

Effect of Nitrile Butadiene Rubber (NBR) on Mechanical and Tribological Properties of Composite Friction Brakes

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ABSTRACT

The aim of this research is to investigate the effect of nitrile butadiene rubber (NBR) as fillers on the mechanical and tribological properties of composite friction brake. Four compositions of specimens, having different NBR volume fractions (0, 4, 8, and 12 %), were manufactured. We assessed their mechanical properties by the three-point bending method according to ASTM D790 standard. We measured their tribological properties under various contact pressures and sliding speeds using a pin on disc tribometer. The results showed that NBR could improve the mechanical properties of composite friction brake materials, and the tribological properties such as wear resistance and friction coefficient increased with increasing NBR volume fraction.

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1. INTRODUCTION

Friction brake materials are widely used for automotive and mass transportation applications such as disc pad and brake block. They serve to reduce the vehicles' speed with a friction mechanism that converts kinetic energy into heat energy. Polymer composites have been commonly used for manufacturing various types of brake linings, ranging from those used in light vehicles to those in heavy vehicles.

The composite friction brake consists of matrix or binder, reinforcing materials (fibrous or non-

fibrous), friction modifiers, and fillers [1,2]. The influence of ingredients is very complex on their tribological properties. The formulations have been developed through various trial-and-error experimental procedures [3].

The filler materials in the composite friction brake have several functions: to reduce production costs, to improve the manufacturing process, and to stabilise the friction coefficient [4,5]. The addition of fillers will lead to an increase in thermal conductivity, which will lower the wear rate during high temperatures in the contact area [6]. Typically, the materials

used as fillers are mineral, metal, ceramic, cashew dust, and rubber [7]. Cashew dust and rubber materials also reduce noise because of their good viscoelastic characteristics [8]. The carbon black reduces specific wear of ethylene/propylene/diene (EPDM) rubber [9]. Furthermore, rubber combined with resin can improve mechanical properties such as hardness, toughness, stiffness, abrasion resistance, and wear resistance after a curing process [10].

Nitrile butadiene rubber (NBR) is a copolymer from acrylonitrile and butadiene [11]. In modern industrial applications, NBR is a polymer material known as an elastic compound of organic macromolecules. It is highly resistant to fatigue and wear, and has good chemical stability, oil resistance, and vibration absorption [12,13]. This polymer is commonly used as a stabiliser to increase the cross-link and to improve the wear resistance of composite friction brake materials containing asbestos fibres [4]. Ghosh et al. [14] reported that NBR could modify phenolic resin and improve friction coefficient performance with the addition of graphite. In addition, NBR improves interfacial strength between fibre and matrix, which in turn improves the mechanical properties of composite materials [15].

In this research, we studied the effect of NBR on mechanical and tribological properties of composite friction brakes. The volume fraction of NBR was varied to understand its effect on the mechanical and tribological properties of composite brakes. Fourier transform infrared (FTIR) spectroscopy analysis, thermal gravimetric analysis (TGA), bending test, and friction test were conducted to investigate the physical, mechanical, and tribological properties of composites. Bending test was chosen because the material used for making brake blocks requires high flexural strength.

2. MATERIALS AND METHODS

2.1 Specimen fabrication for bending and friction test

In this study, the cantala fibres were used as reinforcement. Cantala fibre is a natural fibre obtained from *Agave cantala* Roxb. The

composite material was composed of a basic mixture, NBR, and CaCO₃. The basic mixture consisted of phenolic resin (25 %), cashew dust (10 %), fly ash (5 %), cantala fibre (8 %), and graphite (15 %). Variations in % volume of NBR and CaCO₃ are shown in Table 1.

Table 1. Composition of specimen.

Composition	% Volume		
	Basic mixture	NBR	CaCO ₃
1	63	0	37
2	63	4	33
3	63	8	29
4	63	12	25

The specifications of the ingredients were:

Novolac phenolic resin:

SUMILITERESIN® PR- 217 I, powder size = 106 µm, melting point = 90 °C (from PT, Indopherin Jaya, Indonesia).

Cashew dust:

Powder size = 100 mesh (from PT, Java Tohuku Industries, Indonesia).

NBR:

Baymode® N XL 38.43, powder size = 120 µm, density = 1.04 g/cm³ (from LANXESS Corp).

Fly ash:

F-class with particle size of 100 mesh.

Cantala fibre:

Alkaline-treated fibre in 5 %wt of NaOH solution for 4 hours, diameter = 131 µm, length = 3–4 mm.

Graphite:

Powder size = 100 mesh, purity = 87 %.

The initial process of specimen fabrication was to mix all ingredients, except fibre, using a blender for 5 minutes that has been weighted according to the composition. The mixture was then added with fibre and mixed again for 5 minutes. A specific amount of the mixture was loaded into a cavity mould to fabricate specimen. Pre-forming was carried out by pressing the mixture under pressure of 20 MPa for the bending test specimen and 40 MPa for the friction test specimen. The pre-formed specimens were placed in the hot mould and

then pressed under pressure of 20 MPa for the bending test specimen and 40 MPa for the friction test specimen at 160 °C. At the initial stage of hot moulding, gas disposal was carried out six times every 10 seconds and then pressed continuously for 9 minutes. During hot moulding, ammonia gas was generated by the reaction of phenolic resin and hexamine [7]. The hot-moulded specimens were then post-cured in the oven. The post-curing process had the following stages: heating from room temperature (29 °C) to 140 °C for 1 hour, heating from 140 °C to 180 °C for 6 hours, and then cooling slowly to room temperature.

2.2 Materials test

a. Fourier transform infrared (FTIR) spectroscopy

FTIR spectroscopy analysis using SHIMADZU IR Prestige-21 analyser was used to check the characteristics of functional groups of NBR, resin, and cross-link bonds that occurred in phenolic resin NBR 4 %, 8 %, and 12 %. FTIR measurement was carried out at room temperature and at a wavelength range of 3000–1000 cm⁻¹.

b. Thermogravimetric analysis (TGA)

TGA was carried out using TGA/DSC Linseis test pt 1600. Specimens weighing 10–25 mg were heated to 550 °C with nitrogen at a flow speed of 60 ml/min and with a heating rate of 20 °C/min. Nitrogen flow was used to remove all corrosive gases involved in degraded material and to avoid thermo-oxidative degradation.

c. Mechanical Properties

Mechanical properties such as flexural strength and modulus of elasticity were measured using a JTM-UTS 510 machine with a support length of 80 mm, crosshead speed of 5 mm/min, and load cell capacity of 100 kg. Five specimens of each formulation with varying sizes, as shown in Fig. 1, were tested.

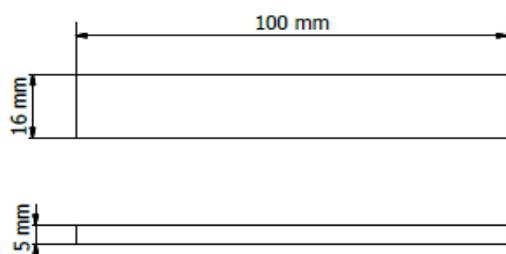


Fig. 1. Specimen size.

d. Friction test

The tribological characteristics of the composite were evaluated by using a pin on disc tribometer, as shown in Fig. 2. The disc material was DIN X 153 CrMoV 12 steel with a hardness of 54 RC. In this research, the composite was developed for brake block materials. On a railway vehicle, tread braking is carried out by pressing the brake block against wheel tread. The railway wheel is made of steel.

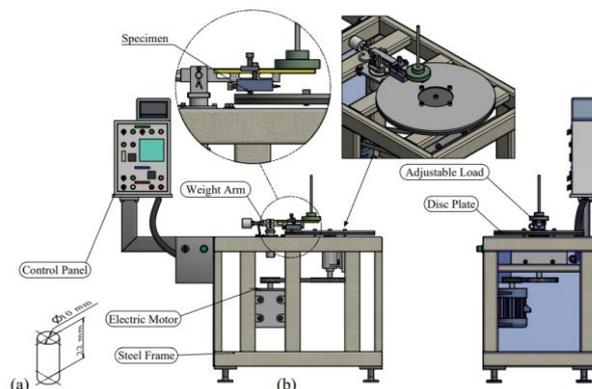


Fig. 2. Friction test apparatus schematic: (a) specimen size, (b) pin on disc tribometer.

Table 2. Variation of friction test parameter.

Variation of friction test parameter	Sliding speed (m/s)	Contact pressure (MPa)
Variation of contact pressure	3 ; 12	0.25 ; 0.5 ; 0.75 ; 1
Variation of sliding speed	3 ; 6 ; 9 ; 12	0.25 ; 1

We conducted the friction test by pressing the specimen against the rotating disc. The adjustable load was equipped to set the normal load (contact pressure) of the friction test. During testing, the load cell measured the friction forces that occurred between the surface of the specimen and the disc. The friction force that resulted from the friction testing process was then recorded by using data acquisition system (Advantech USB-4176). Variations of the parameters of friction test are shown in Table 2. We carried out the friction test on two specimens for each composition and thrice for each specimen. The coefficient of friction was calculated using Eq. (1), where F_f is the friction force, and F_N is the normal load (N).

$$\text{Coefficient of friction} = \frac{F_f}{F_N} \quad (1)$$

We performed the friction test for specific wear measurements at contact pressure of 1 MPa, sliding speed of 12 m/s, and sliding distance of 5338 m. The specific wear was calculated using Eq. (2), where W_s is the specific wear ($\text{mm}^3/\text{N.m}$), ΔV is the lost volume (mm^3), and L is the sliding distance (m).

$$W_s = \frac{\Delta V}{F_N L} \quad (2)$$

3.1 RESULTS AND DISCUSSION

a. Fourier transform infrared (FTIR) spectroscopy

We estimated the occurrence of crosslink bonds between phenolic resin functional groups with NBR by analysing FTIR spectra. The results of FTIR spectroscopy specimens from NBR, phenolic resin, phenolic resin/4% NBR, phenolic resin/8% NBR, and phenolic resin/12% NBR are shown in Fig. 3.

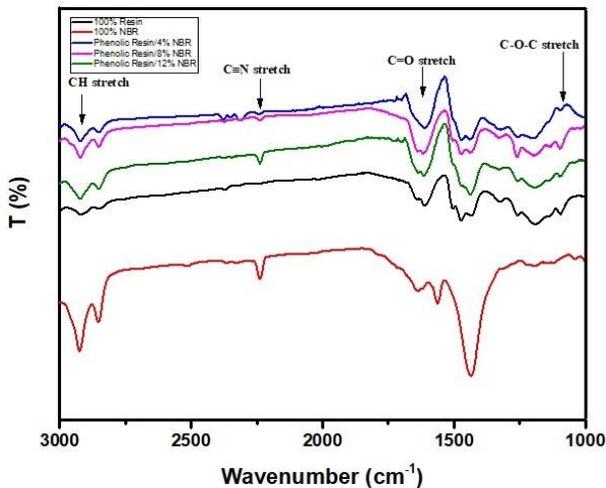


Fig. 3. FTIR spectra of phenolic resin, NBR, phenolic resin/4% NBR, phenolic resin/8% NBR and phenolic resin/12% NBR.

There are several peak characteristics of the spectra. At the peaks of 2941 cm^{-1} and 2944 cm^{-1} , there are CH absorption of phenolic resin [16] and NBR [17], respectively. The absorption area of 2233 cm^{-1} , which is a functional group of $\text{C}\equiv\text{N}$ stretch [18] of NBR, also appeared in the resin mixture with 4, 8, and 12 % NBR. The peaks of absorption at the area of 1645 cm^{-1} and 1719 cm^{-1} show a bond of C=O stretch on phenolic resin [16] and NBR [18], respectively. The same absorption areas with higher peaks appear on composites 4,

8 and 12 % NBR. The area absorption peak of 1109 cm^{-1} is related to the C-O-C group [19]. It indicates that the addition of NBR in composite causes partial cross-linking between NBR and phenolic resin to form C-O-C bond [20] because of the heating (post-curing) process. Curing with the appropriate temperature will improve the mechanical properties of the composite because it increases the number of cross-linking bonds in the composite.

b. Thermogravimetric analysis (TGA)

Figure 4 shows the results of TGA testing of phenolic resin, NBR, and phenolic resin mixed with 4, 8, 12 % NBR, and composite 12 % NBR. It also shows the temperature and mass degradation that occur on each specimen. The initial temperature at which the material undergoes mass degradation is known as the onset temperature [5].

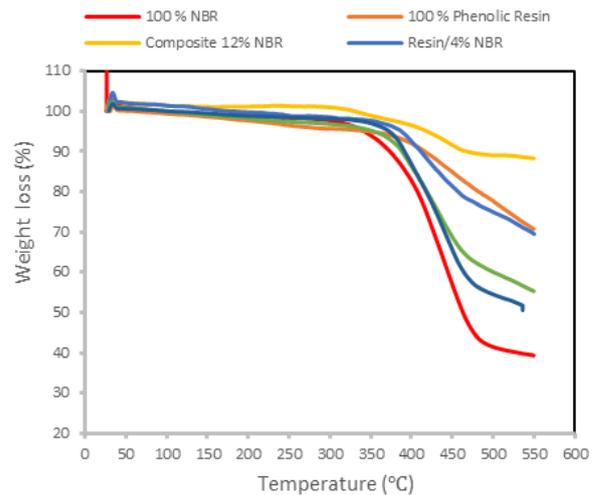


Fig. 4. TGA analysis of specimens.

Table 3. Weight loss and onset degradation temperature.

Specimen	Weight loss (% at 550 °C)	Weight loss at T onset	
		T onset (°C)	Weight loss (%)
100% NBR	-60.7	375	-2.4
100% Phenolic Resin	-29.3	390	-5.5
Resin/4 % NBR	-30.5	375	-2.5
Resin/8 % NBR	-44.7	375	-4.5
Resin/12 % NBR	-49.4	375	-2
Composite 12 % NBR	-11.8	370	-0.8

Table 3 shows that the onset temperature of 100 % phenolic resin specimen is 15 °C higher than 100 % NBR specimen. Resin/4% NBR, Resin/8% NBR and Resin/12% NBR have the same onset

temperature. Thermal decomposition of resin materials, NBR and composite with 12% NBR occurs in several stages. Reduction in mass takes place at a temperature of 300 °C to 500 °C due to degradation of resin and NBR [21]. Abdolmohammadi [22] reported that CaCO₃ material was degraded at a temperature range of 720 °C to 840 °C.

c. Mechanical properties

Figure 5 shows the effect of NBR on the flexural strength of a composite friction brake. The results indicate that flexural strength increases along with the increasing NBR volume fraction. The mechanical properties of a composite depend on the interactions between the fibre and matrix in the interface area. The NBR improves interfacial adhesion between the matrix and fibre [23] such that it increases the composite flexural strength. A previous study had reported that resin modified with NBR could increase the composite tensile strength [14].

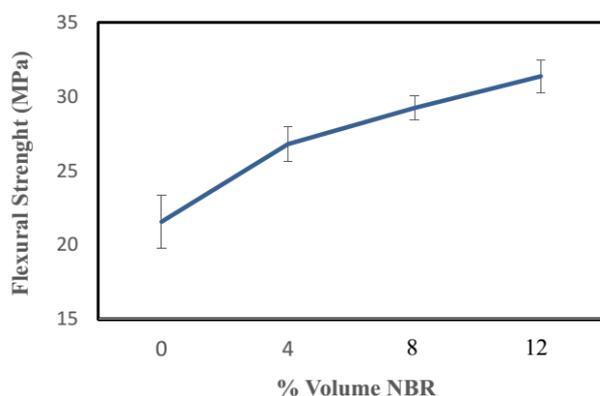


Fig. 5. Effect of NBR on the composite flexural strength.

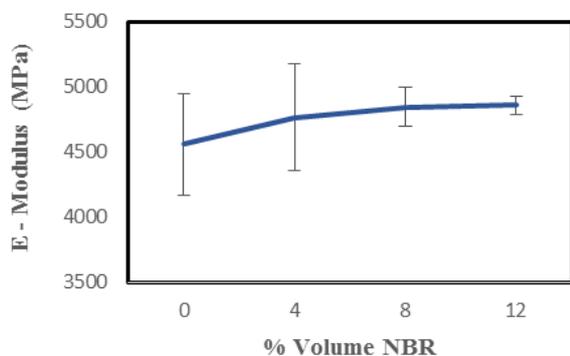


Fig. 6. Effect of NBR on elastic modulus of composite.

Figure 6 shows the relationship between the elastic modulus of composite friction brake and the NBR volume fraction. Composite elasticity modulus increases along with the increase of NBR

volume fraction. This phenomenon takes place because NBR increases the interfacial adhesion between the fibre and matrix, and hence the mechanism increases the ability to transfer the load from the matrix to the fibre [15].

Figures 7 and 8 show the results of SEM observations about the fracture surface of the specimen without NBR and with 12 % NBR that are obtained from the bending test. Figure 7 reveals the fracture surface of the specimen without NBR. The image indicates that the composite fails due to fibre pull-out. The strength of a fibre-reinforced composite is affected by an applied load that can be transmitted to the fibres by the matrix. It is influenced by the fibre–matrix bond strength (interfacial adhesion between the fibre and matrix). When the composite is the applied load, the matrix will deform around the fibre because of the low fibre–matrix bond strength. This condition causes a fibre pull-out on the composite, as shown in Fig. 7.

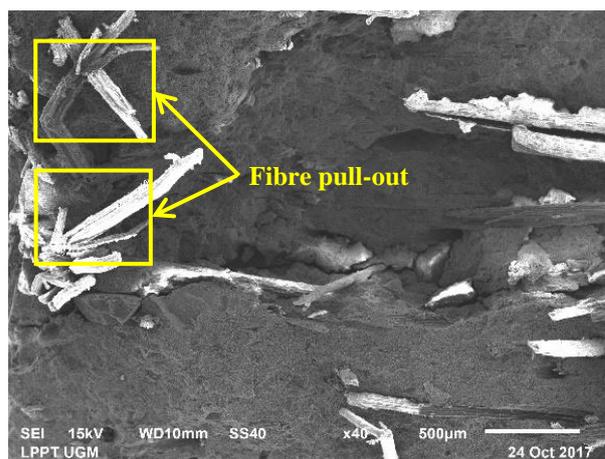


Fig. 7. SEM image of fracture surfaces on specimen without NBR.

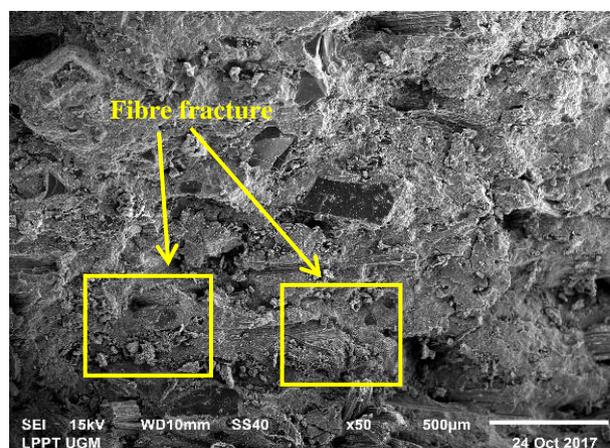
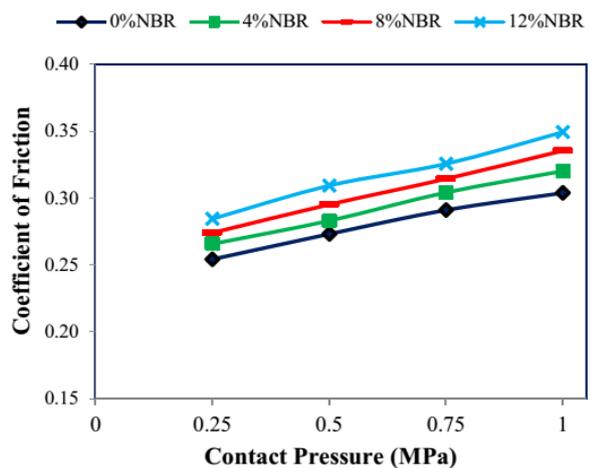


Fig. 8. SEM image of fracture surfaces on specimen 12 % NBR.

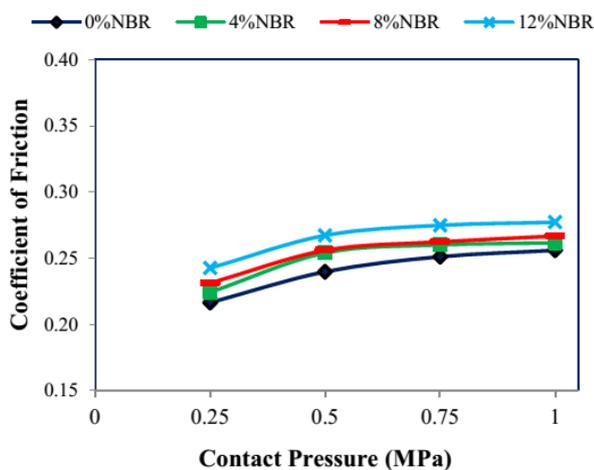
Figure 8 reveals the fracture surface of specimen 12 % NBR which has the highest flexural strength. There are many fibre fractures at the fracture surface. Composite failure begins as the fibres start to fracture when interfacial adhesion between the fibre and matrix is greater than the fibre strength. This condition allows the fibre to maximise the composite strength. Fibre fracture as shown in Fig. 8 indicates that NBR increases the fibre-matrix bond strength. However, a few fibre pull-outs are also found in this fracture surface.

d. Effect of Contact Pressure and NBR on Coefficient of Friction

Figure 9 shows the coefficient of friction of the composite material as a function of contact pressure at a constant friction speed of 3 m/s and 12 m/s.



(a)



(b)

Fig. 9. Effect of NBR and contact pressure on coefficient of friction at a constant sliding speed of: (a) 3 m/s, and (b) 12 m/s.

It is observed that the addition of the NBR increases the coefficient of friction of composite for each contact pressure variation. The phenomenon is due to the fact that there is adhesion in the area of contact between NBR and counter disc, which contributes to the friction. NBR in composite also increases the bonding strength between matrix and other ingredients so that the shear stress on interface sliding contributes to the high magnitude of the coefficient of friction. The increase in the friction coefficient with increasing rubber component and contact pressure is also reported by a previous study [24]. Modification of resin with NBR increases the coefficient of friction and decreases the fade value of the composite [25]. The actual contact between the specimen and the disc surface increases with a rise in contact pressure such that this condition increases the friction coefficient [26]. Increasing the actual contact leads to heightened interaction of hard particle in the specimen with asperities of disc surface. However, in contrast to this result, previous researchers have reported that the coefficient of friction of composite brakes decreased with a rise in contact pressure [27,28].

The presence of wear debris that compacted at contact surface also causes an increase in the actual contact area at the interface. Friction at the contact surface results in material which is easily worn-out, such as resin, filler and lubricant, changing into wear debris. The debris produced by friction between the disc and composite is trapped and attached to materials that are more resistant to friction such as fibre and abrasive materials. Then, the debris is compressed by heat and pressure that are produced at the contact area or contact plateau [1].

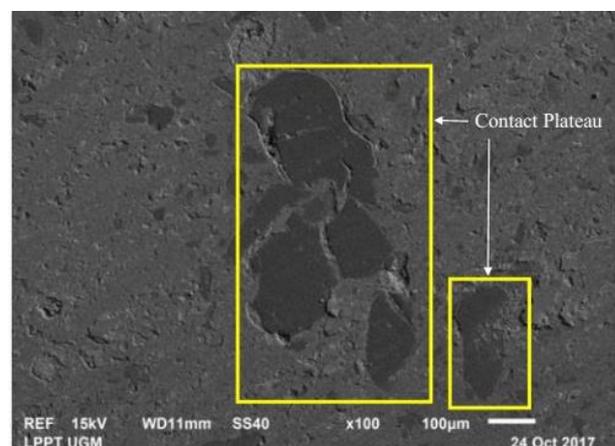


Fig. 10. SEM observation of contact plateau on specimen 0 % NBR.

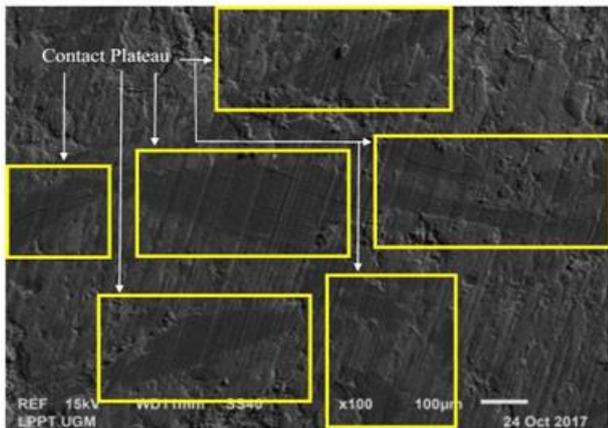


Fig. 11. SEM observation of contact plateau on specimen 12 % NBR.

The SEM observations depicted in Fig. 10 and Fig. 11 show the differences in the contact plateau of 0 % NBR and 12 % NBR specimen. More contact plateaus are formed on the surface of the 12 % NBR specimen compared to the 0 % NBR specimen. The contact plateaus are formed by organic materials such as NBR, which have been compacted during friction [14].

e. Effect of Sliding Speed and NBR on Coefficient of Friction

Figure 12 shows the coefficient of friction of the composite material as a function of sliding speed with a constant contact pressure of 0.25 MPa and 1 MPa. The results showed that the composite brake friction coefficient decreases with a rise in sliding speed. This phenomenon occurs because the increasing sliding speed raises the temperature on the contact surface between the specimen and the disc. Blau and McLaughlin reported that high interface temperatures would reduce the shear strength of brake pads and result in reduction of the frictional force between the brake pads and discs [29].

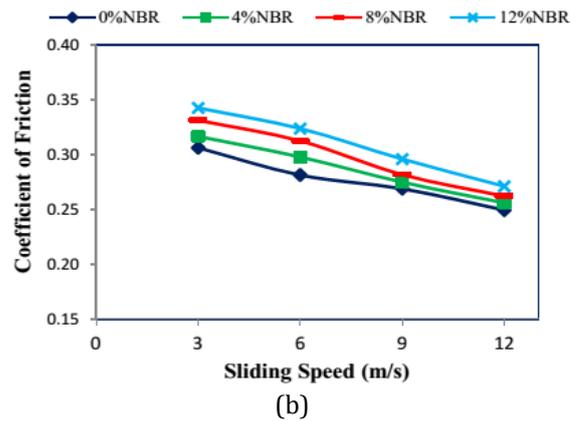
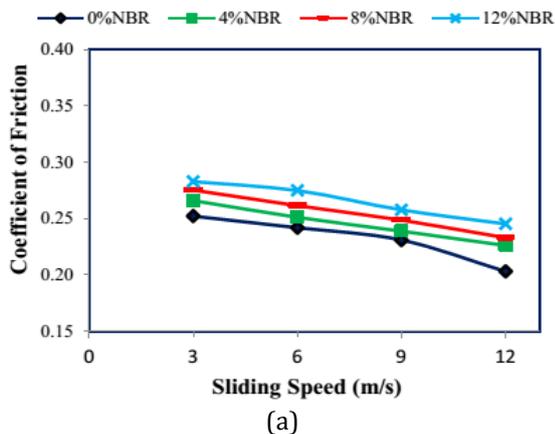


Fig. 12. Effect of NBR and sliding speed on coefficient of friction at a constant contact pressure of: (a) 0.25 MPa, and (b) 1 MPa.

The strength of the material on the contact surface decreases as temperature increases. This condition leads to the easy rupture of interfacial bonds between resin and other ingredients at higher sliding speeds. Rubber material loses its physical and mechanical properties quickly when the temperature reaches more than 270 °C [30].

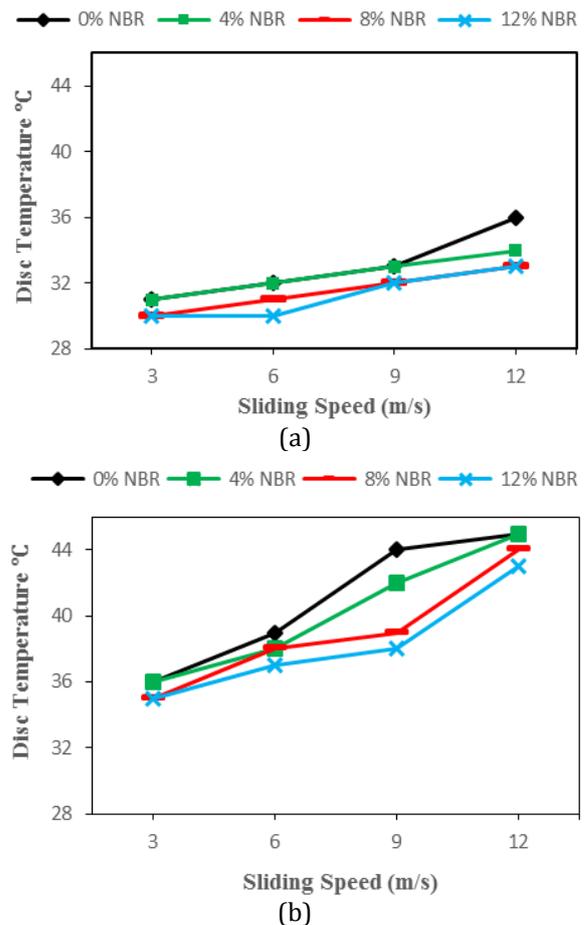


Fig. 13. The effect of sliding speed and NBR on disc temperature at a constant contact pressure of: (a) 0.25 MPa, and (b) 1 MPa.

Figure 13 shows the effect of sliding speed on temperature on the disc surface. The disc temperature was measured at the end of the friction test. The temperature of the disc surface increases with a rise in the sliding speed. Figure 13 shows that increasing the NBR content in the composite tends to decrease the disc temperature.

f. Effect of NBR on Specific Wear

Figure 14 shows the effect of NBR on the specific wear of composite. This specific wear decreases along with the increase in NBR volume fraction. On decreasing the specific wear by increasing the NBR volume fraction, it was observed that the wear resistance of composite was better with NBR than it was without NBR. During the friction test, the composite surface is subjected to mechanical and thermal load due to friction. This load converts some parts of the composite at contact surface, such as matrix and other ingredients, into wear debris.

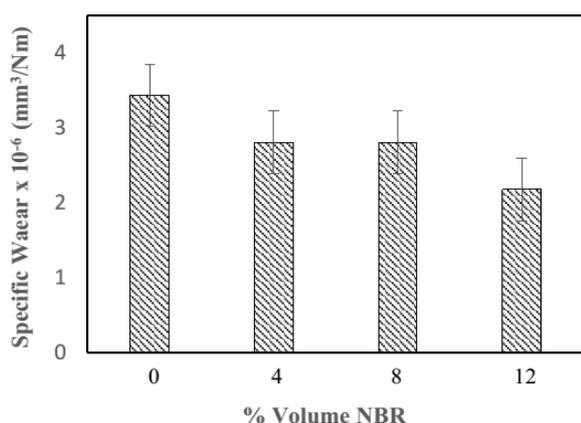


Fig. 14. Effect of NBR on specific wear.

Wear debris are produced by abrasive wear mechanism, debonding of reinforcement fibre, or other wear mechanisms. The debonding of the ingredients from the matrix is affected by the bonding strength between the ingredients and the matrix. NBR improves interfacial adhesion between matrix and other ingredients in such a way that ingredients in the composite are held stronger by the matrix. This condition causes NBR to have an effect in terms of reducing the wear debris. In addition, the curing process conducted on resins and rubber materials can improve abrasion resistance, tensile strength and chemical resistance [11]. The quantity of acrylonitrile (acrylonitrile content) can increase wear resistance and heat resistance [31]. The

acrylonitrile content in the NBR used in this study is 34 %.

4. CONCLUSION

The objective of this study was to determine the effect of NBR on the mechanical and tribological characteristics of composite friction brakes. The conclusions are as follows:

- The flexural strength and elastic modulus of the composite increased with a rise in NBR volume fraction.
- NBR had a role in increasing the coefficient of friction and decreasing specific wear of the composite friction brake.
- NBR was able to form crosslink bonds with phenolic resin. The formation of crosslinking bonds could improve the mechanical properties and friction characteristics of the composite friction brake.

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