RESEARCH ARTICLE

Weibull approach to brake pad wear analysis in the Nigerian market

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Abstract: In this study, we evaluated the wear properties of four brands of brake pad available in the Nigerian market. In particular, we assessed the tribo performance and service life of the brake pads. We purchased four commercial brands of brake pads used in light duty cars and coded them as AU, SN, TY and SM, respectively. A small piece of the brake pad lining materials was carefully chiseled from the back plates to obtain samples for the experiments. We conducted Brinell hardness tests using a tensometer and a pin-on-disc test rig to determine the coefficient of friction and the wear characteristics of the materials. We then correlated the wear on each set of brake pads with the running time and used Weibull's equation to determine average service life. Sample TY exhibited the highest hardness value (29.09) and sample SN the lowest (10.05). The determined coefficients of friction ranged between 0.3–0.36, with sample AU exhibiting the lowest value and sample SM the highest. Sample SN showed the lowest wear rate of 3.53×10^9 g/min, while the wear rates of samples TY, AU, and SM were 5.64×10^8, 8.19×10^9, and 2.10×10^8 g/min, respectively. The relative service life of samples SN, TY, and AU were similar, with average values of 2778.09, 2725.41, and 2717.34 min, respectively, and SM had a relatively low service life (2017.82 min). We conclude that the overall performances of Nigerian brake pads do not meet all the specifications for friction materials used in road vehicle brake linings and pads.

Keywords: Weibull; wear rate; service life; brake pads; friction composite

1 Introduction

No two manufactured parts are exactly the same, no matter how carefully they are made. Although the differences may be small, they do exist and have an important bearing on experimental design analysis. Basic statistical tools are also necessary in the design of engineering experiment analysis.

The Weibull distribution is widely used in the field of engineering because of its versatility. Originally proposed for the interpretation of fatigue data, its use has been extended to many other engineering problems. Although the Weibull distribution is applicable to many engineering situations, its principal use is in the analysis of life data. The real usefulness of the Weibull distribution is its use of straight line plots to represent scattered data.

The Weibull distribution can be applied in situations where the percentage of occurrences may decrease, increase, or remain constant with an increase of the characteristic being measured, such as parts needing repair or wearing out, and the likelihood of failure at various stages of product life. In addition to predicting their lifetime corrosion and overall deterioration, Weibull analysis can be used in product-life test cases of engineering components such as electronic tubes, antifriction bearings, transmission gears, and many other mechanical and electrical components.

The significant effects of wear, particularly in the brake pads of disc brake systems, is the reduction in life span. The greater the wear, the sooner the brake

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pads must be replaced [1]. Investigations of brake-pad wear processes have been conducted primarily experimentally. The wear process is typically evaluated in terms of it wear rate, weight loss, volume loss, and thickness reduction.

A variety of brake pads have been developed [2] and are available commercially, either as original equipment from the manufacturer (OEM) or after-market (replacement) pads. While Weibull distribution has been applied to the analysis of individual brake pad performance, these analyses have not focused on wear.

This paper analyzes the wear characteristics of some commercial brake pads that were purchased randomly using a statistical tool. We subjected samples of the purchased pads to wear experiments and then comparatively analyzed the results using the Weibull distribution approach.

2 Materials and methods

2.1 Hardness test

To determine the resistance of brake lining material to indentation, we conducted a Brinell hardness test, using a tensometer (Model 10055, Monsanto, UK), by pressing a hardened steel ball into a test specimen. According to ASTM specifications (www.astm.org, 2012), we used a 10-mm diameter ball.

In the tests, the diameter of the ball D was constant at 10 mm, and the load applied W was maintained at 300 kg. The specimen was mounted in the holding device and the ball location was fixed. A hand wheel was rotated so that the ball moved toward the specimen. The desired load was applied mechanically by a gear-driven screw pressing the ball into the specimen. The diameter of the indentation made in the specimen by the pressed ball was then measured using a veneer caliper. The indentation diameter d was measured in two places at right angles to each other, and the average of these two readings was taken. We then calculated the Brinell hardness number (BHN), which is the pressure per unit surface area of the indentation in kg per square meter, using Eq. (1):

$$\text{BHN} = \frac{w}{(\pi D/2)(D - \sqrt{D^2 - d^2})} \tag{1}$$

where w is the load on the indenter in kg, d is the average measured diameter of indentation in mm, and D is diameter of the steel ball (mm).

2.2 Tribological characteristics of the brake pads

Investigations of the tribological characteristics of the brake pads were conducted using dry friction on a pin-on-disc tester, as shown in Fig. 1. The sample was mounted perpendicularly on a rotating disc and was driven against a steel counterpart that was fixed on a lever mechanism. The coefficient of friction of each sample was determined using the following expression:

$$\mu = \tan\theta \tag{2}$$

In this study, we consider two important parameters: load and time. While speed was kept constant at 300 rpm, we varied the load from 100 to 500 g in experimental runs of 10 to 40 min. The wear track formed on the rotating sample was a circle of radius 14 mm, and all parameters were kept constant in each experimental run. We based our method on that used by Rabishankar [3] in the study of the wear behavior of a rice-husk ceramic composite and by Jaykant [4] in the study of the wear properties of carburized mild steel samples.

After each test, we only considered the mass loss of the sample as wear, and this was determined by weighing the specimen before and after the test using a precision electronic scale (Model TB153, SNR 1117220699, Mettler Soledo, Switzerland).
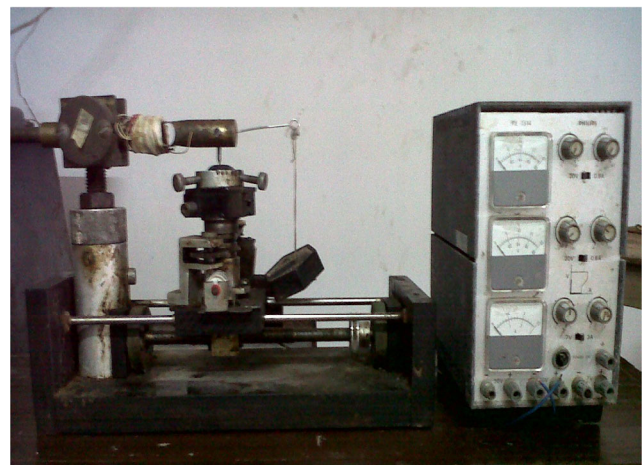

Fig. 1 The pin-on disc wear tester machine.

The mass loss was then converted to wear volume loss, based on the density of the various commercial brake pad samples. The wear rate was then calculated [5] as

$$W_r = \frac{W_v}{S_d} \qquad (3)$$

where W_r is the wear rate (g/min), W_v is the wear volume, and S_d is the sliding distance (m).

2.3 Computation of service life

Next, we used the estimated degrees of wear in the four brake pad samples to project the service life. When the sample had not failed, we estimated the service life [6] as shown in Eq. (4):

$$T = \frac{t_1}{\Delta D} D_{Rest} + t_1 \qquad (4)$$

where T is the (life time variable) operating time in minutes, t_1 is the moment at which the degree of wear was measured, ΔD is the degree of wear, and D_{Rest} is the brake pad thickness remaining.

All these variables were used to determine the parameters of the Weibull functions. We derived the expected service life values *(T)* for the four commercial brake pad samples from the Weibull plots. The Weibull parameters obtained from the plot were then used to predict service life, using Eq. (5):

$$F(x) = 1 - \exp\left[-\left(\frac{x - x_0}{\theta - x_0}\right)^b\right] \qquad (5)$$

where x is the expected life projection in days, x_0 is the assumed lower bound, θ is the characteristic life, and b is the Weibull slope.

The estimated operating time *(T)* for each brand of brake pads is an accumulated time, which is a life variable obtained from Eq. (2). We can make an adequate deduction regarding the failure characteristics of the component in question using the Weibull evaluation. Instead, of the mean, the characteristic life *T*, at which 63.2% of the components fail, is specified from a linearized Weibull distribution. This Weibull analysis approach was also used as a prediction of tensile failure for Kevler-29 fiber materials [7].

In the linearized form:

$$ln\left[ln\left(\frac{1}{1-F(x)}\right)\right] = bln(x - x_0) - bln(\theta - x_0) \qquad (6)$$

and compared with a linear equation of the form;

$$y = mx + c \qquad (7)$$

$$b\ln(\theta - x_0) = c \qquad (8)$$

$$\theta = x_0 + \exp(c/b) \qquad (9)$$

where Eq. (6) is the intercept of the linear equation and Eq. (7) is the shape parameter.

According to Roninnger [6], it is well recognized that if:

$b < 1$, early-type failures (premature failures), e.g., due to production/assembly faults, will prevail;

$b = 1$, chance-type failures (random failures) and a constant failure rate, with no connection to the actual life characteristic, will prevail;

$1 < b > 1.4$, time-dependent (aging effect) failures within the design period will prevail.

3 Results and discussion

3.1 Hardness test result

The BHN values for the four brake pad samples are shown in Table 1. Statistical analysis results (Table 2) for the four experimental samples, using one-way analysis of variance (ANOVA), shows significant difference samong the four samples at $p \leqslant 0.05$. Evidently, only the TY samples meet the Standards Organization of Nigeria (SON) recommendation of a BHN of at least 27 (NIS 323, 1997).

3.2 Tribological behavior of the brake pads

Based on the obtained coefficients of friction shown in Table 1, the sample SM friction composite has a higher coefficient of friction on mild steel, in the 0.36 range, compared to those of samples AU, SE, and TY, which are within the 0.30 to 0.35 range. These values are in good agreement with SON specifications, which recommend a friction coefficient of at least 0.3. Therefore, the four commercial friction linings meet this SON specification.

Table 1 Physical-mechanical properties of the sampled brake pads.

Test	Sample size	Brands				
		TY	AU	SN	SM	SON[+]
BHN	3	29.09 (1.79)[*]	22.31 (0.98)	10.05 (2.30)	15.24 (0.88)	$\leqslant 27$
Friction coefficient on steel	3	0.35 (0.14)	0.30 (0.30)	0.31 (0.24)	0.36 (0.20)	$\leqslant 0.3$
Average wear rate (g/min)	5	5.64×10^8 (0.0008)	8.19×10^9 (0.0008)	3.53×10^9 (0.0078)	2.10×10^8 (0.0047)	

* Numbers in parenthesis are the standard deviations. SON[+]: Standard Organization of Nigeria.

Table 2 Multiple comparisons of the BHN values of the four commercial brake pads.

Pad type (I)	Pad type (J)	Mean difference (I-J)	Significance	95% confidence interval	
				Lower bound	Upper bound
AU	SN	12.2733333[*]	0.000	8.100270	16.446397
	TY	−6.7800000	0.004	−10.953063	−2.606937
	SM	7.0666667	0.003	2.893603	11.239730
SN	AU	−12.2733333	0.000	−16.446397	−8.100270
	TY	−19.0533333	0.000	−23.226397	−14.880270
	SM	−5.2066667	0.017	−9.379730	−1.033603
TY	AU	6.7800000	0.004	2.606937	10.953063
	SN	19.0533333	0.000	14.880270	23.226397
	SM	13.8466667	0.000	9.673603	18.019730
SM	AU	−7.0666667	0.003	−11.239730	−2.893603
	SN	5.2066667	0.017	1.033603	9.379730
	TY	−13.8466667	0.000	−18.019730	−9.673603

The average wear, as presented in Table 1 for the 5 sample specimens, shows that sample SN had the lowest wear rate of 3.53×10^9 g/min, while samples TY, AU, and SM had rates of 5.64×10^8, 8.19×10^9, and 2.10×10^8 g/min, respectively. We estimated the wear rates of the four commercial brake pads under different loads from the slope of the wear plotted against time. The four brake pads showed different wear rate trends (in µg/min in Table 3) under different loads. For a 100 g

load, the wear rate of sample SM (0.02) was lower than that of SN and TY, and higher than that of AU. As load increased from 200–500 g, AU showed the least rate of wear (0.16) at 400 g, and the highest wear rate was observed at 500 g in sample SN. Statistical analysis results show that the mean wear rates of the four experimental brake pads are not significant at the $\alpha = 0.01$ confidence level with $p \leqslant 0.52$. The correlation of the wear of the four commercial brake pads (Y)

Table 3 Wear rates for the four commercial brake pads from the polynomial curves.

Load (g)	Wear rates (µg/min)			
	TY	AU	SN	SM
100	79.9	4,086	59.9	0.02
200	400	1.97	11.07	1.10
300	2,000	2.33	2.26	2.93
400	140	0.16	162.99	10,500
500	200	2.69	17,400	2.2

with time (*X*) is a third-order polynomial curve, as shown in Figs. 2–5, and the corresponding coefficients of determination r^2 are shown in Table 4, with their corresponding equations for the most significant values of r^2.

3.3 Predicted characteristic life based on Weibull analysis

The calculated results of the expected service life of the four brake pad samples in this study were projected from their degree of wear using Eq. (5). Based on the

test results, the relative service lives of samples TY, SN, and AU are similar, with values of 2725.41, 2778.09 and 2717.34 min; while the expected service life of sample SM was lowest (2017.82 min). This shows that the AU sample will last longer than samples SM, SN, and TY in identical field applications. However, the actual service life of the friction composites must be determined in drag tests using inertial dynamometers (full-scale and sub-scale hardware) and laboratory tribometers in tests involving programmed changes in contact pressure, speed, temperature, and repetitive contacts to simulate vehicle braking events (SAE J 1652). These facilities were not available for this study.
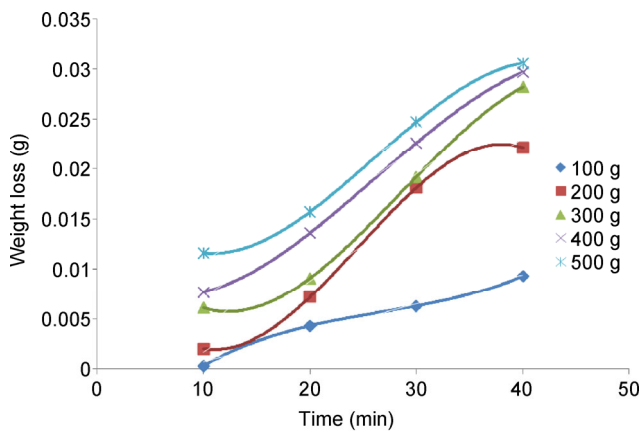

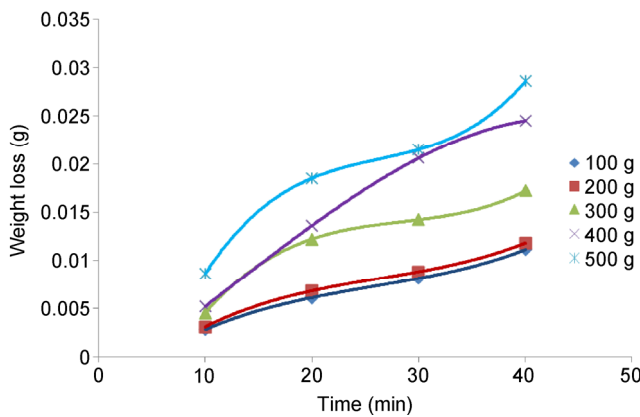
Fig. 2 Weight loss against time for sample TY.

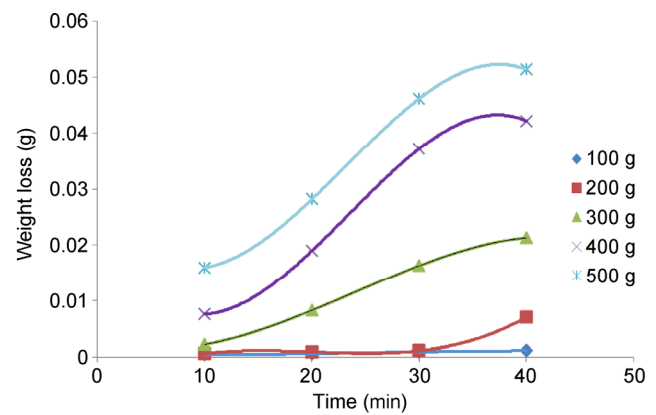**Fig. 3** Weight loss against time for sample SN.

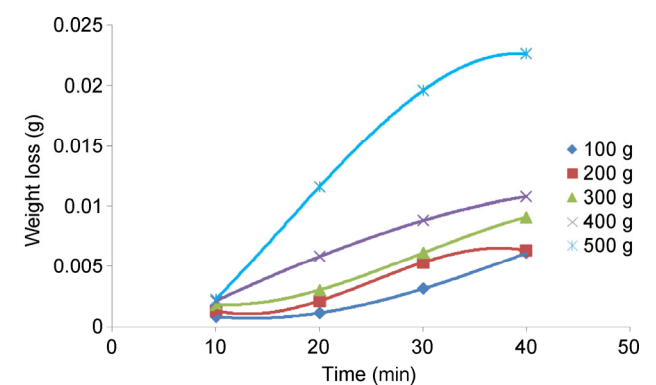**Fig. 4** Weight Loss against Time for Sample SM.

Fig. 5 Weight Loss against Time for Sample AU.

Table 4 Correlation of weight loss and loading time for the commercial brake pads.

Brand	Load (g)	Equation	Correlation coefficient (r^2)
AU	400	$Y = -5 \times 10^{-8}x^3 - 5 \times 10^{-5}x^2 + 0.0004x - 0.002$	0.9999
SN	400	$Y = -3 \times 10^{-7}x^3 + 1 \times 10^{-5}x^2 + 0.0007x - 0.0029$	0.9993
TY	400	$Y = -8 \times 10^{-7}x^3 + 7 \times 10^{-5}x^2 - 0.0008x + 0.0099$	0.9943
SM	300	$Y = -8 \times 10^{-7}x^3 + 6 \times 10^{-5}x^2 - 0.0006x + 0.0029$	0.9944

4 Conclusion

In this study, we examined the physical-mechanical and tribological characteristics of some locally available brake pads in Nigeria to gain a better understanding of the tribo performance of Nigerian brake pads. From the analysis results, we can make the following conclusions: sample TY exhibited the highest hardness value (29.09) and sample SN the lowest (10.05). The determined coefficient of friction of the samples ranged from 0.3–0.36, with sample AU exhibiting the lowest value and sample SM the highest. The brake pads exhibited different wear rates, ranging from 3.53×10^9–5.64×10^8 g/min as load increased, and relative characteristic lives ranging from 2017.82–2778.09 min of operation against a hardened steel surface.

Consequently, the study results revealed that the overall experimental performance of Nigerian brake pads do not meet all the standard specifications recommended by SON for friction materials in road vehicle brake linings and pads (NIS 323).

We recommend that appropriate machinery be installed according to the Standards Organization of Nigeria to counter the proliferation of substandard brake pads in the Nigerian marketplace.

Acknowledgement

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