DEVELOPMENT AND OPTIMIZATION OF ASBESTOS-FREE FRICTION LINING MATERIAL BASED ON EVALUATION OF TRIBOLOGICAL PROPERTIES, FOR AUTOMOTIVE DRUM BRAKE APPLICATIONS

Synopsis submitted

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I. Title of the thesis and abstract

Development and Optimization of Asbestos-free Friction Lining Material Based on Evaluation of Tribological Properties, for Automotive Drum Brake Applications

ABSTRACT

Brake is a critical system of every automobile, in which the friction lining materials wears progressively to provide the necessary braking effect to stop or control the automobiles. They play very important role sacrificing own materials loss. In the present work, initially a test set up was developed to test the tribological properties of drum brake friction liner and used to investigate the tribological properties of asbestos-free friction lining materials. A mathematical model for estimating the coefficient of friction between brake drum and friction liner was developed and simulated using MATLAB Simulink. To evaluate the tribological properties of commercially available friction lining materials, an experimental study was carried using pin-on-disc friction and wear monitor and the influence of different surface finish of the contacting disc were studied. A novel asbestos-free friction lining material was developed using coconut shell powder as filler. Two variants of friction lining materials are developed using coconut shell powder (CSP) of nano scale as filler with other ten constituents; designated as CSP15 and CSP30. The developed material is compared with commercial asbestos-free friction lining material (CSP0), manufactured by Universal Brakes, Jalgaon (MS, India), where the proposed materials were also prepared. All the three materials were subjected to Thermal Gravimetric-Differential Thermal Analysis (TG-DTA), X-ray Diffraction Spectroscopy (XRD) studies, Chase friction test and mechanical properties determination. Subsequently, the results of the chase friction test were used in multi-objective decision making for selecting optimum composition using Grey Relation Analysis (GRA). Finally, the wear analyses of the developed materials were carried out using Finite Element Analysis and results were endorsed with experimental test. Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) techniques were effectively used to characterize the asbestos-free friction lining materials at different stages of analysis. Based on the studies, it can be concluded that the addition of CSP results in a reduction of thermal decomposition rate, enhancement in mechanical and tribological properties of the developed friction materials compared to the commercial material. The microstructural study using

SEM/EDS revealed that the developed materials are more wear-resistant than commercial material. Moreover, they do not contain eco-hazardous asbestos as well as copper.

II. Brief description of the state of the art of the research topic

The friction lining materials are the category of material which should wear progressively giving desired frictional effect and also sustain their properties at elevated temperature generated during braking. The friction lining materials are categorized into metallic, semi-metallic, and non-metallic (organic). The composition of the organic friction lining material consists of binder, reinforcing fiber, friction modifier and filler. Being a polymer composite, the organic friction lining material has phenolic resin matrix, which is a major part of the composition. Different set of material combinations can be used to form the friction lining materials. Till the early 90's, asbestos was used in the friction lining materials, but due to serious issues related to health hazard for the handling personals during manufacturing of friction lining material, it needed to replaced (Berry and Newhouse, 1983) (Bijwe, 1997). This led the foundation to the development of asbestos-free friction lining materials. Researchers have tried different materials to replace the asbestos in the friction lining materials. Cho et al (2005) used barium sulfate and cashew, Filip et al (Filip, Weiss and Rafaja, 2002) applied graphite with other ingredients resulting in a stable coefficient of friction (CoF) and less wear rate, Kukutchova et al (Kukutschová et al., 2009) utilized the Nitrile Butadiene Rubber (NBR) as a major constituent, whereas Chang et al (Chang et al., 2018) applied tire rubber particles along with steel wool and barite, Verma et al (Verma et al., 2015) utilized 31% zirconium silicate. Al_2O_3 was also being tried as one of the components in the materials composition. Furthermore, Vlastimil et al (Matějka et al., 2013) used jute fiber and hazelnut shell filler, Ibhadode et al (Ibhadode and Dagwa, 2008) used palm kernel fibers, Wang et al. (Wang and Liu, 2014) utilized palm slag, hazelnut shell (Akıncıoğlu et al., 2018), etc. were utilized to obtain asbestos-free i.e. eco-friendly friction materials. These are some materials used to develop the friction materials as reported in literature. However, use of Coconut Shell Powder (CSP) for manufacturing asbestos-free lining material is not reported in the published literature.

The friction lining materials should be investigated for the tribological properties

before it can be put to use. Researchers have used different test methodologies, e.g. Pin-on-disc tester, pad-on-disc tester, etc. for this purpose. (Federici, Straffelini and Gialanella, 2017) (Federici et al., 2018) But the tests are not performed under actual braking conditions. Thermal Gravimetric-Differential Thermal Analysis (TG-DTA), X-ray Diffraction Spectroscopy (XRD) studies, Chase friction test of the brake lining material is not reported in the literature.

Researchers have used simulation techniques like MATLAB Simulink, Finite element analysis to understand the frictional coefficient of the friction lining materials (Belhocine and Abdullah, 2020) (Khairnar, Phalle and Mantha, 2015). However, the mathematical model for the coefficient of friction between the brake drum and friction liner surface with its simulation was elaborated considering automotive braking parameters.

Various scholars have studied the contact surface dependence of the friction lining materials (Okamura, 2011) (Rodríguez et al., 2014). However, the influence of surface topography of braking surface over the tribological performance of the friction lining materials was not explored focusing the material characteristics. Despite of large waste material of our country, the coconut shell has desirable tribological materials properties. Amin et al (Amin et al., 2013) used them to developed lactic acid composites. Risby et al (Risby et al., 2008) utilized them in epoxy-based composites for ballistic applications. Green composite has been developed by Verma et al (Verma and Singh, 2016) using coconut shell particles. Abutu et al (Abutu et al., 2019) tried to compose the brake pad using coconut shell powder as one of the ingredients. Although the waste coconut shell powder was utilized in many applications, its use for replacement of asbestos in the friction lining material with applications of actual brake was not reported in past.

In last part of the present work, the automotive drum brake was simulated using finite element analysis (FEA) under actual braking conditions. The FEA model was validated using experimental test for the wear analysis of the friction lining material.

III. Definition of the problem

Being a critical component of an automobile, the brake should have excellent tribological properties along with reliability and consistency, . Until the '90s, asbestos was used as a major constituent in the friction lining materials due to its dominant

mechanical and physical properties. But the health hazard and environmental issues related to asbestos, laid the necessity of development of asbestos-free friction lining materials. Many countries have banned the use of asbestos in the friction lining materials.

The functional requirement of the friction lining materials motivates to develop tribologically superior and nature friendly materials. The investigation of these materials for their sustainability and performance evaluation is another challenge to the industrial engineers in the field of tribology of friction materials. The composition of the asbestos-free friction materials plays significant role in the operating characteristics, thus selection methodology for best material, based on the critical evaluation is required. The alternative material thus developed based on the functional requirements needs to pass through appropriate tests. The cost effectiveness of the simulation methodologies such as, MATLAB Simulink, Finite element analysis, etc. makes them useful in the analysis of the complex machine elements such as drum brake, which not only saves the money, but also the time involved.

IV. Objective and Scope of work

- The objective of the research work is to develop non-asbestos brake lining material, mainly for four wheelers, with tribological properties superior then the existing brake lining material. The scope of work includes the steps required to achieve the objective which are as follows:
- Design and Development of drum brake tribological test set up in accordance with SAE J661 Standard Brake lining quality test procedure.
- Characterization of existing non-asbestos friction lining material for effect of surface finish of the discs on Coefficient of friction and wear.
- Development and testing of an eco-friendly asbestos-free (non-asbestos) composite brake friction lining material with required characteristics.
- Optimization of asbestos-free composite friction lining material using Grey Relation Analysis.
- Testing the developed friction lining material through standard test procedures like Chase test, SEM, EDS etc. to ascertain the suitability of the friction lining material for the given application.
- Finite element analysis of drum brake for prediction of wear of friction lining material.

V. Original Contribution by Thesis

In present work the development and investigation of an asbestos-free friction lining material with application of automotive drum brake was carried out. A dedicated experimental test set up was developed for the tribological investigation of the friction lining materials used in drum brakes. Initially, the available friction lining materials were analyzed for various tribological characteristics using the experimental drum brake set up developed for this purpose according to standard procedure. Also, the drum brake was simulated using MATLAB Simulink. Microstructural analysis was carried out using Scanning Electron Microscopy (SEM) to understand the wear behavior of the material.

The influence of surface roughness of the contacting surface on the tribological properties of the available friction lining materials has been studied with help of pin-on-disc experimental friction and wear monitor. Three, disc shaped specimens with varying surface roughness were subjected to sliding against a specimen pin of existing non-asbestos friction lining material. Microstructural analysis was carried out using Scanning Electron Microscopy (SEM) & Energy Dispersive Spectroscopy (EDS).

Superior asbestos-free friction lining materials were developed using nano particles of coconut shell powder (CSP) as filler and investigated for its sustainability. Two specimen samples were prepared according to industrial manufacturing process. The specimens were tested using standard quality test procedure: SAE J661 i.e. Chase friction test at commercial laboratory. Mechanical properties like, compressive strength, density, hardness, porosity, etc. of the samples were estimated according to respective standard procedures.

Microstructural analysis of the specimens was carried out using Scanning Electron Microscopy (SEM) Energy Dispersive Spectroscopy (EDS). Composition of the developed asbestos-free friction lining material were optimized for the tribological properties using Grey Relation Analysis (GRA). Seven different criterions were chosen based on the Chase friction test results. The wear analysis of the developed asbestos-free friction lining material applied in automotive drum brake were carried out using experimental as well as finite element analysis. The simulation model for the drum brake was verified using experimental results. Microstructural analysis was carried out using Scanning Electron Microscopy (SEM) Energy Dispersive Spectroscopy (EDS) to understand the wear behavior of the developed friction lining material.

VI. Methodology of Research

The research work has been carried out in five phases given below:

- Development of a dedicated experimental tribological test facility for the drum brake

The experimental test set up was developed according to standard quality test procedure (SAE J661) for the friction lining materials considering drum brake. The selection, fabrication and assembly of the component were carried out. The purpose behind this is to test the performance of friction lining materials under actual braking conditions.

The experimental set up is shown in Figure 1, was developed. The drum brake was driven by electric motor, using brake lever braking force has been applied and the braking torque has been recorded using dynamometer and load cell unit.

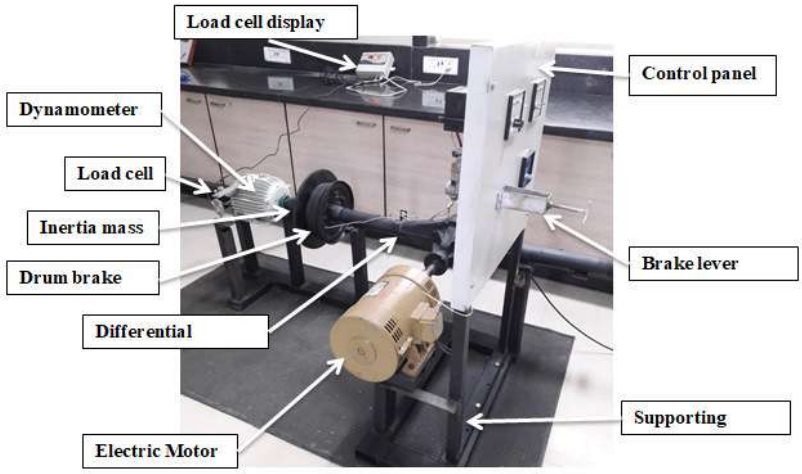


Figure 1: Experimental set up.

- Investigation and theoretical simulation of drum brake for commercially available asbestos free friction lining material

The commercially available asbestos free friction lining materials were analyzed for various tribological characteristics using an experimental drum brake set up developed. Also, the drum brake was simulated using MATLAB Simulink. The simulation and experimental results were compared with each other. Microstructural analysis was carried out using Scanning Electron Microscopy (SEM) to understand the wear behavior of the material.

- Tribological investigation of commercially available friction lining materials for the influence of surface finish

The influence of surface finish of the contacting surface on the tribological properties of the available friction lining materials has been studied using pin-on-disc experimental friction and wear monitor. Three specimen discs varying the surface roughness were subjected to sliding against a specimen pin of the friction lining material. Microstructural analysis was carried out using SEM & EDS.

- Development and selection of compositions of the asbestos-free friction lining material

The friction lining materials were developed with asbestos-free materials composition using coconut shell powder (CSP) as filler and investigated for their sustainability. Two specimen materials (CSP15 & CSP30) were prepared according to industrial manufacturing process and tested using standard quality test procedure: SAE J661 i.e. Chase friction test at commercial laboratory. Mechanical properties like, compressive strength, density, hardness, porosity, etc. of the samples were estimated according to respective standard procedures. Microstructural analysis of the specimens was carried out using SEM-EDS. The proposed materials compositions for the asbestos-free friction lining material were optimized for the tribological properties using Grey Relation Analysis (GRA).

- Wear Analysis of asbestos-free friction lining material applied in drum brake using experimental and finite element analysis

Wear analysis of the developed asbestos-free friction lining material applied in automotive drum brake were carried out using experimental as well as finite element analysis. The simulation model for the drum brake was verified using experimental results. Microstructural analysis was carried out using SEM-EDS to understand the wear behavior of the developed friction lining material.

VII. Results Achievement with respect to objectives

- **Investigation and theoretical simulation of drum brake for commercially available friction lining material**

The available friction lining materials have been investigated through an experimental study using experimental set up shown in Figure 1. Also the drum brake used in the experimental set up was simulated using MATLAB Simulink for estimation of coefficient of friction. The variation of coefficient of friction and wear with vehicle

speed and braking force was studied. The coefficient of friction was found to be maximum at highest braking and low speed. Whereas it is opposite case in wear i.e. it is maximum at highest vehicle speed and lowest braking. The response surface curve for sliding distance as 1 km was analyzed. It reflects that when the high braking force is applied at low speed of the vehicle the coefficient of friction found to be maximum, whereas it follows opposite strategy in case of wear, which discussed earlier.

The performed experiments based on the RSM design were used for fitting an empirical model to approximately describe the coefficient of friction and wear. A standard statistical software package MINITAB 17.0 was used for performing the regression analysis. The ANOVA results for the reduced response surface quadratic model for coefficient of friction and wear of drum brake friction lining material is shown in Table 1. The significance of model can be identified by a high F-value which is found as 4.19 at 95 % confidence. Value of term "P value" less than 0.05 indicate that particular term is significant (Tibadia et al. 2018) (Kalita, Shivakoti & Ghadai 2017). It shows that the current model is acceptable.

Table 1: ANOVA results

Source	DF	Adj SS	Adj MS	F-value	P-value	
Regression model	3	0.30286	0.10095	1.92	0.0245	Significant
Vehicle speed, V (Kmph)	1	0.01288	0.01288	0.24	0.628	
Braking force, F (N)	1	0.26025	0.26025	4.94	0.041	Significant
Sliding distance, S (Km)	1	0.02973	0.02973	0.56	0.463	
Error	16	0.84283	0.05268			
Lack-of-fit	11	0.60003	0.05455	1.12	0.480	Confidence interval 95%
R-sq	9.23%	R-sq (adj)	0.00%	R-sq (pred)	0.00%	

The microstructural analysis was carried on the worn specimens using SEM and EDS. The higher phase presence of carbon and oxygen was seen which is because of the tribo-oxidation between the surfaces. The copper and iron found in the lower phase directly came out with the wear debris. Magnesium, Tin and lead were constituted to be the overall resistance of wear of the friction lining material.

- **Tribological investigation of commercially available friction lining materials to study the influence of surface finish**

The specimen pin was prepared with the available friction lining material and subjected to sliding against the three different discs at three different load and sliding speeds based on the parameter combination. After experimental study it was observed that disc 2 (disc with moderate surface finish) is desirable surface to have better performance of the contacting friction lining material.

The microstructural analysis of the worn pin on the three different pins were analyses for the surface wear behavior using SEM & EDS. Sample 2 shows a lesser amount of presence of secondary plateau than sample 1, which confirms that the further sliding will give lower wear than sample 1. Sample 3 shows similar surface characteristics, as that of sample 2. The elemental distribution (EDS) confirms the proper mixing and homogenization of the friction lining material. The copper and iron was spotted at lower energy distribution are came out as a wear debris (Straffelini, Pellizzari and Maines, 2011) (Straffelini and Molinari, 2011) (Leonardi et al., 2018).

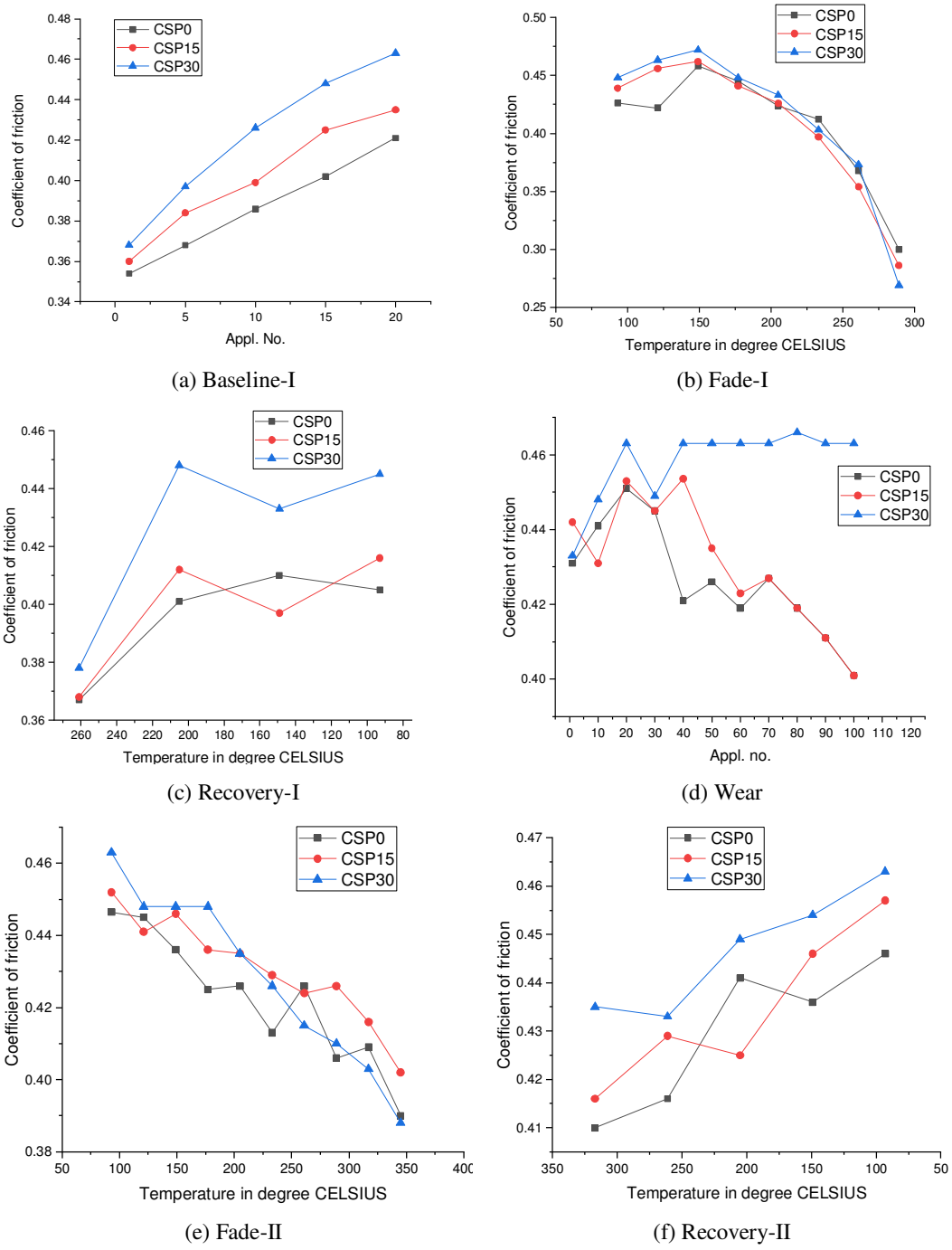
- **Development and selection of compositions of the asbestos-free friction lining material**

The developed friction lining materials were tested for TG-DT analysis in the temperature range of 30 to 950^0C. The overall decomposition rate is lower in the case of CSP30 (7.89%) compared to the other two materials (11.12 & 16.98 respectively), indicates that CSP30 possesses good thermal stability.

The mechanical and physical properties of the developed friction materials were also interpreted. It was observed that the density and hardness of the material increases with their CSP content, this shows the effect of the addition of nano-particles in the materials. The porosity of the developed materials was found to be decreasing, which signifies superior material properties. The crystallographic structure of the friction lining material was nanlyzed using XRD spectum of the developed materials relative to copper. The spectra reveal peaks at a different angle of diffractions (2θ), which indicates that the materials are of crystalline structure. All the materials have shown a strong peak at a 2θ angle of around 30^0, which exhibits a similar structure to commercial friction materials (Solomon and Berhan, 2007).

Figure 2 shows the Chase friction testing response of the materials during each stage of operation as per the schedule. The data for testing of the commercial material (CSP0)

is obtained from the manufacturer and plotted here with CSP15 and CSP30, for comparison. Based on the assessment, it was observed that CSP30 revealed the best performance.



(a) Baseline-I (b) Fade-I

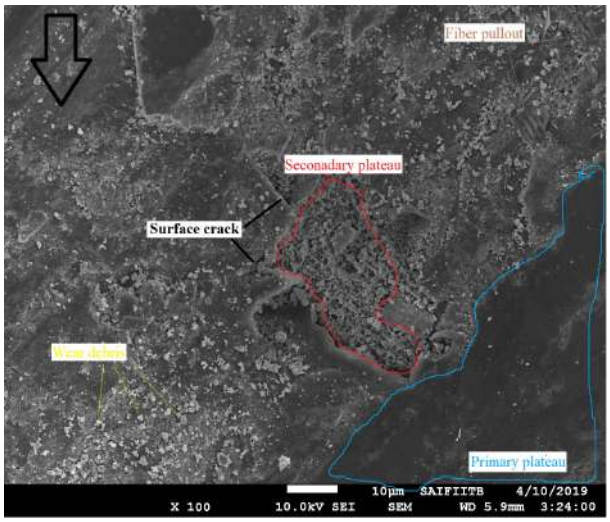
(c) Recovery-I (d) Wear

(e) Fade-II (f) Recovery-II

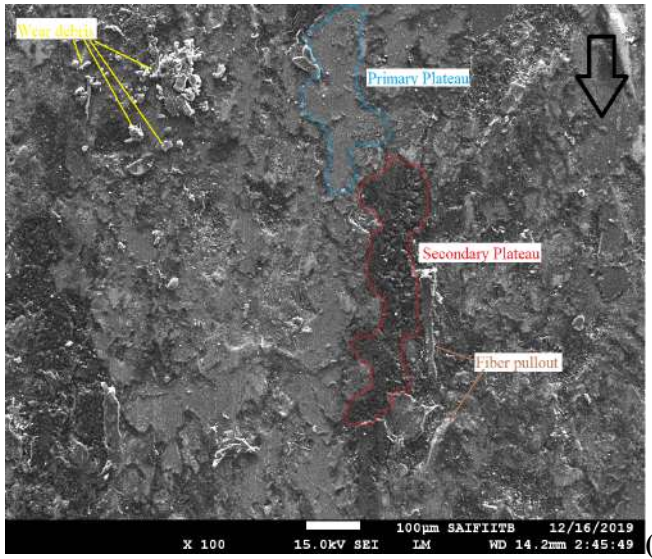
Figure 2: Chase friction test results

To study the surface wear behavior of the developed FMs, microstructural studies were accomplished using Scanning Electron Microscopy (SEM) and Energy Dispersive

Spectroscopy (EDS), after the chase testing shown in Figure 3&4. In case of micrograph of CSP0, wear debris are seen in large number compared to CSP15 and CSP30. Lesser secondary plateaus as well as the wear debris are observed in CSP15 & CSP30 compared to CSP0, which proves that they are wear-resistant. Surface cracks are also seen on the surface of the CSP0. Proposed materials CSP15 & CSP30 have not shown metallic components like copper, iron, lead, etc. unlike CSP0 in EDS spectra. The metallic compositions (Cu, Mg, Pb, Fe, etc.) are from tribo-oxidation of the brake drum, whereas non-metallic elements (C & O) are due to friction materials.



(a)



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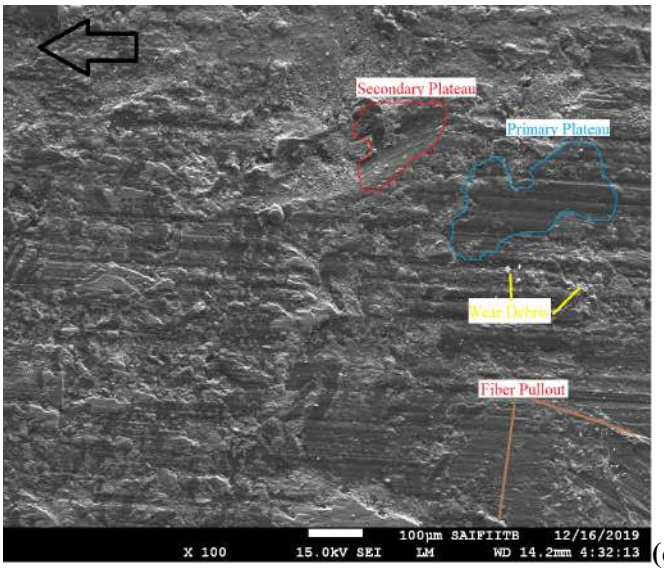
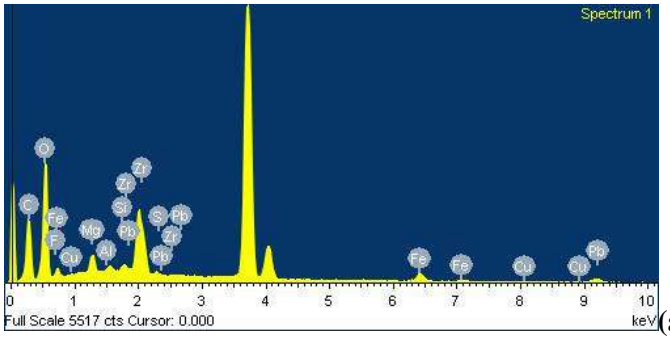
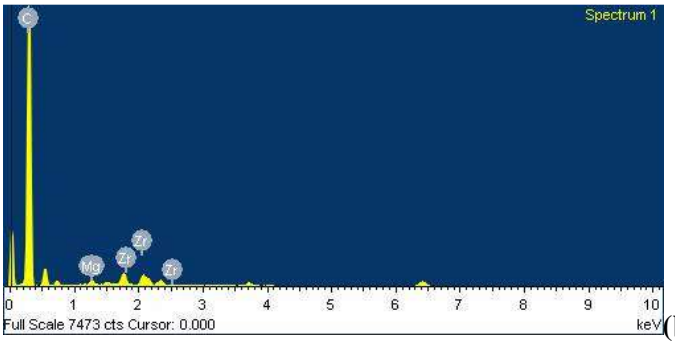


(c)

Figure 3: SEM micrographs for (a)CSP0, (b)CSP15, & (c)CSP30



(a)



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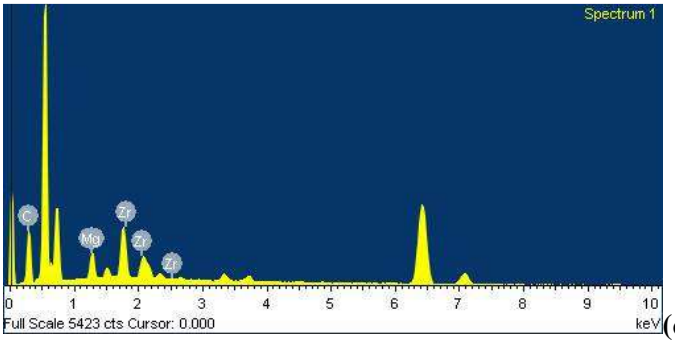

(c)

Figure 4: EDS spectrum for (a)CSP0, (b)CSP15, & (c)CSP30.

The materials were critically evaluated using the Grey Relation Analysis with the help of criterions respective to their tribological performance recorded in Chase friction test. Relatively Grey relation grades (GRGs) were seen to be higher in the case of CSP30. The GRA method applied here converts the multi-objective problem into single objective, the GRG are the significant parameter which the alternative possess in all the criteria. It was observed that CSP30 is the most desirable material formulation among the three, which conforms to the chase test results.

- **Wear Analysis of asbestos-free friction lining material applied in drum brake using experimental and finite element analysis**

The wear measurement was carried out using experimental study and FEA. A novel wear measurement methodology were developed and used. Multiple numbers of trial runs were carried out to increase the accuracy of the measurement. The experimental and FEA results were compared. It was observed that the FEA model developed was predicted closer results to the experimental analysis (Figure 5). The surface wear behavior of the FLM was studied using microstructural analysis with the help of SEM & EDS micrographs. Three samples were tested and it was observed that CSP30 is highest wear resistant among the three materials.

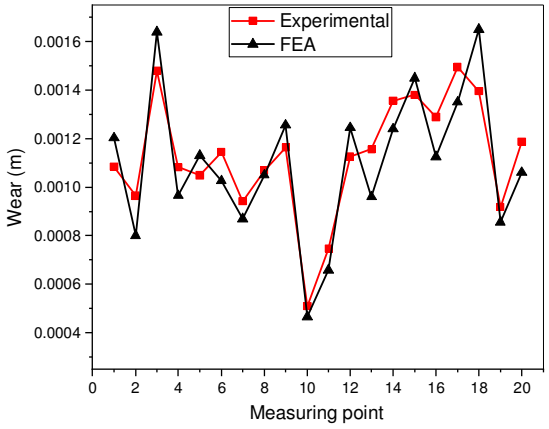

Figure 5: Comparison of wear results

VIII. Conclusions

- The experimental test set up developed in the present research is effective in estimation of tribological properties of the brake lining material under the brake

performance conditions. The experimental study carried out in this work to investigate the available friction lining material, revealed that the higher F-value (1.92 & 4.19) and P-value less than 0.05 indicated the regression model as well as the performance parameter braking force, are significant.

- Mathematical model derived and simulated for predicting of coefficient of friction of the friction lining material applied in drum brake using robust mathematical tool MATLAB Simulink, matches with experimental results with average variation of 7.86%.
- The use of waste material like coconut shell powder for manufacturing friction lining material for cars performed better than commercially available non-asbestos material as demonstrated by GRA. The material with 30% of CSP (CSP30) exhibited 6.34% better property as demonstrated by GRA when seven parameters were considered.
- The microstructural analysis using SEM micrographs reveals the wear mechanism of the friction lining material at different vehicle speeds. The secondary plateaus, plateaus responsible for surface wear, formed in case of CSP30 are 12-15 % lesser than those formed in commercially available friction lining material (CSP0), revealing the wear resistance of CSP30.
- The EDS spectra have shown the presence of various elements over the surface of the friction lining material, due to tribo-oxidation during sliding friction between the surfaces. However the environment polluting metallic elements like, copper, iron, lead, etc. was observed in case of CSP0.The experimental study carried out to study the topographical effect on the performance of the friction lining material reveals that the disc-2 with surface roughness (Ra) 3.77μm gives competent wear with 5% higher coefficient of friction compared to disc-1 & disc-3.
- The FEA model estimated the surface wear of the friction lining material closer to the experimental values with average deviation of 9.84%, which shows that the FEA model is effective to elaborate the surface wear of the friction lining materials used in drum brake.

IX. Research paper publications and a list of all publications

1.Dinesh Shinde, Kishore N. Mistry, Suyog Jhavar, Sunil Pathak. “A Review on Non-Asbestos Friction Materials: Material Composition and Manufacturing”. *Advanced*

Material Research, Vol. 1150, 2018, 22-42. **[SJR, Google scholar]** https://doi.org/10.4028/www.scientific.net/AMR.1150.22

2.Dinesh Subhash Shinde, KN Mistry, Mukesh Bulsara. Theoretical and experimental investigation of non-asbestos friction lining material applied in automotive drum brake. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, Vol. 234(6), 2019, pp. 972-985. **[SCIE with IF 1.137]** https://doi.org/10.1177/1350650119877775

3.Dinesh Subhash Shinde, Mukesh Bulsara, KN Mistry. Tribological Performance of non-asbestos friction lining materials in Contact with Brake Disc with Varying Topography. *Industrial Lubrication and Tribology*, Vol. 72(10), 2020, pp. 1277-1283. **[SCIE with IF 1.037]** https://doi.org/10.1108/ILT-04-2020-0120

4.Dinesh Shinde, Mukesh Bulsara, KN Mistry. Finite element analysis of automotive drum brake for prediction of wear of friction liner. *IOP conference series: Materials Science and Engineering,* Vol. 810, 2019, pp. 1-12**. [SCOPUS]** https://iopscience.iop.org/article/10.1088/1757-899X/810/1/012040/meta

5.Dinesh Shinde, Mukesh Bulsara, KN Mistry. Multi Objective Optimization of Nano-composite Non-asbestos Friction Lining Material using Grey Relation Analysis (GRA). *IOP conference series: Materials Science and Engineering, Vol. 1004 (2020), pp. 789-796.* **[SCOPUS]** https://iopscience.iop.org/article/10.1088/1757-899X/1004/1/012014/meta

6.Dinesh Shinde, Mukesh Bulsara, Jeet Patil. Wear Analysis of Eco-friendly Non-asbestos Friction lining Material applied in Automotive Drum Brake: Experimental and Finite Element Analysis. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology,* 2021. **[SCIE with IF 1.137]** https://journals.sagepub.com/doi/full/10.1177/13506501211016730

7.Dinesh Shinde, Mukesh Bulsara, KN Mistry. Selection of materials formulation for non-asbestos friction materials using mutli-criteria decision making. *International Journal of Materials Engineering Innovation.* **[SCOPUS][In Press]** https://www.inderscience.com/info/ingeneral/forthcoming.php?jcode=ijmatei

8.Dinesh Shinde, Mukesh Bulsara, KN Mistry. Development and Investigation of Non-asbestos Organic (NAO) Friction Materials with Coconut Shell Powder as filler. *International Journal of Materials & Product Technology*. **[SCIE with IF 0.759][Accepted for publication]**

References

Abutu, J., Lawal, S.A., Ndaliman, M.B., Lafia-Araga, R.A., Adedipe, O. and Choudhury, I.A. (2019) 'Production and characterization of brake pad developed from coconut shell reinforcement material using central composite design', *SN Applied Sciences*, vol. 1, p. 82.

Akıncıoğlu, G., Öktem, H.A.S.A.N., Uygur, I. and Akıncıoğlu, S. (2018) 'Determination of friction-wear performance and properties of eco-friendly brake pads reinforced with hazelnut shell and boron dusts', *Arabian Journal for Science and Engineering*, vol. 43, pp. 4727–4737.

Amin, A., Sarkar, R., Moorefield, C.N. and Newkome, G.R. (2013) 'Preparation of different dendritic-layered silicate nanocomposites', *Polymer Engineering & Science*, vol. 53, pp. 2166–2174.

Belhocine, A. and Abdullah, O.I. (2020) 'Design and Thermomechanical Finite Element Analysis of Frictional Contact Mechanism on Automotive Disc Brake Assembly', *Journal of Failure Analysis and Prevention*, vol. 20, pp. 270–301.

Berry, G. and Newhouse, M.L. (1983) 'Mortality of workers manufacturing friction materials using asbestos.', *Occupational and Environmental Medicine*, vol. 40, pp. 1–7.

Bijwe, J. (1997) 'Composites as friction materials: Recent developments in non-asbestos fiber reinforced friction materials—a review', *Polymer composites*, vol. 18, pp. 378–396.

Chang, Y.H., Joo, B.S., Lee, S.M. and Jang, H. (2018) 'Size effect of tire rubber particles on tribological properties of brake friction materials', *Wear*, vol. 394, pp. 80–86.

Cho, M.H., Kim, S.J., Kim, D. and Jang, H. (2005) 'Effects of ingredients on tribological characteristics of a brake lining: an experimental case study', *Wear*, vol. 258, pp. 1682–1687.

Federici, M., Gialanella, S., Leonardi, M., Perricone, G. and Straffelini, G. (2018) 'A preliminary investigation on the use of the pin-on-disc test to simulate off-brake friction and wear characteristics of friction materials', *Wear*, vol. 410, pp. 202–209.

Federici, M., Straffelini, G. and Gialanella, S. (2017) 'Pin-on-disc testing of low-metallic friction material sliding against HVOF coated cast iron: Modelling of the contact temperature evolution', *Tribology Letters*, vol. 65, p. 121.

Filip, P., Weiss, Z. and Rafaja, D. (2002) 'On friction layer formation in polymer matrix composite materials for brake applications', *Wear*, vol. 252, pp. 189–198.

Ibhadode, A.O.A. and Dagwa, I.M. (2008) 'Development of asbestos-free friction lining material from palm kernel shell', *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 30, pp. 166–173.

Khairnar, H.P., Phalle, V.M. and Mantha, S.S. (2015) 'Estimation of automotive brake drum-

shoe interface friction coefficient under varying conditions of longitudinal forces using Simulink', *Friction*, vol. 3, pp. 214–227.

Kukutschová, J., Roubíček, V., Malachová, K., Pavlíčková, Z., Holuša, R., Kubačková, J., Mička, V., MacCrimmon, D. and Filip, P. (2009) 'Wear mechanism in automotive brake materials, wear debris and its potential environmental impact', *Wear*, vol. 267, pp. 807–817.

Leonardi, M., Menapace, C., Matějka, V., Gialanella, S. and Straffelini, G. (2018) 'Pin-on-disc investigation on copper-free friction materials dry sliding against cast iron', *Tribology International*, vol. 119, pp. 73–81.

Matějka, V., Fu, Z., Kukutschová, J., Qi, S., Jiang, S., Zhang, X., Yun, R., Vaculík, M., Heliová, M. and Lu, Y. (2013) 'Jute fibers and powderized hazelnut shells as natural fillers in non-asbestos organic non-metallic friction composites', *Materials & Design*, vol. 51, pp. 847–853.

Okamura, T. (2011) 'Effect of directional surface finish of brake discs on friction behavior during running-in', *SAE International Journal of Passenger Cars-Mechanical Systems*, vol. 4, pp. 1445–1452.

Risby, M.S., Wong, S.V., Hamouda, A.M.S., Khairul, A.R. and Elsadig, M. (2008) 'Ballistic Performance of Coconut Shell Powder/Twaron Fabricagainst Non-armour Piercing Projectiles', *Defence Science Journal*, vol. 58, p. 248.

Rodríguez, A., de Lacalle, L.N.L., Fernández, A. and Braun, S. (2014) 'Elimination of surface spiral pattern on brake discs', *Journal of Zhejiang University SCIENCE A*, vol. 15, pp. 53–60.

Solomon, D.G. and Berhan, M.N. (2007) 'Characterization of Friction Material Formulations for Brake Pads.', World Congress on Engineering, 2–4.

Straffelini, G. and Molinari, A. (2011) 'Mild sliding wear of Fe–0.2% C, Ti–6% Al–4% V and Al-7072: a comparative study', *Tribology letters*, vol. 41, pp. 227–238.

Straffelini, G., Pellizzari, M. and Maines, L. (2011) 'Effect of sliding speed and contact pressure on the oxidative wear of austempered ductile iron', *Wear*, vol. 270, pp. 714–719.

Verma, P.C., Menapace, L., Bonfanti, A., Ciudin, R., Gialanella, S. and Straffelini, G. (2015) 'Braking pad-disc system: wear mechanisms and formation of wear fragments', *Wear*, vol. 322, pp. 251–258.

Verma, A. and Singh, V.K. (2016) 'Experimental investigations on thermal properties of coconut shell particles in DAP solution for use in green composite applications', *J Mater Sci Eng*, vol. 5, pp. 1–5.

Wang, F. and Liu, Y. (2014) 'Mechanical and tribological properties of ceramic-matrix friction materials with steel fiber and mullite fiber', *Materials & Design*, vol. 57, pp. 449–455.