Development and Tribological Analysis of Bio Friction Brake Pad Materials

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Abstract

Brake pads are a crucial part of a vehicle when it comes to safety because they make it possible to create friction and force to stop your vehicle. Asbestos, ceramics and synthetic composites are the most common materials used in brake pads leaving toxic particles in nature. Inhaling these can cause pleural, peritoneal, pericardial, etc. diseases. To overcome this there is a need to develop a bio-friction material that can replace the commercial brake pads. Hence, the objective of the project was to develop an eco-friendly brake pad material using natural fiber hemp reinforced polymer composite. The material was classified into several types according to the percentage of NaOH solution named HFRC. Different testings were done on fiber composite as it was straightened, chopped, and prepared into homogeneous mixtures in a blender. Compression-molded parts were heat-treated at 150ºC in a hot air oven for 3hrs and the cutting process was done on the specimens with accurate dimensions. Tribological testing was performed by using the pin-on-disc method and analyzed for better composition using Taguchi analysis, Analysis of variance was carried out on coefficient of friction and specific wear rate. Surface topography was understood with the help of scanning electron microscopy (SEM). Optimum compositions were classified concerning the different parameters and calculations with HFRC P20 6 performing well in all the required aspects and it can be used as a brake pad material.

Key words: - Hemp fiber, Tribological Testing, Taguchi Analysis, Pin-on-disc Method.

1. Introduction

Synthetic fibers are being widely incorporated in polymer-based composites due to their mechanical properties. But, these fibers lack in terms of biodegradability, initial processing cost, recyclability, abrasion, and health hazard. An alternative to tackle these drawbacks can be found in natural fibers. Also, a significant increase in the automotive and construction industries emphasized the alternative to conventional materials. The natural fiber polymer composites give an advantage in terms of strength to weight ratio, ease of availability, and biodegradability. In line with this, the present research work focuses on hemp fibers due to their strength property which might be one of the most widely contributing factor to the coefficient of friction. Literature shows many works on the mechanical and tribological characterization of natural fiber-reinforced polymer matrix composites and most of the studies came to the same conclusion that natural fiber improves the mechanical properties and wear resistance of the material however it is not attuned to the synthetic fibers and conventional materials [1].

In line with those in the present study hemp fiber composite used with the phenol-formaldehyde resin and its tensile strength, impact strength, hardness, flexural strength, water absorption rate, and wear properties were evaluated and compared with the different materials. The hemp fiber was selected due to its high strength, chemical resistivity, high-temperature range, large growth rate, good source of cellulose and strength ranging from 690 MPa to 873 MPa, and density of 1.48 g/cc. Manufacturing the composite material was the primary objective of this project. The fibers were treated with different percentages of NaOH solution and then heated at several degrees. The treated fibers were named HFRC n, where n is the number of samples. Different tests were performed on fiber composite as it was straightened, chopped, and prepared into homogeneous mixtures in a blender. Compression molding was done before the heat-treatment at 150oC in a hot air oven for 3hrs and the cutting process was done on the specimens with precise dimensions [2]. Tribological testing was done by using the pin-on-disc method and analyzed for better composition using Taguchi analysis, Analysis of variance was carried out on specific wear rate and coefficient of friction. Surface topography and material interstitial bonding were understood with the help of scanning electron microscopy (SEM).

The results from every test were analyzed for better composition throughout the procedure. The coefficient of friction was given by the pin-on-disc experimentation, while the specific wear rate was manually calculated. It has been observed that HFRC 4, 5 and 6 performed well in all tests than the remaining samples. SEM provides high-resolution imaging useful for evaluating various materials for surface fractures, flaws, contaminants or corrosion and the bonding between the matrix and reinforcement materials.

2. Materials and Methods

2.1 Materials:

(i) Reinforcement materials: Hemp fiber which is being shown in Fig. 9 used as reinforcement material and was purchased from the market. Hemp fiber is obtained from the bast of the plant Cannabis Sativa L. It can grow up to a height of 4 m without any agrochemicals and captures large quantities of carbon. It has strength up to 900 MPa and a density of 1.48g/cm3 [3]. Hemp has been widely used in paper, textile, construction, composites, food, medicine and fuel. The reinforcement material was the same for both phases.

Fig. 1. Raw hemp Fibers.

(ii) Binder: Phenol formaldehyde was used as a binding material to form a cross-linking reaction. PF's have been widely used for the production of molded products including billiard balls, laboratory countertops and as a coating and abrasives. This was obtained from a chemical store located in Pune. The binder is basically a homogeneous and monolithic material in which a fiber system of a composite is embedded. It is a composite material composed of a variety of short or continuous fibers bound together by a matrix of organic polymers. Phenol formaldehyde basically transfers loads between fibers of a matrix. In phase I, the percentage of phenol-formaldehyde was 10% with the hemp at 25%.

(iii) Friction Modifier and abrasive material: Reagent grade Aluminium oxide was purchased from a commercial chemical shop situated in Pune, Swargate which served as an abrasive. Graphite powder was used as a friction modifier. Filler materials were added to the resin to improve tensile strength, toughness, and heat resistance and it can also make the product cheaper or a mixture of both. Vermiculite and barium sulfate were used as fillers in this project. The percentage of filler materials varies with the reinforcement and binder percentage. Table 1 and 2 shows the percentage contribution of different materials.

Table No. 1. Percentage weight contribution (%) - Phase I

	HFRC 2	HFRC 3	HFRC 4	HFRC 5	HFRC 6
Hemp	25	25	25	25	25
Phenol Formaldehyde (PF)	10	10	10	10	10
Vermiculite	5	5	5	5	5
Aluminium Oxide	5	5	5	5	5
Graphite Powder	5	5	5	5	5
Barium Sulphate ($BaSO_4$)	50	50	50	50	50

Table No. 2. Percentage weight contribution (%) – Phase II

	HFRC 4	HFRC 5	HFRC 6
Hemp	25	25	25
Phenol Formaldehyde (PF)	20	20	20
Vermiculite	5	5	5
Aluminum Oxide	5	5	5
Graphite Powder	5	5	5
Barium Sulfate ($BaSO_4$)	40	40	40

2.2 Method:

The development of brake pads involved the preparation of filler materials, compression molding process, heat treatment, mechanical and tribological examination as well as optimization using Taguchi Analysis (TA). The methodology used for both the phases was the same with respect to the tests performed.

2.2.1 Pre-treatment of natural fiber:

(i) *Water treatment*: Hemp was rinsed in the 2, 3, 4, 5, and 6 percent NaOH solution for 24hrs to remove the impurities. After this process, Scanning Electron Microscopy was performed observing HFRC 4, 5 and 6 giving better results than the 2 and 3 percent. So, further enhancements were carried out in phase II keeping 4, 5, and 6 as working samples.

(ii) *Sunlight treatment*: The fibers were dried in the sunlight for at least 10hrs. The hemp should be properly dried before use. For proper removal of moisture from the hemp, it should be dried inside an oven.

(iii) *Heat treatment:* Fibers were heat-treated at 60ºC for 5hrs. This process was the same for both phases.

2.2.2 Material Preparation:

Hemp was straightened with the help of a comb and then chopped using a scissor. The hemp had to chop about 3 to 5 mm in length. A homogeneous mixture of Aluminium oxide, barium sulfate, vermiculite, graphite powder and phenol-formaldehyde was prepared. The mixture was well mixed in the blender at 300rpm and kept in a closed air-tight bag.

Fig. 2. Straightened fibers

Fig. 3. Chopped fibers

2.2.3 Manufacturing Processes:

(i) Compression Molding Process: Prior to the mixture being poured into the lower mold silica gel was applied over plastic for easy removal of a part after compression. The compression molding process was done on a hot press machine at temperatures of 160ºC and 150 bar pressure [4]. Curing was executed for 10 min. and then water cooling was processed for cooling down the temperature of the material.

Fig. 4. Hot Press machine

(ii) Hot Air Oven:

Fig. 5. Hot air oven machine

After the compression molding process, the temperature of the material was approximately 50ºC, for more fiber and matrix bonding specimens were heated up to 170ºC in a hot air oven for 3hrs. So far, the plastic residue on the specimens was not removed. Hence, after the final heat treatment, they were easily removed.

(iii) Cutting Process (ISO 9013:2002):

In the basic idea of the water jet cutting process, 50000psi pressure was applied to the material and cut according to the required dimensions. The cut specimens are shown below in Fig. 14. The water jet cutting was done in phase I only in order to get precise dimensions. But because of it, the material had absorbed more water percentage than recommended. Hence, for phase II the material had been cut into different specimens manually with the help of a cutting machine.

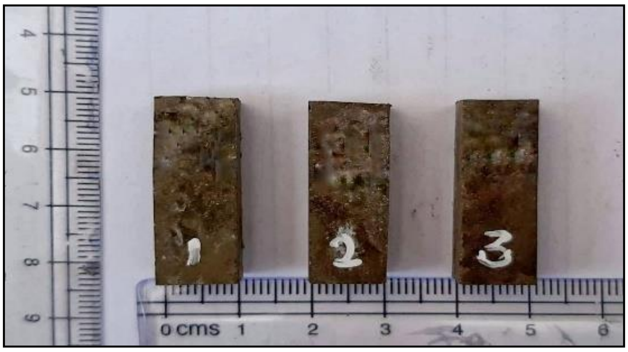


Fig. 6. Tribological testing specimens

3. Tribological testing: Pin-on-disc Method

Tribology is the science of wear, friction and lubrication and encompasses how interacting surfaces and other tribological elements behave in relative motion in natural and artificial systems. The testings done in tribology are pin-on-disc and chase friction testing. In this project, the pin-on-disc method was done.

The pin-on-disc method consists of a fixed pin that is placed on a rotating disc that runs through a motor. The specimen was attached to the pin by means of an Allen key. Before doing that, the disc should be cleaned with acetone with the help of a cloth. Checked whether all the surface was in contact with the disc or not. The pin was attached to the load on the backside by means of a fulcrum at the center. The setup was further connected to an electric controller where one can set the speed and time for which the test has to be done. The data from which one can take the readings was calculated by using Minitab software. Phase I contains 5 levels due to 5 samples and phase II has 3 because of 3 samples.

Table No. 3. Factors and levels of phase I

Factors	Units	Level 1	Level 2	Level 3	Level 4	Level 5
Composition	-	HFRC 2	HFRC 3	HFRC 4	HFRC 5	HFRC 6
Load	N	30	50	70	90	110
Sliding Velocity	m/s	2.6	3.9	5.2	6.5	7.8

Table No. 4. Factors and levels of phase II

Factors	Unit s	Level 1	Level 2	Level 3
Compositio n	-	HFR C 4	HFR C 5	HFR C 6
Load	N	30	50	70
Sliding Velocity	m/s	2.6	3.9	5.2

For calculating a change in the mass, the specimens were weighed on the digital weighing machine which had the least count of 0.01g from Wensar Weighing Scale Limited. The following image had been showing results, while it was weighed on a weighing machine. The setup shown in Fig. 15. was designed to apply a load of 200N and speeds starting from 200 to 2000rpm. The least count of pin-on-disc was of 1rpm.

Table No. 5. Weighing machine Specifications

Maximum Weight	220 g
d	1 mg
e	1 mg
Min	0.01 mg

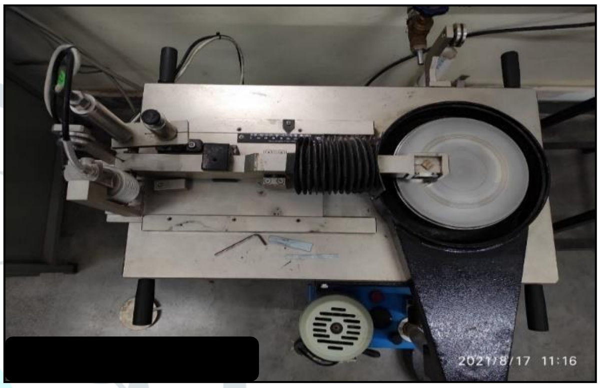


Fig. 7. Pin-on-disc setup

The speed and the load were set on the digital controller through the computer. Then the motor was turned on by clicking on the start button and the disc starts rotating. Graph of Friction Vs Time, Wear Vs Time and coefficient of friction Vs Time were obtained on the screen. The graphs and the data points were saved in a file. The same process was done for the rest of the specimens and readings were taken.

Fig. 8. Weighing machine

The information about specific wear rate, coefficient of friction and S/N ratios of both. The specific wear rate was calculated by the following Equation,

SWR=$\Delta m/\rho.D.L$ .... (i)

Where, $\triangle m$ = Change in a mass of specimens (g)

ρ= Density of the specimen (g/cc)

D= Distance Travelled (m)

L= Load (N)

The coefficient of friction was calculated by using the following formula:

COF=FF/L ....(ii)

Where, FF= Frictional Force (N)

L = Normal Load (N)

S/N ratios of specific wear rate and coefficient of friction were calculated from the Minitab software by Taguchi Analysis.

3.1 Taguchi Design of Experiments:

Taguchi method optimizes design parameters to minimize variation before optimization design to hit mean target values for output parameters. The Taguchi method uses special orthogonal arrays to study all the design factors with a minimum of experiments. The experiments were designed using design of experiments (DOE) methods. The combination of process parameters to each of the experiment has been obtained by using Taguchi L9 and L25 algorithm [5].

ANOVA (Analysis of variance): It helps you to find out whether the differences between groups of data were statistically significant. It works by analyzing the levels of variance within the groups through samples taken from each of them. ANOVA was done on the specific wear rate and coefficient of friction where; It shows that load is contributing more than the other two factors for specific wear rate.

Optimum factors were decided from the main effect plots of S/N Ratios. It can be observed that HFRC 4 is performing well as a composition at 110N of load and 2.6m/s of velocity for a specific wear rate. The smaller the better was chosen from the Taguchi Analysis Design options for S/N Ratios because the smaller the value, lesser the wear rate.

Composition is the major part contributing to the Coefficient of Friction, followed by velocity and load. The coefficient of friction was found to be better for HFRC 4 composition at 50 N of load and 7.8 m/s of velocity.

Fit Regression Analysis: A fit Regression model was done by the Minitab software to find out the Regression equation of Specific Wear Rate and Coefficient of Friction. Regression Analysis is a reliable method of identifying which variables have an impact on a topic of interest the process of performing a regression allows you to determine which factors were significant, which factors can be ignored and how these factors influence each other.

The values from the software were compared with the actual and predicted values calculated by the equations. The following table shows the experimental validation of optimum factors.

3.2 Scanning Electron Microscopy (SEM):

SEM analysis provides high-resolution images which were useful for evaluating various materials for surface fractures, flaws, voids, surface topography, bonding of materials and corrosion. In addition to surface evaluation, SEM analysis is utilized for particle characterization, such as wear debris generated during mechanical wear testing. The high magnification imaging of SEM analysis supports the determination of the number, size and topography of small particles, allowing others to understand the wear properties of their material.

Fig. No. 9. Scanning Electron Microscopy (SEM)

As the hemp act like an insulating material, it had plated with gold for the transfer of electron beam through it. The samples were then attached to the disc fixture and placed inside the chamber. The chamber was vacuumed so that no small particles or dust could get inside and contaminate the electron source. The vacuum also allows the user to create high-resolution images. Different level of magnified images was captured at various locations on the surface of a particular specimen.

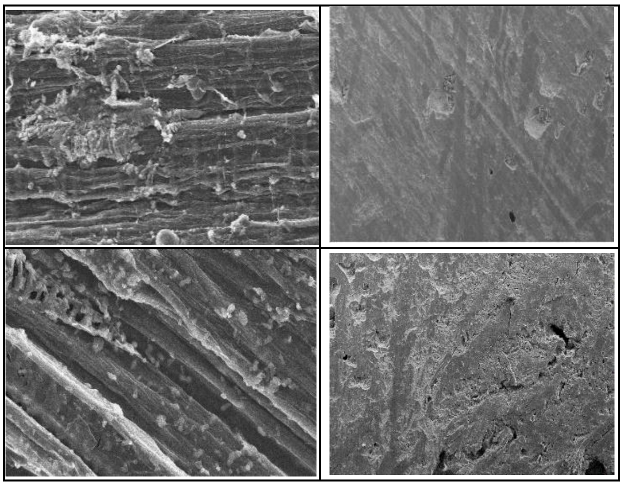


Fig No. 10. Surface Magnification Images of Hemp Fiber after NaOH treatment

One can observe the transfer layers in the first image, it indicates that the more the uniformity in the transfer layers, the less would be the wear and coefficient of friction is stable. The second image consists of 500x magnification. There one can see less debris formation, matrix debonding fiber debonding and mediocre transfer layer breaking. The third one shows small pits formation in the material at 1000x magnification. The wear particles generated while the pin-on-disc method gets compacted because of continuous action of load on the specimen and those particles are stuck inside the pits and form a layer known as primary plateaus. Lesser the formation of the primary plateaus, the lesser the wear.

4. RESULTS AND DISCUSSION

4.1 Phase I: The strength and stiffness of hemp fiber increased after increasing the percentage of NaOH treatment. Due to the cellulose getting exposed more in the fiber it leads to an intrinsic stiffness of fibers resulting in better interstitial bonding of fibers.

After putting all the factors and levels in the Minitab software, it analyses and performs experimentation and gave the results shown in the following Table No.8. The values of SWR were calculated from the formula given in equation (i) and COF was calculated from Eq. (ii). Minitab software calculates a separate signal-to-noise ratio (S/N) for each combination of control factor levels in the design. i.e. SWR and COF.

The graph of friction force VS time shows the variation of friction force with respect to time and load resulting as the load increases the friction force increases.

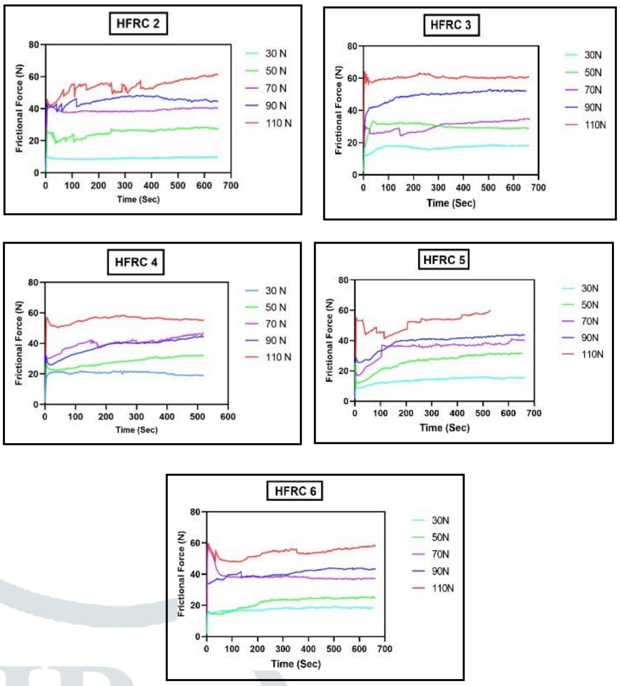


Fig No. 11. FF VS Time of HFRC 2, 3, 4, 5, 6

The trend in the graph is such that there was an increase in frictional force in the first place. This was due to the initial adhesion between the specimen surface and the rotating disc. Then the asperity deformation takes place and the trend goes in uniformly till the end of the experimentation. This shows more the uniformity in the trend, the better the coefficient of friction. So, from all the above graphs HFRC 4 has been showing better results than the others.

Performing ANOVA gave the contribution percentage of all the factors and resulted in load contributing more to specific wear rate than the other two factors. This means as the load increases SWR increases. The same for COF composition was contributed more than the other two factors. Hence, the composition has more influence on the change in the coefficient of friction.

Fit Regression Analysis was done to analyze the regression equation for calculating the SWR and COF values. The values calculated by using these formulas gave the predicted values of the SWR and COF.

Regression Equation for SWR Phase I

SWR= 7.287 - 0.03560 Load + 0.086 Velocity

Regression Equation for COF Phase I

COF = 0.5447 - 0.000374 Load + 0.00751 Velocity

After plotting the graphs of SWR and COF, the variation in the wear and friction with respect to the normal load was shown. The wear must be increased in the primary stage and after the formation of transfer layers, it should have to decrease uniformly. But in phase I, due to certain conditions, the specimens had not shown proper results in wear and friction. The material integrity failed to co-operate with the friction and wear. Hence, in phase II, the percentage of matrix material was increased.

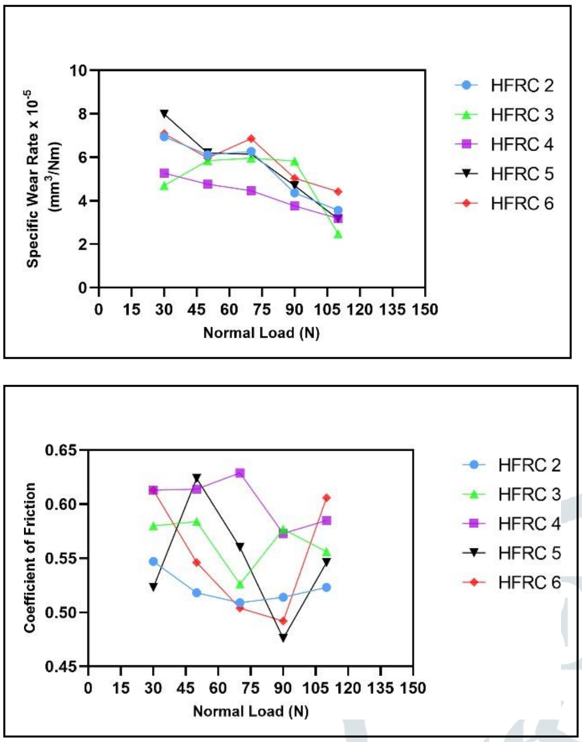


Fig. No. 12. SWR VS Normal Load and COF VS Normal Load **(**P-I**)**

The specific wear rate and coefficient of friction of HFRC 4 was better as per the following figures. It can be observed that the wear rate is uniform in HFRC 2, HFRC 4, HFRC 5, HFRC 6. But the coefficient of friction is more stable in HFRC 4 only. Hence, HFRC 4 was chosen for further research work. Coefficient of friction needed to be more stable for better results. After optimizing all the results and validating with the experimentation, the following table shows the percentage errors of SWR and COF.

Table No. 6. Experimental Validation of optimum factors

Specific wear rate			**Coefficient of friction**		
	Actual	**Predictd**		**Actual**	**Predicted**
Factor level	**8.3892**	L: 110N V: 2.6m/s C:HFRC4	**Factor level**	L: 50N V:7.8 m/s C: HFRC 4	L: 50N V: 7.8 m/s C:HFRC 4
SWR	4.8893×10^{-5}	4.4721×10^{-5}	**COF**	0.603	0.552
S/N ratio	-8.9793	-8.2132	**S/N ratio**	-3.5499	-3.2521
% Error	**8.5321**		**% Error**	**8.3892**	

4.2 Phase II: The same process was done for Phase II. But the only difference was reducing the testing materials from 5 to 3. As the previous results of the first two specimens were not good resulted in neglecting them. The PF percentage was changed to 20x and that was the reason for changing the nomenclature to HF4 P20, HF5 P20 and HF6 P20.

The figure below showed the frictional force vs time graphs of three samples. Here, HF6 P20 gave better results than the other two samples. The uniformity in the trend showed that the coefficient of friction was better than the remaining.

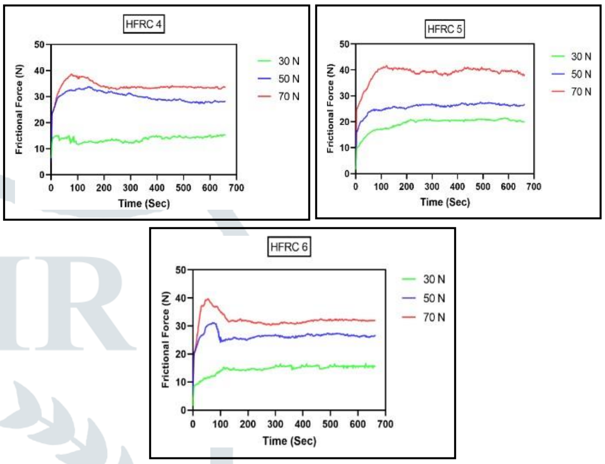


Fig. No. 13. FF vs Time HFRC P20 6

The ANOVA in phase II also showed that the load contributed more than the other two factors for SWR and the composition contributed more for coefficient of friction.

Optimum factors were decided from the main effect plots of S/N Ratios. It can be observed that HFRC 6 is performing well as a composition at 70N of load and 2.6m/s of velocity for a specific wear rate. The smaller the better was chosen from the Taguchi Analysis Design options for S/N Ratios because the smaller the value, the lesser the wear rate.

Composition is the major part contributing to the Coefficient of Friction, followed by velocity and load. The coefficient of friction was found to be better for HFRC 6 composition at 70 N of load and 2.9 m/s of velocity.

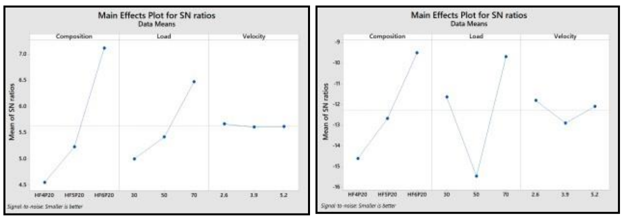


Fig. No. 14. Main Effect plots for S/N ratios of SWR and COF

A fit Regression model was done by the Minitab software to find out the Regression equation of Specific Wear Rate and Coefficient of Friction. Regression Analysis is a reliable method of identifying which variables have an impact on a topic of interest the process of performing a regression allows you to determine which factors were significant, which factors can be ignored and how these factors influence each other.

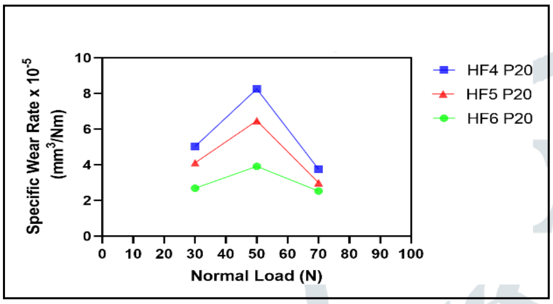
Regression Equation for SWR Phase II:

SWR = 5.00 - 0.0213 Load + 0.125 Velocity

Regression Equation for COF Phase II:

COF = 0.638 - 0.00219 Load + 0.0000 Velocity

The specific wear rate and coefficient of friction of HFRC 6 were better as per the following figures. It can be observed that the wear rate is uniform in HFRC 4, HFRC 5, HFRC 6 and the coefficient of friction was more stable in HFRC 6 and HFRC 4. Hence, HFRC 6 was chosen for further research work. Also, the physio-mechanical properties of HFRC 4, HFRC 5 and HFRC 6 were better.



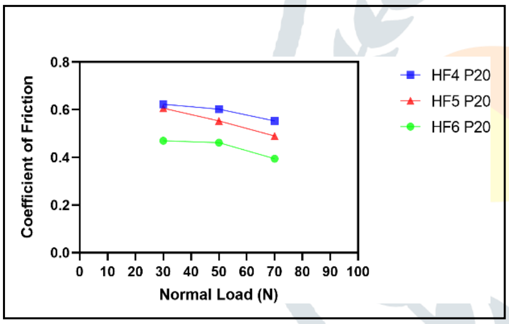


Fig. No. 15. SWR VS Normal Load and COF VS Normal Load (P-II)

Graph of specific wear rate shows us that HFRC 6 has the lowest wear rate than the other compositions. It can be observed that the lower the wear rate higher will be efficiency and life of brake pads. From the coefficient of friction graph, one can observe HFRC 4 has COF more than that of 0.6 which is not suitable. The ideal value of the coefficient of friction has to be in the range of 0.4 to 0.55 [6].

Table No. 7. Optimum S/N Ratios for SWR and COF

Parameters	Composition	Load (N)	Velocity (m/s)
SWR	HFRC 6	70	2.6
COF	HFRC 6	70	2.6

The values from the software were compared with the actual and predicted values calculated by the equations. The following table shows the experimental validation of optimum factors.

Table No. 8. Experimental Validation of optimum factors

	Specific Wear Rate			Coefficient of friction	
	Actual	**Predicted**		**Actual**	**Predicted**
Factor Level	L: 70 N	L: 70 N	**Factor Level**	L: 70 N	L: 70 N
	V: 2.6 m/s	V: 2.6 m/s		V: 2.6 m/s	V: 2.6 m/s
	C: HFRC 6	C: HFRC 6		C: HFRC 6	C: HFRC 6
SWR	3.5417	3.8340	**COF**	0.4496	0.4847
S/N Ratio	-10.9842	-11.6730	**S/N Ratio**	6.9434	6.2905
% Error	**7.624**		**% Error**	**7.232**	

5. CONCLUSION

The aim of the project was to identify the effect of friction coefficient and wear rate of composites. From the Taguchi analysis, it can be revealed that load contributes more than velocity and composition towards the change in the specific wear rate. Also, the composition percentage had an adverse effect on coefficient of friction. Specific wear rate was observed uniform in HFRC 6 but the coefficient of friction at different load conditions was more than the required range. The HFRC 4, HFRC 5 also shows prominent results in coefficient of friction but need to be addressed for the wear rate.

In comparison with phase I, the compositions showed better results in phase II. According to the objective, the composition with a lower wear rate and good coefficient of friction has to be selected as per the results and that has been seen in the HFRC 6 composition.

6. FUTURE SCOPE

- Fade recovery analysis has to be done on HFRC 6 for using appropriate equipment and with ASTM standards.

- Vibration analysis of the material can be done for better understanding.
- Thermal conductivity of material needs to be addressed for betterment.
- Changing the matrix material or the filler material could give better results.

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