CHAPTER 4

ALTERATION OF MOLECULAR WEIGHT IN THE RESIN
MATRIX IN RELATION TO FADE AND WEAR IN A SEMI
METALLIC BRAKE PAD: AN INTERFACE STUDY

4.1 RESIN AND FADE

The range of properties and behavior patterns of brake linings depends to a great extent on the nature and quality of the binders being used. The coefficient of friction as a function of temperature resulting from speed (during braking) is affected by many factors including the organic components of the brakes and also the phenolic resin fraction. Good fading behaviour, i.e., the temperature-dependent coefficient of friction remains constant to an acceptable degree, is a technical consideration. In addition, the brake lining must afford the longest possible service life, i.e., undergo lower wear, should spare the other contact material – for example the brake disc as much as possible, and be resistant to the effects of weather. As a function of temperature, pad wear is highly dependent on the type and level of the organic binder. The wear may be reduced by the special modification of the binder.

Presently brake pad materials are made free from asbestos. The type and amount of resin in the friction material are very critical for structural integrity of the composites. The binder should not deteriorate under any diverse conditions. However, when the interface temperature exceeds the
normal limit, changes in the properties of the resin can worsen its performance.

Accordingly, the thermal stability of friction materials and its capacity to bind its ingredients collectively under diverse conditions depend upon the quality and proportion of resin.

Brake fade is the reduction in stopping power that can occur after repeated or sustained application of the brakes, especially in high load or high speed conditions. On release of the brakes and cooling to the room temperature, the regain of the original magnitude of it is referred as recovery. According to Blau 2001, high interfacial temperature leads to a decrease in shear strength of the pad due to degradation of the resin, and consequently a decrease in frictional force, which induces fade. Herring et al 2003, proposed that fade is due to release of gaseous by products formed by degradation of phenolic resin at braking interface. In Non asbestos semi metallic friction composites, resin, friction dust and some organic fibers that are most vulnerable to thermal degradation undergo charring, which results in glazing and deterioration in friction performance.

**Design and Control of Phenolic Resin properties**

In order to meet performance requirements of friction materials, various kinds of phenolic resins have been developed.

Non-modified or straight phenolic resins have been widely used because of their low cost and high performance. Brake manufacturers select the resin with the specific inclined plate flow and hexa content best suited to optimize the performance of brake formulations. Flow distance and hexa content directly impact physical properties such as porosity, mechanical
strength, hardness and elastic modulus. Among the various types of modified phenolic resins Alkyl benzene modified phenolic resin have been developed to improve heat resistance such as disc pad wear due to thermal decomposition of resin binder during high temperature braking.

The concept of contact area on the friction surface is shown in Figure 4.2. It is assumed that true contact area increases with increased flexibility.

![Actual Contact Length](image)

**Figure 4.1 Concept of true contact area**

Additionally, flexible resins are effective for decreasing the brake noise because the contact between the disc pad and rotor is more uniform. Fast curing phenolic resins are required more often today due to availability of fast cure press moulding equipments. It is important to understand the relationship between resin physical properties and performance of friction materials as summarized in Figure 4.3.
Moisture content affects the flow of powdered phenolic resins. Therefore, storage conditions are important to control moisture pickup and maintain low moisture content. Key characteristics of phenolic resins are its molecular weight distribution, as it has a significant effect on the end use properties of the resin. Characterizing and understanding the molecular weight distribution of resin materials is therefore key to their performance.

Currently there is no unified understanding of exactly how the intrinsic properties (like molecular weight, cross-link density) of the resin affect the resultant mechanical performance. It is the glass transition temperature of the polymer matrix that bounds the upper useful service temperature of the polymer composite system. This work is carried out to present the results of and discuss an experimental study that considers the effect of molecular weight of the resin matrix in relation to fade and wear of a non asbestos brake pad. Three distinct variations in molecular weight of Alkyl Benzene modified Phenolic resin were used to evaluate the differences in tribological performance of the non asbestos brake pad.

Figure 4.2 Relationship between resin properties
(Courtesy Pilato et al 2000)
4.2 RESIN CHARACTERIZATION

Alkyl Benzene modified phenolic matrix resin with three different molecular weight was synthesized by varying the melting point from Xpro Thermoset division, Pune, India. It was characterized for curing temperature and thermal degradation temperature by the standard DSC and TGA studies and the functional groups through Fourier transform spectroscopy (FT-IR) respectively. GPC (Gel Permeation Chromatography) was carried out to find the number average molecular weight (Mn) and the weighted average molecular weight (Mw). The results are displayed in the Table 4.1. Resin was also characterized for the various properties like flow distance (horizontal), Gel Time, hexa content (%) and Moisture content with standard methods and the resin with low molecular weight distribution was designated as L-resin and the resin with medium molecular weight as M-resin and the higher molecular weight as H-resin. The results obtained are given in the Table 4.1. The figure 4.1 shows the relationship between the requirements of disc brake pads and the requirements of phenolic resins.

Figure 4.3 Relationship between disc pad properties and resin properties (Courtesy Pilato et al 2000)
4.2.1 Flow Distance: (Norton Flow Test)

Scope: Applicable for Phenolic Resin to know the curing time.

Apparatus:

- Electric Oven
- Pallet Mould
- Fixture of apparatus to held glass plate under define inclination
- Smooth Glass Plate
- Thermometer
- Balance
- Measuring Scale

PROCEDURE

1. Weigh 0.5 ± 0.1 gm. on a paper.
2. Transfer it on pallet mould to make a tablet.
3. Carefully transfer the tablet on one edge of the glass plate.
4. Start oven and maintain temp. 125°C ± 3°C throughout the process.
6. Keep a glass plate along with tablet on Norton flow apparatus for 3 minutes and start stopwatch simultaneously.
7. Tilt the Norton flow apparatus to 65° by using external mechanism and ensure that the plate edge having tablet is on the upper end.

8. Left it for 10 minutes and start stop watch simultaneously.

9. Bring back the Norton flow apparatus into horizontal position and remove the glass plate from oven and allow it to cool down.

10. Measure the length of flow (Tip to Tip) using a standard measuring scale.

4.2.2 Hexa Content

Scope: Applicable for Phenolic resin

Apparatus

1. Heating Mantle
2. Hard Glass Test Tube
3. Thermometer

Procedure

1. Weigh approximately 5 gms of 10.11.13 in the clean test tube.
2. Take cellophane paper & weigh it.
3. Take pre dried hexamine powder on cellophane paper & weigh it equivalent to 7.5 % of 10.11.13 on balance.
4. Add hexamine powder slowly into 10.11.13 test tube. (In case same particle of hexamine stick on the periphery of test tube. Push it in to 10.11.13 using a glass rod.)

5. Start heating metal keep liquid paraffin in a beaker and keep beaker on heating metal & raise the temp. of paraffin bath to 152 + 3°C. Maintain this temp. throughout the process.

6. Immerse ¾ level of test tube mentioned in Para 3 into paraffin bath & hold it by using stand & clamp.

7. Start the stop watch after 1 minutes of immersion of the test tube.

8. Stir vigorously till rubbery texture obtain.

4.2.3 Melting Point

Title: Determination Of Melting Point By Capillary Method

Scope: Applicable for powder (resin)

Apparatus

1. Melting Point Apparatus

2. Capillary Tube

3. Thermometer

Procedure

1. Seal the capillary tube for one end & fill ¾th capillary tube with the material.
2. Place the capillary tube in the hole provided in the melting point apparatus.
3. Put one thermometer in the hole provided for temperature checking in the melting point apparatus.
4. Start heating. Raise the temp. slowly & watch the inside material through the sight glass.
5. Record temp. at which material starts shrinking / melting.

4.2.4 Number and Weighted Average Molecular Weight

Gel Permeation Chromatography (GPC) is an ideal analytical tool for the examination of the molecular weight distribution. These resins are non-polar so they are analyzed in the THF using PS/DVB columns. In the GPC analysis, detailed below, three distinct grades of Alkyl benzene modified PR have been analyzed by GPC using a resipore column set and the values are plotted in the figures (4.4 - 4.6). The values obtained from the GPC of each resin sample have been presented in the table 4.1.

Figure 4.4 Molecular weight distribution of L-resin
Figure 4.5 Molecular weight distribution of M-resin

Figure 4.6 Molecular weight distribution of H-resin
The polydispersity index is obtained by finding the ratio of Weight average to the Number average. For a good performance resin, as per friction application is concerned, the weight and number average should be as close as possible. That is, it may approach unity. For all the three resins which are designated as L, M and H resin, it was found that for M type and H type the variation is much larger (weight average is six times greater than the number average) which may have impact in the performance.

4.3 FOURIER TRANSFORM SPECTROSCOPY (FT-IR)

The IR spectral studies were taken using Shimadsu UV – visible spectrometer, and the graph is plotted between the wave number (1/cm) vs % Transmittance. The plots were displayed in the figures (4.7 – 4.9). It shows that the polymer sample designated M has a broad peak in the range of 3190 – 3481 cm$^{-1}$. It reveals the formation of hydrogen bonding in the polymer resins. In the case of low & high molecular weight resin samples, a broad peak of 3300 cm$^{-1}$ is obtained, but it is not very intense.

Figure 4.7 Fourier transform spectroscopy (FT IR) for L-Resin
Figure 4.8 Fourier transform spectroscopy (FT IR) for M-Resin

Figure 4.9 Fourier transform spectroscopy (FT IR) for H-Resin
Table 4.1  Details of the selected resin characterization

<table>
<thead>
<tr>
<th>Properties</th>
<th>Alkyl Benzene modified phenolic resin (L)</th>
<th>Alkyl Benzene modified phenolic resin (M)</th>
<th>Alkyl Benzene modified phenolic resin (H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point 0°C</td>
<td>75</td>
<td>82</td>
<td>98</td>
</tr>
<tr>
<td>Gel Time at 150 0°C (sec)</td>
<td>93</td>
<td>85</td>
<td>79</td>
</tr>
<tr>
<td>Flow Distance (mm) at 135°C At Horizontal for 50 min</td>
<td>25-40</td>
<td>35-50</td>
<td>50-70</td>
</tr>
<tr>
<td>Hexa content (%)</td>
<td>9.58</td>
<td>10.11</td>
<td>6.4</td>
</tr>
<tr>
<td>Moisture content(%)</td>
<td>Max 1.5</td>
<td>Max 1.5</td>
<td>Max 1.5</td>
</tr>
<tr>
<td>Initial degradation temperature from TGA (T&lt;sub&gt;i&lt;/sub&gt;) (0°C)</td>
<td>428</td>
<td>489</td>
<td>510</td>
</tr>
<tr>
<td>Curing Temp from DSC (0°C)</td>
<td>144</td>
<td>155</td>
<td>160</td>
</tr>
<tr>
<td>Number average Mol weight (M&lt;sub&gt;n&lt;/sub&gt;)</td>
<td>555</td>
<td>737</td>
<td>822</td>
</tr>
<tr>
<td>Weighted average mol weight (M&lt;sub&gt;w&lt;/sub&gt;)</td>
<td>2412</td>
<td>4544</td>
<td>5223</td>
</tr>
</tbody>
</table>

4.3.1  Inference

- As the molecular weight increased, the melting point increased. This increase in melting point increased the degradation temperature of the resin.
- As the molecular weight increased, the flow distance (combination of curing properties and melt viscosity) increased, which made the resin to flow easily and hence quicker was the cross linking thereby increasing the binding
force. This in turn increased the rigidity of the pad which showed poor resilience as noticed by the shear strength value.

- Faster cross linking reduced the gel time, which shortens the moulding time as noticed in the acetone extraction which is good for increasing the productivity.
- Higher molecular weight resin affords high hardness and high thermal resistance, which in turn leads to poor flexibility.
- Use of a low hexa level achieves relatively low hardness, which in turn leads to improved flexibility and good comfort properties.

4.4 MATERIALS AND METHODS

As a trial, a base formulation containing 15 ingredients was developed as asbestos free friction materials. It is arrived after conducting several trials using the design of experiments as shown in the Table. The final formulation consisted of reinforcing fibers such as Kevlar, cellulose fibre, steelwool, lapinus and Rockwool fiber, Alkyl benzene modified phenolic resin as binder, barytes, vermiculite Dug, tyre peels, china clay, yellow iron oxide and zinc oxide as fillers while Green chrome oxide, Friction dust and Graphite powder as friction modifiers.
Table 4.2 Characteristics of commonly used materials in brake pad

<table>
<thead>
<tr>
<th>Material</th>
<th>In process Handling</th>
<th>Bulk Density</th>
<th>Hardness</th>
<th>Sp. Gravity</th>
<th>Friction</th>
<th>Wear</th>
<th>Ther. Stab.</th>
<th>CB S</th>
<th>Cold Shear</th>
<th>Hot Shear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic Fibers</td>
<td>Ve</td>
<td>-Ve</td>
<td>-ve</td>
<td>Ve</td>
<td>-ve</td>
<td>-ve</td>
<td>Ve</td>
<td>-ve</td>
<td>-ve</td>
<td>-ve</td>
</tr>
<tr>
<td>Mineral Fibers</td>
<td>Ve</td>
<td>+Ve</td>
<td>+ve</td>
<td>Ve</td>
<td>+ve</td>
<td>+ve</td>
<td>Ve</td>
<td>+ve</td>
<td>+ve</td>
<td>+ve</td>
</tr>
<tr>
<td>Friction Dust</td>
<td>Ve</td>
<td>-Ve</td>
<td>-ve</td>
<td>Ve</td>
<td>-ve</td>
<td>-ve</td>
<td>Ve</td>
<td>-ve</td>
<td>-ve</td>
<td>-ve</td>
</tr>
<tr>
<td>Filler [BaSO4]</td>
<td>+Ve</td>
<td>Ve</td>
<td>Ve</td>
<td>Ve</td>
<td>Ve</td>
<td>Ve</td>
<td>Ve</td>
<td>Ve</td>
<td>Ve</td>
<td>Ve</td>
</tr>
<tr>
<td>Phenolic Resin</td>
<td>+Ve</td>
<td>Ve</td>
<td>Ve</td>
<td>Ve</td>
<td>Ve</td>
<td>Ve</td>
<td>+ve</td>
<td>Ve</td>
<td>Ve</td>
<td>Ve</td>
</tr>
<tr>
<td>Organic Fibers</td>
<td>Ve</td>
<td>-Ve</td>
<td>-ve</td>
<td>Ve</td>
<td>-ve</td>
<td>-ve</td>
<td>Ve</td>
<td>-ve</td>
<td>-ve</td>
<td>-ve</td>
</tr>
</tbody>
</table>

+ ve – Positive Impact [Better Effect]

-Ve – Negative Impact [Adverse Effect]

Ve – No Change
The points that are considered for the design of experiments is shown in the Table 4.3

**Table 4.3 Points considered for the design of experiments**

<table>
<thead>
<tr>
<th>S.no</th>
<th>Properties</th>
<th>Values as per O.E standards for passenger cars</th>
<th>Remarks.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Specific Gravity</td>
<td>2.51</td>
<td>Weight of Caliper increases and may cause Judder during Braking</td>
</tr>
<tr>
<td>2</td>
<td>Hardness</td>
<td>90</td>
<td>Low Hardness May cause faster wear rate of the pads.</td>
</tr>
<tr>
<td>3</td>
<td>Heat Swell</td>
<td>0.07</td>
<td>Higher Heat swell value may affect severe Braking at high speed.</td>
</tr>
<tr>
<td>4</td>
<td>Bonding Shear Strength</td>
<td>45</td>
<td>Higher bonding strength is better for high speed driving of the vehicle</td>
</tr>
<tr>
<td>5</td>
<td>Friction as per SAE-J661</td>
<td>0.42</td>
<td>Higher friction level is good, for achieving minimum stopping distance at higher speed of the vehicle.</td>
</tr>
<tr>
<td>6</td>
<td>Wear Loss</td>
<td>4.0</td>
<td>Lower the wear loss higher the life of the pads.</td>
</tr>
</tbody>
</table>
4.5 MOULDING OF BRAKE PADS

The friction materials were fabricated in four steps which are mixing of the ingredients, preforming and curing in a Hydraulic Press and post baking which was explained in detail in the chapter 2. Three pads were developed with these three resins and for our reference it is designated as FCL (friction composites made with low molecular weight resin), FCM (with medium molecular weight resin) and FCH (made with high molecular weight resin). Three friction composites containing 15 ingredients were fabricated differing only in the molecular weight of the resin. The additions of ingredients are mixed in a drum mixer with feeder and chopper. The addition of ingredients during mixing was in a particular sequence. Kevlar and cellulose fibers are added initially followed by other pulpy materials and finally by powdery materials.

The brake friction composites in the form of Pads were molded in hydraulic Press. Mix weight of 880g was taken and was put in compaction die. A preform pressure of 16.6 MPa was applied with two vents. The preform was taken and placed in a two cavity mould supported by the adhesive- coated back plates. The top and the bottom temperature of the die were maintained between130°C and 160°C. The curing temperature of each resin was given in the Table 4.1. A pressure of 17 MPa to 21 MPa was applied. The curing cycle was maintained for 8 minutes. Eight breathing was followed during final curing. The breathing cycles helped to remove entrapped gases evolved during cross linking reaction of the resin. The molded composites were post baked at different temperatures 100 – 160°C for 8 hours to relieve the residual stresses. The surfaces of the pads were then polished with the grinding wheel to attain the desired thickness and remove the resinous skin.
4.6 EVALUATION OF MECHANICAL PROPERTIES

The physical, chemical and mechanical properties evaluated by using the procedure discussed in the chapter 2 are tabulated below:

Table 4.4 Physical and mechanical properties

<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
<th>FCL</th>
<th>FCM</th>
<th>FCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td></td>
<td>2.13, 2.15</td>
<td>2.56,2.60</td>
<td>2.63, 2.75</td>
</tr>
<tr>
<td>Hardness</td>
<td>HRS</td>
<td>85,86,88,90,91,95</td>
<td>89, 91,97,98,99</td>
<td>105,110,118,120,125</td>
</tr>
<tr>
<td>Acetone Extraction</td>
<td>%</td>
<td>0.89, 0.90</td>
<td>0.78, .95</td>
<td>0.58, 0.87</td>
</tr>
<tr>
<td>Loss of Ignition</td>
<td>%</td>
<td>13.35, 13.85</td>
<td>37.12, 37.14</td>
<td>36.24, 36.79</td>
</tr>
<tr>
<td>Cold Shear Strength</td>
<td>MPa</td>
<td>3.974, 4.131</td>
<td>4.118, 4.216</td>
<td>3.935, 4.089</td>
</tr>
<tr>
<td>Hot Shear Strength</td>
<td>MPa</td>
<td>2.402,2.517</td>
<td>2.501, 2.549</td>
<td>2.386, 2.499</td>
</tr>
<tr>
<td>Adhesion (Visual)</td>
<td>%</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

4.6.1 Discussion Based on Mechanical Properties

Table (4.2) presents the data on specific gravity, hardness, Acetone Extraction, Loss of Ignition, Cold and Hot shear strength of the Friction composites developed with Low, Medium and high molecular weight resins. The chemical properties did not show any fixed trends. The hot and cold shear strength properties are mainly attributed either due to the preparation of the back plates or due to the formulation itself. Since the formulation is same for all the composites with the same type shot blasted back plates being used for all the composites, modification in the resin tended to improve the strength related properties of the composite.
4.7 EVALUATION OF FADE & RECOVERY PROPERTIES

4.7.1 Frictional Response of Friction Composites

Results of fade and recovery behavior of composites FCL, FCM and FCH are presented in the form of the plots in the figures (4.10-4.12).

Figure 4.10 Fade and recovery plot of FCL

Figure 4.11 Fade and recovery plot of FCM
Fade indicates the loss in braking effectiveness of a friction material at elevated temperature, typically in the range of 482-752 °F (Ming Zeng 2011). It has been reported that the fade behavior could be dominated by the decrease in the mechanical strength, thermal degradation of the organic matrix and the formation of load-carrying friction film causing an effective increase in the real contact area and consequently reduction in applied pressure on the friction material (Herring 2005).

In this investigation, the fade behavior is evaluated by the variation of COF with temperature during the Fade and the recovery stage of friction test. Figures 4.10-4.12 illustrates the variation of COF with temperature in the entire cycle i.e. Baseline, Fade and Recovery.

As seen from Fig 4.12 for FCL, the fade seems to decrease with the increase in temperature; a term called negative fade exists. During the II fade cycle the overall magnitude of $\mu$ dropped down marginally and remained almost same until 1112 °F. Beyond 1112 °F fade increased drastically and went to the lowest value which is marginally lesser than the O.E. standards. But dropping of $\mu$ was more prominent in the first recovery cycle. During the
second recovery cycle, there is not much appreciable gain in the friction value. In the first fade cycle, even though as the temperature at the pad surface is increased due to the combined effect of electric heater and the friction induced heat, a negative fade cycle was observed to an appreciable extent during 932°F. Several reasons are possible for this behavior. One of the reasons may be due to the flexible rubber components which have low thermal stability (Shojaei 2011) than the binder resin like NBR Rubber and Crumb rubber. Another main factor is due to the lower molecular weight of the resin. The thermal mobility of the low molecular weight is higher, resulting in the easier plastic deformation, which leads to a larger contact area and hence the friction value increases. Hence under moderate operating conditions the lower molecular weight chain enhanced the $\mu$ (Bijwe 2005).

The recovery characteristics of this resin are very poor. One of the reasons may be due to the poor hydrogen bonding as shown in the IR spectral studies.

As per FCM is concerned, the fade is noticeable after 968°F. The thermal mobility of the medium molecular weight chain is lesser than for the low molecular weight chain making it less flexible (Tanaka 1997). This reduces the real contact area. Further the possibility exists that sliding contact work hardened the metallic particles in the composite, which caused the worst abrasive wear, which compensated for the loss in $\mu$ due to fade in the first cycle. These possibilities have yet to be verified. The rubber particles in the composite helped to more effectively restore its higher friction behavior during recovery tests. Further, in the FT-IR tests it was clearly evident that there is an effective hydrogen bonding in the sample FCM, which also aids in the very good recovery of the friction composite.

As per the FCH is concerned, as shown in the fig 4.10, the second fade is more vigorous when compared to the other two resins. For mid-size passenger cars, in general, the required brake $\mu$ range from 0.35 – 0.4 Here at
1202°F, the $\mu$ value goes down up to 0.257 which is an unacceptable performance.

The reason may be due to its higher molecular weight. Higher the molecular weight, the higher is its rigidity and hence lesser the size of the contact area reducing its COF value (Yang 1997). Various friction $\mu$ obtained for the three composites are listed in the table 4.5.

**Table 4.5  SAE J 661a (or) equivalent Indian IS 2742 frictional response of the friction composites**

<table>
<thead>
<tr>
<th>Properties</th>
<th>FC L</th>
<th>FC M</th>
<th>FC H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot friction or Fade $\mu$</td>
<td>0.364</td>
<td>0.389</td>
<td>0.360</td>
</tr>
<tr>
<td>Normal or Recovery $\mu$</td>
<td>0.396</td>
<td>0.474</td>
<td>0.435</td>
</tr>
<tr>
<td>First Fade by Calculation (%)</td>
<td>-21.28</td>
<td>12.2</td>
<td>-9.00</td>
</tr>
<tr>
<td>First recovery by Calculation (%)</td>
<td>76.38</td>
<td>138.1</td>
<td>107.00%</td>
</tr>
<tr>
<td>Second Fade by Calculation (%)</td>
<td>16.95</td>
<td>21.4</td>
<td>33.76</td>
</tr>
<tr>
<td>Second Recovery by Calculation (%)</td>
<td>83.95</td>
<td>111.4</td>
<td>112.86</td>
</tr>
<tr>
<td>Max $\mu$</td>
<td>0.453</td>
<td>0.499</td>
<td>0.458</td>
</tr>
<tr>
<td>Min $\mu$</td>
<td>0.273</td>
<td>0.307</td>
<td>0.257</td>
</tr>
<tr>
<td>Wear loss by wt %</td>
<td>4</td>
<td>3.6</td>
<td>3.6</td>
</tr>
</tbody>
</table>

**4.7.2  Fade $\mu$ of the Brake Pads**

The magnitude of fade $\mu$ and % fade for all the composites was in the following order (Table 4.3)

- Fade $\mu$ : FC M (0.389) > FC L (0.364) > FC H (0.360)
- First % Fade : FC L (-21.28) < FC H (-9.0) < FC M (12.2)
- Second % Fade : FC L (16.95) < FC M (21.4) < FC H (33.76)
Modification in the molecular weight brought significant deterioration in fade resistance, especially for higher molecular weight resin. For lower molecular weight, however the trends were opposite. The fade % is acceptable for the FCM.

4.7.3 Recovery µ of the Composites

Overall order for Recovery µ is as follows (Table 4.3)

Recovery: FC M (0.474) > FC H (0.435) > FC L (0.396)

First % Recovery: FC M (138.1) > FC H (107.0) > FC L (76.38)

Second % Recovery: FC H (112.86) > FC M (111.4) > FC L (83.95)

In case of all the three composites, % recovery was more than 100 except for the FC L where it is very low. The % recovery for FCM and FCH are almost constant Overall FCM is best, followed by FCH resin composite.

4.8 WEAR OF THE COMPOSITES EVALUATED UNDER FADE-RECOVERY CONDITIONS

Wear (loss by weight %): FC L (4) > FC H (3.6) = FC M (3.6)

The changes in the molecular weight of the Alkyl Benzene modified phenolic resin did not reflect any noticeable changes in wear behavior.
4.9 SUMMARY

Based on the comparative studies (fade and recovery mode) of selected friction materials based on three different molecular weight resins, following conclusions was drawn.

Modification in the molecular weight of the Alkyl benzene modified Phenolic resin improved the shear strength, both the hot and cold.

Brake pads made of resin with lower molecular weight ($M_w = 2412$) showed excellent fade resistance. It has 20% greater fade resistance than pads made with medium molecular weight ($M_w = 4544$) and 50% greater than pads made with higher molecular weight ($M_w = 5223$) The reason being mobility of the low molecular weight resin is higher resulting in the easier plastic deformation, which leads to a larger contact area and hence the friction value increases. Hence, under moderate operating conditions ($344^\circ C$) the lower molecular weight chain enhanced the $\mu$. The recovery characteristics of pad with this resin are very poor. One of the reasons may be due to its degradation temperature ($328^\circ C$) well below the maximum temperature recorded ($344^\circ C$) before the start of the recovery cycle.

Brake pads made of resin with higher molecular weight ($M_w = 5223$) showed poorer fade resistance. But it has 25% greater recovery than pads made with lower molecular weight ($M_w = 2412$) and 1.2% greater recovery than pads made with medium molecular weight ($M_w = 4544$). The fade resistance is poorer as the mobility of the higher molecular weight resin is lower making the pad to be more rigid, which reduces the real area of contact and hence the friction value decreases. Brake pads made of resin with a molecular weight ($M_w = 4544$) showed the consistent friction level. However, no significant difference was noted in the wear pattern. Hence, Alkyl benzene modified phenolic resin with molecular weight ($M_w = 4544$)
was selected for further study. Having selected the resin, it become imperative to see its optimum loading level in the formulation which is carried out in the forthcoming chapter.