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Effect of Volume Fraction and Matrix of Forged Fibreglass Composite on Wear Rate for Brake Pad Application

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ABSTRACT

Brake pads are one of the components of motorised vehicles that play an important role in slowing down or stopping the vehicle. This study aims to determine the effect of using variations in volume fraction and type of resin/matrix used on the wear rate that occurs, and the temperature generated during braking by utilising glass fibre as reinforcement. The research method uses experiments where the manufacture of brake pads composites was carried out by mixing all the ingredients then poured in a mold with a curing time of 1 day and the next process was testing using a disc brake system braking simulator and a thermal imaging camera with a variation in the percentage of glass fiber 45%, 55%, 65%, 75% and the type of resin used was epoxy resin and polyester. The results of this study indicate the effect of the type of resin/matrix used on the value of the wear rate that occurs. The test results show that the smallest wear rate is owned by specimen code D of 0.000000081 g/mm^2.second with epoxy as the type of resin used. Then the largest wear rate is owned by specimen A1 of 0.000000154 g/mm^2.second with polyester as the type of resin. It can be concluded that the higher the density of the polymer material, the lower the wear rate. It is expected that the composite brake pads have improved physical and mechanical properties that are better than the original brake pads.

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1. Introduction

The automotive industry is currently progressing at a rapid pace. Many two-wheeled and four-wheeled vehicle manufacturers continue to develop technology, especially in improving engine performance to produce more power. Along with that, an optimal braking system is needed to ensure driver safety. The braking system is essential in every vehicle because it serves to slow down or stop the vehicle. Therefore, this system must work well, remain efficient throughout use, and be able to function properly despite changing weather or environmental conditions. The most important part of the braking system is the brake pad [1]. The brake pad is a quite complex component. Thanks to technological advances, materials can now be developed with various compositions and ratios, then permanently combined through a fully controlled process. All these factors affect the damage coefficient, resistance to wear and high temperatures, and the service life of the brake pad [2].

Determining the optimal material composition for brake pads and understanding its influence on the quality of the final product is a complex process which requires in-depth scientific studies and sufficient practical experience. The selection of the composition must also consider the intended use of the brake pads and the operational conditions faced. In addition, the final properties of the brake pads are influenced by the manufacturing technology applied, which is often part of the manufacturer's trade secret. The application of effective production technology can significantly improve the tribological performance of brake pads, even up to 100% [3].

The use of natural materials in composites has ushered in a new era in technology and material development, due to their superior physicochemical and tribological properties. However, limitations on the bond strength between components and the noise disturbances caused by friction remain major obstacles that limit their widespread application. The use of natural materials in composites has limitations in resistance to chemical and moisture exposure, and shows a relatively low level of durability [4].

Composite materials in brake pads are specifically designed to improve their durability and wear resistance due to the friction between the disc and the brake pads. In the composite structure, resin functions as a binder, while asbestos fibres were widely used until the 1980s to provide the required mechanical strength. However, after that period, alternative materials such as cotton fibres, minerals, metals, organic materials, and synthetic materials began to be applied as substitutes for asbestos. The use of these materials aims to improve the mechanical properties, heat resistance, and wear resistance of the brake pads. Even the presence of a small number of components can have a significant effect on the maintenance performance and wear of the material [5][6].

The development of polymer-based composites is driven by a number of factors, including their ability to form in various shapes and sizes, non-corrosive properties, good resistance to chemicals and moisture, light weight, and high durability. In the reinforcement section of composite materials, various forms are used, such as particles, fillers, flakes, and fibres, where fibres are more often chosen because they have superior mechanical properties compared to other reinforcements. The existence of composite materials is the result of industrial and technological advances to meet the need for new materials that have specific characteristics, as well as an alternative to conventional engineering materials. Polymer-based composites are widely applied to vehicle braking systems because of their advantages, such as stable operation, long service life, low braking interference levels, and light weight [7].

Glass fibre is a material made of fine fibres produced by melting glass at high temperatures to form long and thin fibres. Chopped Strand Matt or CSM E-glass is glass fiber that has been cut into small pieces and can be used as reinforcement or main material in the manufacture of brake pads composites that require strength and wear resistance. Glass fiber has lightweight yet strong, durable, and corrosion-resistant properties, making it one of the leading composite materials [8].

Based on the above description, the manufacture of composites from glass fibre and epoxy-polyester matrix is expected to increase mechanical strength. Researchers attempted to combine these materials for the manufacture of brake pads for motorcycle braking systems.

2. Materials and Method

The research method used is experimental by testing brake pad specimens. This study aims to determine the effect of variations in volume fraction and type of resin used on wear rate and braking temperature. The materials used in this composite brake pads research include chopped glass fibre, epoxy resin, polyester resin, hardener catalyst, iron glue, and margarine. The tools used in this research include a braking simulator, a thermal imaging camera, a digital analytical balance, a mould, and a pressure gauge. After the test results were obtained, a comparison was made with the original brake pad.

Fig. 1. Glass fibre

Fig. 2. Epoxy Resin

Fig. 3. Polyester Resin

Glass fibre is shown in Fig. 1 as a reinforcement in composite brake pads. It is the main material in composite brake pads. Then in Fig. 2 and 3 are epoxy resin and polyester resin as binders or matrices in composite brake pads that have different mechanical properties.

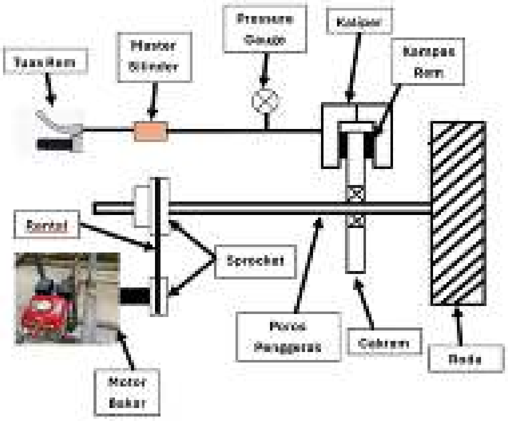

Fig. 4. Schematic of Wear Rate Test

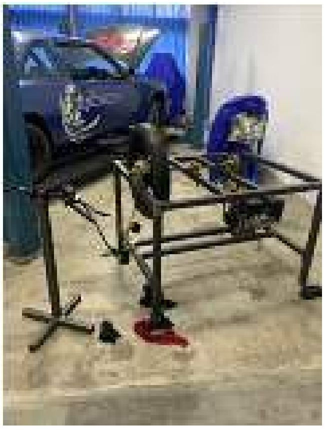

Fig. 5. Braking Simulator

Fig. 6. Braking Temperature Test

Fig. 5 shows the braking simulator which is one of the tools used to test the wear rate on composite brake pads. In general, the wear rate test equipment has several main parts, such as frame, combustion motor and transmission, disc brake braking set and pressure gauge measuring instrument. The frame serves as the main structure that supports all components of the braking simulator, such as the combustion motor, brake disc, and calliper. The pressure gauge is used to measure the hydraulic pressure generated by the brake system when the brake handle is pressed. Fig. 4 is a schematic of the wear rate test expressed by the amount of material loss/reduction per unit area of contact and the length of wear. The wear rate is expressed by the following formula [7]:

$$W = \frac{W_0 - W_1}{A.t} \tag{1}$$

where W is wear rate (g/mm^2.second), W_0 is weight before wear rate (g), W_1 is weight after wear rate (g), t is testing time(second), and A is cross-sectional area (mm^2). Before testing the wear rate, the first step is to weigh the brake pad to determine its initial weight. The compressive force on the brake pads was generated by the brake lever, with the pressure adjusted using a pressure gauge to 15 psi. The rotation speed of the brake disc is measured with a tachometer. The testing process was carried out by pressing the brake lever using a predetermined force, and then maintaining it for a certain time while observing the rotational speed parameter. After the test is completed, the weight of the brake pad is reweighed after friction has occurred. During the test, it is important to ensure that the combustion motor has enough gasoline and that the brake master tube is filled with brake fluid to avoid problems. The wear rate test was conducted for one minute at a rotational speed of 800 rpm.

The temperature test in Fig. 6 was carried out while wear rate testing was in progress. This test was conducted to determine the ability of the brake pad composite to withstand high temperatures during friction. Measurements using a thermal imaging camera tool are directed at the brake pad during the braking process. Then each thermal imaging that shows the temperature value was observed and recorded The hypothesis in this study are the greater the percentage of glass fibre added, the smaller the wear rate produced and also the higher the density value of the polymer material, the smaller the wear rate will be and the greater the hardness value.

The independent variables in this study are volume fraction as shown in Table.1 and polymer type [10]: epoxy resin and polyester resin. The dependent variables in this study are brake pad wear rate and temperature during braking. The controlled variables in this study are (i) gasoline engine rotation speed 800 rpm and brake lever pressure 15 psi, (ii) wear time 1 minute, (iii) manufacture and testing of brake pads specimens were carried out at a room temperature of 25°C (iv) curing time of brake pads specimens for 24 hours. (v) epoxy resin and hardener ratio of 1:1, and (vi) ratio of polyester resin and catalyst 100:1.

Table 1. Volume Fraction [9]

Specimen No.	Specimen Code	Volume Fraction (%)		Resin Type
		Fiberglass	Resin	
1	A	45	55	Epoxy
2	B	55	45	Epoxy
3	C	65	35	Epoxy
4	D	75	25	Epoxy
5	A1	45	55	Polyester
6	B1	55	45	Polyester
7	C1	65	35	Polyester
8	D1	75	25	Polyester
9	N	**Sample Comparison**		

Brake pads composites use several materials such as glass fiber, epoxy resin and polyester resin. The mechanical properties of them can be seen in Table 2, 3, and 4.

Table 2. Mechanical Properties of E-glass [8]

Property	Value
Density ($g/cm^{3)}$	2.56
Tensile Strength (MPa)	3.445
Modulus of Elasticity (GPa)	76
Tensile Elongation (%)	2.75

Table 3. Mechanical Properties of Polyester Resin [11]

Property	Value
Density (g/cm$^{3)}$	1.4
Tensile Strength (MPa)	40.6
Modulus of Elasticity (GPa)	3
Tensile Elongation (%)	2

Table 4. Mechanical Properties of Epoxy Resin [12]

Property	Value
Density (g/cm$^{3)}$	1.6
Tensile Strength (MPa)	74
Modulus of Elasticity (GPa)	5
Tensile Elongation (%)	4

3. Results and Discussion

Research on the effect of volume fraction and matrix type on the wear rate and temperature of fiberglass composites processed using the forged method was carried out using mold design steps. Each mold was custom-made for wear rate and temperature testing, using specimens that match the size of the original brake pad. The mold was made of mild steel and processed by a laser cutting machine. For specimens, the volume fraction between chopped glass fiber and matrix was weighed based on the mold volume. First, the glass fiber was put into the mold, then the resin was poured. After all the ingredients were added, the mold was covered with a steel plate to reduce trapped air bubbles. The curing process took one day to produce maximum specimens [13].

Fig. 7. Brake Pad Specimen

Brake pad specimens can be seen in Fig.7. While, Tables 5 and 6 presents data of wear rate and braking temperature.

Table 5. Wear Rate

Resin Type	Specimen Code	Wear Rate (g/mm^2.s)	Wear Rate (mg/mm^2.s)
Epoxy	A	0.000000118	0.000118
	B	0.000000109	0.000109
	C	0.000000095	0.000095
	D	0.000000081	0.000081
Polyester	A1	0.000000154	0.000154
	B1	0.000000149	0.000149
	C1	0.000000130	0.000130
	D1	0.000000139	0.000139
Comparation (Original)	N	0.000000147	0.000147

Table 6. Braking Temperature

Specimen Code	From 0 s	2	3	4	5	6	7	8	Average
A	32.2	34.8	34.8	35	34.5	35.2	35.9	34.5	**35**
B	32.7	34.2	35.2	33.5	34	34.7	35.1	35.6	**34**
C	33.5	33.7	34.4	35.6	35.7	35.2	34.5	35.4	**35**
D	33.8	34.6	33.7	37	36.7	34.7	35.1	36.4	**35**
A1	33.5	35.9	36.4	35.2	35.3	36.9	38.8	38.2	**36**
B1	33.9	35.6	35.2	35.9	37.3	37	37.7	38.3	**36**
C1	33.2	34.5	33.9	34.1	34.3	35.5	34.6	33.9	**34**
D1	33	34.8	36.4	35.5	34.8	36.1	35.5	35.6	**35**
Comparator (N)	33.1	33.6	33.8	35.6	34.7	34.9	36.7	38.2	**35**

Fig. 8 presents a combined graph of wear rate values for each type of resin and fiber volume fraction. It can be observed that the composite with a fiber volume fraction of 75% with 25% epoxy resin shows the lowest wear rate, recorded at 0.000082 mg/mm^2.s. Based on the graph, the wear rate shows a decreasing trend as the fiber volume fraction increases [14]. Higher glass fiber content in the composite tends to result in lower brake pad wear rates. This indicates that increasing fiber volume fraction positively contributes to increasing material hardness, which ultimately leads to a decrease in brake pad wear rates [15].

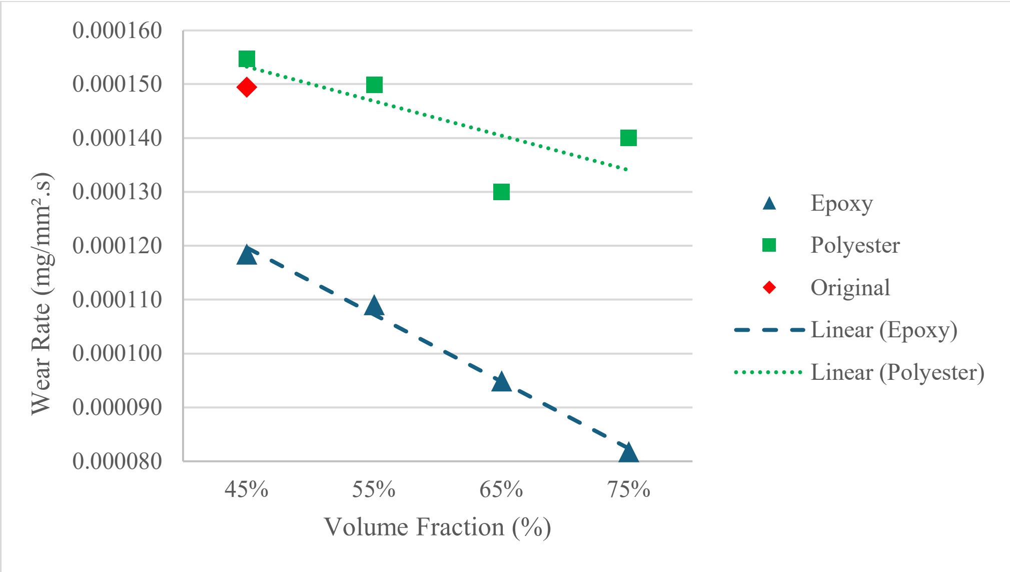

Fig. 8. Volume Fraction vs. Wear Rate

In this research, data processing used is full factorial method analysis (ANOVA). The data obtained was processed using the Minitab 21 application, and then analysis and discussion was carried out to conclude the results of the research that had been carried out.

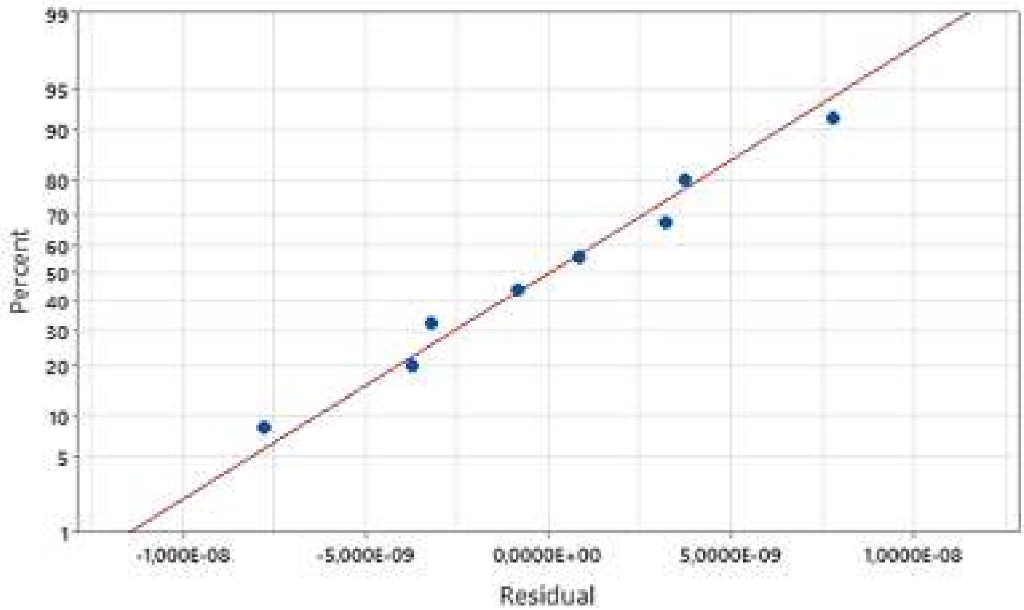

Fig. 9. Normal Probability Plot of Wear Rate

Fig. 9 shows that the residual points have a tendency to follow and approach the diagonal line. Thus, it can be concluded that the data is normally distributed, where the research data meets the statistical requirements.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	4	0,000000	96,40%	0,000000	0,000000	20,08	0,017
Linear	4	0,000000	96,40%	0,000000	0,000000	20,08	0,017
RESIN	1	0,000000	76,14%	0,000000	0,000000	63,44	0,004
FRAKSI VOLUME SERAT	3	0,000000	20,26%	0,000000	0,000000	5,63	0,095
Error	3	0,000000	3,60%	0,000000	0,000000		
Total	7	0,000000	100,00%				

Fig. 10. ANOVA of Wear Rate Data

From Fig.10, it is known that the resin type variable has a significant effect on the wear rate (response) because the P-Value is less than the specified alpha (α) (P-Value < α), namely 0.05, for the P-Value of the resin type variable the value 0.017, then the research hypothesis is appropriate (H_1 is accepted). Meanwhile, the volume fraction variable does not have a significant effect on the wear rate (response) because the P-Value is more than the specified alpha (α) (P-Value > α), namely 0.05, for the P-value of the volume fraction variable it is 0.095, then (H_0 is accepted and H_1 is rejected).

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
0,0000000	96,40%	91,60%	0,0000000	74,39%	-188,40	-271,92

Fig. 11. Model Summary of Wear Rate

Based on the R-sq value or the coefficient of determination in the Fig. 11, it shows that the variable type of resin and volume fraction has an effect of 96.40% on the wear rate, and the remaining 3.60% is an error or error caused by other variables that are not in the study.

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	0,000000	0,000000	(0,000000; 0,000000)	45,75	0,000	
RESIN						
EPOXY	-0,000000	0,000000	(-0,000000; -0,000000)	-7,96	0,004	1,00
FRAKSI VOLUME SERAT						
45	0,000000	0,000000	(-0,000000; 0,000000)	3,07	0,055	1,50
55	0,000000	0,000000	(-0,000000; 0,000000)	1,54	0,221	1,50
65	-0,000000	0,000000	(-0,000000; 0,000000)	-2,14	0,122	1,50

Fig. 12. Cofficients of Wear Rate

Fig. 12 is the result of the regression coefficient value of this research. Where in this study a multiple linear regression model was used because there were two independent variables used in this study, namely resin type and volume fraction. Fig. 13 shows variations in the type of resin that uses epoxy resin which is lower in wear rate. Meanwhile, the wear rate test was greatest for the polyester resin type.

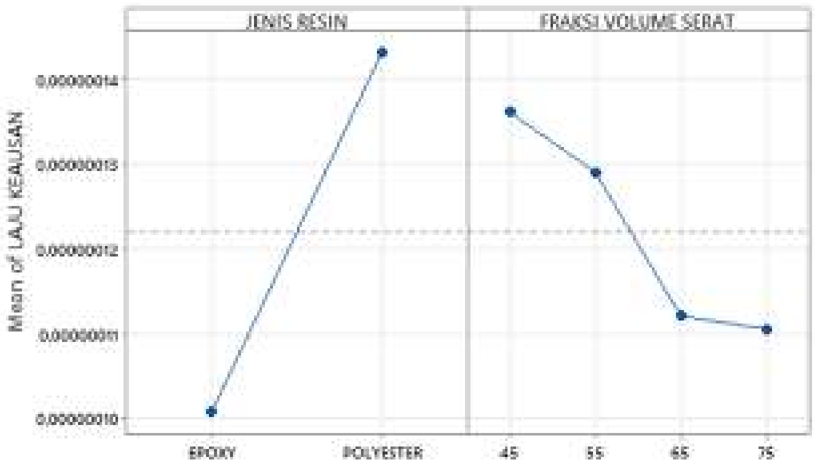

Fig. 13. Main Effects Plot for Wear Rate

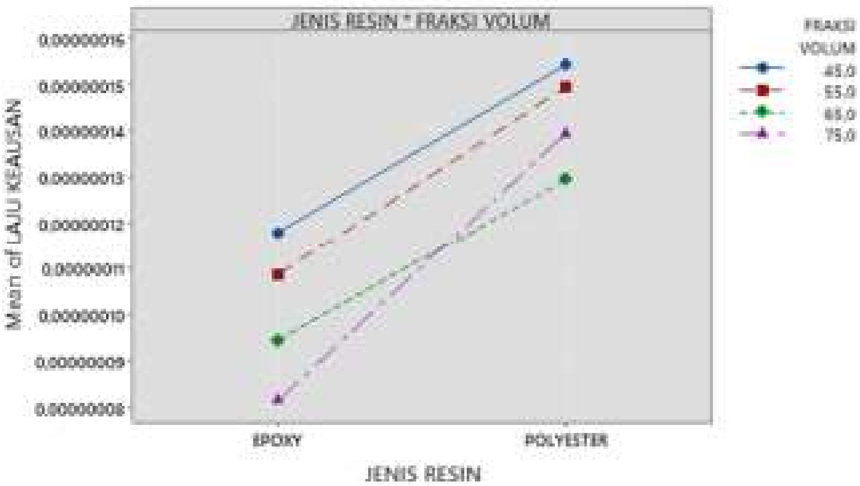

Fig. 14. Interaction of Independent Variables on Wear Rate

Fig. 14 shows a significant interaction between variations in resin type and fiber volume fraction used on the rate of wear that occurs. The interaction graph shows that the wear rate varies depending on the level of variation in the type of resin and the percentage of fiber volume fraction used. The graphic results also show that using the same type of resin with different volume fraction percentages produces different wear rates. The greater the percentage of fiber volume fraction added is proportional to the smaller the wear rate. The fiber volume fraction of 75% has the smallest wear rate in epoxy resin, while the polyester resin has the second largest wear rate after the fiber volume fraction of 65%. Glass fibers help in load distribution and resistance to friction.

Varying resin types influence wear rates, with epoxy resins showing better performance due to their higher density and hardness [16]. The volume fraction of glass fibers has no significant effect on the wear rate in the tested range. The use of epoxy resin with a high fiber volume fraction tends to produce brake linings with lower wear rates, indicating potential for improved practical applications.

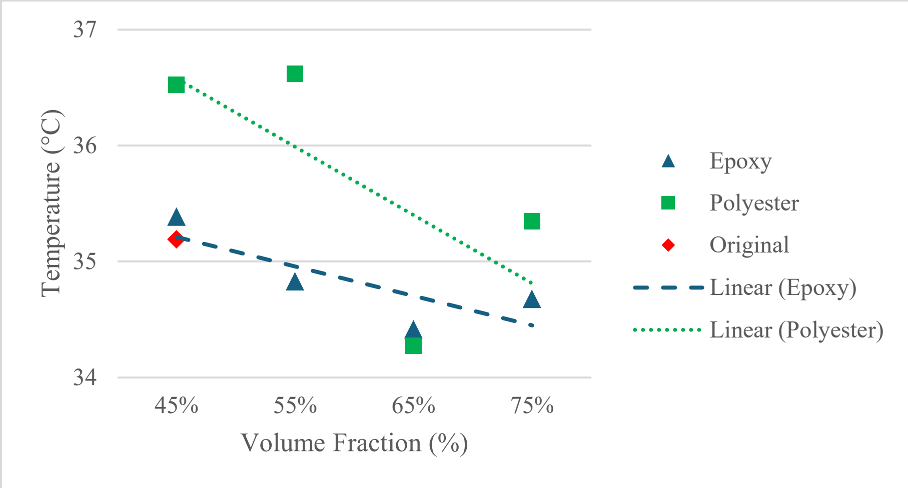

Fig. 15. Volume Fraction vs Temperature

Fig. 15 presents the combined temperature graph for each resin type and fiber volume fraction. It can be observed that as the fiber volume fraction increases, the temperature tends to stabilize or decrease. Furthermore, composites with epoxy resin exhibit lower average temperatures across all specimens compared to those with polyester resin. The tested composite brake pads demonstrate relatively uniform heat distribution, with temperature ranges not significantly different from the original brake pads used as a reference [17]. Data analysis of braking temperature test results using the full factorial method (ANOVA) is as follows:

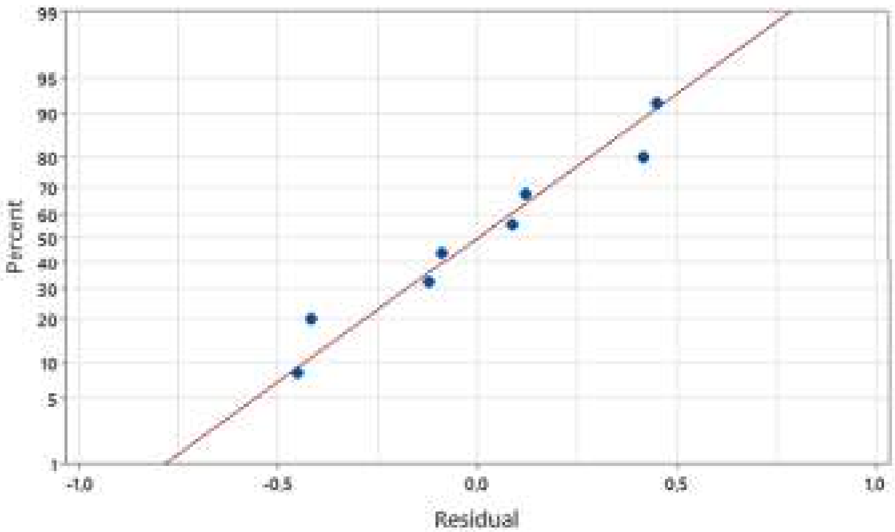

Fig. 16. Normal Probability Plot of Braking Temperature

Based on Fig.16, it is seen that the residual points have a tendency to follow and approach the diagonal line, thus it can be concluded that the data is normally distributed.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	4	3,8054	82,59%	3,8054	0,9513	3,56	0,163
Linear	4	3,8054	82,59%	3,8054	0,9513	3,56	0,163
RESIN	1	1,2110	26,28%	1,2110	1,2110	4,53	0,123
FRAKSI VOLUME SERAT	3	2,5944	56,31%	2,5944	0,8648	3,23	0,180
Error	3	0,8022	17,41%	0,8022	0,2674		
Total	7	4,6076	100,00%				

Fig. 17. ANOVA of Braking Temperature

From Fig.17, it is known that the resin type variable does not have a significant effect on the temperature value (response) because the P-Value is more than the specified alpha (α) (P-Value > α), namely 0.05, so the research hypothesis is appropriate (H_0 is accepted and H_1 is rejected). Meanwhile, the volume fraction variable also has no significant effect on temperature (response) because the P-Value is more than the specified alpha (α) (P-Value > α), namely 0.05, so (H_0 is accepted and H_1 is rejected).

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
0,517122	82,59%	59,37%	5,70486	0,00%	100,30	16,78

Fig. 18. Model Summary of Braking Temperature

Based on the R-sq value or coefficient of determination value in Fig. 18, It can be seen that the resin type and volume fraction variables have an effect of 82.59% on the temperature value, and the remaining 17.41% is an error caused by other variables that are not in the research.

Coefficients

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	35,136	0,183	(34,554; 35,718)	192,18	0,000	
RESIN						
EPOXY	-0,389	0,183	(-0,971; 0,193)	-2,13	0,123	1,00
FRAKSI VOLUME SERAT						
45	0,627	0,317	(-0,381; 1,634)	1,98	0,142	1,50
55	0,420	0,317	(-0,587; 1,428)	1,33	0,276	1,50
65	-0,823	0,317	(-1,831; 0,184)	-2,60	0,080	1,50

Fig. 19. Coefficients of Braking Temperature

Fig. 19 is the result of the regression coefficient value of this research. Where in this study a multiple linear regression model was used because there were two independent variables used in this study, namely resin type and volume fraction.

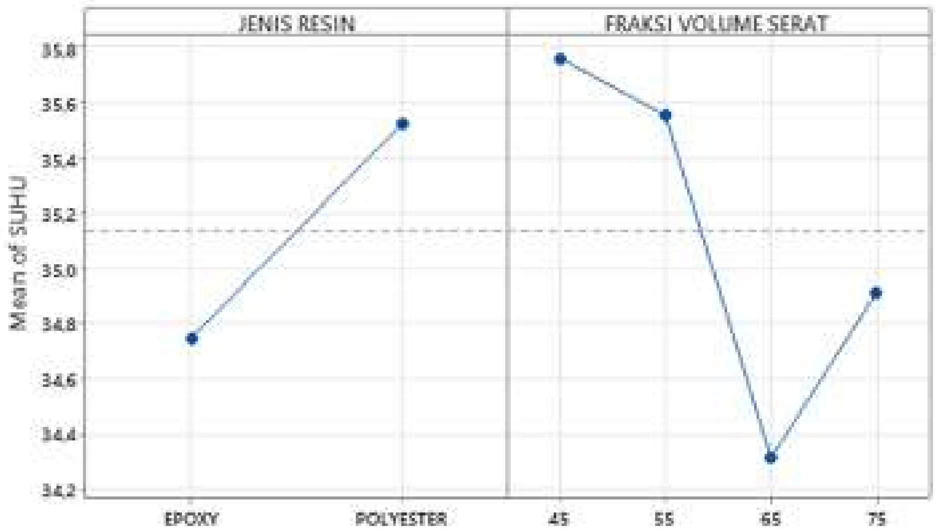

Fig. 20. Main Effects Plots for Braking Temperature

Fig. 20 shows variations in resin types that use smaller epoxy resins for braking temperature values. Meanwhile, the braking temperature value is greatest for the polyester resin type. At a volume fraction, the greater the concentration of glass fiber added, the lower the braking temperature, however at a volume fraction of 65% the fiber has the smallest temperature value.

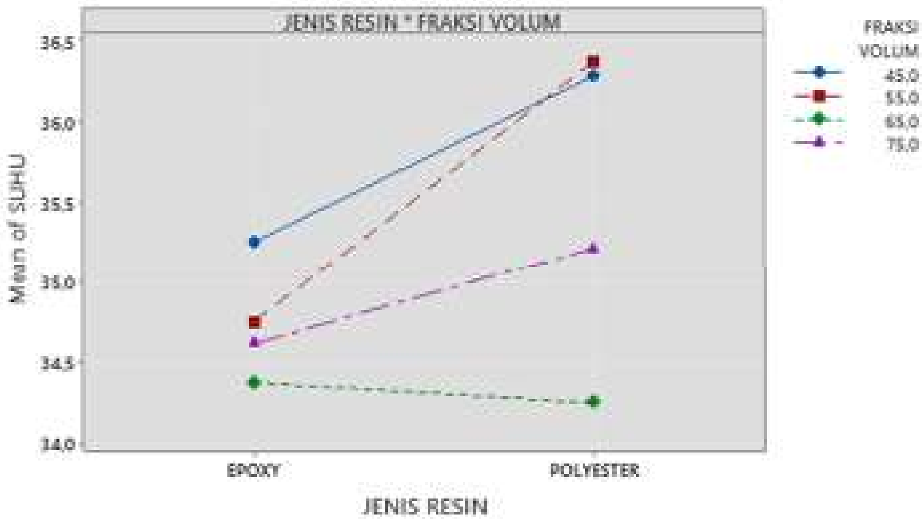

Fig. 21. Interaction of Independent Variables on Braking Temperature

As shown in Fig. 21, the blue color shows a brake pads composite specimen with a glass fiber volume fraction of 45% and 55% resin, the brown color has a glass fiber volume fraction of 55% and 45% resin, and the green color has a fiber volume fraction of 65% and 35% resin, and the purple color shows a glass fiber volume fraction of 75% and 25% resin.

Based on the data processing that has been carried out, it has been shown that variations in the type of resin used in making brake pad composites do not have a significant effect on braking temperature. The types of resin used are epoxy resin and polyester resin. A comparison of the temperature during braking shows that the composite brake pad specimens with epoxy and polyester resins are not much different. All samples for braking temperature are in the range 34 °C - 36.5 °C.

4. Conclusion

The results of the research from the testing and analysis of the specimens that have been carried out indicate that good brake pads can be obtained by choosing materials that have better mechanical properties, seen from the yield and tensile strength values, elastic modulus. Variations in resin types affect the wear rate of composite brake pads. The higher the density value of the polymer material, the smaller the resulting wear rate will be. The smallest wear rate with the same fiber volume fraction of 75% with different types of resin, namely code D with epoxy resin type for a wear rate of 0.000081 $mg/mm^2.s$ while the polyester resin type for a wear rate of 0.000139 $mg/mm^2.s$. Variations in resin type and glass fiber volume percentage did not significantly affect the temperature during the braking process. Specimens with different resin types and glass fiber volume fractions showed a relatively small temperature difference compared to the comparison brake pads (original), which was in the range of 34°C to 36.5°C. This indicates that the heat distribution in the composite material is evenly distributed.

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