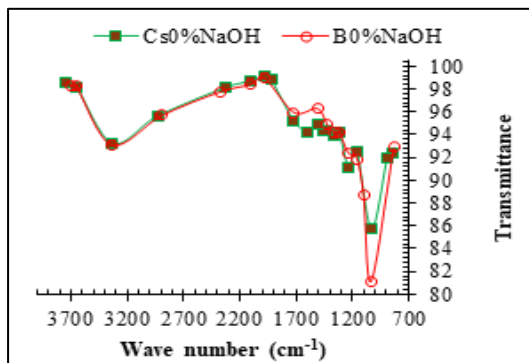


Figure 3. Untreated Bagasse and Coconut Shell FTIR

In Fig. 4, a marked increase in friction coefficient and rapid wear was observed at the onset of the simulation. There was transience when the simulation reached 0-60m distance. Beyond the transient stage, there was high lubricity and steady-state (running-in) at the 60-150m sliding distance. The polymeric materials produced different values of the friction coefficient. The reasons for the evolution of varied friction coefficient, within the transient stage, are not yet well understood.

However, it is reasonable to suggest that the stabilization of the friction coefficient at the lubricity steady state is associated with the formation of a protective film, where the transience corresponds to the transfer film's formation kinetics. It could be inferred that as the cycle progressed, the 10N load initiated mechanical stress on the tribo-pairs, and wear debris were formed. The debris formed, merged with the carboxylic acid on

the surface of the tribo-pairs to produced transfer films. This prevented the direct interaction of the tribo pairs' surface asperities. The unfilled polymeric materials C1, at the level of the static friction force (0 to 60m), had a high friction coefficient that occurred because of the delay in the transition from the transient to the lubricity steady state. This was enhanced by the formation of transfer film on the tribo-pairs. The carboxylic acid in the filled polymeric material initiated and accelerated the transfer film formation on the counterface. And the transition of the friction coefficient from the transient state to the lubricity steady-state was enhanced. Thus, the filler particles interactions in the polymeric materials caused a lower shear rate than the unfilled polymer.

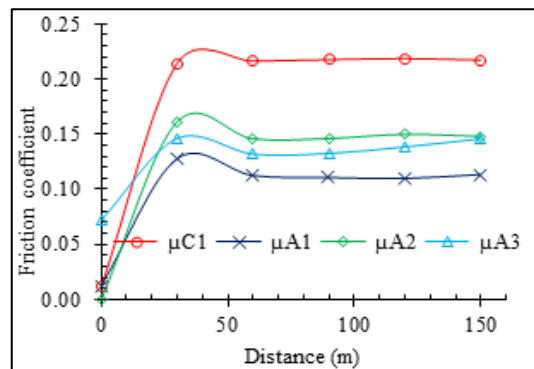


Figure 4. Friction Coefficient at 10N Load and 5cm/sec

A. Friction Coefficient of Polypropylene-based composites

In Fig. 5, the polypropylene-based bagasse and coconut shell polymeric materials had a friction coefficient lower than the unfilled polymer. The friction coefficient of polypropylene-based coconut shell-filled polymeric material is slightly lower than that of polypropylene-based bagasse-filled polymeric material at the different filler concentrations 30%, 50%, and 70%. The presence of the OH functional group and the low level of carboxyl (C=O) acid in bagasse filler probably affected the friction coefficient of polypropylene -based bagasse filler.

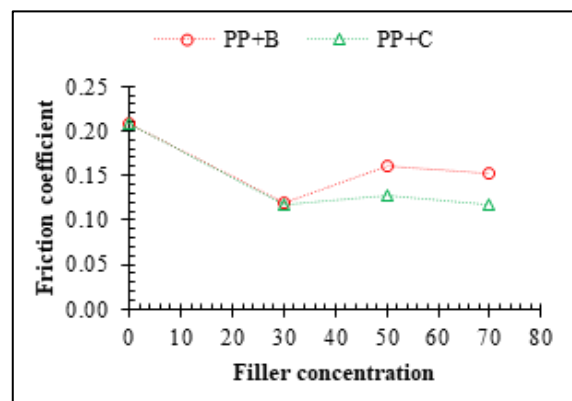


Figure 5. Friction coefficient, polypropylene-based bagasse and coconut shell

In Fig. 6, the effect of filler on the polymeric material is noticed in both the PP-based coconut shell-filled and bagasse-filled composite as the wear rate (k) generated has a magnitude of the order $10^{-3}\text{mm}^3\text{N}^{-1}\text{m}^{-1}$. As the filler concentration increased, the PP-based coconut shell-filled polymeric material wear rate decreased linearly.

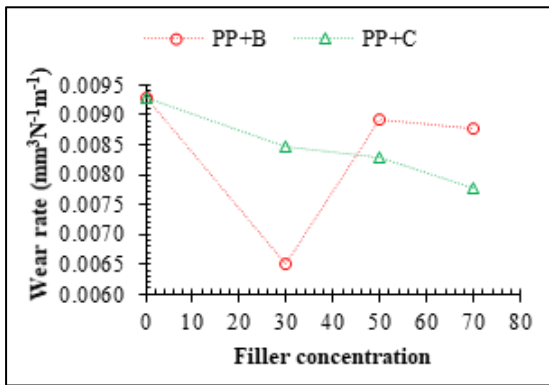


Figure 6. Wear rate of polypropylene-based bagasse and coconut shell

The PP-based bagasse filled PMs did not show a linear trend, the low level of carboxylic acid in the bagasse filler may have initiated inconsistency, in the wear rate. Thus, the result for PP-based coconut filler agreed with the filler hypothesis by [8], [15] and [7] that effective filler improved transfer film quality, reduced friction coefficient and wear rate of composites.

B. Friction Coefficient of Polyethylene-based composites

In Fig. 7, polyethylene with 50% coconut shell-filled polymeric material has the lowest friction coefficient compared to those of the unfilled polyethylene, 30%, and 70% filled polyethylene-based coconut shell filler.

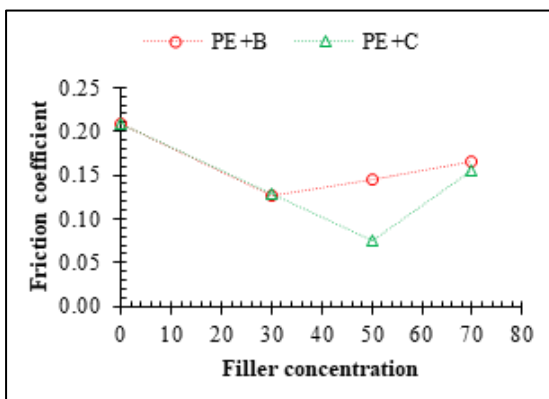


Figure 7. Friction coefficient of polyethylene-based bagasse and coconut shell

Also, in the polyethylene-based bagasse-filled polymeric material, the friction coefficient increased as the filler

concentration was increased. However, the friction coefficient of the filled polymeric materials was lower than that of the unfilled polymer. But the nonlinearity of the friction coefficient of the polymeric material as a function of the filler concentration could be attributed to the poor dispersion of the filler, which resulted in a polymer-rich and filler rich area as a result of the filler agglomeration in the polymer matrix.

In Fig. 8, the wear rate of PE-based coconut shell-filled polymeric material increase as the filler concentration was increased. For the PE-based bagasse-filled PMs, the wear rate did not follow a linear increment. Thus, it could be inferred that the presence of the carboxyl (C=O) functional group in coconut shell filler propelled transfer film formation and adhesion on the steel surface.

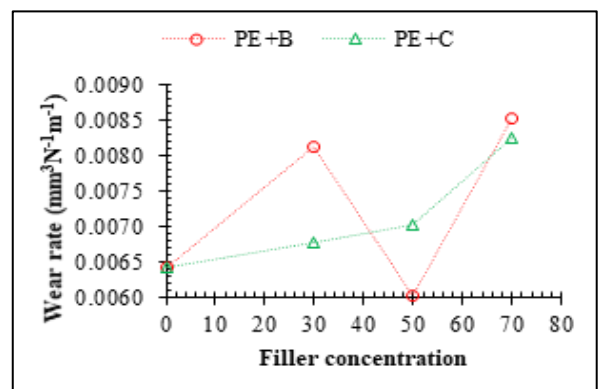


Figure 8. Wear rate of polyethylene-based bagasse and coconut shell

In Fig. 8, the wear rate of PE-based coconut shell-filled polymeric material increase as the filler concentration was increased. For the PE-based bagasse-filled PMs, the wear rate did not follow a linear increment. Thus, it could be inferred that the presence of the carboxyl (C=O) functional group in coconut shell filler propelled transfer film formation and adhesion on the steel surface. However, an increased wear rate rather than a decrease in the PE-based coconut shell-filled polymeric material could be linked to the affinity of the counterface (steel) used for the carboxylic acid reaction. Evident in [7], [17], [18], and [19] carboxyl (C=O) acid end groups can adhere to the exposed metal on a counter surface in tribo-pairs and form transfer film. However, the high carboxylic acid in coconut shell filler was not effective on the steel counterface, hence the disparity in the friction and wear rate of the polymeric materials.

IV. CONCLUSION

Polymeric materials are generally the most used materials in the oil and gas industry, prosthetic joints, water transportation equipment, and boreholes. In these applications, these materials rub against different particle sizes of sand in operation. Thus, under different environmental and operating conditions, some factors propel the ageing and failure of polymeric materials. Also, in a tribological application, the

presence of transfer film of polymeric materials on the counterface of tribo-pairs mitigates high friction coefficient and wear rate.

The following conclusions were drawn from the study:

1. Polypropylene-based bagasse and coconut shell-filled polymeric materials and polyethylene-based bagasse and coconut shell polymeric materials gave a good compromise between friction and wear under dry conditions.
2. The best-performed filler candidate in both polypropylene-based and polyethylene-based polymeric materials is coconut shell filler.
3. The improved tribological behaviour of PP-based and polyethylene-based coconut shell-filled polymeric materials is attributed to the high Carboxyl (C=O) functional group present in coconut shell filler.
4. Also, the improved but low tribological behaviour of polypropylene-based and polyethylen-based bagasse filled polymeric materials is attributed to the presence of OH, the functional group, in bagasse filler.
5. Low friction coefficient and wear rate can be obtained from varieties of materials, not just from the most obvious lamellar

Treatment of the filler with an acid or a base and Fourier transform infrared (FTIR) analysis of the resultant polymeric material is suggested for future work.

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