

Republic of Iraq  
Ministry of Higher Education  
and Scientific Research  
Babylon University  
College of Engineering



# **STUDY OF RESINS AND FIBERS CONTENT FOR FRICTION MATERIALS INDUSTRY**

*A Thesis*

*Submitted To Babylon University, College of Engineering in  
Partial Fulfillment of the Requirements for the Award of  
Degree of Master of Science in Material Engineering*

*BY*

*Abeer Adnan Abd*

*B.Sc.*

*Supervised By*

*Asst. Prof. Dr. Najim A. Saad*

*Lecture. Dr. Falah. K, Matloub*

*April 2009*



جمهورية العراق  
وزارة التعليم العالي و البحث العلمي  
جامعة بابل  
كلية الهندسة

## دراسة محتوى الراتنجات و الألياف في صناعة مواد الاحتكاك

أطروحة  
مقدمة إلى جامعة بابل كلية الهندسة كجزء من متطلبات نيل  
شهادة الماجستير في هندسة المواد

أعدت من قبل

**عبير عدنان عبد**

بكالوريوس 2001

بإشراف

د.فلاح كفي

أ.م.د.نجم عبد الأمير سعيد

مطلوب

نيسان 2009

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

يَرَفَعُ اللَّهُ الَّذِينَ ءَامَنُوا مِنْكُمْ وَالَّذِينَ  
أوتُوا الْعِلْمَ لَوْجًا تَوَالَّهُ بِمَا تَعْمَلُونَ  
خَيْرٌ

(11) الْحَجَّازِ

صَبْرًا وَاللَّهُ الْعَظِيمُ

# Acknowledgments

First of all, all praises are due to **ALLAH** who gave me the ability and desire to complete this work.

I wish to express my deepest gratitude and sincere thanks to my supervisors **Dr. Najim A. Saad and Dr. Falah K. Matloub** for their guidance, invaluable discussions and constructive comments, which greatly improved the structure and presentation of the thesis.

Sincere thanks are also expressed to the staff of the material engineering department especially the head of the department **Dr. Ahmed Ouda Jasim** for the encouragement during this work.

Many thanks to be due to **Dr. Mohammad Al-Mamory** for cooperation and help in many intangible ways.

I would like to present my deep thanks to Mr. Jamil Abdulhur, Mr. Hussein H. Rashid, in laboratories of material engineering department / Babylon University for their help in building the rig.

I record my sincere gratitude to my parents and my husband for their love, patience and support during the period of preparing this work.

Finally, I am grateful to all those who have helped me in carrying out this work.

*Abeer*

/ /2009

# Certification

We certify that this thesis entitled “**STUDY OF RESINS AND FIBERS CONTENT FOR FRICTION MATERIALS INDUSTRY**” was prepared by **Abeer Adnan Abd** under our supervision at Babylon University/ Department of Material Engineering, in Partial Fulfillment of the Requirements for the Award Degree of Master of Science in Material Engineering

We recommend that this thesis be forwarded for examination in accordance with the regulation of the University of Babylon.

Signature:

Assist. Prof. Dr. **Najim A. Saad**

/ November /2008

Signature:

Assist. Prof. Dr. **Falah. K. Matloub**

/ November /2008

Approved by the Material Engineering Department

Assist. Prof. Dr. **Ahmed A.**

Head of the Department

/ /2008

## **Abstract**

In the present study the rubber was added to novolac resin as a binder to improve the mechanical properties. Glass fibers and steel fibers were used at different ratios to improvise their effect as a reinforcing fibers, molybdenum trioxide and calesuim carbonate as a filler, zirconium oxide as abrasive material and copper sulfides as a lubricant. The current work investigates the characteristics of three resins: (i) SIR with novolac resin (ii) NBR with novolac resin (iii) SBR with novolac resin. The addition of SIR or NBR was used because it undertakes the high temperature and has good chemical resistance. The SIR was used with deferent weight ratio of fibers to compare its effect on the mechanical properties. The samples were prepared by using cold press technique at (250MPa) pressure .The samples were curing at (80°C). Hot press was used at (140°C) under (40MPa) pressure. Wear test was carried out by using pin on disc test system which was designed, and manufactured. Results from the present study showed that the friction coefficient and wear rate varied with the change of the resin and fibers ratio. The result showed that NBR and SIR addition proved best in terms of impact strength, hardness, wear rate and friction coefficient result but SBR showed poor result. The NBR addition had better wear results than SIR. The high ratio of fibers decreases the wear rate and increases the impact strength and friction. Cold press showed better result than hot press.

# الخلاصة

في هذه الدراسة تم تحسين الخواص الميكانيكية للمادة الرابطة بإضافة المطاط. تم استخدام ألياف الزجاج بنسب مختلفة لتحسين تأثيرها كألياف تقوية, اوكسيد المولبدنيوم الثلاثي و كربونات الكالسيوم استخدمت كمادة مالئة, اوكسيد الزركونيوم استخدم كمادة حاكة و كبريتات النحاس كمادة مزيته. الدراسة الحالية حسنت مواصفات ثلاث راتنجات هي (1) المطاط السليكوني (SIR) للنوفلاك (2) مطاط (SBR) للنوفلاك (3) مطاط (NBR) للنوفلاك. استخدم المطاط السليكوني و (NBR) لأنه يتحمل درجات الحرارة العالية وقد تم استخدامه مع عدة نسب للألياف لمقارنة تأثيرها على الخواص الميكانيكية. حضرت النماذج باستخدام تقنية الكبس على البارد تحت ضغط (MPa) 250 وعولجت حراريا بدرجة (80 °C). استخدم الكبس على الساخن بدرجة (140 °C) و تحت ضغط (40MPa). تم اختبار البلى باستخدام نظام (pin on disk) والذي تم تصميمه وتنفيذه ضمن الجانب العملي لهذه الدراسة. من نتائج هذه الدراسة نلاحظ إن معامل الاحتكاك ومعدل البلى يتغير مع نوع الراتنج وتغير نسبة الألياف. إن إضافة مطاط SIR و NBR برهنت أفضل النتائج من حيث مقاومة الصدمة والصلادة و معدل البلى ومعامل الاحتكاك مما في ال (SBR). إن إضافة NBR أعطت نتائج للبلى أفضل من SIR وان النسبة العالية من الألياف يقلل معدل البلى ويزيد مقاومة الصدمة ومعامل الاحتكاك. الكبس على البارد أعطى نتائج بلى أفضل من الكبس على الساخن.

# Contents

<b><u>Subject</u></b>	<b><u>Page</u></b>
<b>Acknowledgment</b> .....	<b>I</b>
<b>Abstract</b> .....	<b>II</b>
<b>Contents</b> .....	<b>III</b>
<b>Nomenclature</b> .....	<b>VI</b>
<b>Chapter One: Theoretical Part</b>	
<b>1.1 General</b> .....	<b>2</b>
<b>1.2 Tribological contact</b> .....	<b>5</b>
<b>1.3 Wear</b> .....	<b>7</b>
<b>1.4 Type of Wear</b> .....	<b>9</b>
<b>1.5 Type of Wear Measurement</b> .....	<b>12</b>
<b>1.5.1 Weighting Method</b> .....	<b>12</b>
<b>1.5.2 Mechanical Gauging Method</b> .....	<b>12</b>
<b>1.5.3 Optical Method</b> .....	<b>13</b>
<b>1.5.4 Measurement of Wear Using Radiotracers Technique</b> .....	<b>13</b>
<b>1.6 Microscopic Contact Situation</b> .....	<b>13</b>
<b>1.7 Worn Surface Analysis</b> .....	<b>18</b>
<b>1.8 Disc Brake Lining Production Process</b> .....	<b>21</b>
<b>1.9 Automotive Brake Systems</b> .....	<b>22</b>
<b>1.10 Brake Materials and Additive Functionality</b> .....	<b>23</b>
<b>1.10.1 Reinforcing fibers</b> .....	<b>26</b>
<b>1.10.2 Binders</b> .....	<b>31</b>
<b>1.10.3 Fillers</b> .....	<b>36</b>
<b>1.10.4 Friction modifier</b> .....	<b>38</b>
<b>1.10.5 Lubricants</b> .....	<b>39</b>
<b>1.10.6 Abrasives</b> .....	<b>40</b>
<b>1.11 Kinds of Rubber Added</b> .....	<b>40</b>
<b>1.13 Aim of the Work</b> .....	<b>42</b>

## **Chapter Two: Literature Survey**

2.1 Introduction .....	44
2.2 Wear of Composite Materials.....	44
2.3 Frictional Materials .....	54
2.4 Final Remarks.....	63

## **Chapter Three: Experimental Analysis**

3.1 Introduction .....	66
3.2 Material Used .....	67
3.3 Sample Preparing .....	69
3.3.1 Cold Press Technique .....	69
3.3.1.1 Dry Press Method.....	69
3.3.1.2 Wet Prepared and Pre-dried Method.....	70
3.3.2 Hot Press Technique .....	70
3.4 Preparations of Row Materials Techniques.....	74
3.4.1 Mould made .....	74
3.4.2 Die finishing.....	74
3.4.3 Preparation of composite material technique .....	74
3.5 The Preparing of commercial sample.....	76
3.6 Used Tests.....	78
3.6.1 Mass measurements .....	78
3.6.2 Impact measurements .....	78
3.6.3 Hardness measurements .....	78
3.6.4 Temperature measurements .....	79
3.6.5 Pressing .....	79
3.6.6 Wear test.....	81
3.7 Friction Coefficient Measurements.....	83

## **Chapter Four: Results and Discussions**

4.1 Introduction .....	86
4.2 Wear Tests Results and Discussions .....	86
4.2.1 The cold Press.....	86
4.2.1.1 The Dry Press .....	86
4.2.1.2 The wet prepared and pre-dried .....	87

4.2.2 Hot Press.....	90
4.2.3 The commercial sample.....	98
4.3 Hardness Tests .....	99
4.4 Impact Strength Test .....	101
4.5 Friction Coefficient Results .....	102
4.6 Curing Temperature .....	103

## **Chapter Five: Conclusions and Recommendations**

5.1 Conclusions .....	106
5.2 Recommendations for Future Work .....	107
<b>References</b> .....	<b>109</b>

# Nomenclature

The following symbols are used generally through the text. Others are defined as when used.

<i>LATIN SYMBOLS</i>		
A	Real contact Area	M <sup>2</sup>
F	Friction force	N
k	Constant	-
L	Sliding distance	m
P	Normal pressure	psi
t	Sliding time	minutes
V	Sliding speed	rpm

<i>GREEK SYMBOLS</i>		
<i>Symbol</i>	<i>Description</i>	<i>Unit</i>
$\mu$	Friction coefficient	-
$\varepsilon$	Strain	-
	Wear lost	grams
$\alpha$	Proportionality factor	-

<i>Symbol</i>	<i>Description</i>
ABS	Anti blocker system
AF	Aramid fiber
ASTM	American Societ for Testing Materials
CAF	Composite containing fabric of aramid (AF)
CCF	Composite containing fabrics of carbon (CF)
CHY	Composite containing fabrics of carbon (CF) and aramid (AF)
CF	Carbon fiber
Co	Unfilled PEI
COPNA	Condensate Polynuclear Aromatic
DTV	Deformation of thickness variations
EDXA	Energy Dispersive X-Ray Analysis
FADE	The Loss in Brake Pad Effectiveness at Elevated Temperature
Gf	Glass fiber
HMTA	Hexamethylene Tetraamine
HY	Hybrid composite
LAOW	Low amplitude oscillating wear
MRRO	Mounted radial run out
NAO	Non asbestos organic
NBR	Nitrile butadiene rubber
PAN	Poly acrylo nitrile
PEEK	Poly ether-ether ketone
PEI	Poly etherimide
PTFE	Poly tetra fluoro ethylene
PV	Pressure-velocity

RECOVERY	The Revival in Brake Pad Effectiveness at Low Temperature
SBR	Styrene butadiene rubber
SEM	Scanning electron microscopy
SF	Cellulose fiber
SIR	Silicon rubber

# REFERENCES

## **References**

1. D Chann and G W Stachowiak, "Review of Automotive Brake Friction Materials", Proc. Instn Mechanical Engineering, vol. 218 part D: Journal of Automobile Engineering, 2004.
2. P. J. Blau, "Compositions, Functions, and Testing of Friction Brake Materials and Their Additives", Oak Ridge National Laboratory, USA, ORNL/TM-2001/64, 2001.
3. Philip S. Sklad, "Application of Innovative Materials" FY Progress Report high strength weight reduction materials, 2004.
4. B. K. Satapathy, and J. Bijwe, "Performance of friction materials based on variation in nature of organic fibers Part II. Optimization by balancing and ranking using multiple criteria decision model (MCDM)", Wear 257, pp. 585-589, 2004.  
<http://www.sciencedirect.com>
5. Mikael Eriksson, "Friction and Contact Phenomenon of Disc Brakes Related to squeal", compressive summaries of Uppsala dissertation, Faculty of Science and Technology, 2000.
6. J. Bijwe, Nidhi and B. K. Satapathy, "Influence of Amount of Resin on Fade and Recovery Behavior of Non-Asbestos Organic (NAO) Friction Materials", Trans. Indian Inst. Met. Vol.57, No. 4, pp. 335-344, 2004.

7. P. V. Gurunath, and J. Bijwe, "Friction and Wear Studies on Brake Pad Materials Based on Newly Developed Resin", *Wear* 263, pp. 1212-1219, 2007. <http://www.sciencedirect.com>
8. Jamal N. Sultan "Sliding Wear of Porous Surfaces under Lubricated Conditions", M.Sc. thesis, University of Technology, Department of Production Engineering and Metallurgy, 1984.
9. D. Suryatama, R. P. Uhlig, S. Vallurupalli and F. Zweng, "Thermal Judder on Drum Brakes due to Mounted Radial Run Out", 2<sup>nd</sup> ANSA &  $\mu$ ETA International congress, Greece, 2007.
10. Z. Humberto Melgarejo "Sliding Wear of Porous Surfaces under Lubricated Conditions", M.Sc. thesis, University of Technology, Department of Production Engineering and Metallurgy, 2006.
11. U. S. Tewari, and J. Bijwe, "On the Abrasive Wear of Some Polyimides and Their Composites", *Tribology International* vol. 24, No. 4, pp. 247-254, 1991.
12. U. S. Tewari, J. Bijwe, J. Mathur, and I. Sharma, "Studies on Abrasive Wear of Carbon Fiber (Short) Reinforced Polyamide Composites", *Tribology International* vol. 25, No. 1, pp. 53-59, 1992.
13. رعد حامد هلال, " دراسة مقاومة الزحف الانضغاطة والبلية الالتصاقية الجاف لمواد متراكبة لدائنية" رسالة ماجستير, الجامعة التكنولوجية, قسم العلوم التطبيقية, 2001.

14. B. K. Satapathy, and J. Bijwe, "Performance of Friction Materials Based on Variation in Nature of Organic Fibers", *Wear* 257, pp. 573-584, 2004. <http://www.sciencedirect.com>
15. B. K. Satapathy, and J. Bijwe, "Analysis of Simulations Influence of Operating Variables on Abrasive Wear of Phenolic Composites", *Wear* 253, pp. 787-794, 2002. <http://www.sciencedirect.com>
16. R. Hashmi, Ajay Naik and Navin Chand "Effects of hybrid composition of LCP and glass fibers on abrasive wear of reinforced LLDPE" *Bull. Mater. Sci.*, vol. 29, No. 1 pp. 49–54., 2006.
17. Bakelite AG, "Resins for the friction material industry", TP Tech. Phenolic Resins, 2004.  
[http://www.mas-handel.de/mas-handel/produkte/PH Resins for the friction material industry.pdf](http://www.mas-handel.de/mas-handel/produkte/PH%20Resins%20for%20the%20friction%20material%20industry.pdf).
18. J. Bijwe, J. Indumathi, and A. K. Ghosh "Role of Fabric Reinforcement on the Low Amplitude Oscillating Wear of Polyetherimide Composites", *Wear* 256, pp. 27-37, 2004.  
<http://www.sciencedirect.com>
19. W. Bolton "Engineering Materials Technology" Butterworth Heinemann, 1998.

21. عبد الفتاح محمود طاهر, "أساسيات علم و تقنية البلمرات" دار المريخ للنشر, 2000.
22. M. RAO, et al, "The Effect of PTFE on the Friction and Wear Behavior of Polymers in Rolling-Sliding Contact" *Polymer Engineering and Science*, vol. 38, No. 12, pp.1946-1958, 1998.
23. J. Bijwe, J. Indumathi, and M. Fahim, "Friction and Wear Behavior of Polyetherimide Composites in Various Wear Modes", *Wear* 249, pp. 715-726, 2001. <http://www.sciencedirect.com>
24. J. Bijwe, J. Rajesh a, U.S. Tewari, and B. Venkataraman, "Erosive wear behavior of various polyamides", *Wear* 249, pp. 702-714, 2001. <http://www.sciencedirect.com>
25. G Srinath and R Gnanamoorthy, "Processing and Tribo Behavior of Nylon Clay Nanocomposites under Abrasive Wear Mode" *International Symposium of Research Students on Materials Science and Engineering*, December 20-22, 2004, Chennai, India.
26. David L. Burris, and W. Gregory Sawyer, "A Low Friction and Ultra Low Wear Rate PEEK/PTFE Composite", *Wear* 261, pp. 410-418, 2006. <http://www.sciencedirect.com>

27. G. Peillex, L. Baillet, Y. Berthier “Numerical and Experimental Study of C/C Composites under Tribological Loading” Tribologie et couplages multiphysiques 22-24 may 2006 – Lille – France.
28. B. Suresha, et al, “The Role of Fillers on Friction and Slide Wear Characteristics in Glass-Epoxy Composite Systems” Journal of Minerals and Materials Characterization & Engineering, Vol. 5, No.1, pp 87-101, 2006.
29. R. Rattan, J. Bijwe, and M. Fahim, "Influence of Weave of Carbon Fabric on Low Amplitude Oscillating Wear Performance of Polyetherimide Composites", Wear 262, pp. 727-735, 2007.  
<http://www.sciencedirect.com>
30. M. Boz, and A. Kurt, "Effect of ZrSiO<sub>4</sub> on the Friction Performance of Automotive brake Friction Materials", J. Mater. Sci. Technol., vol. 23 No. 6 , pp. 843-850, 2007.
31. David L. Burris, et al, “Polymeric Nanocomposites for Tribological Applications” Journal of Macromol. Mater. Eng. vol. 292, pp. 387–402, 2007.
32. Hua Fu, et al, “Thermal Stability of Poly (ether ether ketone) Composites under Dry-sliding Friction and Wear Conditions” Iranian Polymer Journal vol. 17, No. 7, pp. 493-501, 2008.

33. J. Rajesh, and J. Bijwe, "Influence of Fillers on the Low Amplitude Oscillating Wear Behavior of Polyamide 11", *Wear* 256, pp. 1-8, 2004.  
<http://www.sciencedirect.com>
34. B. K. Satapathy, and J. Bijwe, "Wear Data Analysis of Friction Materials to Investigate the Simultaneous Influence of Operating Parameters and Compositions", *Wear* 256, pp. 797-804, 2004.  
<http://www.sciencedirect.com>
35. J. Bijwe, S. Sen, A. Ghosh, "Influence of PTFE Content in PEEK-PTFE Blends on Mechanical Properties and Tribo-Performance in Various Wear modes", *Wear* 258, pp. 1536-1542, 2005.  
<http://www.sciencedirect.com>
36. J. Bijwe, Nidhi, N. Majumdar, and B. K. Satapathy, "Influence of modified Phenolic Resins on the Fade and Recovery Behavior of Friction Materials", *Wear* 259, pp. 1068-1078, 2005.  
<http://www.sciencedirect.com>
37. K. Keriman "Tribological Properties of a Tightly Woven Carbon /Carbon Composite", M.Sc. thesis, University of Technology, Department of Metallurgical and Material Engineering, 2005. Turkey.

38. B. K. Satapathy, and J. Bijwe, "Composites Friction Materials Based on Organic Fibers: Sensitivity of Friction and Wear to Operating Variables", *Composites: Part A* 37, pp. 1557-1567, 2006. <http://www.sciencedirect.com>
39. Masoomi, M., et al, et al, "Damping Behavior of the Phenolic Based Composite Friction Materials Containing Thermoplastic Elastomers (TPEs)" *Iranian J. Chem. Chem. Eng.* vol. 25, No. 3, pp. 35-40, 2006.
40. Zhaobin Chen, et al, "Friction and Wear Mechanisms of PA66/PPS Blend Reinforced with Carbon Fiber" *Journal of Applied Polymer Science*, vol. 105, pp. 602–608, 2007. [www.interscience.wiley.com](http://www.interscience.wiley.com)
41. ASTM D 256-02 "Standard Test Method for Determining the Izod Pendulum Impact Resistance of Plastics" *Annual Book of ASTM standards.* [www.astm.org](http://www.astm.org)
42. ASTM D 256-03 "Standard Test Method for Determining the Izod Pendulum Impact Resistance of Plastics" *Annual Book of ASTM standards.* [www.astm.org](http://www.astm.org)
43. ASTM D 256-034 "Standard Test Method for Determining the Izod Pendulum Impact Resistance of Plastics" *Annual Book of ASTM standards.* [www.astm.org](http://www.astm.org)

## *References*

---

44. Rawa A. A. Hasan “Study of Impregnation Process of Preparation of Short Fiber Reinforced Poly Phenylene Sulphides Composites for Air Frame Structure”, M.Sc. thesis, Babylon University, College of Engineering, 2007.
  
45. Maurice Morton “Rubber Technology” Van Nostrand Reinhold Company, 1973.

# Certification

We certify, as an examining committee, that we have read this thesis, "**STUDY OF RESINS AND FIBERS CONTENT FOR FRICTION MATERIALS INDUSTRY**", presented by **Abeer Adnan Abd**, and examined the candidate in its contents and in our opinion it meets the standard of a thesis for the degree of MSc. in Material Engineering.

Assist. Prof. Dr. **Najim A. Saad**

(Supervisor)

//2009

Assist. Prof. Dr. **Falah. K. Matloub**

(Supervisor)

//2009

Assist. Prof. Dr. **Emad S. Ali**

(Member)

//2008

Assist. Prof. Dr. **Arkan Kh. Al-Tai**

(Member)

//2008

Prof. Dr. **Jabir Shanshool**

(Chairman)

//2008

Approved by the Al-Mustansiriya University

Assist. Prof. Dr. **Ali M. Al-Athary**

Dean of the College

//2008

# CHAPTER ONE

## *Theoretical Part*

## **Chapter One**

### **Theoretical Part**

#### **1.1 Introduction**

Friction materials are materials for which the properties of many components have been combined in long series of empirical tests. They are divided into two types, dry materials and wet materials. Dry materials are meant to be operating mostly under dry conditions but also under wet conditions such as braking a car in the rain. Wet materials are designed specifically for use in a wet environment only such as wet clutches and oil immersed brakes [1].

The purpose of friction brakes is to decelerate a vehicle by transforming the kinetic energy of the vehicle to heat, via friction, and dissipating that heat to the surrounding. As a part of the commercial truck or automobile, brake material have additional requirements, like resistance to corrosion, long life, low noise, stable friction, low wear rate, acceptable cost, dimensional stability, appropriate thermal properties, and light weight that will enable new technologies to raise the fuel efficiency of a vehicle without compromising its safety and reliability [2, 3].

In order to achieve the properties required of brakes, most brake materials are not composed of single elements or compounds, but rather are composites of many materials. More than 2000 different materials and their variants are now used in commercial brake components. Table (1.1) shows the general classifications of brake pads in the brake industry [1, 3].

The performance of friction materials is controlled by the selection of the constituents, their relative volume fractions, shape, orientation and distribution [4]. Brake pads typically comprise the following subcomponents [5]:

1. Frictional additives, which determine the frictional properties of the brake pads and comprise a mixture of abrasives and lubricants.
2. Fillers, which reduce the cost and improve the manufacture ability of brake pads.
3. A binder, which holds components of a brake pad together.
4. Reinforcing fibers, which provide mechanical strength.

Asbestos fibers have been used as reinforcing material brake pads as early as 1908. In the late 1980s it was public knowledge that asbestos is a car carcinogen and brake pads manufactures started looking for suitable alternatives such as steel fibers, glass fibers, ceramic fibers, and carbon fibers. In conclusions ceramic fiber appear to be the most suitable for use as reinforcing fibers in brake friction material while the high cost of the ceramic fiber lead to use a mixture of different types of reinforcing fibers with complementing properties such as using a mixture of steel fiber with glass fiber [1].

Organic part in non-asbestos organic (NAO) friction composites is most vulnerable to thermal degradation, charring leading to glazing and subsequent deterioration in performance due to heat generated at the interface as a result of increase the severity of braking. Thermal degradation of the material results in a decrease in the applied force at elevated temperature. So the selection of resin with higher thermal stability and oxidation resistance is of immense importance in controlling fade (loss in braking effectiveness at elevated temperatures) [6].

Binder is the heart of a system which binds the ingredients formally so that can perform the desired function in the friction materials. Phenolic resins are invariably used as binder in friction materials due to low cost along with a good combination of mechanical properties such as high hardness, compressive strength, moderate thermal resistance, and creep resistance and very good wetting capability with most of the ingredients [7].

Semi metallic brake pads with a mixture of metallic and organic compounds having varying thermal expansion coefficients would require a large amount of molybdenum trioxide to prevent lining cracking [1].

Graphite cannot be used too liberally in phenolic resins as a lubricant because the weak bonding strength between graphite and phenolic resin, leading to low shear strength [1].

Metal sulphides such as copper sulphides are very popular in friction materials of today as they are able to provide good lubrication as well as having lower conductivities than graphite [1].

Table (1.1) Classification of brake pads [1]

<b>Classification</b>	<b>Ingredients</b>
Metallic	Predominantly metallic, such as steel fibers, copper fibers, etc.
Semi-metallic	Mixture of metallic and organic ingredients
Non-asbestos organic.	Predominantly organic, such as mineral fibers, rubber, graphite, etc

## **1.2 Tribological Contact**

Friction is the resistance to motion which is experienced whenever slid body slides over another. If a block is dragged over a horizontal floor, the lateral force required to move the block is equal to the friction force between the two surfaces. Contacts situation between two rough surfaces which describes only small parts of the surfaces are in real contact with each other. The area of real contact increases with increase load and with decrease hardness as shown in figure (1.1) [8].

Tribological contact in automotive brakes constitute one of the few applications where a material is supposed to slide against another, at high sliding velocities with a high coefficient of friction. This puts extreme demands on the friction materials. They need a stable friction at different temperatures, loads, environments and stages of wear. Furthermore, seizure, excessive wear rates and macroscopic fracture must be avoided [5].

An illustration of the power development in a car brake is given by the following example. A modern midsize car weighs about 1500 kg. When driving at 28 m/s (~100 km/hr), the kinetic energy of the vehicle is 600 kJ. The shortest possible distance within which the car can be stopped is about 40 meters. Assuming that the retardation is constant, which is reasonable since the friction between tire and road controls the retardation force, this will take 2.9 seconds. As a result, the average power developed will be 206 kW and the maximum power, in the beginning of the stop, will be 412 kW [5]. In the front wheel, disc brake pads absorb a major amount up to 80 % of the total kinetic energy of an automobile. Frictional contacts between brake linings and rotors will initiate temperature increase to cause thermal deformations. These deformations may induce the generation of disc thickness variations (DTV) which in turn creates localize high temperature areas commonly known as hot spots [9, 5].

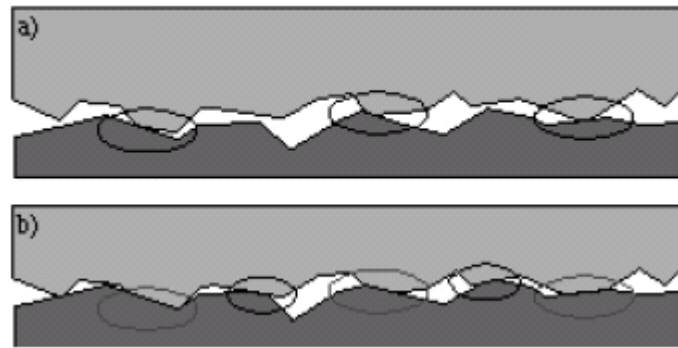


Figure (1.1) contact situation between two rough surfaces [5]

- a. low load and/or high hardness
- b. high load and/or low hardness

### **1.3 Wear**

Wear is an important topic from an economical point of view because it represents one of a very limited number of ways in which material objects lose their usefulness. Unfortunately the inherent interdependence among those factors and properties encumber a straightforward analysis of this phenomenon [10,11].

The surface damage without exchange of material can be classified as: structural changes such as aging, tempering, phase transformations, recrystallization, etc; and plastic deformation which is the damage characterized by residual deformation of the surface layer, either locally or extensively. The latter is often revealed as a change in shape; surface cracking is the damage caused by excessive local contact strains or cyclic variations of thermally or mechanically induced strains. The latter case can

cause dense patterns of parallel cracks whereas thermal cycling lattice generates a network of cracks [10].

Surface damage involving loss of material (wear) is based on the loss of material of the surface, which leaves behind wear scars of various shapes and sizes. Fundamental elements in the process of material removal can be shear fracture, extrusion, chip formation, tearing, brittle fracture, fatigue fracture, chemical dissolution, and diffusion. Finally surface damage involving gain of material explores, first, the phenomenon of picking up loose particles, transfer of material from the counter surface, etc, and the corrosion event consisting of material degradation by chemical reactions with ambient elements or elements from the counter surface [12].

The fact that the damage observed on a tribologically loaded surface normally is a combination of two or more of the types illustrated as shown in Figure (1.2) Wear may be defined as the surface damage or removal of material from one or both of two solid surfaces in a sliding, rolling, or impact motion to one another as a result of mechanical action. It is characteristic that the amount of material removed in the wear process is quite small. Wear is generally based on loss of material, but it should be emphasized that damage due to material displacement on a given body, with no net change in weight or volume, also constitutes wear. In addition, wear as friction, is not a material property, it is a system response [10, 13].

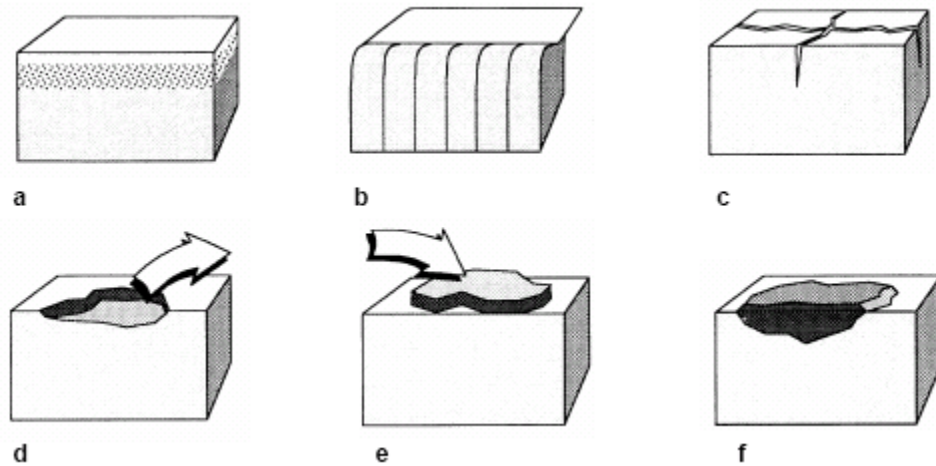


Figure (1.2) Classification of surface damage a) Structural changes b) Plastic deformation c) Surface cracking d) Wear e) Gain of material f) Corrosion [10].

#### **1.4 Types of Wear**

Adhesive wear occurs when two smooth bodies are in sliding contact, whether lubricated or not. Adhesion (or bonding) occurs at the asperity contacts at the interface and these contacts are sheared by sliding, which may result in detachment of a fragment from one surface and attachment to the other surface. Later these fragments may come off the surface on which they are formed and be transferred back to the original surface, or else form loose wear particles. Adhesive wear arises from the strong adhesive forces set up whenever atoms come into intimate contact [7, 10].

In an early theory of sliding wear, it was suggested that shearing can occur at the original interface or in the weakest region in one of the two bodies. In most cases, interfacial adhesion strength is expected to be small as compared to the breaking strength of surrounding local regions; thus, the break during shearing occurs at the interface in most of the contacts and no wear occurs in that sliding cycle. In a small fraction of contacts, break may occur in one of the two bodies and a small fragment may become attached to the other surface. In another mechanism, plastic shearing of successive layers of an asperity contact results in detachment of a wear fragment [10].

Abrasive wear occurs when asperities of a rough, hard surface or hard particles slide on a softer surface and damage the interface by plastic deformation or fracture. In the case of ductile materials with high fracture toughness, hard asperities or hard particles result in the plastic flow of the softer material. Most metallic and ceramic surfaces during sliding show clear evidence of plastic flow, even some for brittle ceramic materials. Contacting asperities of metals deform plastically even at the lightest loads. In the case of brittle materials with low fracture toughness, wear occurs by brittle fracture. In these cases, the worn zone consists of significant cracking. There has sometimes been confusion between fine abrasive wear a form of relatively benign adhesive wear [10, 13].

Corrosive wear occurs when sliding takes place in a corrosive environments. In air, the most dominant corrosive medium is oxygen. Therefore chemical wear in air is generally called oxidative wear. In the absence of sliding, the products of corrosion will form a film on the surfaces. This film tends to delay or even detain the corrosion. However, the sliding action wears the film away, so the corrosive attack continues. Thus chemical wear requires both chemical reaction (corrosion) and abrasion [13, 10].

Surface fatigue wear is observed during repeated sliding or rolling over a track. The repeated loading and unloading cycles to which the materials are exposed may induce the formation of surface or subsurface cracks, which eventually will result in the break up of the surface with the formation of large fragments leaving large pits in the surface [10].

Studies of the wear process indicate that the adhesive wear is the most common and least avoidable form of wear. As far as is known, this form of wear is universal in all mechanical systems in which two solids slide in contact with each other. It cannot be eliminated but only reduced [2].

The relative wear is calculated using the general relationship [2]

$$\Delta w = \alpha P^a V^b t^c \quad (1.1)$$

Where  $\Delta w$  = wear lost [grams],  $P$  = normal pressure [psi],  $V$  = sliding speed [rpm], and  $t$  is the sliding time [minutes]. Proportionality factor  $\alpha$  depends on testing geometry. Values of exponent  $a$ ,  $b$ , and  $c$  are material pair-related.

## **1.5 Methods of Wear Measurements**

### **1.5.1 Weighting method:**

It is the simplest way to measure the wear. The sample is weighted before and after running and the wear rate is calculated by the difference in the mass [8, 13].

### **1.5.2 Mechanical gauging method**

Micrometer is used to measure the wear in the large volume parts like the cylinder in the car engine [8, 13].

### **1.5.3 Optical method**

There are many optical ways to measure the wear; one of these methods is the studying of the small micro hardness indentations on a surface then study how its size is reduced during sliding [8, 13].

### **1.5.4 Measurement of wear using radiotracers technique**

It is a developed way to measure the wear volume and it is used for two kinds of studies the first one when the required wear measurement is very small the second was used when there is a need to know the describes of the notch. It consists measurement of nuclear radiators and the measurement of adhesive wear debris [8, 13].

## **1.6 Microscopic Contact Situation**

Normally, brake pads are composites of materials with very different properties. The weakest components, such as resins and solid lubricants, have a hardness of around 200 MPa, while the abrasive particles and fibers in some cases may have a hardness of up to 20 GPa. The components show a correspondingly wide spectrum of wear resistances. These differences result in a complex contact situation. Unevenly distributed wear and compaction of wear debris results in a surface characterized by flat plateaus, rising above the rest of the surface. The plateaus can be spotted with the naked eye as shiny spots scattered over the pad surface [5].

A scanning electron microscope (SEM) or a profilometer reveals that the plateaus are of varying sizes, typically between 50 and 500  $\mu\text{m}$  in diameter and a few microns high. They can be defined as the areas of the pad showing signs of sliding contact with the disc. Typically, these signs involve a relatively flat surface with shallow grooves in the sliding direction. The number of plateaus on one pad is typically in the order of 105 and their total area is 10-30% of the nominal area of the pad. To facilitate an effective description of the contact situation, two new expressions have been coined: primary and secondary plateaus as shown in figure (1.3). The primary and secondary plateaus together form the contact plateaus [5].

The primary plateaus first form due to the lower removal rate of the mechanically stable and wear resistant ingredients of the pad. In a second stage, these protruding hard phases may form nucleation sites for the growth of secondary plateaus. The normal pressure, shear forces and the friction heat combines to compact the debris and the secondary plateaus grow [14].

The build-up of compacted areas requires supply of wear debris, a limited space between pad and disc, friction energy and normal load. Thus, the formation of the secondary plateaus is a gradual process. Nevertheless, during favorable conditions it can form in less than a second. The propensity to form plateaus, affects the in-stop friction increase. It could not be confirmed by microscopy that larger plateaus form at low humidity, but the friction behavior gave such indications. When braking in dry air, the average friction and the in-stop friction increase is high. The lowlands

surrounding the plateaus consist of less wear resistant pad constituents, such as polymeric resins, fillers, and friction modifiers. These are mechanically weak and worn mainly through three-body abrasion [5].

The microstructure of the secondary plateaus varies with the depth from the surface. Close to the surface, the material is dense and extremely fine-grained. A continuous tribofilm with grain sizes in the nanometer range is formed, as shown in figure (1.4). Figure (1.5) shows the surface of a secondary plateau in high magnification. A diffuse structure can be spotted in, or just below the surface, with 5-10 nm grains. On top of the nanoparticle layer, an extremely thin and fine-grained, or amorphous, layer is believed to be found. This layer is only a few nanometers thick and can therefore only be discerned as a blur, covering the grains in figure (1.5) [5].

The backside of a detached piece of a secondary plateau is characterized by loosely compacted particles that are considerably larger than the particles that seen in the front surface. The fine-grained top-layer is less than 1  $\mu\text{m}$  thick. Below this layer, the particle size is fairly independent of depth, as shown in figure (1.6). High pressure, shear force and surface temperature is believed to be responsible for the homogenization, sintering, of the top-layer. The fine-grained surface layer is much harder than the underlying layer of compacted debris. These values can be compared to the hardness of the steel fibers [5].

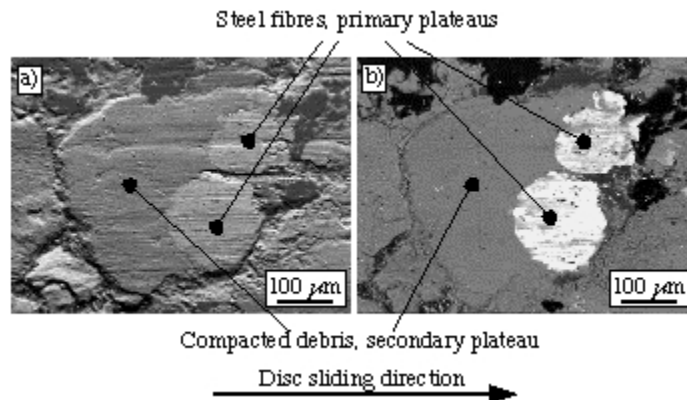


Figure (1.3) One of the  $10^5$  contact plateaus seen on the surface of an organic brake pad. Note the two primary plateaus, steel fibers, supporting the secondary plateau, compacted debris to their left. (SEM)

a) Enhanced topographical contrast. b) Enhanced compositional contrast [5].

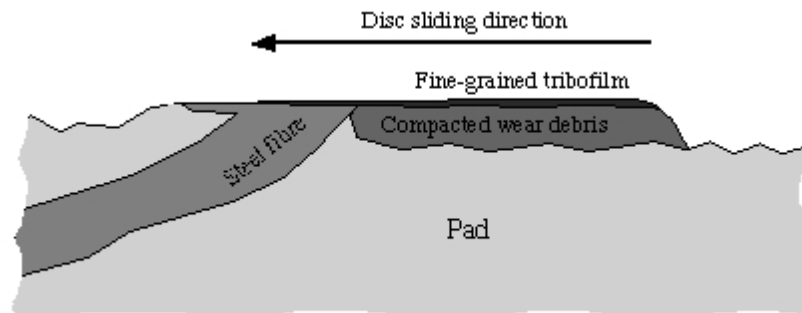


Figure (1.4) Schematic cross-section of the wear debris, fine-grained tribofilm and fiber forming a contact plateau [5].

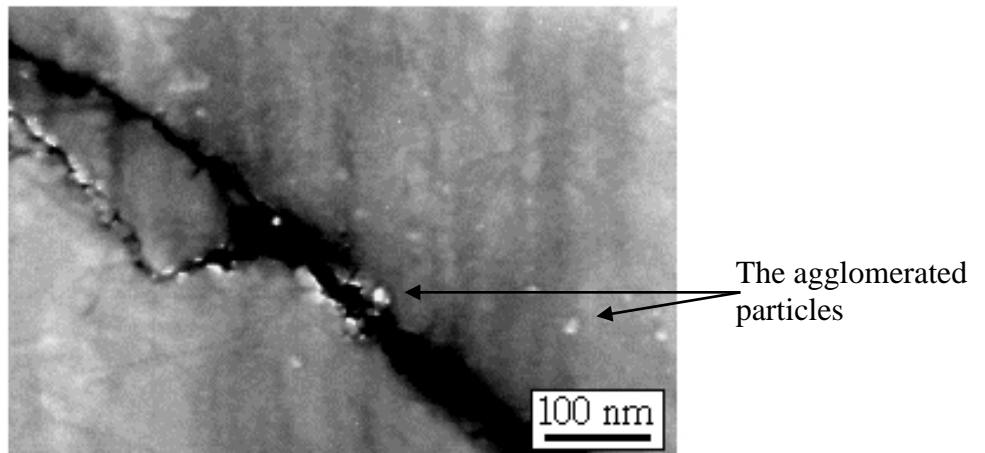


Figure (1.5) Surface of a secondary plateau on an organic brake pad as formed by the contact against the disc. The agglomerated particles forming the tribofilm covering the plateau surface are smaller than 10 nm. (SEM) [5].

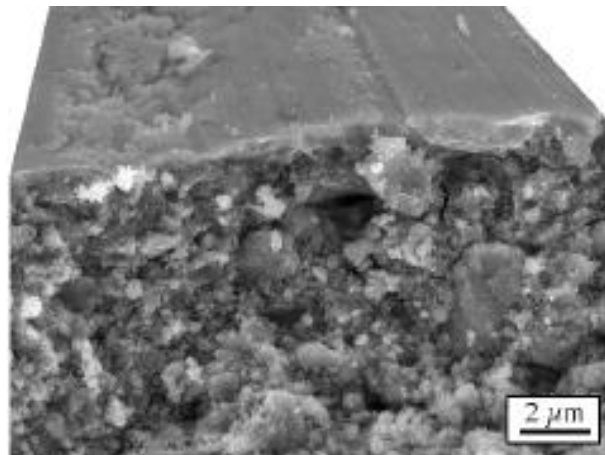


Figure (1.6) Fracture cross-section of a secondary plateau. Note the thin homogeneous top layer and the transition to a coarser structure below. Sliding direction of the disc: inwards. (SEM) [5]

### **1.7 Worn Surface Analysis**

The surfaces of some composites worn under 1.2 kg load are shown as SEM micrographs in Figure (1.7). The characteristic features apparent on the worn surfaces are: development of fatigue cracks in the direction transverse to the abrasion, wavy patterns marked by the circles of the fine cracks, absence of plastic deformations as evident from the sides of the furrows and material removal by brittle fracture. Phenolic matrix being thermoset the energy absorption is less as compared to the thermoplastics. This leads to the development of the various types of cracks on the surface, for example, fatigue cracks as is evident from micrographs, Figure (1.7 a-f ), representing 0% (neat resin), 5, 15 and 20%  $\text{Al}_2\text{O}_3$  filled composites. Similarly, wide cracks were observed in 15%  $\text{Al}_2\text{O}_3$  filled phenolic composite as shown in Figure (1.7e). A general topography of the worn surface with 5%  $\text{Al}_2\text{O}_3$  filled composite is shown in Figure (1.7 b). In the case of thermosetting composites, cracks initiate at the filler–matrix interface and propagate very easily through the matrix towards the other filler–matrix interfaces. When the network of cracks intersects, the filler particles become loose and are removed in the form of wear debris. The resin also gets removed in the form of fine wear debris caused by brittle fracture of the resin. Thus the material removal is easier for thermoset than for thermoplastics. Figure (1.7 f) shows 20% filler composite. The corresponding EDAX image for Figure (1.7 f) is in Figure (1.7 g) and indicates the distribution pattern of alumina in the form of Al dot density. Higher percentage of filler may lead to less widely distributed particles, which in turn reduces the inter-particle distance [15].

When the load is increased the micro cutting and micro cracking process also increase proportionally. It is assumed that abrasive wear volume increases with the real area of contact, sliding distance and the probability of debris particle formation is related to actual ratio between the rupture stresses for a given polymer. The wear volume is therefore, a function of a normal load, friction coefficient, sliding distance and rupture stress [16].

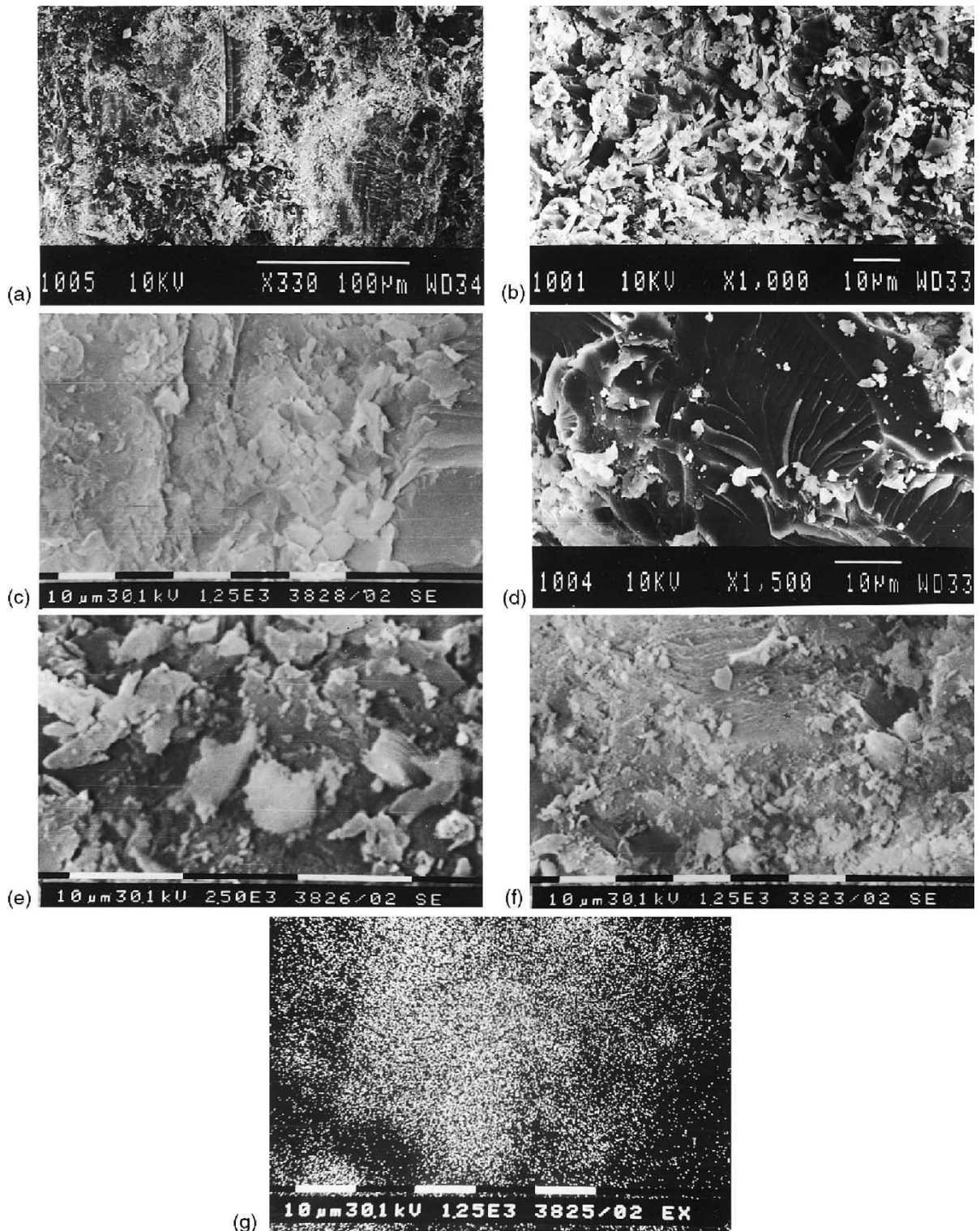


Figure (1.7) SEM micrographs of worn surfaces (80 grade SiC paper under 12N load): (a) neat resin; (b) 5% Al<sub>2</sub>O<sub>3</sub> filled composite; (c) 5% Al<sub>2</sub>O<sub>3</sub> filled composite with fatigue marks; (d) 15% Al<sub>2</sub>O<sub>3</sub> filled composite; (e) 15% Al<sub>2</sub>O<sub>3</sub> filled composite showing micro cracks; (f) 20% Al<sub>2</sub>O<sub>3</sub> filled composite with fatigue cracks; (g) EDAX micrograph of 20% Al<sub>2</sub>O<sub>3</sub> filled phenolic composite [15].

### **1.8 Disc Brake Lining Production Process**

There are three methods of disc brake lining processing [17]:

- **Dry processing:** Dry processing produced by mixing the components with intensive mixer or kneader, then shaping the components by compression molding. There are two types of molding hot press molding and cold press molding. Hot press molding is preferred at a temperature of (140-180) °C under pressure of (20-80) MPa with molding time of (0.5-1) minutes per millimeter of layer thickness. Cold press molding is preferred under pressure (100-250) MPa.
- **Wet processing.** Wet processing includes cold press molding and warm press molding. Cold press molding is at room temperature under pressure of (100-250) MPa.
- **Wet prepared and pre dried mixing** which is divided into two types cold press as for dry mixing and hot press. Hot press is preferred at (140-180) °C under (30-60) MPa with molding time of (0.5-1) minutes per millimeter of layer thickness.

## **1.9 Automotive Brake Systems**

An automotive brake system can be divided into three main parts [5]:

1. The rotor, as the name is indicating, is rotating with the wheel. It is the first part in the friction couple. Rotors made of grey cast iron have always dominated the market. During the last couple of years, other materials, although still having only a small commercial importance, have been introduced. Some examples are SiC-reinforced aluminum, carbon-SiC composites and sintered carbon.
2. The brake lining is the second, stationary, part of the friction couple. During a brake application, the pad is pressed against the rotor with a hydraulic piston. The friction forces between the stationary lining and the rotating disc will turn the kinetic energy of the vehicle into heat.
3. The hydraulic system transfers and amplifies the brake force from the brake pedal to the hydraulic piston pressing the linings against the rotor. In modern brakes the hydraulic system also includes the ABS-system (Anti-Blockier System, German) and different kinds of traction systems.

Figure (1.8) illustrates the two brake systems, the disc brake and the drum brake.

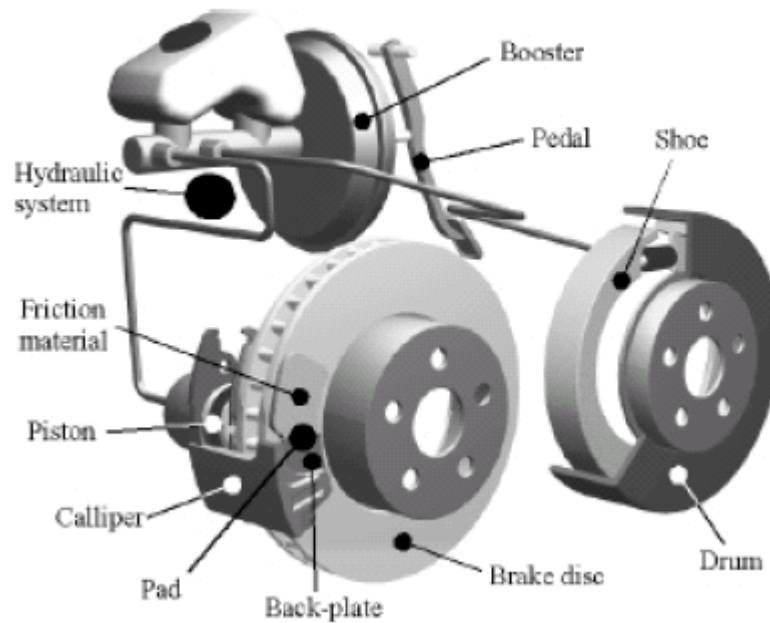


Figure (1.8) Illustration of the two brake systems, the disc brake and the drum brake. [5]

### **1.10 Brake Materials and Additive Functionality**

Non-asbestos organic (NAO) based friction materials are essentially multi ingredient systems (containing more than 10 ingredients, in general) in order to achieve the desired amalgam of performance properties. Though the list of ingredients used for formulation of such composites exceeds the number 700, these are classified into four major categories binder, fibers, friction modifiers and fillers based on the major function they perform apart from controlling friction and wear performance [14].

Binder is the heart of a system which binds the ingredients firmly so that they can perform the desired function in the friction materials. Fibers in combination are added mainly for strength while friction modifiers are used to manipulate the desired range of friction. Fillers are of two types functional fillers (to improve particular characteristic feature of composites such as resistance to fade, etc.) and space/inert fillers (mainly to cut the cost) [14].

Sample compositions of certain automotive brake pads based on information from the United States Patent and Trademark Office are shown in figure (1.9). Brake pad additives serve a variety of functions. Even a difference of a percent or two of additives concentrations can affect performance, so composition control is important [1, 2].

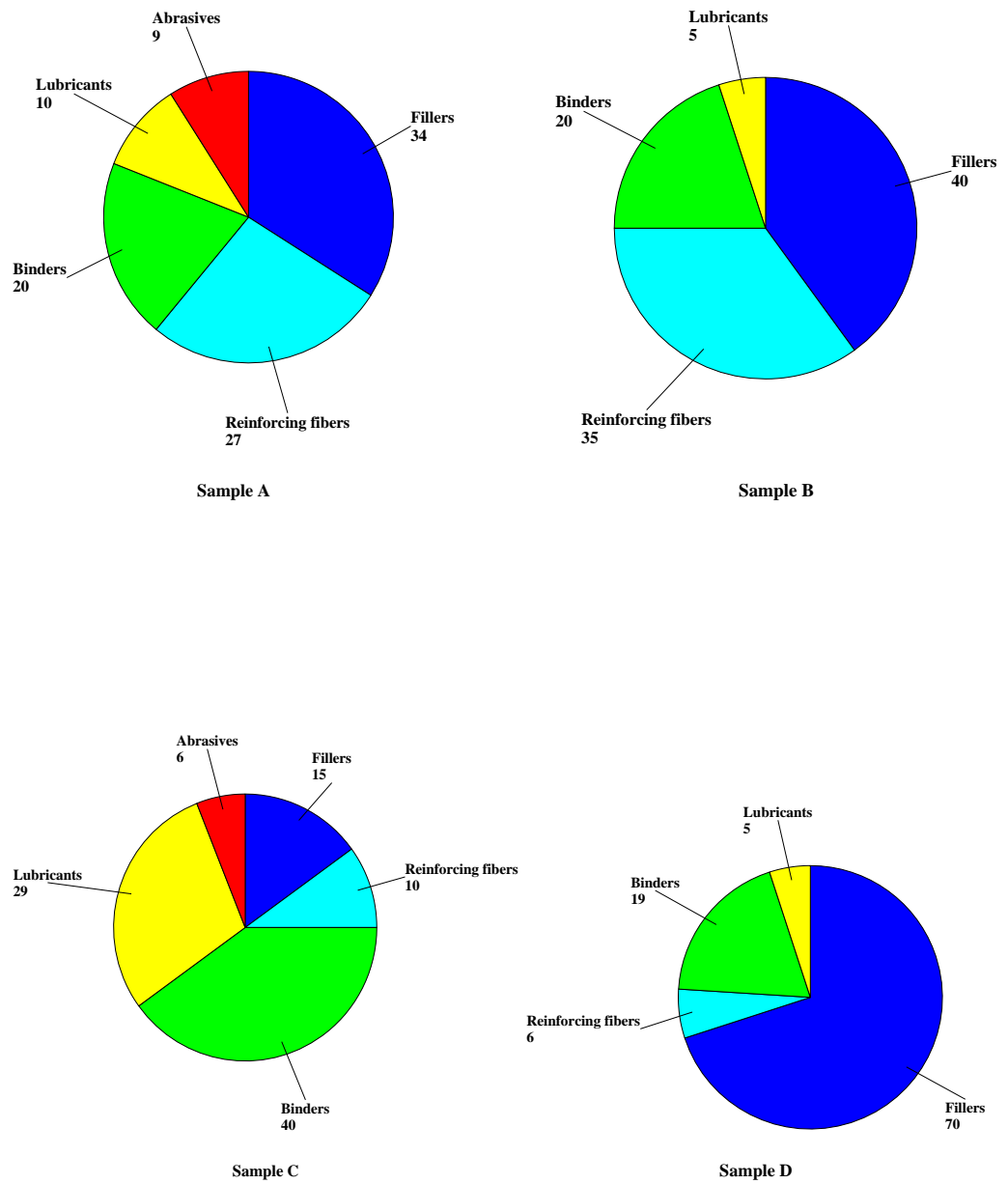


Figure (1.9) Composition of brake pad [1]

### 1.10.1 Reinforcing fibers

The purpose of reinforcing fibers is to provide mechanical strength to the friction material. Recent research has shown that the braking load is actually carried by tiny plateaus that rise above the surrounding lowlands on the friction material [1, 2, 5]. These plateaus are formed by the reinforcing fibers surrounded by the softer compacted components. Therefore the importance of the reinforcing fibers in friction material cannot be underestimated. Friction materials typically are a mixture of different types of reinforcing fibers with complementing properties. The plateaus are formed by compacted debris and cannot exist without a primary support such as the reinforcing fiber illustrated in Figure (1.10) [1]. Therefore, it is reasonable to expect that friction material wear will increase with a decreasing amount of reinforcing fibers. Among the different varieties of reinforcing fibers available, ceramic fibers has the highest thermal stability and hardness while being one of the lightest materials around [1].

- **Glass fibers** being physically strong when bonded together with resinous binders. Glass fibers are suitable for use as reinforcing fibers as they also exhibit thermal resilience. Typical glass has a melting point of 1430 °C, which is much higher than the melting point of 800–850 °C for asbestos. However, typical glass fibers only have a conductivity of 0.04 W/mK, which is even lower than that of asbestos of 0.15 W/mK and very much less than metallic fibers such as copper. The brittleness of glass means that it cannot be the sole reinforcement in brake friction materials [1].

- **Metallic chips or granules** are commonly used as reinforcing fibers and hence they are referred to as metallic ‘fibers’ although they may not strictly be thread- like. Examples of metallic fibers include steel, brass and copper. The drawback of using steel fibers is that they will rust, especially if the vehicle has an extended rest period or if the vehicle has been operating near a coastal environment. Steel fibers attacked by rust will be less resilient, thereby compromising their functionality as reinforcing fibers. Therefore, certain brake pads include metals such as zinc distributed over the cross-section of the friction lining, thereby forming a sacrificial anode for rusting to occur. Another drawback of using steel fibers is that they might cause excessive wear of the brake disc if they are present in large proportions. Steel fibers have also been shown to increase friction coefficient fluctuations, the likely reason being due to the fact that they abrades the transfer film between braking surfaces, which is responsible for friction coefficient stabilization. On the other hand, a significant advantage of using metal fibers is that they have very high conductivities, able to remove heat from the frictional surfaces very quickly [1].

- **Potassium titanate fibers** have high melting point temperature 1250°C-1310°C; however they have the potential to cause mesothelioma, a type of cancer that is predominantly caused by asbestos [1].
- **Sepiolite** is a hydrated magnesium silicate mineral. Sepiolite has excellent properties in water, while also being stable in high temperature environments. It retains its micro porous and fibrous structure even at temperatures of 1000°C. Sepiolite is able to absorb traces of fluid between the frictional surfaces. Sepiolite is a potential health hazard [1].
- **Ceramic fibers** are typically made of various metal oxides such as alumina as well as carbides such as silicon carbides. With a high thermal resistance (melting points rating from 1850 °C to 3000°C), light weight and high strength, they are very suitable as reinforcing fibers [1].

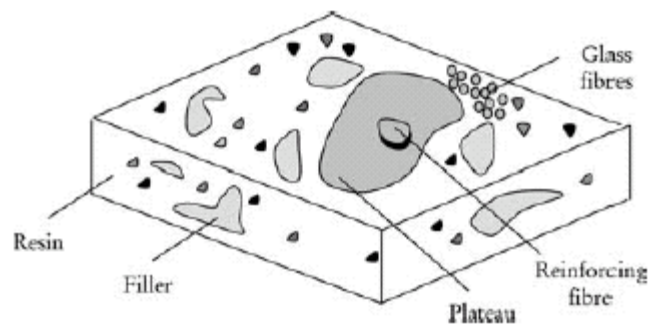


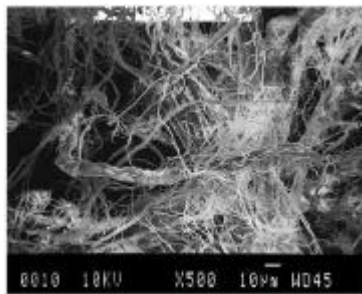
Figure (1.10) Enlarged isometric view of a used brake pad [1]

- **Organic fibers:** The types of organic fibers are aramid (AF), PAN (polyacrylonitrile), carbon (CF), and cellulose (SF). Organic fiber inclusion in friction materials plays multiple roles. It improves toughness and strength of the product along with increasing the organic contents without increasing level of resin. Several organic fibers such as Aramid (AF), carbon (CF), poly-acrylo-nitrile (PAN), cellulose (SF), etc. have been tried in an attempt to replace the asbestos. Figure (1.11) [14] shows the SEM micrographs of various organic fibers.

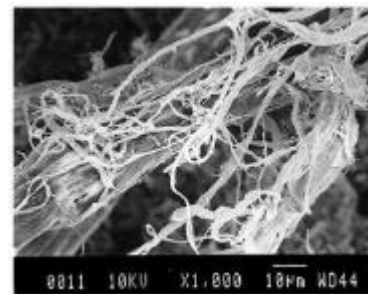
The Aramid fiber has been successfully employed in many non-asbestos organic (NAO) formulations because of its contribution in improving the operational life expectancy of the brakes, imparting low squeal, smooth friction performance, and toughness and friction stability. Similarly PAN fibers (a pre-cursor of carbon fiber) forms a rigid ladder like molecule at temperatures above 180 °C and thereby increases the strength of the friction material and are mainly used to enhance the pre-form strength of the friction materials [18].

While carbon fibers have been used in many of the friction compositions in which their outstanding thermal characteristics, capability of reinforcing, moderating friction performance and enhancing wear behavior are exploited. Cellulose fiber inclusion on the other hand reduces squeal and imparts resiliency to the friction material apart from improving the pre-form strength. The composite based on carbon fibers shows the highest resistance to fade behavior (the loss in effectiveness at elevated temperature) while the composite based on

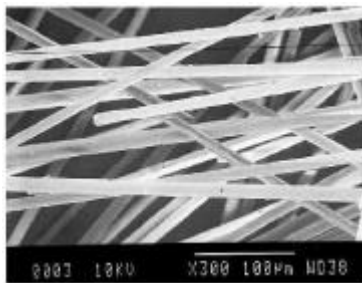
cellulose fibers show the least resistance. The composites containing AF and SF show the highest and lowest wear resistances respectively. The porosity of the sample increase when the ratio of the fibers content increases that's due to the fiber density is smaller than the filler density. Figure (1.10) shows micrographs of various organic fibers: (a) Aramid; (b) PAN; (c) carbon; (d) cellulose [14].



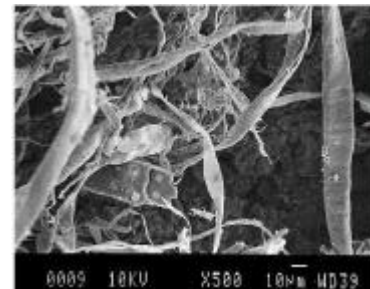
A



B



C



D

Figure (1.10) SEM micrographs of various organic fibers: (a) Aramid; (b) PAN; (c) carbon; (d) cellulose. [14]

### 1.10.2 Binders

A binder holds the other components together and forms a thermally stable matrix. Thermosetting phenolic resins are commonly used, often with the addition of rubber for improved damping properties [1, 5].

The choice of binders for brake pads is an important issue because if it doesn't remain structurally intact at all times during the braking operation, the other constituents such as the reinforcing fibers or lubricants will disintegrate. Therefore it has to have a high heat resistance for this reason. Table (1.2) [1] describes the advantages and disadvantages of the binders. The main types of binders are as shown below:

Phenolic resin, epoxy, and silicon modified resin would generally be used as a binder. Phenolic resin is the most common resin binder used in brake friction material and it cheap to produce. Phenol resin is a type of polymer formed by a condensation reaction between phenol and formaldehyde, and is able to act as a matrix for binding together different substrates. This condensation reaction may be initiated by acidic or alkali catalysts, resulting in different classes of phenolic resins. For example, phenolic resins produced using an acid catalyst and reacted with insufficient formaldehyde are called novolac resins. When these phenolic resins are cured, they change from a thermoplastic state to a densely, cross-linked thermoset matrix with relatively high heat resistance [1, 14].

In high-energy braking applications, the temperature induced can be high enough to decompose the phenolic resin via means of high-temperature oxidation. Phenolic resins carbonize at approximately 450°C; at temperatures beyond this, it decomposes by charring and evaporation. This process decreases the density of the brake friction material at the wear surface and also increases its porosity, thereby losing its structural integrity [1, 14].

These phenolics suffer from serious drawbacks and limitations such as evolution of noxious volatiles (viz. NH<sub>3</sub> (ammonia), HCHO (formaldehyde), etc.) during ambient temperature curing also, very short shelf life posing serious problem of storage and transportation, shrinkage, cracks and voids in the final products, need of catalyst which is mixed in the powdery resin before dispatching to the commercial market, etc. leading to increased cost. In spite of these facts, the choice of binders in non-asbestos friction materials is still largely limited to phenolics and its modified versions because of non-availability of right type of alternate resin along with viable cost [7].

- **Copna resin** is an abbreviation of condensate polynuclear aromatic, resin. As the molecular structure is similar to graphite (a lubricant used in brake friction material) the bonding strength between the latter and COPNA resin will be very high. This means that the structural integrity of graphite-containing brake friction materials will be improved with the use of COPNA resin, giving rise to higher shear strengths than if phenolic resin are used. Its heat resistance is not significantly better than

phenolic resin as it decomposes at approximately the same temperature (400–500)°C, although the volume of decomposed gas is in a smaller volume than that of phenolic resin [1].

- **Silicon modified resin** are typically reacted by reacting silicone oil or silicone rubber with phenolic resins. They are also referred to as phenolic siloxane resins because the base materials are still phenolic. As mentioned earlier, phenolic resins are typically modified with toughness to reduce their brittleness. Phenolic siloxane resins having enhanced impact resistance, yet these phenolic siloxane resins have equal or better heat and chemical resistance than conventional phenolic resins. Also, silicone-modified resins have the property of preventing the frictional layer from adsorbing water due to its improved water repellency [1].
- **Cyanate ester resins** formed from polyfunctional cyanate monomers are stable at elevated temperatures, chemically inert and have damping properties. However, they are brittle like the phenolic-based resins. Brake pads that use cyanate ester resins as binders maintain their friction coefficients at elevated temperatures above 350 °C and are also able to maintain good adhesion with the backing plate during service life [1].
- **Epoxy modified resin:** A pure epoxy resin is unable to withstand high temperatures. At temperatures above 260 °C, typical epoxy resin binders degrade. To increase the operating temperatures of epoxy resins, special curing agents have to be used [1].

- **Thermoplastic polyimide resin** is the product of fluoro resin and calcium carbonate. It is abrasion resistant and does not exhibit thermal fade commonly experienced melt with phenolic-based resins or induce excessive brake disc wear. Such a resin is easily produced using injection molding or other melt-processing methods. Additional heat treatment can improve its heat resistance, as well as mechanical and sliding properties [1].

Table (1.2) Binders advantages and disadvantages [1].

<b>Binder</b>	<b>Advantages</b>	<b>Disadvantages</b>
Phenolic resin	Cheap and easy to produce	Brittle, low impact resistance, highly toxic, decomposes at relatively low temperatures (450 °C)
COPNA resin	High bonding strength with graphite (a common lubricant); therefore has better wear resistance than pure phenolic resin	Decomposes at relatively low temperatures (between 450 and 500 °C)
Silicone-modified phenolic resin	Better impact resistance than pure phenolic resin; better heat and chemical resistance than pure phenolic resin; enhanced water repellency	Base is still phenolic and highly toxic
Cyanate ester resin	High heat resistance, chemically inert, vibration dampener	Brittle, low-impact resistance
Epoxy-modified phenolic resin	Better heat resistance than pure phenolic resin	Base is still phenolic and highly toxic
Thermoplastic polyimide resin	Abrasion resistant; does not exhibit thermal fade	Thermal conductivity three times lower than phenolic resin

### 1.10.3 Fillers

The fillers in brake pad are present for the purpose of improving its manufacture ability, also to reduce cost. They are used to maintain the overall composition of the friction material. Fillers divided into two types: organic and inorganic fillers as shown in table (1.3). Fillers play an important role in modifying certain characteristics of brake friction material. The actual choice of fillers depends on the particular components in the friction material as well as the type of friction material. For example, a metallic pad that generates a lot of braking noise would require more filler such as cashew and mica (noise suppressors) than barium sulphate (heat stability). On the other hand, semi-metallic brake pads with a mixture of metallic and organic compounds having varying thermal expansion coefficients would require a large amount of molybdenum trioxide to prevent lining cracking. Cashew dust and rubber in the form of dust are commonly used examples of organic fillers [1, 2, 5].

Table (1.3) describes organic and inorganic fillers [1]

<b>Filler</b>	<b>Description</b>
Barium sulphate	Imparts heat stability to friction material, aids friction characteristic
Calcium carbonate	Imparts heat stability to friction material
Mica	Suppresses low-frequency brake noise, but causes interlayer splitting in friction material
Vermiculite	Suppresses low-frequency brake noise, but has low heat resistance
Alkali metal titanate	Promotes stability of the friction coefficient
Molybdenum trioxide	Prevents thermal fade and cracking of friction lining under high-temperature conditions
Cashew dust	Suppresses brake noise, but does not adhere well to friction material
Rubber dust	Suppresses brake noise, but does not adhere well to friction material

#### **1.10.4 Friction modifier**

Frictional additives are components added to brake friction materials in order to modify the friction coefficients as well as the wear rates. They are divided into two main categories: lubricants, which decrease the friction coefficients and wear rates, and abrasives, which increase friction coefficients and wear rates. It is also important to note here that certain frictional additives may be loosely regarded as fillers by certain manufacturers if they are present in large quantities [1].

Brake pads with increased lubricant content show increased stability of the friction coefficient. Brake pads with increased abrasive content show increased friction coefficient variation (instability).

Metal sulphides appear to be better alternatives to graphite as lubricants. Because of the current high energy braking demands in the automotive industry, the low bonding strength between phenolic-based resin (most common binder) and graphite would result in accelerated wear of the friction material [1].

### **1.10.5 Lubricants**

The main purpose of a lubricant is to stabilize the developed friction coefficient during braking, particularly at high temperatures. Commonly used lubricants include graphite and various metal sulphides. Graphite is widely used as it is able to form a lubricant layer on the opposing counter friction material rapidly. This self-sustaining layer ensures a stable friction coefficient. The graphite used in brake friction materials can be of natural or synthetic origin, and can exist in flake or powder form. However, graphite cannot be used too liberally in phenolic resins because the bonding strength between graphite and phenolic resin is very weak, leading to low shears strengths [1].

Graphite will increase the overall heat conductivity of the friction material. While this may assist in removing the heat away from the friction surfaces, excessive graphite will result in an increase in the temperature of the hydraulic braking fluid. If the temperature of the hydraulic braking fluid is brought to its boiling point, failure of the braking application system will occur. Metal sulphides such as antimony sulphides, copper sulphides, and lead sulphides are very popular in friction materials of today as they are able to provide good lubrication as well as having lower conductivities than graphite [1].

### 1.10.6 Abrasives

The abrasives in a friction material increase the friction coefficient while also increasing the rate of wear of the counter face material. They remove iron oxides from the counter friction material as well as other undesirable surface films formed during braking. However, friction materials with higher abrasive content exhibit a greater variation of friction coefficient, resulting in instability of braking torque. Examples of abrasives are hard particles of metal oxides and silicates. The abrasives have to be hard enough to at least abrade the counter friction material, which is typically cast iron. A few examples of the commonly used abrasives include zirconium oxide, zirconium silicate, aluminum oxide and chromium oxide [1].

### 1.11 Kinds of Rubber Added

- **Silicon rubber:** Silicon polymers are produced by condensation polymerization. The silicon rubber has a service temperature up to 250 °C and its fusion temperature is at 150 °C. The silicon rubber has a good strength to weather and oil. Silicon rubber has the ability to dissolve in an organic solvent, such as heptanes and toluene [19, 20].

- **Styrene-Butadiene Rubbers (SBR):** The SBR are copolymers produced from butadiene and styrene. The molecular chains are cross-link by vulcanization with sulphate and reinforced with black carbon. SBR is cheaper than natural rubber. SBR has good properties, good wear resistance, and good weather resistance at low temperature [19].
- **Butadiene acrylonitrile rubbers (NBR):** Butadiene acrylonitrile rubbers (NBR are commonly referred to as nitrile rubbers. The acrylonitrile component is varied between about (20-50) % by weight of copolymer. NBR is vulcanized by either sulfur or peroxides and reinforced by carbon black. Such a rubber has excellent resistance to fuels and oil [19]. Table (1.4) gives the properties of SBR and NBR.

Table (1.4) SBR and NBR properties [19]

Property	SBR	NBR
Tensile strength	24 MPa	28 MPa
Percentage elongation	600	700
Glass temperature	-58°C	-55°C
Service temperature	(-50-80) °C	(-50-100) °C
Resistance to oil and gas	Poor	Excellent
Resilience	Good	fair

**1.12 Aim of the Work**

The aim of the presented work can be recorded as:

1. Study the effect of rubber addition to novolac resin.
2. Study the effect of the change in fiber ratio and its affect on the impact strength, wear rate, hardness, and friction coefficient.
3. Study the effect of the curing temperature.
4. Study the technique of hot and cold press.
5. Study the effect in the change of filer ratio (molybdenum tri-oxide) on the wear rate.
6. Reduce the cost by using cheap and active materials.

# CHAPTER TWO

## *Literature Survey*

## **Chapter Two**

### **Literature Survey**

#### **2.1 Introduction**

The interest of this work is directed towards modify the wear of composite material and the frictional materials for brake pad disk. Hence the literature survey is directed toward the wear of composite materials and frictional materials.

#### **2.2 Wear of Composite Materials**

The effect of PTFE on the Tribological behavior of polymers in rolling sliding contact has been investigated by **M. RAO, et al, [18], 1998**. The two most widely used polymers - nylon 66 and polyacetal-were used as the base material. Tests were conducted over a wide range of running conditions using a twin disc rolling-sliding test rig for both the unfilled materials and for the base materials filled with 20 % of PTFE by weight. The experimental results showed that the friction and wear performance of the PTFE filled polymers was superior to that of the unfilled polymers. In addition the surface cracking that was found in unfilled PA66 and thought to be responsible for premature fracture of components such as gear teeth was suppressed by the PTFE. It is suggested that a combination of high surface temperature and high surface tensile stress, produced by friction, is required to initiate these cracks.

A high performance engineering polymer, polyetherimide (PEI) and its two composites, one containing only short glass fibers (GF) 20% and the other, commercially established bearing material containing 25% GF and three solid lubricants were selected for studying the wear behavior in four types of wear modes by **Bijwe, et al [19], 2001**. A bearing grade material proved to be extremely good in adhesive and fretting wear modes. The same composite, however, proved very poor in abrasive and erosive wear modes. Neat polymer performed best in these two modes. Thus, performance rankings of three materials in adhesive and fretting wear modes were identical while for abrasive and erosive wear modes, exactly the reverse trend was observed.

**Hilal, [13], 2001**, studied dry adhesive wear strength for composite material which contains epoxy resin as a matrix reinforced by hybrid fibers (carbon and glass fibers). Another composite material based on epoxy resin as a matrix reinforced by aluminum powder were also tested. The result showed that the wear ratio increases with the load, the slipping distance, the surface roughness, and the room temperature. The hybrid fibers reinforced composite had higher wear strength than that reinforced by aluminum powder.

A series of polyamides (PAs), namely, PA 6, PA 66, PA 66/610, PA 11, PA 12 and aromatic PA (brittle, hard and amorphous) was selected for investigating the effect of chemical structure and hence, mechanical properties on erosive wear behavior by impinging silica sand particles of 90–180\_μm size at various angles and doses by **Bijwe et al, [20], 2001**. The results indicated that five polyamides including brittle PA showed maximum wear versus impact angle relation at 30° confirming their ductile failure behavior. For two PAs, however, wear be maximum at 15°. Good correlation was observed in erosion rate and brittleness index of polyamides at incidence angles of 90 and 60°. Worn surface analysis was done using scanning electron microscopy to investigate wear mechanisms.

**Satopathy, and Bijwe [21], 2002**, deal with the abrasive wear investigations on various composites of phenolic resin filled with alumina powder and abraded against silicon carbide paper under dry and single pass condition. The data analysis was done using orthogonal experimental design method. The objective was to study the influence of variables such as filler concentration, load, sliding speed and abrading particle size on the abrasive wear performance of phenol-formaldehyde-based composites. Regression analysis of the data was carried out to develop equations for the composites in which the wear volumes of the specimens were expressed in terms of simultaneous contribution from the influence of load, abrading particle size, sliding speed and their mutual interactions. It was confirmed that among these factors load was the factor contributing most strongly to the wear of these composites. Sliding speed seemed to have least effect on the wear performance in the selected operating conditions. Worn surfaces were

studied by scanning electron microscopy (SEM) and energy dispersive X-ray analysis (EDAX) to have an insight into the wear mechanisms and particle dispersion in the bulk of the composites.

**Chan and Stachowiak, [1], 2004**, strived to eliminate the cloud of uncertainty by providing an insight into the pros and cons of the common ingredients and make-up used in contemporary dry and wet friction pads and shoes. In this study typical brake materials are reviewed and their advantages and disadvantages in contemporary brake applications are discussed.

Results on the low amplitude oscillating wear of three composites, viz. CF, CAF and CHY containing fabrics of carbon fiber (CF), aramid (AF) and combination of both (hybrid, HY) based on PEI matrix were presented by **Bijwe, et al [15], 2004**. After characterizing for physical and mechanical properties, these composites along with the unfilled PEI (C0) were evaluated for their low amplitude oscillating wear performance on SRV optimal tester under different loads and temperatures using ball-on-pin configuration. It was concluded that the carbon fabric proved to be significantly beneficial in improving the friction and wear performance of PEI under all loads and temperatures. AF inclusion on the other hand, proved beneficial for improving the friction behavior moderately. It also improved the wear performance of PEI under high loading conditions but not under high temperature conditions. At 100 °C, the wear performance was as poorer than that of unfilled PEI. Interestingly, friction behavior of hybrid composite was almost similar to that of CAF but not the wear

behavior. The wear performance of CHY under high loading condition was little lower than that of CAF, but significantly better than that of unfilled PEI. The CHY had clear edge over CAF in the high temperature wear performance. At temperatures up to 150 °C, it exhibited improved wear performance unlike CAF. Beyond that, however, the performance deteriorated.

The abrasive wear resistance and wear mechanism of polymer clay nanocomposites was reported by **Srinath and Gnanamoorthy, [22], 2004**. The Nylon clay nanocomposites used in the study were prepared by melt intercalation technique. Abrasive wear resistance was studied by using the pin-on-disk tribometer against the SiC abrasive paper. Presence of clay in nano size reduces the ductility and reduces the abrasive wear resistance.

The hybrid of liquid crystalline polymer (LCP) fibers and glass fibers (GF) provide a combination of modulus and toughness to semi-crystalline linear-low-density-polyethylene (LLDPE). LCP and GF fibers reinforced composites were studied using two-body abrasion tester under different applied loads by **HASHMI, et al, [23] 2005**. Two sets of fiber reinforced LLDPE, 10 and 20 vol%, were investigated. The contents of LCP and glass fibers were varied as 25, 50, 75 and 100 vol% of overall volume of fibers in LLDPE. The effect of replacing glass fiber with LCP fiber on wear is reported. Wear loss increased with the applied loads and glass fiber contents in LLDPE. The replacements of glass fibers with LCP fibers improved abrasive wear resistance of composite. The composite containing 20 vol% of glass fibers in LLDPE showed the specific wear rate nearly double to

that of LCP fiber reinforced LLDPE. Incorporation of LCP fiber improved wear resistance of glass fiber reinforced LLDPE. Worn surfaces were studied using SEM. Glass fibers were broken in small debris and removed easily whereas LCP fibers yielded to fibrillation during abrasive action.

A PEEK filled PTFE composite that exhibits low friction and ultra-low wear was presented by **Burris, and Sawyer [24], 2006**. It is hypothesized that a synergistic effect shuts down the dominant wear mechanism of each constituent. The friction coefficient and wear rate of this composite material on lapped stainless steel were evaluated for samples with PEEK wt. % of 0, 5, 10, 20, 30, 40, 50, 70 and 100 using a linear reciprocating tribometer. Tests were performed in filtered, standard laboratory conditions with a nominal contact pressure of 6.35MPa, a speed of 50 mm/s and total sliding distances ranging from 0.5 km for the unfilled PTFE to 140 km for a 20 wt.% PEEK filled sample. The friction coefficients, averaged over an entire test, ranged from  $\mu^- = 0.111$  for a 50 wt. % composite to  $\mu^- = 0.363$  for unfilled PEEK. Wear rates ranged from  $K = 2.3 \times 10^{-9} \text{ mm}^3 / (\text{Nm})$  for a 20 wt. % PEEK sample to  $K = 6 \times 10^{-4} \text{ mm}^3 / (\text{Nm})$  for unfilled PTFE. Scanning electron microscopy revealed a unique interfacial connection between the PTFE and PEEK that is likely responsible for the ultra low wear rates observed in these experiments.

**Peillex, et al, [25], 2006**, devoted to the numerical study of a composite under dynamic Tribological loading. The aim of this study is to define a homogeneous model, obtained for static loading and built from a heterogeneous one, which represents the real behavior of the composite. The equivalence of the vibratory behavior between homogeneous and heterogeneous models is emphasized. This equivalence has been studied under dynamical loading without contact. Then a non linear dynamical explicit finite element model is used to check if the homogeneous model represents the heterogeneous ones under dynamic Tribological loading. Finally an experimental work, that confirms presence of high frequencies obtained numerically, is discussed.

The comparative performance of Glass-Epoxy (G-E) composite systems interfaced with graded fillers has been examined by **Suresha et al, [26], 2006**. In this study, composite materials were experimentally investigated under varying load and sliding velocities by using a Pin-on-Disc type wear tester. The influence of two inorganic fillers, silicon carbide particles (SiC) and graphite, on the wear of the glass fabric reinforced epoxy composites under dry sliding conditions has been investigated. For increased load and sliding velocity situations, higher wear loss was recorded. The coefficients of frictional values show an increasing trend with subsequent increase in load/sliding velocities. It was observed that the Graphite filled G-E composite shows lower coefficient of friction than the other two composites irrespective of variation in the load/sliding velocities. SiC filled G-E composite exhibited the maximum wear resistance.

Three composites were fabricated based on Polyetherimide (PEI) matrix and carbon fabric (CF) (55 vol. %) of different weaves, viz. plain, twill and satin (4H) by impregnation technique by **Rattan, Bijwe, and Fahim, [28], 2007**. These composites were evaluated for various mechanical properties and Tribological performance in low amplitude oscillating wear (LAOW)/fretting wear mode. It was observed that CF reinforcement led to a significant enhancement in all strength and modulus properties of PEI except elongation to break ( $\epsilon$ ). Twill weave proved to be the most effective followed by satin and plain weave in almost all the properties. The LAOW mode evaluation under various loads revealed that the wear performance order was exactly opposite to the above trend. Overall, plain weave composite was the best performer followed by twill and satin. The ability of plain weave to hold back the debris was maximum that resulted in lowest wear while satin weave had the minimum retention ability that led to the highest wear. The proposed wear mechanisms were supported by SEM studies.

Friction-wear properties of the  $ZrSiO_4$  reinforced samples were measured and compared with those of plain bronze based ones by **Boz and Kurt, [28], 2007**. For this purpose, density, hardness, friction coefficient wear behavior of the samples was tested. Microstructures of samples before and after sintering and worn surfaces were also investigated by scanning electron microscopy (SEM), and the wear types were determined. The optimum friction-wear behavior was obtained in the sample compacted at 500 MPa and sintered at 820°C. Density of the final samples decreased with increasing the amount of reinforcing elements ( $ZrSiO_4$ ) before pre-

sintering. However after sintering, there is no change in density of the samples including reinforcing elements ( $ZrSiO_4$ ). With increasing friction surface temperature, a reduction in the friction coefficient of the samples was observed. However, the highest reductions in the friction coefficients were observed in the as-received samples containing 0-5% reinforced  $ZrSiO_4$ . The SEM images of the sample indicated that bronze-based break lining material without  $ZrSiO_4$  showed abrasive wear behavior, increasing the amount of  $ZrSiO_4$  result a change in abrasive to adhesive wear mechanism. With increasing the amount of reinforcing  $ZrSiO_4$ , wear resistance of the samples was increased. However samples reinforced with 5% and 6%  $ZrSiO_4$  showed the best results.

Polymer nanocomposites operate in applications where fluid and grease lubricants fail, and have superior Tribological performance to traditional polymer composites. Nanoparticle fillers have been a part of notable reductions in the wear rate of the polymer matrix at very low loadings. Despite instances of remarkable wear reductions at unprecedented loadings (3000 times at 0.5% loading in one case), there is a lack of general agreement within the literature on the mechanisms of wear resistance in these nanocomposites. In addition, results by **Burris et al, [29], 2007**, appear to vary widely from study to study with only subtle changes of the filler material or blending technique. The apparent wide variation in Tribological results is likely a result of processing and experimental differences. Tribology is inherently complex with no governing laws for dry sliding friction or wear, and the state of the art in polymeric nanocomposites .Tribological complexities with the complicated mechanics

of poorly characterized nanocomposites makes interpretation of experimental results and the state of the field extremely difficult.

By using X-ray diffraction (XRD), infrared spectrometry (IR), scanning electron microscope (SEM) and transmission electron microscope (TEM), the worn specimens of poly (ether ether ketone), (PEEK), composites tested under unlubricated sliding friction and wear conditions at a constant sliding speed were investigated by **Hua Fu, et al, [30], 2008**, in order to reveal structural changes of polymer as well as wear mechanisms as a function of temperature. The results showed that the PEEK composites exhibited stable friction coefficient and lower wear ratio. The wear mechanism is that the particle abrasion occurs at low temperature, the adherence abrasion and particle abrasion take place at the temperature between 200~350°C as revealed through wear morphology and wear debris analysis. The thermal degradation of PEEK does not occur until its temperature rises to higher than 350. The stainless steel and carbon fibers bind strongly with the matrix PEEK and may be responsible for improving stability of the friction coefficients of the materials. Surface film, transition layer and matrix composed the superficial structure of friction material after wear test. Two kinds of surface film structures are formed: one is cystiform microstructure with PEEK matrix surrounded by single or multicrystal powder of fillers; the other is meshwork generated by resin base and friction fillings.

### **2.3 Frictional Materials**

Multiple criteria decision model (MCDM) was used for optimization of several conflicting criteria dependent systems by **Satapathy, and Bijwe [4], 2003**. A multiple criteria decision model (MCDM) approach taking into account the performance defining attributes (PDAs) such as fade, recovery, performance, wear and temperature rise in the rotor disc was adopted to determine the performance ranking of five non-asbestos fiber reinforced organic friction materials. The out-ranking matrix is derived, indicating the frequency of the relative superiority of options with respect to each other based on each criterion. The method has been used to rank a series of friction materials (FMs) based on the combinatorial variation of the fibers, in particular, the organic fibers. The carbon fiber based composite (C) was found to be functioning optimally for its practical selection and implementation in similar evaluating conditions. Cellulose fiber based composite (S) was found to be the poorest in this regard.

Three friction composites containing ten ingredients along with straight phenolic resin as a binder in three different concentrations viz. 10, 12.5 and 15% (by weight) were formulated and evaluated for physical, mechanical and Tribological performance properties. Fade and recovery studies on these three composites were done according to ECE R-90 regulation by **Bijwe, Nidhi and Satapathy, [6], 2004**. The  $\mu$  -performance,  $\mu$  -fade and  $\mu$  -recovery, wear and mechanical properties were significantly influenced by the amount of resin. With increase in percentage of resin, performance  $\mu$  and fade  $\mu$  decreased while extent of fade increased. Wear was highest for intermediate phenolic resin contents.

**Satapathy, and Bijwe [14], 2004**, deal with the influence of four selected organic fibers, viz. Aramid (AF), PAN (poly-acrylo-nitrile), carbon (CF) and cellulose (SF), on the fade behavior (The loss in braking effectiveness at elevated temperatures) and recovery behavior (the revival brake effectiveness at lower temperature) of friction composites. It was found that the type of fiber significantly influenced the fade behavior and recovery behavior. It was found that the carbon fiber based composite showed the highest resistance to fade behavior whereas the composite based on cellulose fiber showed the least resistance. The recovery behavior of all the composites was more than 100% and the extent depended on the type of fiber inclusion. The composites containing AF and SF showed the highest and the lowest wear resistances, respectively, while the highest and the lowest fade were recorded for SF based and CF based composites, respectively.

PA 11 and its three composites containing short glass fibers (GF) and metallic powdery fillers such as bronze and copper were investigated by **Bijwe, and Rajesh [31], 2004**. Experiments were carried out on the SRV Optimal instrument in pin on disc configuration, under various loads at room temperature. It was found that the GF reinforcement greatly improved the friction and wear performance of PA 11. Incorporation of bronze and copper powders in GF reinforced composite further improved the friction and wear behavior of PA 11. Copper proved to be beneficial filler than the bronze in this context. Worn surface studies were also done to investigate the wear mechanisms. The SEM and EDAX studies on the copper-

containing composite indicated that the film transfer on the disc was very thin, uniform and coherent. It showed evidence of Cu transfer on the disc, which was thought responsible for strong adherence of the film to the mild steel disc resulting in the best friction and wear behavior of the composite.

**Bijwe, and Satapathy [32], 2004**, deal with the wear data analysis of friction composites where, the nature and the concentration of the abrasives were varied systematically in steps of 2%. The abrasives selected were; SiC, SiO<sub>2</sub>, ZrO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> in the concentration range of 2–6%. The wear studies on the composites were carried out on a pad-on-disc type tribotester. It was concluded that, the braking pressure was the most influential operating parameter on wear performance of such friction composites. The influencing patterns of sliding speed and concentration of abrasives on the other hand seemed to be composition dependent. The Al<sub>2</sub>O<sub>3</sub> based composite proved to be moderately sensitive towards operating parameters such as braking pressure and sliding speed, while ZrO<sub>2</sub> was much sensitive to both the parameters. This confirmed the unsuitability of ZrO<sub>2</sub> as an abrasive in friction material.

**Bijwe, Sen, and Ghosh [33], 2005**, five injection-molded blends of PEEK with PTFE (in the range of 0–30 wt. %) were evaluated on a pin-on-disc configuration on an SRV Optimal Tester for their tribo-behavior in the low amplitude oscillating wear mode. The data in the abrasive wear mode were generated by abrading a pin loaded against an abrasive paper fitted on the rotating disc. It was observed that inclusion of PTFE affected the adhesive wear and low amplitude oscillating wear (LAOW) in a beneficial

way. With an increase in PTFE contents, coefficient of friction in both the wear modes (adhesive and low amplitude oscillating) decreased but the trends in wear performance differed. In the adhesive wear mode, the specific wear rate showed minima for 7.5% PTFE inclusion followed by a slow increase for further PTFE addition. In the case of LAOW mode, on the other hand, the wear rate continuously decreased for the selected compositions. The 30% PTFE blend showed excellent combination of  $\mu$ , wear rate and limiting pressure–velocity (PV) values. Unfilled PEEK proved to be fairly good wear-resistant material but exhibited high  $\mu$ , a stick-slip tendency and a low PV limit value. Abrasive wear performance of the blends on the other hand, deteriorated with increasing amount of PTFE.

**Bijwe, et al [34], 2005** investigate the characteristics of five resins: (i) straight phenolic resin, (ii) alkyl benzene modified resin, (iii) cashew nut shell liquid modified resin, (iv) NBR modified resin, and (v) linseed oil modified resin. The same weight percent of each resin (10%) was used to make friction materials containing similar additions of 10 additives. The mechanical properties of these materials were characterized using ASTM standards. Fade and recovery studies were carried out on a Krauss testing machine following the Economic Commission for Europe regulation for replacement brake linings (ECE R-90). Friction and wear characteristics varied with the type of resin, and no resin proved best for all the selected performance parameters. Alkyl benzene modified resin composite proved best in terms of strength, friction, fade and recovery, but was poorest in wear performance. Results for linseed oil based phenolic resin composites showed exactly the opposite behavior. Scanning electron microscopy was

used to help understand the wear mechanisms and the causes for these differences.

Tribological properties of a tightly woven Carbon/Carbon (C/C) composite were assessed experimentally in accord with the ASTM pin on disk technique studied by **Karaveli, [35], 2005**. The C/C composite used in this study was a commercial material (K-Karb) obtained in a panel form. The composite consists of graphite fiber reinforced graphite matrix developed for aerospace applications. The fiber reinforcement was in a plain weave woven fabric form. The tests were conducted by sliding zirconia ball against the C/C composite. The friction coefficient and wear rate were determined as functions of applied load, sliding speed, sliding distance and lubrication in ambient laboratory conditions. Mean friction coefficient of the composite was  $0.135 \mu$  when tested at ambient atmosphere and  $0.113 \mu$  in lubricated environment at a load of 5 N, sliding speed of 0.5 cm/s, and sliding distance of 100 m. The specific wear rates of the composite were  $0.754 \times 10^{-4} \text{ mm}^3/\text{N.m}$  at ambient atmosphere and  $0.437 \times 10^{-4} \text{ mm}^3/\text{N.m}$  in lubricated environment at the load of 5 N, sliding speed of 0.5 cm/s, and sliding distance of 100 m. The specific wear rate of the composite decreased with increasing sliding distance, sliding speed, applied load and also, decreased in lubricated environment.

**Satapathy, and Bijwe [36], 2006** , discusses the sensitivity of friction and wear behavior of selected composites based on variation in inclusion of organic fibers, viz., aramid, PAN, carbon and cellulose, to braking pressure and sliding speed. The studies on the sensitivity of  $\mu$  and wear to the operating variables have been carried out on a subscale brake-test-rig, following four loads, three speeds experimental design. Inclusion of cellulose fiber tended to increase the friction coefficient while aramid fiber improved the wear resistance. The fibers of carbon and PAN made the friction composites least sensitive to dynamic variations in braking pressure and sliding speed.

An attempts have been made to produce a friction material with thermal sensitive modulus by the inclusion of combined plastic/rubber properties of thermoplastic elastomers (TPE) as viscoelastic polymeric materials into the formulation for the purpose of increasing the damping behavior by **Masoomi, et al, 2006, [37]**. In order to evaluate the viscoelastic parameters such as loss factor ( $\tan \delta$ ) and elastic modulus (E) for the friction material, dynamic mechanical analyzer (DMA) was used. Styrene-butadiene-styrene (SBS), styrene-ethylene-butylene-styrene (SEBS) and nitrile rubber/polyvinyl chloride (NBR/PVC) blend systems were used as TPE materials. However, NBR/PVC and SEBS were found to be more effective in damping behavior. All the friction materials containing TPEs exhibited more damping behavior at a wide range of temperature compared with the reference sample.

The mechanical and Tribological properties of carbon fiber (CF) reinforced polyamide 66 (PA66)/polyphenylene sulfide (PPS) blend composite were studied by **Zhaobin Chen, et al, [38], 2006**. It was found that CF reinforcement greatly increases the mechanical properties of PA66/PPS blend. The friction coefficient of the sample decreases with the increase of CF content. When CF content is lower (below 30%), the wear resistance is deteriorated by the addition of CF. However, the loading of higher than 30% CF significantly improves the Tribological properties of the blend. The lowest friction coefficient (0.31) and the wear volume (1.05 mm<sup>3</sup>) were obtained with the PA66/PPS blend containing 30% CF. The transfer film and the worn surface formed by sample during sliding were examined by scanning electron microscopy. The observations revealed that the friction coefficient of PA66/PPS/CF composite depends on the formation and development of a transfer film on the counterface. The abrasive wear caused by ruptured CFs (for lower CF content) and the load bearing ability of CFs (for higher CF content) are the major factors affecting the wear volume. In addition, the improvements of mechanical properties, thermal conductivity, and self lubrication of bulk CFs are also contributed to the wear behavior of PA66/PPS/CF composite.

Brake torque variation is a phenomenon which induces seat, steering and body vibration on passenger vehicles these days. One form of the phenomenon is popularly known as brake judder. One root cause of the brake judder is the non-uniform radial thermal expansion of rear brake drums due to localized temperature increase, or known as hot spots. Non-uniform temperature distribution causes ovality which is a deformed oval shape of the circular drum rubbing surface. The ovality was measured by **Suryatama, et al, [9], 2007**, as the Mounted Radial Run out (MRRO) which is the difference between the longest and shortest drum expanding radii. The objective was to study analytically the generation and reduction of drum MRRO. ABAQUS code was used to analyze the MRRO finite element simulations while ANSA and  $\mu$ ETAPOST were used to pre- and post-process simulation results. Explicit heat transient analyses would be selected to correctly predict the phenomenon. Simulation results would be plotted as graphs to illustrate the MRRO and probable deformation scenarios of brake drums.

Phenolics or their modified versions are invariably used as binder materials for friction composites. However, poor shelf life, evolution of harmful volatiles during processing, need of inclusion of curing agent before dispatching to the market, shrinkage in final products along with voids, etc. are the major problems associated with phenolics. In order to overcome these, an alternative resin was synthesized by **Gurunath, and Bijwe [7], 2007**, and tribo-evaluated to explore the possibility of replacing currently used phenolics. A monomer capable of polymerizing through ring opening by thermal activation was synthesized in the laboratory and used as

a binder for friction composite. Two types of non-asbestos organic (NAO) friction composites with identical ingredients but differing only in the type of resin (10 wt. %) were developed and characterized for physical, thermal and mechanical properties. The brake pads were then tribo-evaluated for their fade and recovery performance as per ECR 90 regulation on Krauss machine. It was observed that the composite with new resin (N) proved better than the composite with traditional phenolic (P) in all the tribo-performance properties including performance  $\mu$  (this is average of coefficient of friction taken after 1s for fade and recovery cycles at temperature greater than 100°C), fade  $\mu$  (the loss in effectiveness at elevated temperature), disc temperature rise, counterface friendliness in terms of less scoring, wear, etc. apart from removing the basic problems associated with the traditional resins.

## **2.4 Final Remarks**

There is a wealth of literature on the performance of friction materials based on the variation in nature of organic fibers. Many researchers presented the influence of modified phenolic resins on the fade and recovery behavior of friction materials. They presented the analysis by using microscopy and wear mechanisms. The researchers presented the sensitivity of friction and wear to operating variables.

The sighted papers mentioned in this chapter concentrated on analyzing the influence of PTFE content in PEEK-PTFE blends on mechanical properties and tribo-performance in various wear modes. Other papers were devoted on the effect of the amount of resin on fade and recovery behavior of non-asbestos organic friction materials.

Hence the present work is intended to develop the binders which work under high temperatures by using different fiber ratios. It will devote more attention to the filler ratios which was added to the sample batch.

There will be another part of this work is the study of hot and cold press technology to produce the sample. The wear test was carried out using pin on disk test system.

Semi metallic brake pads were used with a mixture of metallic and organic compounds having varying thermal expansion therefore the chosen materials must have the following demands:

1. Maintain a sufficiently high friction coefficient with the brake disc.
2. The friction materials are not decompose or break down in such away that the friction coefficient with the brake disk is compromised, at high temperature.
3. The friction materials must exhibit to a stable and consistent friction coefficient with the brake disc.

# CHAPTER THREE

*Experimental*

*Analysis*

## **Chapter Three**

### **Experimental Analysis**

#### **3.1 Introduction**

This chapter describes the experimental equipment and measuring system used to investigate experimentally the effect of adding rubber to novolac or by using Teflon matrix as a replacement.

A wear measurement device was built up to measure weight lost of the friction materials which formed in the present study.

The experimental work is divided as:

- The preparation of the raw materials fibers, binder, lubricant, abrasive, and filler to make blends, composite materials and evaluate their properties.
  
- Description the procedure which are used to prepare samples of blends and composite materials for all the used tests, with their standard dimensions.
  
- Description the tools and equipment in this work, their photographs, and the supply company. The experimental rig consists of the wear test device, impact test device, and hardness test device.

### 3.2 Materials Used:

The materials used in the specimens are:

- **Binder (matrix):** Novolac are the matrix material used.
- **Reinforcing fibers:** Steel fibers, glass fibers, and copper powder are used as reinforcing fibers.

**Lubricant:** Copper sulphides are very popular in friction material of today as they are able to provide good lubrication as well as having lower conductivities than graphite.

- **Filler:** Molybdenum trioxide and calcium carbonate are used as filler.
- **Abrasive material:** Zirconium oxide has hardness of (1000-1400) HV, therefore the zirconium oxide used as abrasive material.  
Figure (3.1) shows a graphical view of the material used.

- **Silicon rubber**

- **Styrene-Butadiene Rubbers (SBR)**

- **Butadiene acrylonitrile rubbers (NBR)**

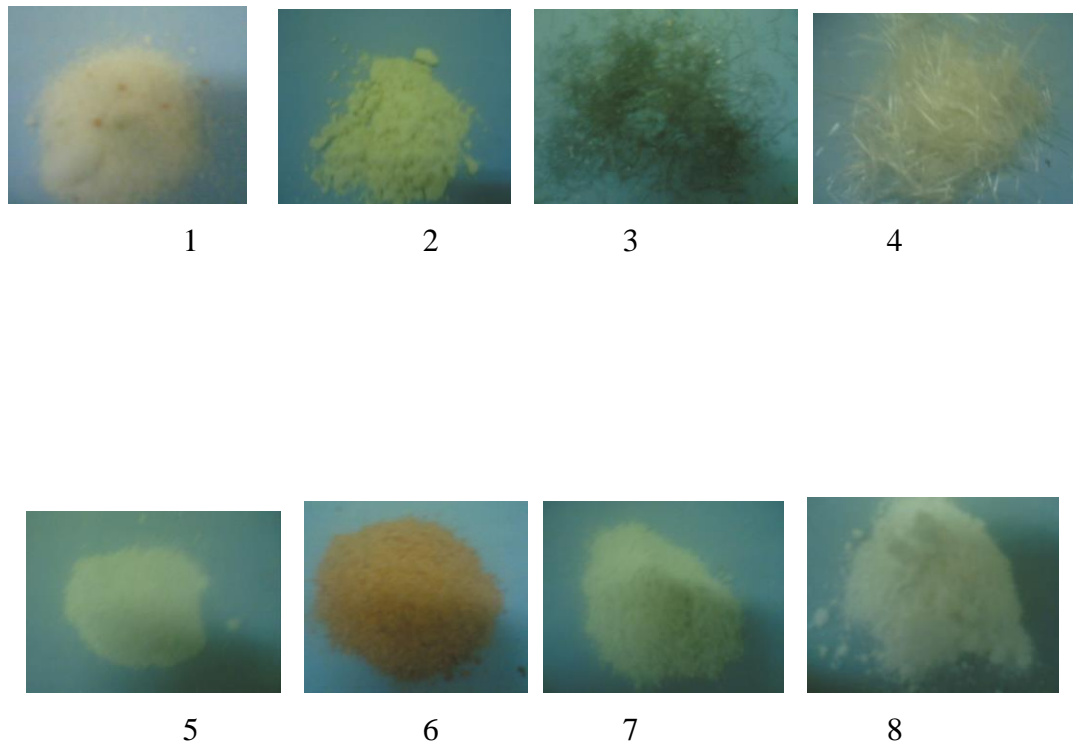


Figure (3.1) 1. HMTA powder 2. Sulfur powder  
3. Steel fibers 4. Glass fiber 5. Molybdenum trioxide  
6. Novolac powder 7. Copper sulfides powder  
8. Zirconium oxides

### **3.3 Samples Preparing**

There were three trying to prepare the samples as follows:

**3.3.1 Cold press technique:** the cold press is deal with dry press and wet prepared and pre-dried press method.

**3.3.1.1 Dry press method:** Table (3.1) shows the samples (1-10) which were prepared by heating the components in the die for (15) minutes at 150°C to fusion the SIR before pressing then the mould was pressed under (45) MPa pressure. The samples were cured by raising the temperature from (80°C) as initial temperature to (250°C) as a final temperature during (14) hours.

Table (3.1) gives the developments in the details of the components of the batch samples. Sample (1) and (2) have the same components except that sample (2) has (SBR) instead of (SIR) in sample (1). The difference between sample (3) and (4) is the ratio of the steel and glass fibers. Sample (5) and (6) have a large weight ratio of fibers compared with the samples (1), (2), (3) and (4). Sample (7) and (8) have a large weight ratio compared with previous samples. Sample (9) has a new addition to the filler family. Kaolin is added because it has a wide range of metal contains. Kaolin is cheap and has good ability for pressing. The samples (1-10) contain SIR in the form of particles while the SBR was added as a liquid by dissolving in heptanes solvent for sample (2) instead of SBR .The samples(1-10) suffer from segregate the fibers as shown in figure (3.2).

**3.3.1.2 Wet prepared and pre-dried method:** The samples (11-16) were prepared by wet prepared method (mixing the components with the liquid rubber) then evaporate the solvent naturally for 48 hours. Sample (11) was pressed at different pressure (45, 80, 200, and 250) MPa at ambient temperature. It was found that the 250 MPa pressure gives the best results. Sample (11) was cured at different temperatures (50, 60, 70, 80, 90, and 110) °C for (6-7) hours. The 80 °C curing gives the best results. Table (3.2) shows the successful samples. Tables (3.3) represent the samples batch contents for different fiber ratios (10%, 27%, and 35%). The rubber was added at 2% weight ratio for the samples (1-8) and 10% for the samples (11, 13, 14, 15, 16). The small weight fraction (0.5 %) of HMTA for the samples (1-10) was increased in the samples (11-16) to 1.5%.

Table (3.4) represents the components of the batch samples which have NBR or SIR rubber as a binder. Sulfur was added at weight ratio of (1.5%) to the samples batch which contain NBR and SBR because the sulfur was the responsible of crosslinking during vulcanization.

**3.3.2 Hot press technique:** The sample (11-c) was pressed by hot press technology. The components mixed with the liquid rubber then dried naturally. The sample was presses under 40 MPa pressure for 12 minutes at 140 °C.

Teflon (poly-tetra-fluoro-ethylene) (PTFE) was added as a binder instead of novolac powder at another sample. This specimen was pressed by cold press and another specimen has the same components was prepared

using hot press technology. Teflon have low wet ability to hold the components together and wet the fibers because it is not flow through the fibers and the other components even it reach the fusion temperature (250 °C) under 350 MPa.

Table (3.1) Components of the samples batch

Batch	Figure (1.9)	Glass fiber (wt. %)	Steel fiber (wt. %)	Copper sulphides (wt. %)	Zirconium oxides (wt. %)	HMTA (wt. %)	Rubber (wt. %)	Novolac resin (wt. %)	Molybdenum oxides (wt. %)	Caesium carbonate (wt. %)	kaolin (wt. %g)
1	C	2.5	7.5	29	6	0.5	2 SIR	37.5	7.5	7.5	0
2	C	2.5	7.5	29	6	0.5	2 SBR	37.5	7.5	7.5	0
3	C	7.5	2.5	29	6	0.5	2 SIR	37.5	7.5	7.5	0
4	C	5	5	29	6	0.5	2 SIR	37.5	7.5	7.5	0
5	A	13.5	13.5	10	9	0.5	2 SIR	17.5	17	17	0
6	A	6.75	20.25	10	9	0.5	2 SIR	17.5	17	17	0
7	B	17.5	17.5	5	0	0.5	2 SIR	17.5	20	20	0
8	B	8.75	8.75	5	0	0.5	2 SIR	17.5	20	20	0
9	D	3	3	5	5	0.5	6 SIR	13	23.3	23.3	23.3
10	C	2.5	7.5	29	6	0.5	0.75 SBR 2.25 SIR	36.5	7.5	7.5	0

Table (3.2) Components of the successful samples batch

Batch	Figure (1.9)	glass fiber (wt. %)	Steel fiber (wt. %)	Copper sulphides (wt. %)	Zirconium oxides (wt. %)	HMTA (wt. %)	Rubber (wt. %)	Novolac resin (wt. %)	Molybdenum oxides (wt. %)	Caesium carbonate (wt. %)	Copper powder (wt. %)	Details
11-a	C	4.5	4.5	29	6	1.5	10 SIR	28.5	7.5	7.5	1	Cured at 80°C
11-b	C	4.5	4.5	29	6	1.5	10 SIR	28.5	7.5	7.5	1	Cured at 110°C
11-c	C	4.5	4.5	29	6	1.5	10 SIR	28.5	7.5	7.5	1	Hot press
12	C	4.5	4.5	29	6	1.5	20SBR	18.5	7.5	7.5	1	Cured at 80°C
13	A	13	13	10	9	1.5	10 BR	8.5	17	17	1	Cured at 80°C
14	C	4.5	4.5	29	6	1.5	10 SIR	28.5	5	10	1	Cured at 80°C
15	A	13	13	10	9	1.5	10 SIR	8.5	17	17	1	Cured at 80°C
16	B	17	17	5	0	1.5	10 SIR	8.5	20	20	1	Cured at 80°C

### **3.4 Preparations of Raw Materials Techniques**

The raw materials of the samples were prepared according to the following procedures:

**3.4.1 Mould made:** To prepare the impact materials specimens an impact samples die was made of carbon steel with the dimensions of (65mmX30mmX12.7mm) then the samples obtained were cut with the dimensions of (65mmX12.7mmX12.7mm) according to ASTM (D256) [39-41].The cylindrical mold used for wear test was with 10mm diameter, and 20mm height according to ASTM (G65) [9].

**3.4.2 Die finishing:** This process was used to ensure the resin doesn't adhesive in the mould, grinding the mold by emery papers at different grade (180, 400, and 800).

**3.4.3 Preparation of composite materials technique:** Wet prepared and pre-dried method was used to prepare the composite materials. Fabrication and characterization of the compositions were designed based on batch consisting of (SIR), copper sulphides as lubricants material, zirconium oxide as abrasive material, steel fibers, and glass fibers as reinforcing fibers, copper powder as a reinforcing particles and molybdenum oxide and calesuim carbonate as a filler. Table (3.2) describes the components of the samples.

---

The preparing processes of the samples are:

1. Weight the components of the batch.
2. The fibers were cut to (5-10) mm length.
3. Novolac powder particle size must be larger than (45)  $\mu\text{m}$  so it shacked using a sieve size (50  $\mu\text{m}$ ) to determine the size of novolac powder.
4. The rubber was added as a liquid by dissolving in heptanes solvent. Each 1gram of rubber added to 10 ml of heptanes.
5. The components were mixed by intensive mixture.
6. After mixing the rubber with the other components the solvent must be evaporated by naturally for 48 hours.
7. The samples were prepared by pressing the components in the die under a pressure of 250 MPa at room temperature.
8. Preparation of specimens for test by trimming the specimens according to the standard dimensions are used in the tests, then grind them by using emery papers at degrees (180, 400, 800)
9. The curing must be occurred in the clamped die at 80 °C depend on die thickness (1 hour for each 1mm of die thickness).
10. Release specimens before coldness of mold to avoid adhesive the sample to the mould.

### **3.5 The Preparing of Commercial Samples**

The commercial samples were prepared by cutting the commercial pads according to the standard dimensions as shown in figure (3.4). There are two types of commercial pads were adopted. The first one was taken from Scania company pad and the other from Mercedes company pad.



Figure (3.2) failed sample

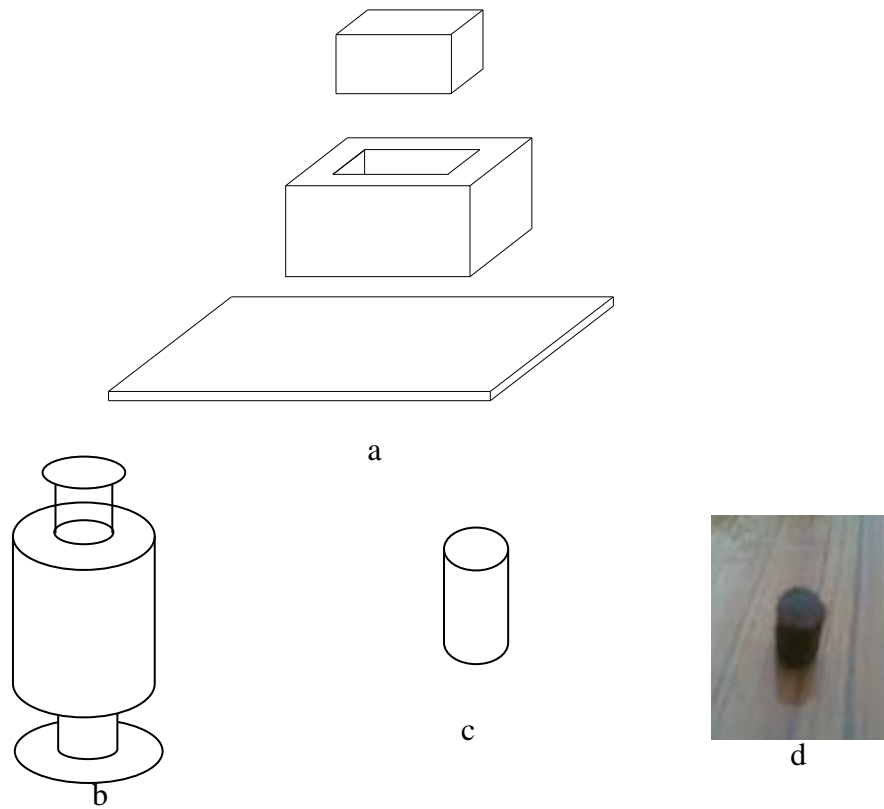


Figure (3.3) (a) Impact strength mold  
(b) Wear die (c, d) Wear sample



Figure (3.4) a-Impact strength sample  
b- Commercial impact strength sample

### **3.6 Tests and Measurements**

To study the chemical composition and mechanical properties after post curing such as impact strength, hardness, wear test. The following equipments were used.

#### **3.6.1 Mass measurements**

The mass measurement was carried out using (Sartorius laboratory) model (L220 s-d) Germany, with accuracy of 0.001g.

#### **3.6.2 Impact measurements**

Impact test was conducted by Izod method. It consists a hammer and energy pointer. Energy is represented by following (weight of hammer multiplied by height of hammer). The impact strength of samples is calculated from the ratio between the required energy of fracture on cross-section area of specimens. Figure (3.7) shows the impact measuring device.

#### **3.6.3 Hardness measurements**

In these tests shore (A) durometer was used to measure the hardness of the samples. This is a hand held device which involves a rounded indenter being press into the surface of the material under the action of a spring or weight, a pointer then registering the hardness value on a scale range as shown in figure (3.5).

### **3.6.4 Temperature measurements**

A non contact infrared thermometer sensor figure (3.6) was used to measure the surface temperature of the sample during wear test. Infrared thermometer measures the surface temperature of an object.

### **3.6.5 Pressing**

Figure (3.7) shows the hydraulic compression device (0-120) tons used to press the samples.



Figure (3.5) the hardness measurement



Figure (3.6) infrared thermometer



Figure (3.7) hydraulic compression device

### 3.6.6 Wear test

The test apparatus design (pin on disc) was made in the present study as shown in figure (3.8).

The disc was connected through an interchangeable flange rotation rate to a shaft which was connected by two pulleys to the motor.

The disc rotation rate was fixed at 660 rpm to conform that test .the movement in the wear device has been carried by two stages:

At the first stage the movement was carried by the pulley which was fixed on the motor. There was a carrier belt for movement kind (v-belt) to the shaft on which the two pulleys were fixed. One of them receives the

movement and the other to carry it. In the second stage the movement was carried from the middle shaft to the shaft on which the disc was fixed.

The load on the pin is (15.225 kg) which was adopted from the literature study for the fade and recovery tests. The high load led to break the samples in the form of brittle fracture so the load was changed to 7.725 kg.

The pin diameter is 10 mm and 20 mm height according to ASTM G65. Three mechanical specimens for each sample were molded in the laboratory and compared with the commercial specimens of heavy vehicles. It must be mentioned that the wear test device are designed and manufactured totally in the present work. The wear test device was designed to under take the heavy loads by using motor power of 2 hours. The wear device also contains a rectangular section arm. At the end of arm there was a holder to fix the sample.

The nominal surface temperature of the pin and the disc was estimated by using non-contact infrared thermometer. The polished pin was fixed above the gray cast iron rotor disc to test the sample. In the present study the weight change of the composite was measured by calculate the deference in weight at the end of each five minutes test.

### 3.7 Friction Coefficient Measurements

The friction coefficient is calculated by divided the friction force by the normal force as shown in equation (3.1). The friction force find by the multiplying of the strain by the coefficient  $k$  as in Equation (3.2) [27]. In the present study the strain gauge was connected with pin on disc test unit under (5 kg) load. The readings of the strain gage are as shown in Table (3.5). Figure (3.9) shows the strain gage device.

$$\mu = \frac{F}{N} \quad (3.1)$$

$$F = k * \varepsilon \quad (3.2)$$

$$k = 0.33$$

Table (3.5) Strain Results

Samples number	Strain ( $\varepsilon$ )
11-a	45
12	42
13	58
15	60
16	62
X-1	63



Figure (3.8) wear test machine

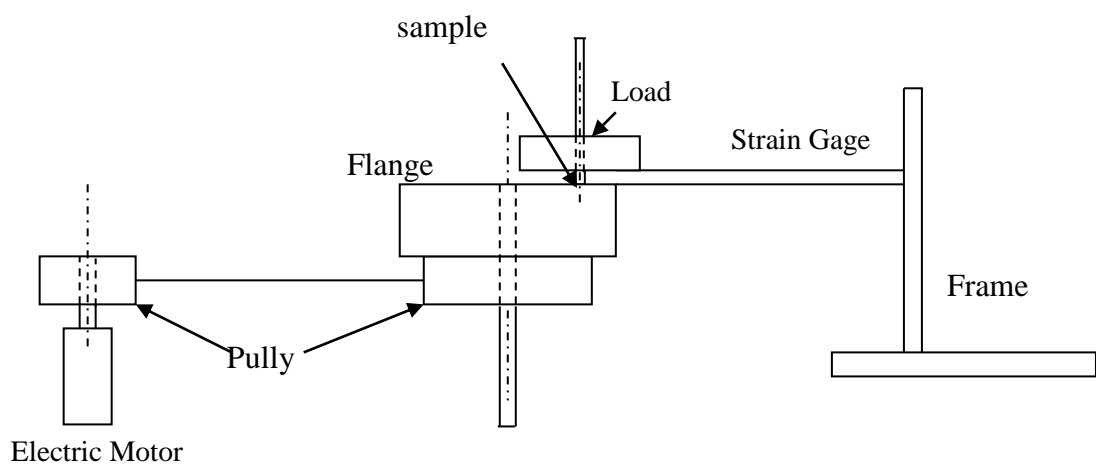


Figure (3.9) strain gage device

# CHAPTER FOUR

## *Results and Discussions*

## **Chapter Four**

### **Results and Discussions**

#### **4.1 Introduction**

This chapter shows briefly all the experimental results and discussions for the effect of the change in weight fraction of fibers, and rubber addition technique on the novolac and other components.

Also, this chapter includes the experimental results and discussions for the affect of the addition rubber of SIR, SBR, and NBR on the mechanical properties (wear lost, impact strength, hardness and coefficient of friction).

#### **4.2 Wear Tests Results and Discussions**

##### **4.2.1 Cold press**

###### **4.2.1.1The dry press**

The samples (1-10) which were containing SIR in the form of particles suffer from segregation of the fibers due to fibers poor wetting ability and its low density. The insufficient pressure (45MPa) and the batch heating before pressing led to curing the novolac resin and make the sample structure like a sponge after curing the sample for (7) hours till (180°C) therefore the samples (1-10) give poor results. The samples charred as the temperature reached above 200 °C.

#### 4.2.1.2 The wet prepared and pre-dried

Table (4.1) gives the wear lost versus time for the samples under 8 kg and 15.225 kg loads. The equations are a second order curve fitting polynomials. The y factor represents the wear lost while x represents the time.

Also, figure (4.1) shows the relation between the wear lost and the time for the sample (11-a) under (7.725 and 15.225) kg load. The ratio of the fibers is 10 percent which represent the minimum weight ratio of fibers. The maximum wear lost occurs at the minimum weight ratio of fibers because of the decrease of the plateaus formed by the fibers. When the wear time increased the work done by the friction force is increased too. That's led to transform the friction work to heat energy which increases the wear lost by the development of the circle fatigue cracks led to remove the material by brittle fracture. Phenolic matrix being thermoset the energy absorption is less as compared to the thermoplastics. Thermosetting composites cracks initiate at the filler–matrix interface and propagate very easily through the matrix towards the other filler–matrix interfaces. When the network of cracks intersects, the filler particles become loose and are removed in the form of wear debris. The resin also gets removed in the form of fine wear debris caused by brittle fracture of the resin [15].

The sample (11-a) was tested under (7.725) kg load and (15.225) kg. As the load increase the wear lost increased. The reason behind that are the surfaces of some composites worn under 1.2 kg load. The increasing in the load led to increase the wear lost of the sample. The reason behind that is the shear strains which were results by the pressure stress when the load applied and these strains caused the material transfer from the sample surface to the disk surface, therefore the coefficient of friction increased with the increase of friction force and that's led to increase the contact area. The wear lost increased as the contact area increase as in equation (4.1).

$$\Delta w = \text{wear rate} * \rho * L * A \quad (4.1)$$

$$\Delta w = \text{wear lost (kg)}$$

$$L = \text{sliding distance (m)}$$

$$\rho = \text{density (kg.m}^{-3}\text{)}$$

$$A = \text{real contact area (m}^2\text{)}$$

Figure (4.2) shows the wear lost as a function of the time with (7.725 and 15.225 kg) load of specimen (15). The increasing in wear behavior due to the increasing in the load led to worn the surface of the sample as it was discussed above. It's clearly shown that the wear lost under 15.225 kg is less than the wear lost of specimen (11-a), the reason behind that is the higher fiber ratio (27%) compared with fiber ratio of specimen (11-a) that has a fiber ratio of (10%).

Figure (4.3) shows the relation between the wear lost and time for specimen (16) under (7.725 and 15.225kg) load. The wear lost of specimen (16) is less than the wear lost of specimen (15) and specimen (11-a) under the same load. That's due to the high ratio of fiber content in specimen (16).

The maximum temperatures through each five minutes was recorded as shown in figure (4.4) with respect to time for specimen (16) under (15.225 kg) load. It's clearly shown that the surface sample temperature increases with time. The ambient temperature was (35°C) and the maximum temperature of the samples through the tests was (55-64) °C. Equation (4.1) gives a second order polynomial curve fitting of the surface sample temperature versus time.

$$y = 0.00117 + 0.002x - 9.142 * 10^{-5} x^2 \quad (4.1)$$

Figure (4.5) gives the wear lost of specimen (12) as a function of time and (7.725kg) load. It is clearly that the wear lost of this specimen is very high compared with the other specimens. The reason behind that is the high ratio of SBR (20%) and the tension strength increase to the maximum with the strain increase when the ratio of rubber addition to the thermoset reach 10% while the strength decrease with the strain increase at 20% of rubber [20, 45].

Figure (4.6) gives the wear lost of specimen (13) as a function of time. Specimen (13) has NBR instead of SIR with fiber ratio of (27%). This led to decrease the wear lost with time comparing with specimen (15) which has the same fiber ratio. Thus NBR addition had better wear results than SIR.

Figure (4.7) shows the wear lost of the sample (11-b) with respect to time under (7.725 kg) load. The wear lost is greater than the wear lost of sample (11-a) inspect of they have the same components. The increase in wear lost is due to the high temperature of curing (110°C) while the curing temperature of specimen (11-a) was (80°C).

#### **4.2.2 Hot press**

Sample (11-c) was pressed by hot press technology. It was tested by the wear test device after curing it at 90°C for 1.5 hours. Figure (4.8) gives the wear lost of sample (11-c). Sample (11-c) lost high weight when it was tested by wear test machine. The cold press technology gives results better than the hot press technology so it was dependent in the presented study. The results show that sample (11-c) weight lost was more than sample (11-a) that's due to the incomplete crosslink process due to the short time available of hot press technology compared to that with cold press technology.

Semi-metallic brake pads with a mixture of metallic and organic compounds having varying thermal expansion coefficients would require a large amount of molybdenum trioxide to prevent lining cracking. Sample (14) has the components of sample (11-a) except that the content of the filler (molybdenum trioxide) decreases to half which shares it in sample (11-a). The wear test results of sample (14) are shown in table (4.2). It must be mentioned that the sample could not undertake the load and break in the form of brittle fracture after two tests because of the little amount of the filler. The rate of wear lost for the samples (11-16) were calculated by dividing the rate of wear lost through 20 minutes per five tests as shown in figure (4.9).

Table (4.1) the wear lost versus time for the samples and loads

Sample No.	Load (kg)	Wear Lost vs. Time
11-a	8	$y = 0.00085 + 0.0027x - 2.857 * 10^{-6} x^2$
11-a	15	$y = 0.00177 + 0.00314x + 0.0014x^2$
15	8	$y = 0.001 + 0.002x + 4 * 10^{-5} x^2$
15	15	$y = 0.00117 + 0.002x - 9.142 * 10^{-5} x^2$
16	8	$y = 0.000171 + 0.00179x - 8.57 * 10^{-6} x^2$
16	15	$y = 0.00057 + 0.0018x + 1.14 * 10^{-5} x^2$
12	8	$y = 0.011 + 0.0173x - 0.00052x^2$
13	8	$y = 0.0019 + 0.0042x + 0.000105x^2$
11-b	8	$y = 0.0278 - 0.00947x + 0.001285x^2$
11-c	8	$y = 5.714 * 10^{-5} + 0.016x - 0.00028x^2$
X-1	8	$y = 0.00137 - 0.00271x - 4.857 * 10^{-5} x^2$
X-2	8	$y = -0.00214 + 0.000702x + 6.285 * 10^{-5} x^2$

Table (4.2) The loss in weight with time for specimen (14)

Time (minutes)	Weight (g)
5	1.997
10	1.939

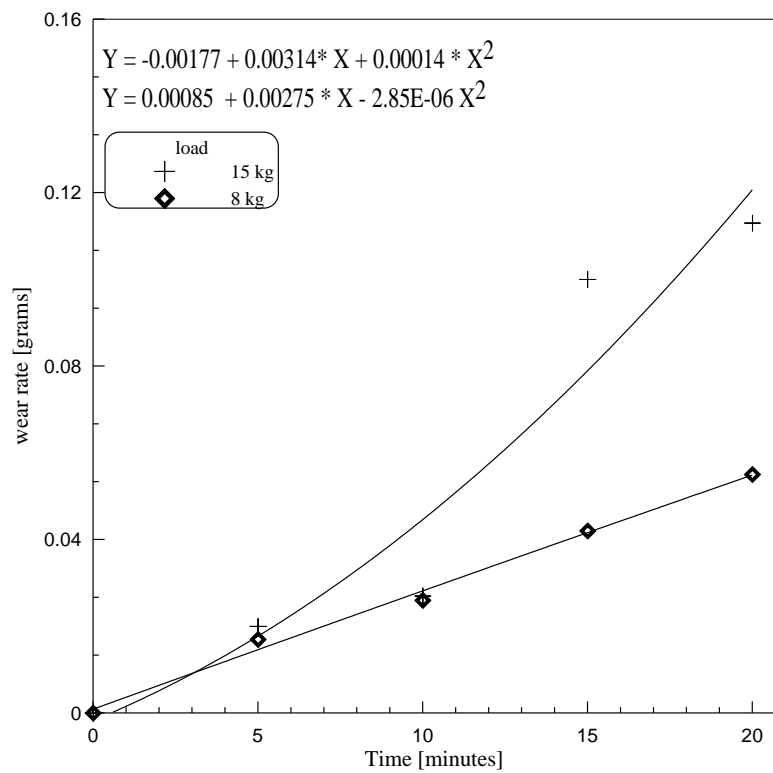


Figure (4.1) The relation between the wear lost and time for the sample (11-a) under (7.725 and 15.225) kg load.

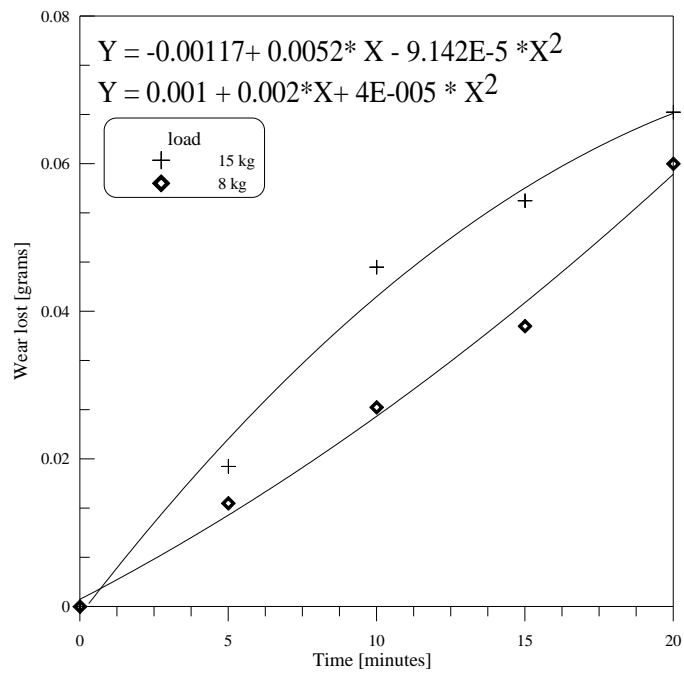


Figure (4.2) The relation between the wear lost and time for the sample (15) under (7.725 and 15.225) kg load.

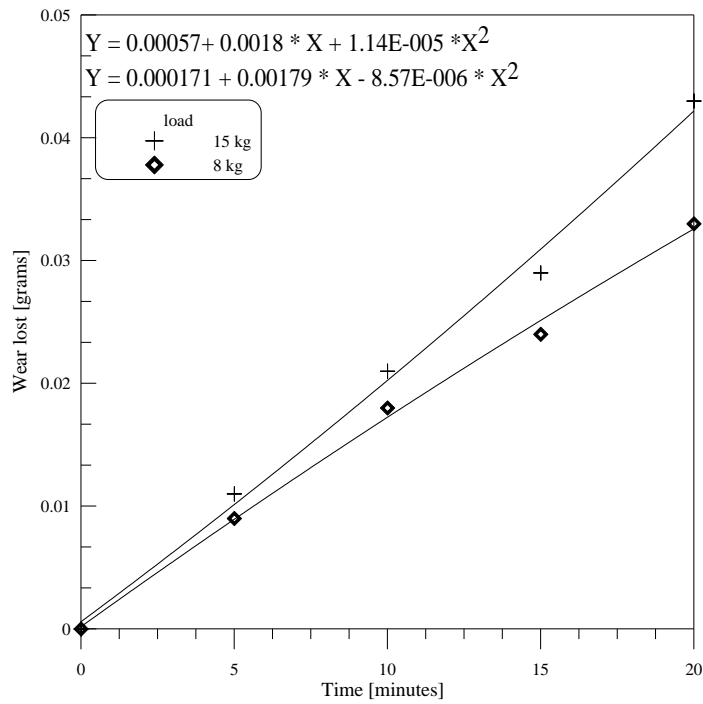


Figure (4.3) shows the relation between the wear lost and time for the sample (16) under (7.725 and 15.225) kg load.

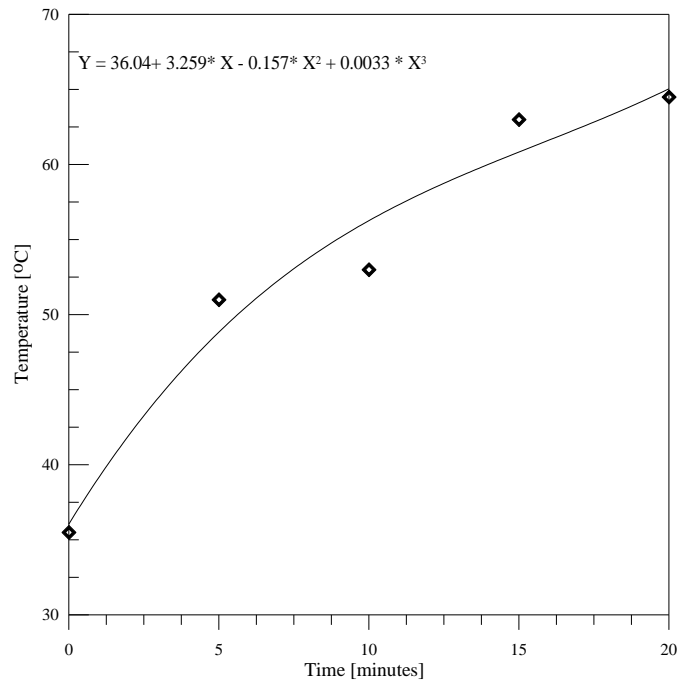


Figure (4.4) The relation between the sample maximum temperatures and respect to time for the sample (16).

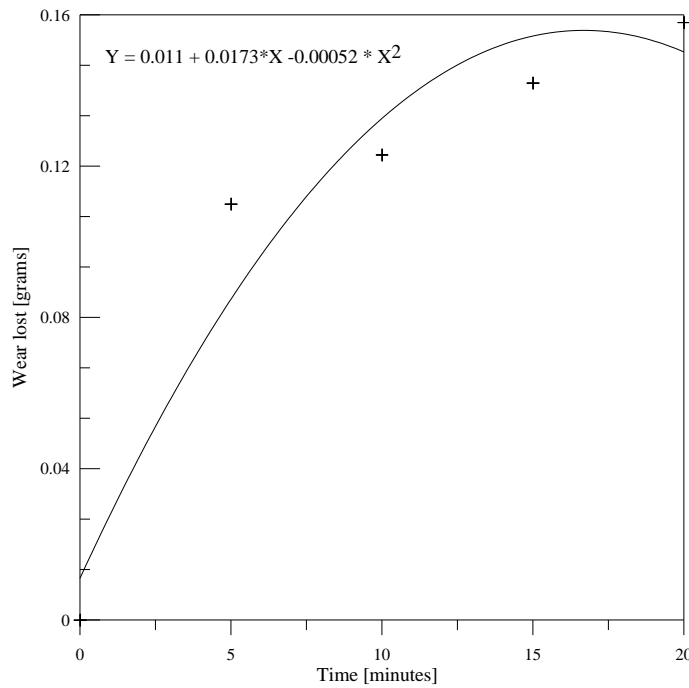


Figure (4.5) The relation between the wear lost and time for the sample (12) under load (7.725) kg.

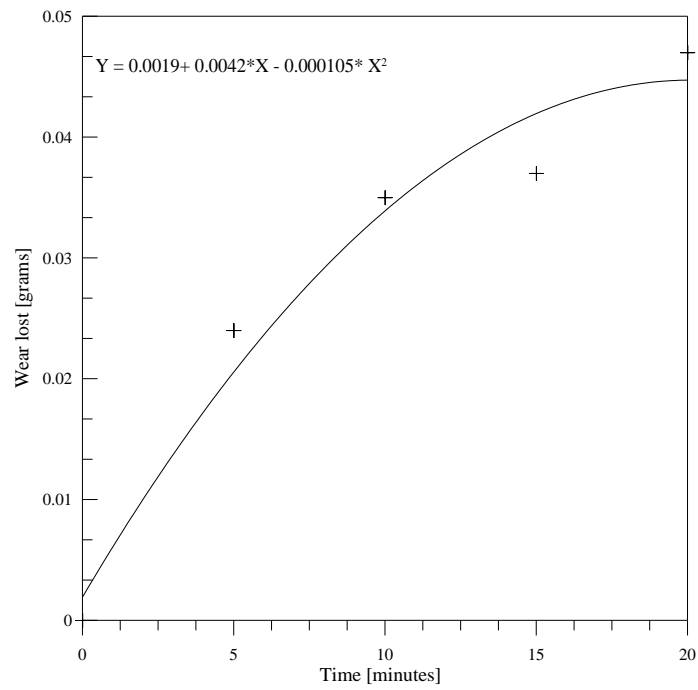


Figure (4.6) The relation between the wear lost and time for the sample (13) under load (7.725) kg.

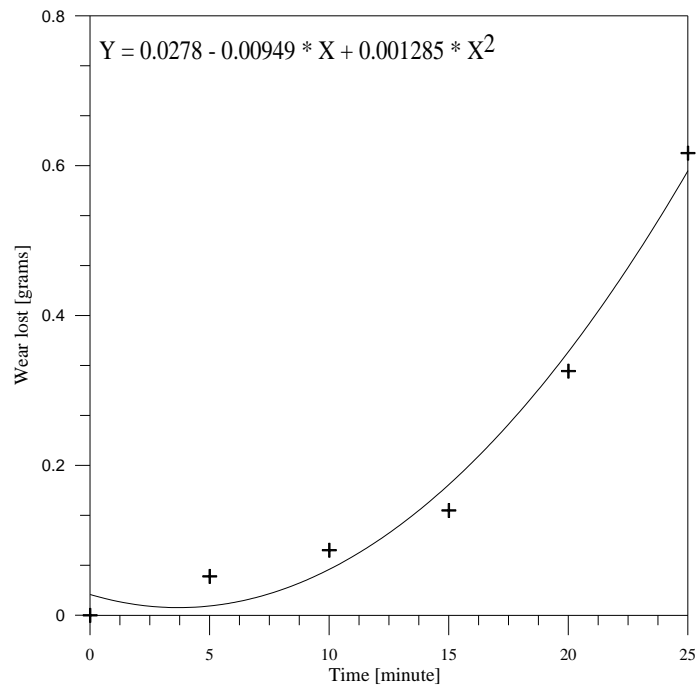


Figure (4.7) shows the relation between the wear lost and time for the sample (11-b) under load (7.725) kg.

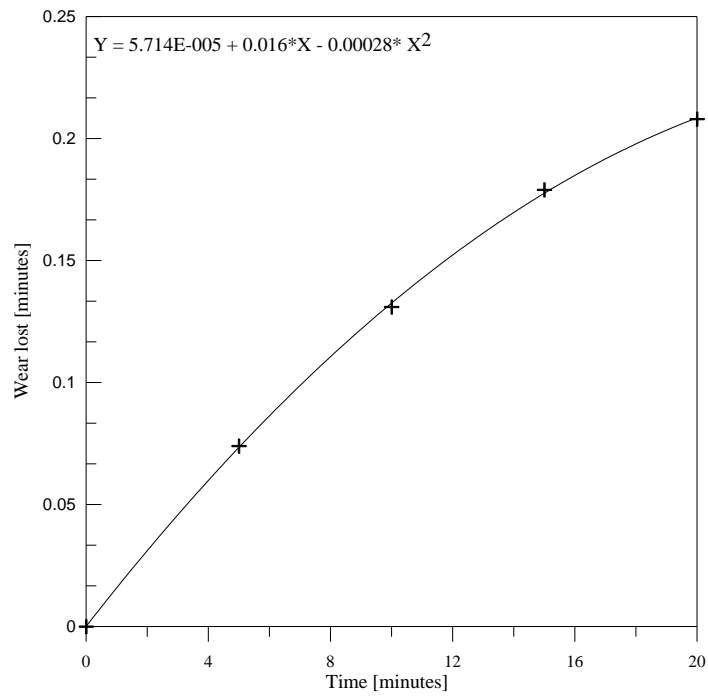


Figure (4.8) The relation between the wear lost and time for the sample (11-c) under load (7.725) kg.

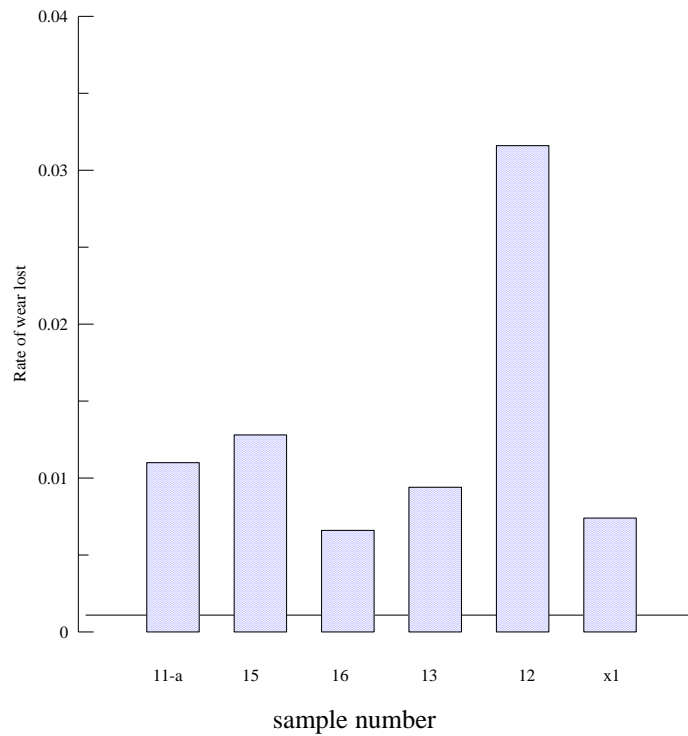


Figure (4.9) The wear lost of selected samples

### 4.2.3 The commercial Samples

Figure (4.10) shows the wear lost of the commercial sample (X-1) with respect to time under (7.725 kg) load.

Figure (4.11) shows the wear lost of another commercial sample (X-2) with respect to time and (7.725 kg) load. It's found that the wear lost is proportion to time. The wear lost found to be higher than specimen (X-1).

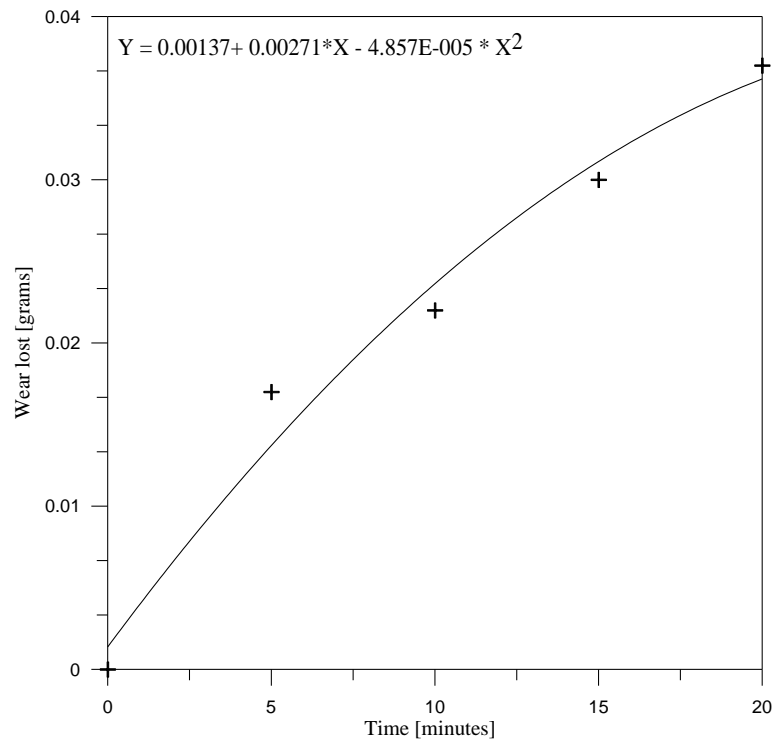


Figure (4.10) the wear lost versus time for the commercial specimen (X-1) under load (7.725) kg

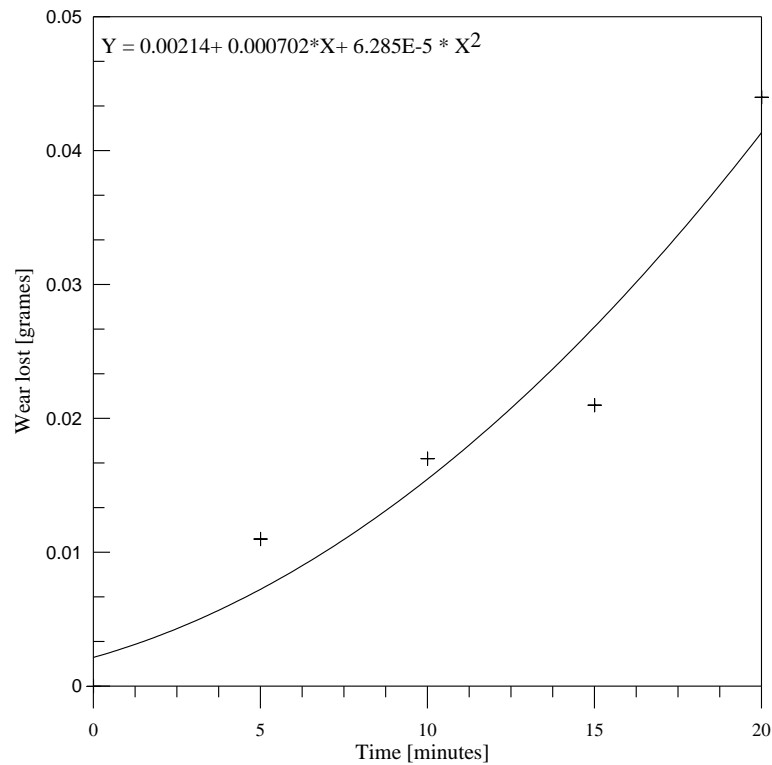


Figure (4.11) the wear lost versus time for the commercial specimen (X-2) under load (7.725) kg.

### **4.3 Hardness Tests**

The hardness of the samples increases with the decrease of the ratio of the fibers as shown in figure (4.12). Table (4.3) shows the hardness of the samples (1-15). The hardness decreases when the fiber ratio increases. The reason behind that is the low weight of the samples as the low density of fibers because the high fiber ratios lead to decrease the penetration of fibers and decrease the filler contents. When the fibers ratio decrease the filler ratio increase and vice versa.

The samples that contain SIR have a higher hardness from the samples containing SBR resin. The reason behind that is the high toughness of SIR compared with SBR and the high weight ratio of SBR (20%).

Table (4.3) Hardness properties of the selected samples

Sample number	Hardness
1	91.5
2	86.5
3	80
4	82
5	75
6	83
7	73
8	56
9	49
10	86
11-a	95.2
12	85
13	92.5
15	83.5
16	76.5
X1	89.5

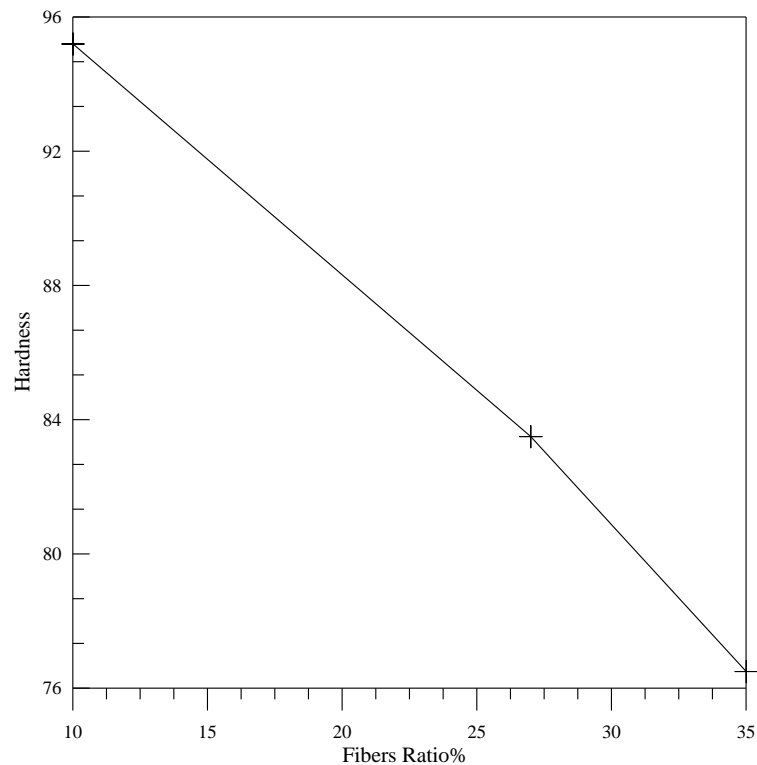


Figure (4.12) the relation between the hardness and fibers ratio.

#### **4.4 Impact Strength Test**

Specimens (11, 12, 13, 15, and 16) were tested using Izod impact strength device. Specimen (12) has the lowest impact strength as it has SBR which has low elasticity compared with NBR and SIR [46]. Sample 12 containing 20% SBR has the lower the mechanical properties. By comparing the impact strength of sample (13) which contains (NBR) with sample (15) which contain SIR; there are good accuracy. The impact strength increases as the rate of fibers ratio increase as shown in figure (4.13).

#### 4.5 Friction Coefficient Results

The friction coefficient results for selected samples are shown in figure (4.14). It's clearly shown that the friction coefficient increases with the increase of fiber ratio. As the fiber ratio increase the tangential force increase too, so the friction coefficient increase as it proportion to the tangential force that's due to its behavior as an abrasive material.

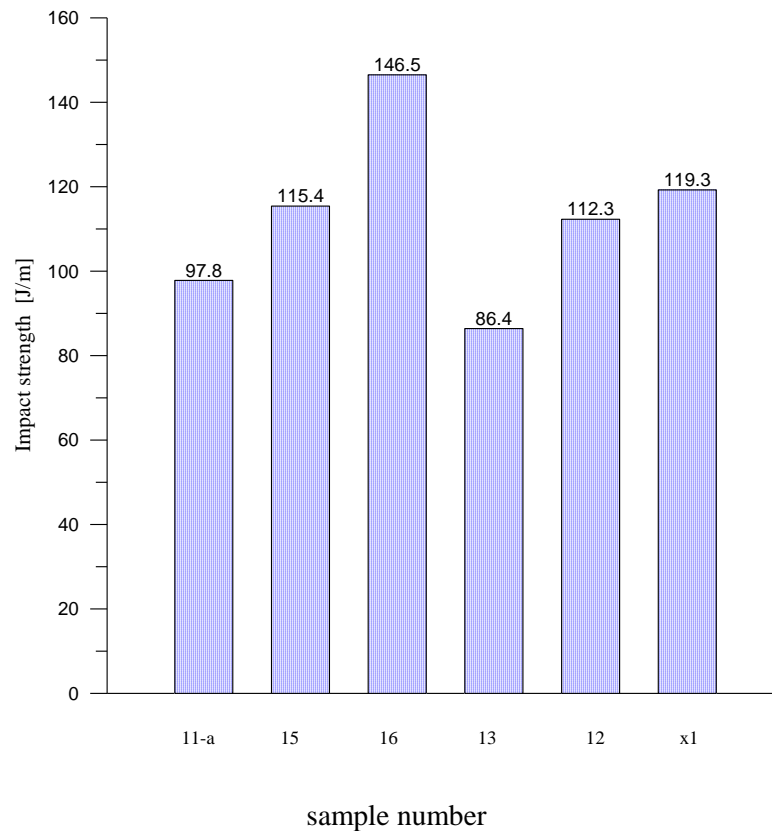


Figure (4.13) The impact strength of selected samples

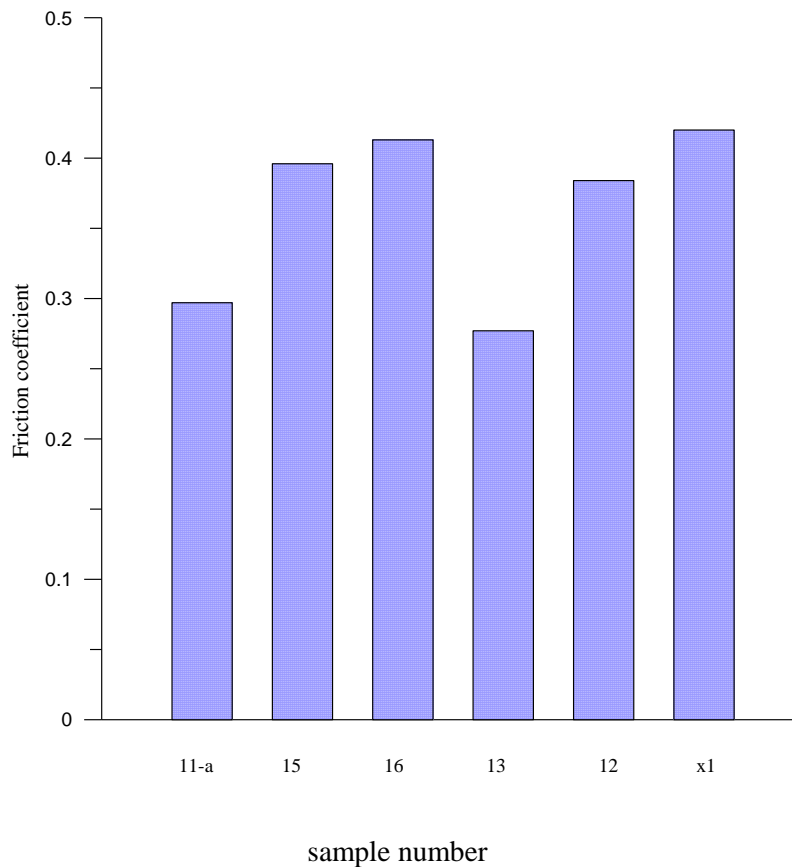


Figure (4.14) The friction coefficient of selected samples

#### **4.6 Curing Temperature**

The curing temperature is the more important factor on the structure of the samples. The reason behind that the curing temperature is the mainly factor affect on the crosslink process. From the experiment tests, it was found that the color of the samples become darker after more than six hours of curing at 80°C. Many specimens were tested with different curing of (3, 4, and 5) hours. All the specimens that have a curing time less six hours. They found with a whiter color and failed through the wear tests because the specimens didn't have the enough time to complete the cross linking

process. The reason of the change in the color of the sample was that the phenol formaldehyde was opaque and initially light in color. It dose, however, with time and so is always mixed with dark pigments to give dark- colored material. It is supplied in the form of a molding powder which includes the resin, fillers and other additives. When this powder is heated in a mould the cross linked polymer chain is produced [19]. The seven hour of curing gives better results of mechanical properties and change the color as shown in figure (4.15).

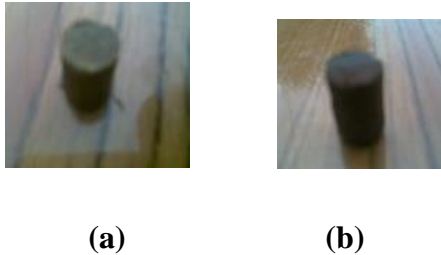


Figure (4.15) (a) Sample after five hour of curing

(b) Sample after seven hour of curing

# CHAPTER FIVE

## *Conclusions and Recommendations*

## **Chapter Five**

### **Conclusions and Recommendations**

#### **5.1 Conclusions**

Based on the results presented and discussed in the previous chapters the following conclusions can be drawn:

1. The rubber addition increase friction, permute good wear resistance in friction materials, increase impact strength, and resistance to objection noise.
2. The NBR has better wear rate result than SIR.
3. The wear lost and hardness decrease with the weight ratios of fibers increase.
4. The wear lost increases with the increases of the temperature of the specimen.
5. The high weight fraction of SBR (20%) leads to increase the wear rate.
6. When the weight ratio of steel fibers (10%) increased to (27%) the friction coefficient increase from (0.3 to 0.4).
7. When the weight ratio of steel fibers (10%) increased to (27%) the impact strength increase from (99 J/m to 118 J/m).

## **5.2 Recommendations for Future Work**

1. Study the effect of addition NBR with novolac at different fiber ratios.
2. Include the effect of Alkyl-benzene modified resin instead of Novolac with NBR.
3. Study the using of linseed oil modified resin.
4. Design organic bad by using organic fibers.
5. Study the worn surface analysis of the brake pad.
6. Study the microscopic analysis (SEM) of the friction materials.
7. Study the design and the analysis of the composite which was reinforced by the alumina fibers in the brake pad.
8. Study the influence of epoxy addition to novolac on the fade and recovery behavior of friction materials.