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Development and modelling of oil-palm-mesocarp fibre polyester resin composite for helical gears

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Abstract
As a result of the ever-increasing need of materials with unique properties that are ecofriendly, the possibility of using Oil-Palm-Mesocarp Fibre (OPMF)as reinforcement for polyester resin was investigated for use as material for helical gears. The OPMF collected was treated with deionized water and NaOH, and then grounded to a particle size of 354 microns. The composite was then produced by adding different quantities of the OPMF (weight % of 40—10 in steps of 10%) to unsaturated polyester resin to obtain comp. 1--comp. 4. Test specimens for the various mechanical tests were prepared for the different compositions and the tests were carried out following standard procedures. SOLIDWORKS was used to simulate the actual behavior of the helical gears. Results obtained showed that the biocomposite material for all composition can be used for designing helical gears for paper shredding machine and comp. 3 had the best properties in terms of displacement.

Keywords: Biocomposite, finite element analysis, mechanical tests, natural fibre

1. Introduction

Oil palm grow abundantly in west Africa [1], cultivated mainly for wide-scale production of palm oil, of which Nigeria is a major player. It is the primary raw material for the palm oil industry which serves as the main source of palm oil for domestic use [2]. Oil palm mesocarp fibre (OPMF), a natural fibre, is a by-product of the palm oil industry. This waste constitutes environmental and air pollution [3] as a result of poor waste management.
Biocomposites, composed of natural fibre and polymer, are having growing importance in engineering applications because they are cheap, non-toxic [4], easily recycled [5] and biodegradable [6]. Natural fibres are being used as reinforcement for polymeric materials to produce suitable materials in the sport [7], aerospace and automobile [8, 9], biomedical industries [10 - 14] and so on.

The main aim of this study is to determine the suitability of Oil Palm Mesocarp Fibre (OPMF) as a reinforcement material for polyester resin for the design of helical gears. When this study is successfully completed, it will solve the pollution problems of OPMF since it will be put into good use and a new biocomposite material with the highlighted positive properties above will be made available for making helical gears.

2. Materials and method

The materials employed in this study are Oil Palm Mesocarp Fibre (OPMF), detergent, sodium hydroxide (NaOH), unsaturated polyester resin, catalyst (Methyl ethyl ketone peroxide), accelerator (Cobalt napthanate), release agent (A - Z grease), de-ionized water and aluminium sheet.

3. Method

3.1 Fibre processing

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The OPMF, obtained from a local palm oil producer in Warri, was hand-washed with clean water to break out oil masses trapped in the fibre and in the process unwanted substances in the OPMF are removed. The washed OPMF was then thoroughly rinsed and sun-dried. After drying, the OPMF was then pulverized using local pepper grinding machine and then sieved using an Automated Shaker Machine (354 microns pore size). The collected powder was then treated with Sodium Hydroxide (NaOH) and rinsed with distilled water. Finally, the fine powder was properly mercerized, sundried and kept ready for mixture with the polymer matrix.

3.2 Mould manufacture

The mould to make specimens were made from aluminium sheet. This is cut to suitable dimensions and shapes as required by the sample specimen testing machine. To the various dimensions an allowance of 5mm created to allow for removal of burrs, mill scales and polishing of surfaces.

3.3 Characterization of the composite

The composite specimens were characterized for mechanical and physical testing. This involves varying the weight of the OPMF fibre and the hardener to 10% increase respectively for the different specimen compositions as shown in Table 1.

Table 1: Percentage Mass of Composites

S/No.	Materials	Comp. 1 Weight %	Comp. 2 Weight %	Comp. 3 Weight %	Comp. 4 Weight %
1	Hardener	60	70	80	90
2	OPMF fibre	40	30	20	10
3	Total Percentage	100	100	100	100

3.4 Composite preparation

The hardener (the unsaturated polyester resin, catalyst and accelerator) was made to fill the mould cavities and weighed using a Pioneer PA2201C Precision Balance. The total weight obtained gave the reference weight for the weight percentage calculation. Before mixture of the OPMF and the hardener is made, their respective weight percentage is calculated and measured out. These are homogeneously mixed and poured into each mould cavity and a test specimen is obtained once the mixture is cured. Before the paste is poured into the mould cavity release agent is applied on the walls of the mould to facilitate easy release of the specimen from the mould on curing. The curing time was observed to range from 15 minutes to 20 minutes. The process is repeated for various characterized test specimens.

3.5 Analysis of physical and mechanical properties

The characterized test specimens produced were machined and made ready for mechanical testing. These are all carried out at the Petroleum Training Institute, Effurun. The tests are as follows:

3.5.1 Tensile strength test

The tensile test will be carried out using a Universal Testing Machine (SM1000) to determine the tensile strength, tensile modulus, and elongation at break of the material. The sample used for the tensile test is shown in Figure 1.

Figure 1: Tensile Test Specimen

3.5.2 Impact strength test

The impact test will be carried out on the test specimens using an Impact Testing Machine (MAT23/1T50). This will determine the toughness of the material. The required length of Impact test specimens is 55mm and the width should be 10mm, while the breadth should be 10mm. Therefore, the cross-sectional area of Impact test specimens will be $100mm^2$. A test sample prepared for the impact test is shown in Figure 2.

Figure 2: Impact Test Specimen

3.5.3 Hardness strength test

Brinell Hardness Number (BHN) of the composites will be determined using a Universal Testing Machine (SM1000). This will reveal the hardness of the materials. A sample of the prepared material used for the hardness test is shown in Figure 3.

Figure 3: Hardness Test Specimen

3.6 Design of the gear

Design considerations like greater contact ratio, greater strength, and some operational requirements, such as noiselessness, smoother engagement of meshing of teeth, makes a preference for the use of helical gears.

On the design of the gear, two approaches will be made. The first consideration is the geometry of the gear, and the other the determination of the bending and contact stresses. All calculation is done according to the American Gear Manufacturers Association (AGMA) standards. Values for various factors were taken from machine design data book according to conditions of the design and all the units are in SI.

The geometry that satisfies the OPMF reinforced composite gear in a paper shredding machine application is proposed following these steps:

Step 1: Specify gear tooth form by selecting a pressure angle, Φ. The standard values for Φ are: 20°, and 25°. 14.5° have been previously used and is now obsolete.

Step 2: Select a helix angle, α, which range from 5° to 35°.

Step 3: Specify a diametral pitch, P, or a module, m.

Step 4: Once P is chosen the next step in defining the geometry would be the face width. Reference [15] recommended a given range of values for the face width with the formula below; where P, is the diametral pitch, and F, is the face width. However, there are other recommendations.

$$\frac{8}{P} < F < \frac{16}{P} \quad (1)$$

Step 5: Choose number of teeth for the pinion (N_p) and gear (N_G) for compactness.

Step 6: Compute the pitch diameters, d_p for pinion and d_G for gear:

$$d_p = \frac{N_p}{P} = N_p m \quad (2)$$

$$d_G = \frac{N_G}{P} = N_G m \quad (3)$$

Where P is the diametral pitch, N_p and N_G are number of teeth for the pinion and gear; m the module of gear.

Step 7: Compute the centre distance, C:

$$C = \frac{d_p + d_G}{2} \quad (4)$$

Where d_p and d_G is the pitch diameter for the pinion and gear respectively.

Step 8: Compute the addendum, a, and the dedendum, b;

$$a = \frac{1}{P} \quad (5)$$

$$b = \frac{1.25}{P} \quad (6)$$

Where P is the diametral pitch.

Step 9: Compute the clearance, c:

$$c = b - a \quad (7)$$

Where b is the dedendum, and a is the addendum.

Step 10: Compute the pitch radius, r:

$$r = \frac{mN}{2} \tag{8}$$

where m is the module, and N is the number of teeth.

Step 11: Compute radius of base circle, r_b:

$$r_b = r\cos\Phi \tag{9}$$

Where r is the pitch circle radius, Φ is the pressure angle.

Table 2 shows the gear design parameters and values obtained using the formulas that have been stated. These were then used to design and produce the helical gear and the pinion using SOLIDWORKS as shown in Figure 4

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Figure 4: The gears in SOLIDWORKS assembly

3.7 SOLIDWORKS simulation

With the OPMF composite tested to reveal its mechanical and physical properties, values obtained from the testing were inputted into SOLIDWORKS software to give a real life structural behaviour of the helical gear. Simulation of the part was carried out, and results for the displacements and von Mises stress were noted.

4. Result and discussion

4.1 Impact Test: The impact test result is summarised in table 5. It can be seen that the impact strength decreased steadily from 0.01805J/mm^2 for comp. 1 to 0.005905 J/mm^2 for comp. 4. This could be as a result of loss in ductility as more fibre was added to the polyester resin.

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Table 2: Gear design parameters and values

S/no.	Parameters	Symbols	Formulas	Pinion values	Gear values	Units
1	Pressure angle	Φ	-	20	20	°
2	Helix angle	A	-	30	30	°
3	Diametral pitch	P	$P = \frac{N_p}{d_p}$	0.18	0.18	mm
4	Face width	F	$\frac{8}{P} < F < \frac{16}{P}$	60	60	mm
5	No. of teeth	N	-	12	20	-
6	Pitch diameters	D	$d = \frac{N}{P}$	66	110	mm
7	Centre distance	C	$C = \frac{d_p + d_G}{2}$	121	121	mm
8a	Addendum	A	$a = \frac{1}{P}$	5.56	5.56	mm
8b	Dedendum	B	$b = \frac{1.25}{P}$	6.94	6.94	mm
9	Clearance	c	$c = b - a$	1.38	1.38	mm
10	Pitch circle radius	r	$r = \frac{mN}{2}$	33.33	55.55	mm
11	Base circle radius	r_b	$r_b = r \cos \Phi$	31.32	52.20	mm

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4.2 Determination of bending and contact stress

Tables 3 and 4 show the bending and contact stress parameters, formulas used and values obtained for the pinion and gear.

Table 3: Bending stress parameters and values

S/N	Parameters	Symbols	Formulas	Pinion Values	Gear Values	Units
1	Pitch line velocity	V	$V = \frac{\pi n_p d_p}{60000}$	2.449	2.448	m/s
2	Tangential force	F_t	$F_t = \frac{1000W}{V}$	28.58	28.59	KN
3	Dynamic factor	K_v	$K_v = \left(\frac{78 + (200V)^{0.5}}{78}\right)^{0.5}$	1.133	1.133	m/s
4	Overload factor	K_o	$K_o = \frac{\text{Actual tangential forc}}{\text{Nominal tangential for}}$	1.25	1.25	-
5	Size factor	K_s	-	0.85	0.85	-
6	Load distribution factor	K_m	-	1.5	1.5	-
7	Face width	b	-	60	60	mm
8	Geometry factor	J	-	0.38	0.38	-
9	Module	m	-	5.5	5.5	mm
8	Bending stress	σ_b	$\sigma_b = \frac{F_t}{bmJ} K_v K_o (0.93K_m)$	0.450	0.450	MPa

Table 4: Contact stress parameters and values

S/N.	PARAMETERS	SYMBOLS	FORMULAS	PINION VALUES	GEAR VALUES	UNITS
1	Dynamic factor	K_v	$K_v = \left(\frac{78 + (200V)^{0.5}}{78}\right)^{0.5}$	1.133	1.133	m/s
2	Overload factor	K_o	$K_o = \frac{\text{Actual tangential for}}{\text{Nominal tangential fo}}$	1.25	1.25	-
3	Load distribution factor	K_m	-	1.5	1.5	-
4	Geometry factor	I	$I = \frac{\sin\varphi\cos\varphi}{2}\frac{i}{i+1}$	0.07	0.07	°
5	Elastic coefficient factor	C_p	$C_p = 0.564\sqrt{\frac{1}{\frac{1-\mu_1^2}{E_1}+\frac{1-\mu}{E_2}}}$	4.204	4.204	$\sqrt{MPa}$
6	Contact ratio	C_R	Refer to Eq. 20	13.55	13.55	-
7	Contact stress	σ_c	Refer to Eq. 21	0.513	0.378	MPa

Table 5: Impact test results

S/No.	Specimens	Cross-sectional Area $(A_n)[mm^2]$	Energy Absorbed (W_n)[J]	Average Energy Absorbed (W_n)[J]	Impact Strength (J/mm^2)
1.	Comp. 1	100	1.78 1.83	1.805	0.01805
2.	Comp. 2	100	1.58 1.57	1.575	0.01575
3.	Comp. 3	100	0.97 0.99	0.980	0.00980
4.	Comp. 4	100	0.56 0.62	0.590	0.005905

4.3 Hardness Test: The Brinell hardness test result, as displayed in table 6, showed similar trend as that of the impact test. The highest and lowest value of 0.274 KN/mm^2 and 0.072 KN/mm^2 was recorded for comp. 1 and comp. 4 respectively.

Table 6: Hardness test results

S/No.	Specimens	Force of Indentation (KN)	Average Force of Indentation (KN)	Indentation Diameter (mm)	Average Indentation Diameter (mm)	Brinell Hardness Number (KN/mm^2)
1.	Comp. 1	18.75 18.92	18.835	8.06 7.92	7.990	0.274
2.	Comp. 2	10.78 11.45	11.115	8.08 8.41	8.245	0.146
3.	Comp. 3	7.42 6.67	7.045	7.10 7.24	7.170	0.140
4.	Comp. 4	4.70 5.13	4.915	8.06 7.91	7.985	0.072

4.4 Tensile Test: From the result of the tensile test carried out, it was observed that the yield strength, ultimate tensile strength and percentage elongation decreased uniformly with increase in the quantity of OPMF while the Young's Modulus increased as more OPMF was added to the samples. The tensile test result is shown in table 7.

Table 7: Tensile test results

S/No.	Specimens	Yield Stress (N/mm^2)	Ultimate Tensile Stress (N/mm^2)	% E (mm)	% R (mm^2)	Poisson Ratio μ	Young Modulus, E (KN/mm^2)
1	Comp.1	5.126	8.544	1.308	0.096	0.073	112.3
2	Comp. 2	3.632	6.054	0.128	0.054	0.422	813.5
3	Comp. 3	2.444	4.074	0.052	0.026	0.480	1347.5
4	Comp.4	1.460	2.433	0.023	0.005	0.217	1819.4

5. Performance evaluation

5.1 Displacement charts

From Figures 5—9, the maximum displacements of the various OPMF composites and that of cast carbon steel are shown to be: 7.519e+005mm for Comp. 1; 8.297e+005mm for Comp. 2; 8.307e+005mm for Comp. 3; 7.938e+005 for Comp. 4; and 4.082e-006mm for cast carbon steel. The color red gives the maximum displacements, while the color blue gives the minimum displacements. Maximum displacement was experienced at the tips of the gear for all compositions and carbon steel. In terms of displacements, comp. 3 stands out.

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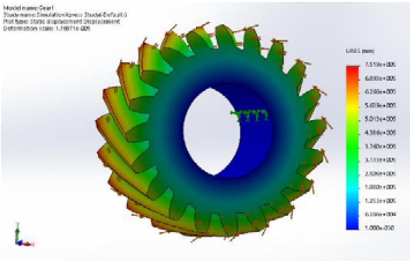

Figure 5: Comp. 1 Displacements

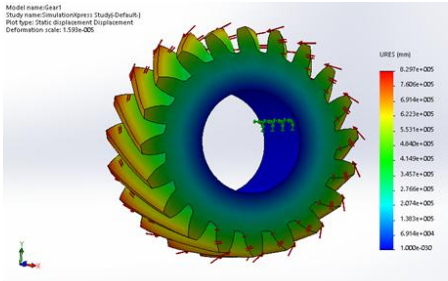

Figure 6: Comp. 2 Displacements

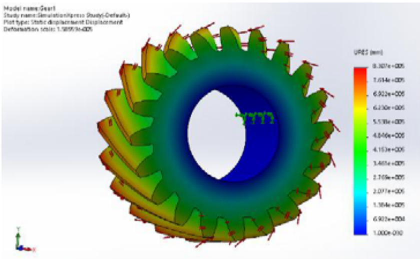

Figure 7: Comp. 3 Displacements

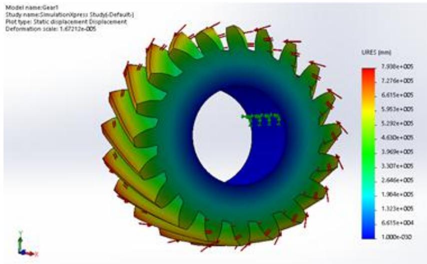

Figure 8: Comp. 4 Displacements

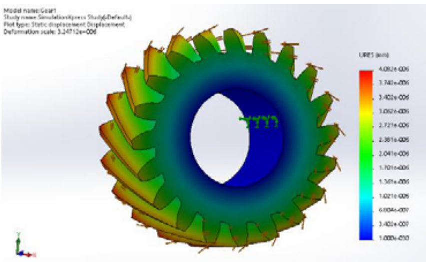

Figure 9: Cast carbon steel Displacements

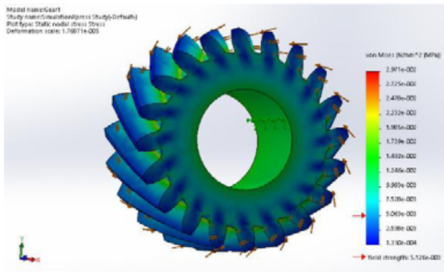

Figure 10 : Comp. 1 Von Mises Stresses

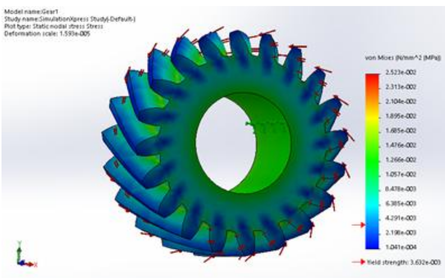

Figure 11 : Comp. 2 Von Mises stresses Stresses

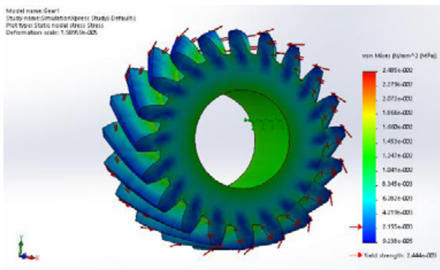

Figure 12 : Comp. 3 Von Mises

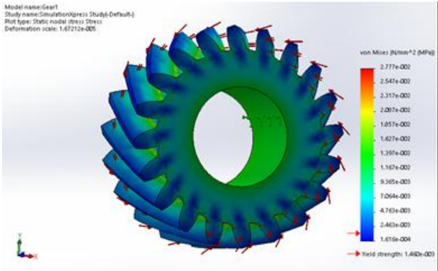
Figure 13 : Comp. 4 Von Mises Stresses

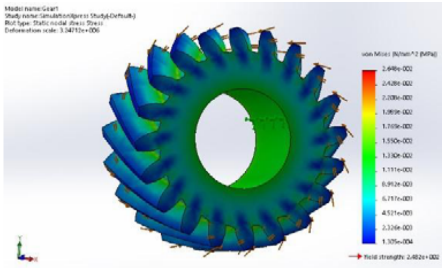
Figure 14: Cast carbon steel Von Mises Stresses

5.2 Von Mises stress chart
From Figures 10—14, the maximum von Mises stress of the various materials are shown to be: 2.971e-002MPa for Comp. 1; 2.523e-002MPa for Comp. 2; 2.485e-002MPa for Comp. 3; 2.777e-002MPa for Comp. 4; and 2.648e-002MPa for cast carbon steel. The von Mises stresses are computed based on the yield strength of the material. Comparing the maximum von Mises stresses of all the samples with their yield stresses as given in table 7, it can be seen that the latter is far higher than the former and so they are not likely to fail when used to design helical gears.

6. Conclusions and recommendations
6.1 Conclusions
The following conclusion was reached at the end of the study:

i. OPMF can be used to improve the mechanical properties of unsaturated polyester resin.
ii. The mechanical properties tested was directly proportional to the weight percent of OPMF added up to the limit used in the experiment.
iii. Although carbon steel had better properties, the material produced was good enough for the purpose of producing helical gears for paper shredding machine.

6.2 Recommendations
From this study the following recommendations can be made:

i. Further studies can be carried out on the OPMF composite to improve the mechanical and physical properties with regards to bi-composites and chemical treatments.
ii. Due to the rigidity and hardness of the OPMF composite, its development can be enhanced and encouraged for applications requiring low impact and tensile forces.
iii. Further studies can also be carried out to investigate and explore mixing techniques and methods better than those employed in this study as this was suspected to have affected the mechanical and physical properties of the OPMF composites produced.

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