12-1-2016

IMPACT OF FRICTION TEST SCALE ON BRAKE FRICTION PERFORMANCE

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By

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B.E., Jawaharlal Nehru Technological University Hyderabad, 2014

A Thesis

Submitted in Partial Fulfillment of the Requirements for the

Master of Science Degree

Department of Mechanical Engineering and Energy Process

Graduate School

Southern Illinois University Carbondale

December 2016

THESIS APPROVAL

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Approved by:

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Southern Illinois University Carbondale

24th October 2016

AN ABSTRACT OF THE THESIS OF

ROHITH REDDA BOYNA, for the Master of Science degree in Mechanical Engineering and Energy Processes, presented on 10/24/16, at Southern Illinois University Carbondale.

TITLE: IMPACT OF FRICTION TEST SCALE ON BRAKE FRICTION PERFORMANCE

MAJOR PROFESSOR: Dr. Peter Filip

It is well known that the friction performance is a system property. The coefficient of friction and its stability, wear rate and the propensity to vibration and noise are always characteristics of a system and it is not easy to predict their performance based on smaller scale friction tests. This paper discusses the relation between performances of different-scale testers and possibility to model the friction performance of real systems in small simpler testers. It addressed the application of “scaling laws,” the application of typically adopted scaling strategies in friction industry and the testing strategies based on understanding of phenomena on the friction surface and in the friction systems. Full scale AKM standard dyno test and small tester (Bruker UMT) are related and the testing strategy is suggested. It is concluded that in spite of the fact that the scaling and simulations do not allow for a perfect prediction of performance (friction is a system property), it is still possible to make educated decisions on the research and development stage, when proper testing strategy on a smaller scale is adopted.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my mentor Dr. Peter Filip, for his guidance, mentoring, patience, and supporting me for doing research.

I would also like to thank Dr. Rasit Koc and Dr. Emmanuel Nsofor for their time of serving on the thesis committee, for their advice and comments on this research.

I would like to acknowledge Tim for helping me in setting up the machine with patience.

Also I would like to acknowledge my parents and brothers Raghu and Ravi for their support in my whole life and making me what I am.

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CHAPTER 1

INTRODUCTION

Friction phenomenon is observed in our everyday lives. It is the resisting motion between two bodies in motion. Friction and wear are system properties. In automotive industry, the study of friction is important. In braking system the concept of friction is observed in the brake pads. There are mainly two types of brakes in automotive industry namely disc and drum brakes. Drum brakes are initially used in which the friction between drum and brake shoe stops the vehicle. In disc brakes the friction between disc and the brake pad stops the vehicle. In many of the present automotive vehicles, disc brakes are used as the disc brakes dissipate the heat more efficiently. So the current study is on the disc brakes.

Disc brakes consists of a rotor and two brake pads. When brake pedal is pushed down by driver, the brake pads are pressed against the rotor. Due to the friction between the rotor and brake pads the vehicle speed is reduced. The kinetic energy of the vehicle is converted to the thermal energy. A better brake pad is the one which effectively stops the vehicle.

The material composition of the brake pads is an important factor which defines the effective breaking. The brake pads types depending upon the material used is classified mainly as Non-asbestos organic, metallic, semi-metallic and low metallic. Typically Non asbestos brake pads is made from organic materials such as fiber, glass rubber and kevlan. Metallic brakes contains more than 65% of metal mostly steel. Semi metallic brakes contains 30-65% of metal. Finally low steel contains less than 30% of steel.

Different types of brake pads are used in the current automobiles based on their requirement. Once a brake pad is manufactured testing is very important in determining the effectiveness of the brake. The testing consists of various on-field tests to laboratory tests such as dyno and other small scale tests. The main purpose of testing is to simulate the laboratory tests as close as possible to the on-vehicle conditions on which the brake pad works.

One of the main laboratory tests conducted by brake manufacturing companies is dynamometer. These consists of a rotor and a caliper holding the brake pads. Brake pads are pressed against the rotor through the hydraulic action simulating the on-vehicle braking system conditions. There are a different dyno testing standards employed by the companies. One of them is the SAE J 2522. The main purpose of SAE J2522 is to compare friction materials under the most equal conditions possible. Bruker has designed a Universal Mechanical Tester (UMT) which can test the brake pads in a much shorter time than dyno. Currently in industry when the tests are conducted in a smaller scale the strategy of maintaining energy and power constant area or time is adopted.

In the present project a comparison between the large scale dyno tests and small scale UMT tests is done. In contrary to the current adopted strategies, scaling laws are adopted to scale down the conditions used in dyno. Two types of samples Low Steel and Non-Asbestos Organic brake pads are used. Then the tests are conducted in dyno and UMT. The friction levels are observed in both tests and the results are interpreted by studying the friction material of the samples using Scanning Electron Microscopy SEM and Energy-dispersive X-ray spectroscopy EDX analysis.

CHAPTER 2

LITERATURE REVIEW

The selection of materials, machine components or coating depends on the screening tests performed. Screening tests are performed mainly during development of a material or machine component. The screening tests must simulate as close as the optimum operating conditions under which materials are used. The screening tests are mainly categorized as functional tests and accelerated tests. Functional tests are conducted in actual machines under the actual operating conditions. Accelerated tests are conducted by the simulation of the exact operating conditions. In development of a material, the samples are tested by accelerated tests and they are ranked and only 2 or 3 samples are selected. This decrease the time and reduces the cost of testing.

In addition this tests must simulate the conditions of the functional tests. For this purpose scaling laws are to be used in which the size, shape, forces and other parameters are simulated properly to match the functional tests. Then selected samples are tested by functional tests. The quantity to be measured to compare both functional tests are also important. This paper discusses various accelerated tests, scaling laws used.

There are numerous tests conducted on evaluating wear performance of brake pads in the laboratory. Laboratory wear methods are not designed to exactly reproduce the real working conditions of the analyzed part itself but serve to engineers and researcher to extrapolate the laboratory results to the real application. Blau [2] postulated that there is no laboratory wear test of vehicle brake materials that can simulate all aspects of a brake's operating environment. So the experiments are designed to simulate the wear results of the materials as close as possible to the operating conditions. In this project small scale laboratory tests are conducted and compared with the real testing field conditions.

Friction and wear properties are not intrinsic material characteristics, but strongly depend on the layout of a tribological system with specific contact geometry, normal load and sliding velocity [6]. Therefore, selection tests have to be performed experimentally for the determination of the friction and wear behavior. In conventional tribotesting, small-scale tests are mainly used because of their cost- and time-effectiveness and the ease of handling little samples. Some test geometries are standardized (ASTM G88, G99, G133). The selection of an appropriate test equipment is not exact. Test conditions can differ from the real application range, while extrapolations towards the real working conditions can hardly be made and often result in important errors. A scheme (Fig. 2) for scaling tribological research was provided by Czichos, going from field tests on original components towards laboratory testing on artificial samples with simple geometry [18]. For each of the test systems, it is assumed to provide the same amount of energy concentration and thermal input.

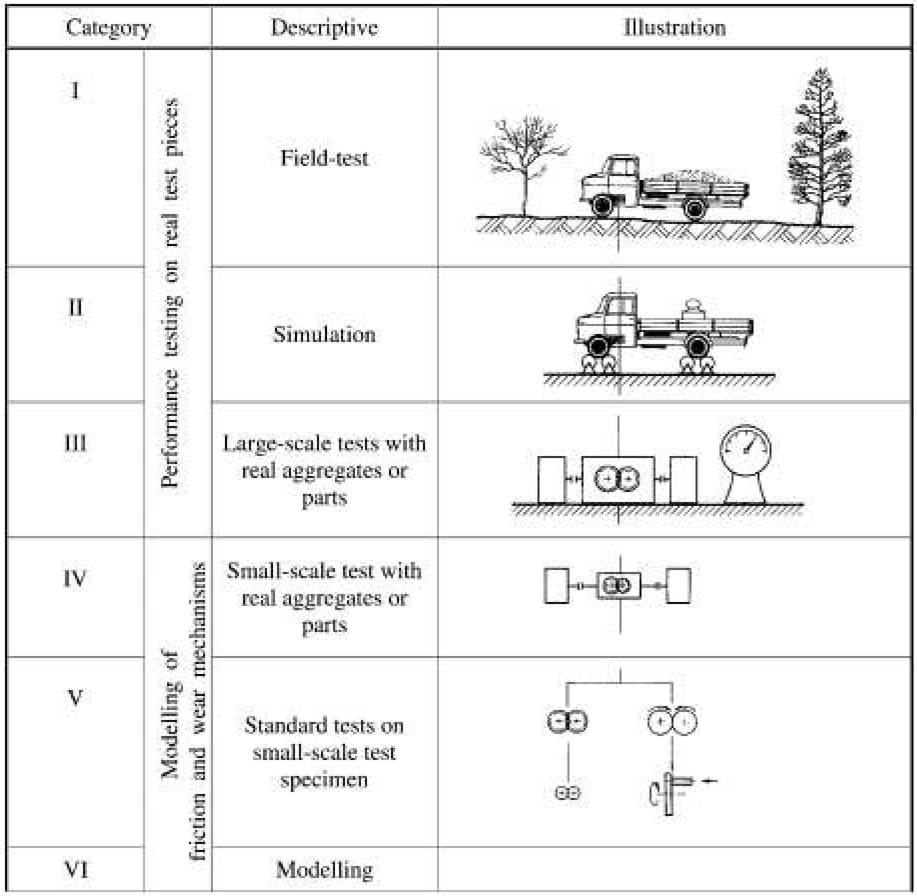


Fig.1 Possibilities for scaling tribotesting, as provided by czichos

The first comparison between wear tests was made in 1989 by A. W. Ruff. He compared three different wear test realized in the same conditions in different laboratories: block on ring, crossed cylinder on cylinder and pin on disk. He reached to the conclusion that this laboratory tests are not sufficiently well controlled in terms of certain critical factors that determine wear rates.

Ertan and Yavuz [17] conducted the friction test using chase type friction test with gray cast iron rotor to study the behavior of wear resistance and friction stability and tribological properties on the pad surface. Result showed that the manufacturing parameters of friction and wear tests play an important part and contribute to improve the tribological behavior of brake lining system.

L. Ferreiro (2010) made another comparison between different wear tests and arrived to a similar conclusion [12]. Some tests reproduce on a more accurate way the variation of hardness on the samples than other do. For that study the best results were obtained for the Pin on Disk and the Wet Sand and Rubber Wheel tests. The comparison between large scale dynamometer and small scale chase machine is also done earlier. These experiments were conducted without using the scaling methodology. Then scaling methodology was used in evaluating the thermal performance of a disc brake at a reduced scale by A. Abdulwahab, A. Barton, C. David, Brooks, C. Peter [13]. In the present project scaling methodology will be considered to evaluate the wear performance at small scale and large scale levels.

Talib Ria Jaafar1, Mohmad Soib Selamat1 and Ramlan Kasiran compared the brake dynamometer tests done by AKM Masters standard, On-road test and chase dyno tests and concluded that the test sequence and parameters of brake dynamometer cannot simulate exactly all the braking parameters and environment of on-road test condition and there is no simple correlation between the brake dynamometer test results with on-road performance results. The final selection of the best formulation is based on on-road performance test results [19].

Blau postulated that there is no laboratory wear test of vehicle brake materials can simulate all aspects of a brake's operating environment (Blau, 2001). Vehicle testing on the test track is the ultimate judge for overall brake performance testing and evaluation.

The two main types of tests used to evaluate the performance under different loading, speed, temperature and pedal force are, namely, inertia-dynamometer and vehicle-level testing. Inertia-dynamometer test procedures or vehicle testing simulation is used as a cost effective method to evaluate brake performance in a laboratory-controlled environment. The automotive industry uses inertia-dynamometer testing for screening, development and regular audit testing.

In the present project a comparison between the brake dynamometer and Universal Mechanical tester is done. Inertia dynamometer is used to evaluate a full size brake lining material or brake system by simulating vehicles braking process but it is time consuming and more expensive. These brake dynamometers has been used to tests friction materials for quality control, lining development and friction materials property assessments in a lab scale rather than having a series of vehicle tests on a test track or road (Sander, 2001). On a smaller scale, UMT features low capital expenditure and shorter test time. UMT uses a small sample of friction material with a size of 10 mm diameter and 7 mm thickness.

2.1 Reasons for performing the Screening tests.

The screening tests to be performed depend on various objectives in the tribological system. The reason to perform varies from one system to another. Main purposes of the screening [3] tests are

1. Characterization of wear and friction properties of materials
2. Studies of friction and wear mechanisms in selected tribological applications.
3. Ranking of materials
4. Selection of new material

2.2 Small scale tests

Small scale tests are employed to reduce the time of testing, cost and can be effectively used to predict the behavior of the large scale tests. Some of the standardized small scale tests according to ASTM standar

1. Pin on disc (ASTM G99)
2. Pin on flat (ASTM G132-96)
3. Block on ring (ASTM G77)
4. Thrust washer (ASTM D3702)
5. Crossed cylinders (ASTM G83)
6. Four ball test (ASTM D2266)

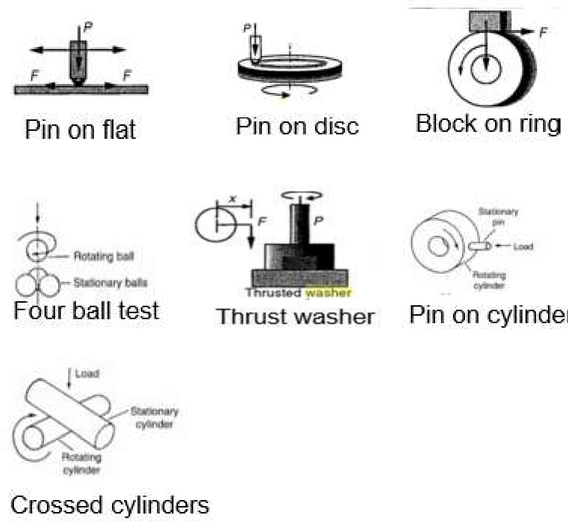


Fig.2 Common types of small scale tests

Chase and Fast are typically used small scale tests in industry now, these are slight modifications of the above mentioned standards.

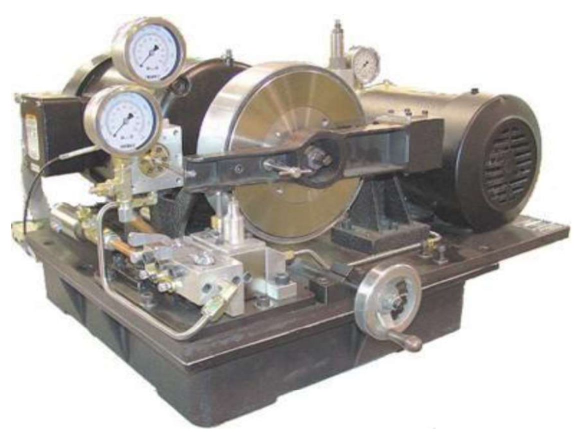


Fig.3 Chase machine

Fig.4 F.A.S.T tester

2.3 Scaling of parameters.

In addition to the above accelerated tests, scaling of various parameters essential in determining size in small scale tests and large scale tests will be taken care. Some of the scaling laws which are essential include the following.

2.3.1 Scaling of Area and Volume

The general rule is called "square law":

$$(\text{ratio of areas}) = (\text{ratio of lengths})^2$$

$$(\text{ratio of volumes}) = (\text{ratio of lengths})^3$$

This two expressions can be expressed in one big equation as [7]

$$(\text{ratio of volumes})^{(1/3)} = (\text{ratio of areas})^{(1/2)} = (\text{ratio of lengths})^1$$

2.3.2 Scaling of mass

Mass is directly proportional to the volume of a body. So whenever we consider scaling of mass, it is similar to scaling of volume.

$$M \propto l^3$$

2.3.3 Scaling of force

Solving dynamical problems involves various types of forces. The most common types of forces and their scaling are tabulated below and following Fig.8 shows the nature of some common types of forces [5].

Table1. Scaling of some common forces

Force	Scaling
Surface tension	l^1
Fluid force/electrostatic force	l^2
Weight/Inertia force/ Electromagnetic	l^3
Electromagnetic force (constant current density)	l^4

where l is the scaling factor.

William Trimmer in 1989 defined a force scaling vector, F as. This column matrix, called the "force scaling vector F" is defined as follows

$$F = l^F = \begin{bmatrix} l^1 \\ l^2 \\ l^3 \\ l^4 \end{bmatrix}$$

2.3.4 Scaling of Acceleration

From the second law of motion, $F = ma$, with m as mass and a as acceleration. So, $a = F/m$ and its scaling for different types of force can be expressed in a compact form as follows:

$$[a] = [l^F] \times [l^3]^{-1} = \begin{bmatrix} l^1 \\ l^2 \\ l^3 \\ l^4 \end{bmatrix} \times [l^{-3}] = \begin{bmatrix} l^{-2} \\ l^{-1} \\ l^0 \\ l^1 \end{bmatrix}$$

2.3.5 Scaling of Time

We have the equation for displacement as

$$s = (1/2)a.t^2$$

where a= acceleration,

s= displacement and

t= time

From that we get $t=(2s/a)^{1/2} = (2sm/F)^{1/2}$

From substituting the scaling of mass and force in the above equation, we get the scaling of time [5] expressed in scalar form as follows.

$$[t] = [s]^{1/2}[m]^{1/2}[F]^{-1/2} = [l^1]^{1/2}\,[l^3]^{1/2}\begin{bmatrix} l^1 \\ l^2 \\ l^3 \\ l^4 \end{bmatrix}^{-1/2} = \begin{bmatrix} l^{1.5} \\ l^1 \\ l^{0.5} \\ l^0 \end{bmatrix}$$

2.3.6 Some important scaling laws

Basic Scaling parameters with their scaling factor are given in the Table.2 [5]. These can be used as reference in determining scaling laws for complex parameters. If the parameter/quantity be *P* then scaling will be $[P] = [l^n]$ where *l* is the scaling factor.

Table.2 scaling in different parameters

Physical Quantity	Scaling exponent (n)
Bending stiffness	1
Mass	3
Mass moment of inertia	5
Second moment of area	4
Strength	2
Shear stiffness	1
Inertia force	3,4
Kinetic energy	4
Potential energy	4
Elastic potential energy	2
Surface tension, van der Walls force	1
Strength to weight ratio	1

In the current project, Universal Mechanical Tester will be considered as small scale test and the brake dynamometer as large scale test. Then using the scaling laws presented parameters like force on brake pad, load acting, size and shape of sample, speed of rotation of disc are determined for Universal Mechanical tester using the brake dyno procedure conditions. Then a comparison is done between both the tests.

In this project, scaling laws are used instead of the commonly used comparison methods for small scale and large scale tests in industry such as Energy/unit mass(E/*m*), Energy/unit area(E/A), Energy/unit mass and time(E/*m*.t) or Energy/ unit area and unit time(E/A.t).

CHAPTER 3

STATEMENT OF OBJECTIVES

1. Wear and friction mechanism will be compared between both the tests. The results may show that wear and friction mechanism will be close between the two tests.
2. To study the effect of scaling methodology instead of the typically used four practices. Then from the results by using these scaling conditions one can use the small scale tests more effectively in future, which is inexpensive and fast when compared to the large scale tests.

CHAPTER 4

Experimental methods

4.1 Dyno Test

Tests are conducted according to the SAE J2522 standard - series of tests conducted at different pressures, speeds and temperatures including Mu green, Bedding, Fade, Pressure series and Characteristic value tests. Inertia Dynamometer Test procedure assesses the effectiveness of a friction material for motor vehicles fitted with hydraulic brake actuation

(a) (b) (c)

Fig.5 Dynamometer (a) caliper and disc, (b) inertia and (c) brake dynamometer

The ITT Company provided the standard AKM masters testing results conducted for the vehicle 2015 Audi Q7 brake pad at different conditions.

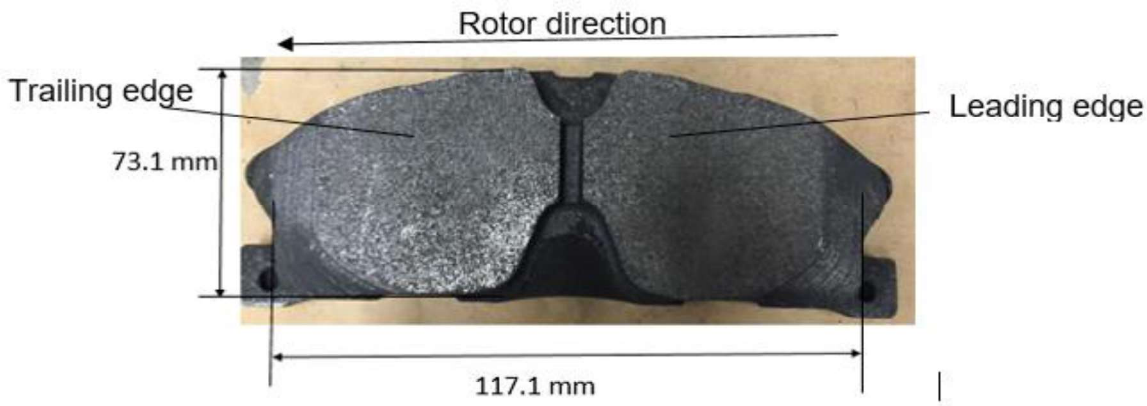


Fig.6 Brake pad trailing and leading edge

The standard AKM procedure has the following tests. The number of stops for each test, initialvelocity, final velocity and pressure in each stop is presented in the table.

Table.3 AK Masters procedure

S.No	Test	Stops	Initial Velocity	Final Velocity	Pressure
1	mu green	30	80	30	30
2	Bedding	64	80	30	Varying pressure
3	Characteristic value	6	80	30	30
4.1	Pressure series	8	40	5	10,20,30,40,50,60,70 and 80
4.2	Pressure series	8	80	40	10,20,30,40,50,60,70 and 80
4.3	Pressure series	8	120	80	10,20,30,40,50,60,70 and 80
4.4	Pressure series	8	160	130	10,20,30,40,50,60,70 and 80
4.5	Pressure series	8	200	170	10,20,30,40,50,60,70 and 80
5	Characteristic value	6	80	30	30
6	Cold	1	40	5	30
7	Motorway	2	100	196	
8	Characteristic value	18	80	30	30
9	Fade 1(a=0.4g)	15	100	5	Varying pressure
10	Characteristic value	18	80	30	30
11	Pressure series	8	80	30	10,20,30,40,50,60,70 and 80
12.1	Temp increase	5	80	30	30
12.2	Pressure 600 C	8	80	30	10,20,30,40,50,60,70 and 80
13	Characteristic value	18	80	30	30
14	Fade 2(a=0.4g)	15	100	5	Varying pressure
15	Characteristic value	18	80	30	30

The scaling of the parameters such as force, load and time will be done based on the sample size. A scaling factor is determined.

4.2 Universal Mechanical Tester

The Tester has a universal base that can be equipped with a range of drive modules simulating rotational, linear, or oscillating motions and an upper carriage that can be fitted with force and torque measuring sensors that allow for nearly every possible tribology and mechanical test to be performed on this single system. Various common tribology test modes are available, including:

1. Pin on Disc/Plate
2. Ball on Disc/Plate
3. 4-Ball Testing
4. Pin on V-block
5. Block on Ring
6. Disc on Disc (flat on flat)
7. Screw in Nut
8. Tension/Compression
9. Scratch testing

The rotary disk used in the pin on disk is made of cast iron as most of the convectional rotors used are made of cast iron. Force acting on the sample, speed of rotation can be controlled.

Fig.7 Bruker's Universal Mechanical Tester

Samples are cut from the brake pad used in dyno has the size with diameter of 11 mm and thickness of 7 mm and tested in the UMT Tribolab "small-scale tester" manufactured by Bruker. 3 samples are cut from the trailing edge of the brake pad and 3 samples are cut from the leading edge.

Fig.8 Circular samples

4.3 UMT with Temperature chamber

Then a temperature control chamber was installed in the Universal Mechanical Tester. It has range from 0 to 400^{0}C and a resolution of 0.1^{0}c

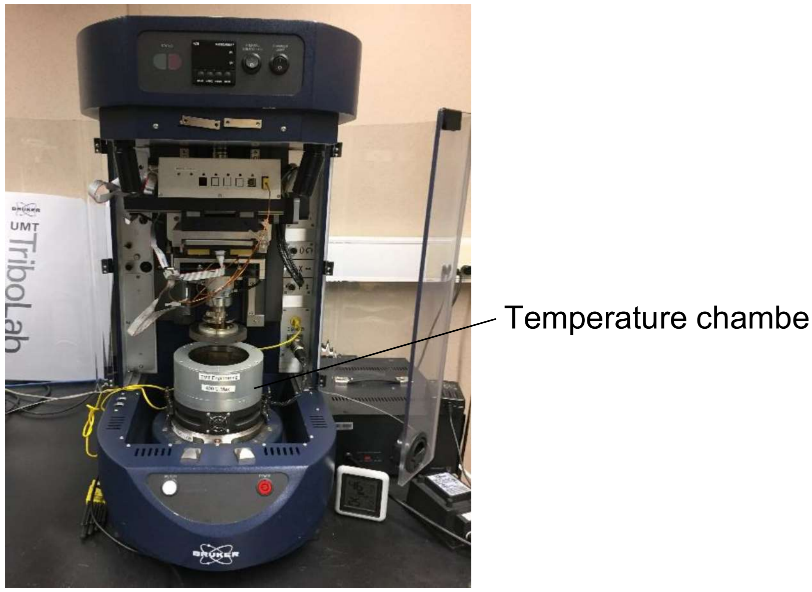
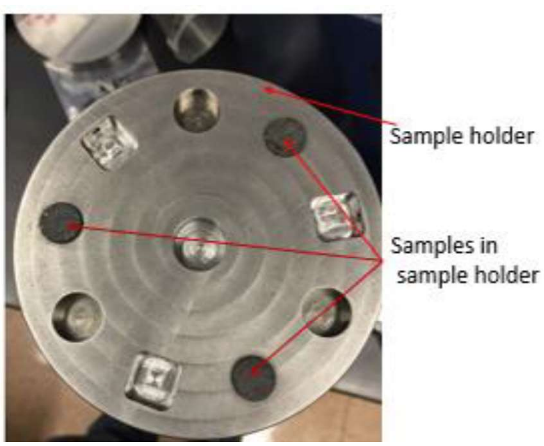


Fig.9 UMT with temperature chamber

4.4 Sample preparation

Brake pads are first tested in Dyno. Then the samples are cut from the brake pads in the size of 11mm diameter and about 7 mm thickness. Then the samples are placed in the sample holder of UMT.



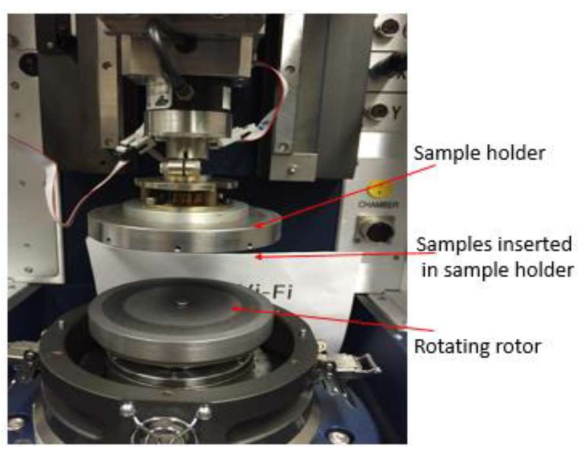


Fig.10 Sample holder

Fig.11 UMT samples and rotor

4.5 Testing conditions

Pearlitic Grey Cast Iron rotor surface is prepared by grinding using a 300 grit sandpaper (Leco metallographic supplies). Three circular brake pad samples of diameter d = 11 mm, thickness t = 6mm, apparent contact area $A = 3 \times PI \times d^2/4 = 235.5\ mm^2$. Distance between the center of rotation and center of circular samples which is considered to be the effective braking radius r = 38 mm) held in the sample holder (diameter D =102 mm, thickness T = 12 mm) are pressed against the rotor with a normal load. Relative humidity is kept constant (at 46%). The two types of samples used are Low Steel and Non-Asbestos Organic.

4.6 UMT Tests

The procedure for testing is adopted from the AK Master's procedure tested in dyno. The conditions are scaled down for UMT tests from dyno using the scaling laws.

The tests conducted are mu green, bedding, fade, pressure series and characteristic value. The conditions in UMT tests are as follows.

Table.4 UMT testing procedure

	Stops	Initial Velocity	Final Velocity	Pressure
Mu green	30	33	12	4.43
Bedding	64	33	12	different constant pressure
Fade	15	42	2	varying
Pressure series	8	33	12	1.5,2.9,4.4,5.9,7.3,8.8,10.3,11.8
Characteristic value	18	33	12	4.43

The tests are conducted at different deceleration time in sec adjusted using the UMT script software.

4.7 Script:

The script has five steps:

1. All the force sensors are zeroed.

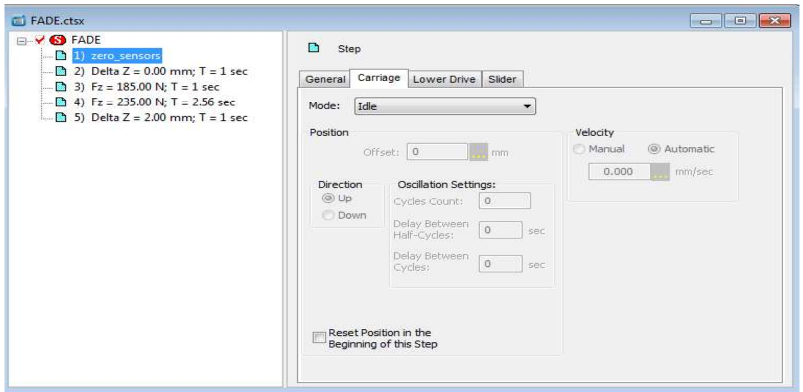


Fig.12 Step 1 in UMT test

2. The rotor achieves a required initial speed for the test.

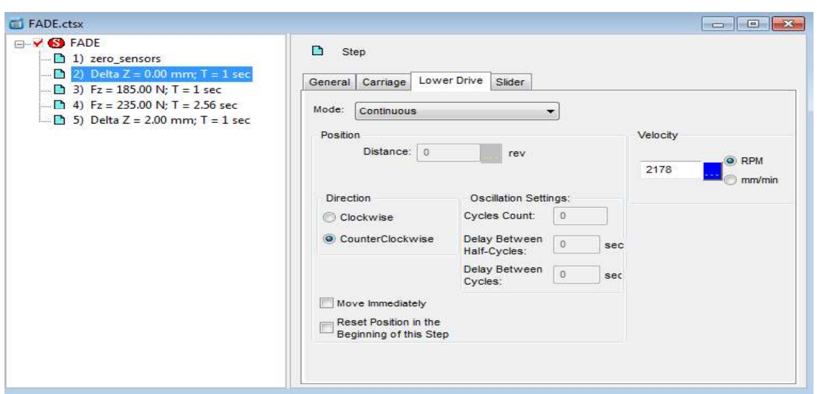


Fig.13 Step 2 in UMT test

3. Then the upper carriage is lowered applying the desired normal load by pressing the samples on rotor.

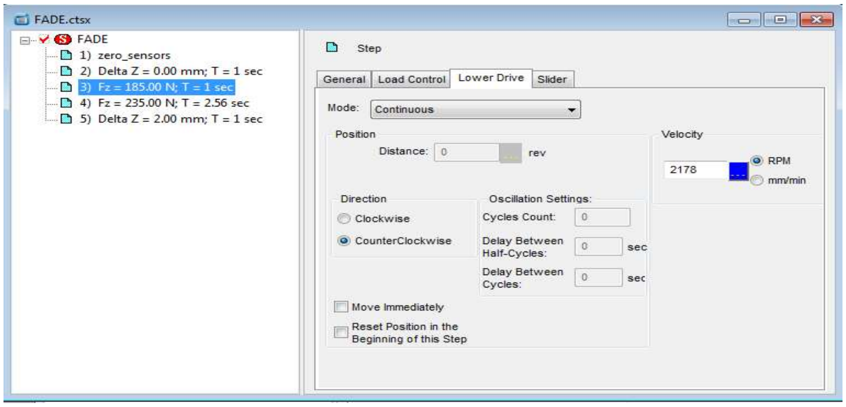


Fig.14 Step 3 in UMT test

4. Then the rotor decelerates to obtain the final velocity in the given deceleration time at the given load (load is constant for mu green, bedding and pressure tests. Varies in the fade tests and reaches the final load in the deceleration time.

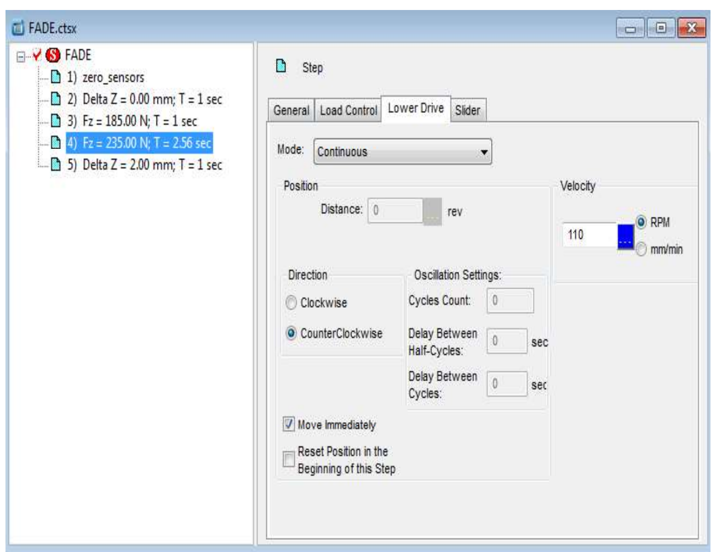


Fig.15 Step 4 in UMT test

5. The carriage moves up releasing the load and rotor reaches the idle state.

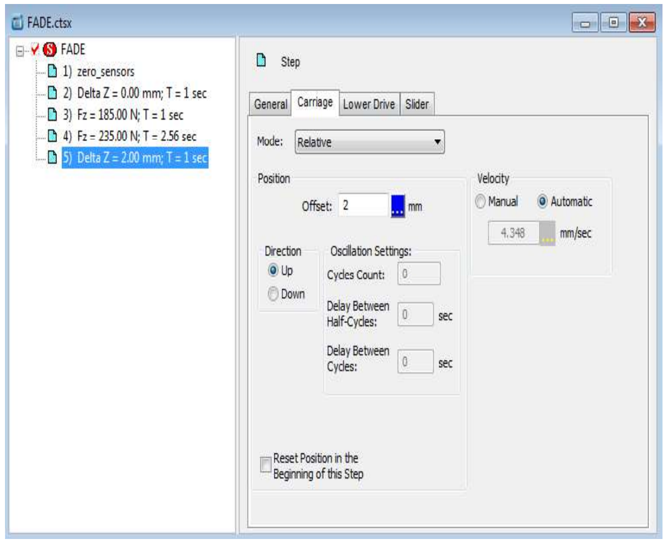


Fig.16 Step 5 in UMT test

4.8 Data collection

Data is collected and graphs are drawn using the data collected between the time the rotor starts decelerating from initial speed and reaches the final speed

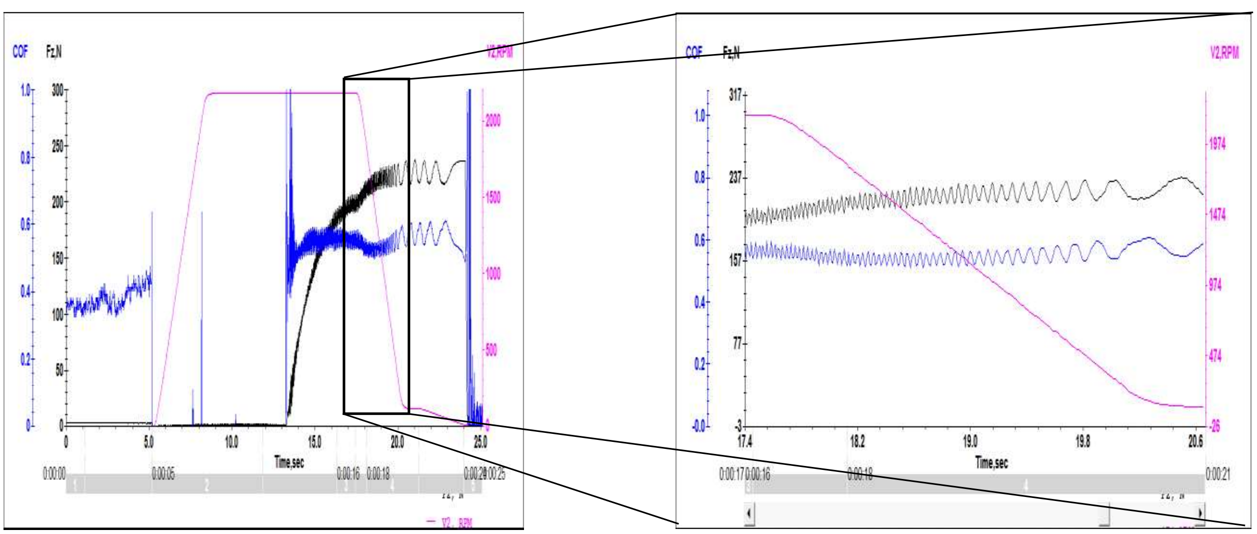


Fig. 17 Data collection from UMT test viewer

4.9 Scanning Electron Microscopy (SEM)

A scanning electron microscope (SEM) scans a focused electron beam over a surface to create an image. The electrons in the beam interact with the sample, producing various signals that can be used to obtain information about the surface topography and composition.

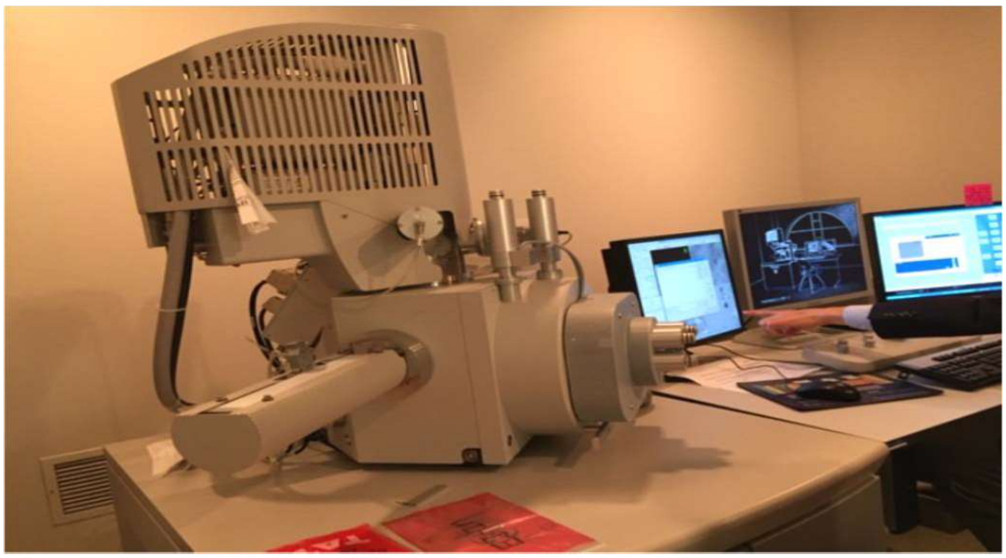


Fig.18 Scanning Electron Microscope

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Scaling calculations

Sample scaling calculations are done for one of the process in the dyno test (mu green). A scaling factor is obtained by comparing the contact area of the samples used in dyno and Universal Mechanical Tester (UMT) and the forces and velocities in dyno are scaled down to be used in the UMT test.

5.1.1 Dyno Calculations

From test procedure

- Dynamic Rolling radius (R)= 321 mm
- Effective radius (r) = 129 mm
- Disc 314x25 mm
- Inertia 87.3 kgm²
- Dimensions of the brake pad tested in Dyno are 117 x 73.1 mm
- Area A_1 of brake pad =6512 mm^2
- Area of 2 samples = 13204 mm^2
- Pressure = 30 bar = 3 n/mm^2

Forces acting

- Force = Pressure *area = 3* 6512 = 19536 N
- Force acting on the system (2 samples) (F_1) = 39072 N

Velocities

- Initial velocity (u_1) = 80 km/hr = 22.2 meters/sec

- Final velocity (v_1) = 30 km/hr = 8.33 meters/sec

Using the dynamic rolling radius(R= 321 mm) of the disc, the angular velocities are calculated

- Initial angular velocity $\omega_{1i} = u_1/R$ = 22.2/0.321= 69.51 rad/sec= 661.07 RPM
- Final angular velocity = $\omega_{1f} = v_1 / R$= 8.33/0.321 = 25.95 rad/sec= 247.90 RPM

We have Equation of motion v= u + at

- Deceleration (a_1) = 2.22 m/sec^2

  8.33= 22.2-2.22*t

  2.22*t= 22.2-8.33 = 13.87

  t_1 = 13.87/2.22 = 6.24 sec

5.1.2 Scaling calculations for UMT

The scaling factor "*l*" was used to establish the conditions for the UMT tests, based on the factors in the dyno test. For obtaining scaling factor, area of the two tests are compared.

A_1 = Area of the real brake pad in dyno = 6512 mm^2

A_2 = Area of sample in UMT = 95.03 mm^2

There are 2 brake pads in the dyno tests and 3 samples in the UMT test, hence

$2A_1/3A_2= l^2$

13204/285.09 = 45.68 = l^2

Scaling factor l = 6.75

The scaling factor obtained was used to calculate the conditions to be simulated in UMT.

5.1.3 Mu green Calculations:

It is one series of tests performed in dyno using AKM standards. The tests are performed at the following conditions

Pressure = 30 bar,

Initial Velocity = 80 km/hr

Final Velocity = 30 km/hr.

And at different deceleration speed.

Scaling Calculation example:

- Force in dyno F_1= 39072
- Force in UMT to be determined = F_2

For determining F_2 we use the scaling factor of force F= l^3

$$\frac{F1}{F2} = l^3$$

- $F_2 = \frac{\mathrm{F1}}{l^3} = \frac{39072}{6.75^3} = 127.04$

Similarly all the conditions are calculated for the UMT test

Table.5 scaling of the parameters for mu green

Parameters	Dyno	Scaling factor for parameter	UMT
Force(N)	39072	l^3 = 307.54	127.04
Initial velocity (meters/sec)	22.2	$l^{0.5}$=2.59	8.57
Final velocity (meters/sec)	8.33	$l^{0.5}$=2.59	3.21
Initial angular velocity (rpm)	661.07	$l^{-0.5}$= 0.38	1739.6
Final angular velocity (rpm)	247.90	$l^{-0.5}$= 0.38	652.36
Energy(J)	421802	l^4=2075	203.27
Time (sec)	6.24	$l^{0.5}$= 2.59	2.40

Similarly the conditions are calculated for all the tests and the tests are performed.

One could use the other parameters for comparison. Some of them are the mass, time, deceleration time.

5.1.4 Mass scaling

For example the sample used in brake pad in UMT is 1.45 g

Brake pad of dyno mass is 440 g

Using the scaling law, $2m_1/3m_2= l^3$

$880/4.35 = l^3$

Scaling factor $l= 5.87$

Then using the scaling factor the other parameters can be calculated as followed for the same table as follows

Table.6 mass scaling of the parameters for mu green

Parameters	Dyno	Scaling factor for parameter	UMT
Force(N)	39072	$l^3 = 202.29$	193
Initial velocity (meters/sec)	22.2	$l^{0.5}=2.42$	9.17
Final velocity (meters/sec)	8.33	$l^{0.5}=2.42$	3.44
Initial angular velocity (rpm)	661.07	$l^{-0.5}= 0.41$	1612
Final angular velocity (rpm)	247.90	$l^{-0.5}= 0.41$	602.4
Energy(J)	421802	$l^4=1187.2$	335.2
Time (sec)	6.24	$l^{0.5}= 2.42$	2.57

But if mass is considered to be scaled between dyno and UMT, the mass of the brake pad cannot be exactly considered as the brake pad has a backing plate and the exact effect of the mass on the braking application cannot be determined. In future work the mass scaling can be used effectively by using the proper strategies such as force, speed, time scaling

5.1.5 Time scaling

The time to be used in UMT is not predetermined. Suppose if UMT testing time is to be reduced by one-third time as in dyno. The scaling calculations for the same mu green tests as presented above are as follows.

Time in dyno test = 6.24

UMT time= 2.08

For obtaining scaling factor,

$T_1/T_2 = l^{0.5}$

Scaling factor = 9

Table.7 Time scaling of the parameters for mu green

Parameters	Dyno	Scaling factor for parameter	UMT
Force(N)	39072	$l^3 = 729$	53
Initial velocity (meters/sec)	22.2	$l^{0.5}=3$	7.4
Final velocity (meters/sec)	8.33	$l^{0.5}=3$	2.77
Initial angular velocity (rpm)	661.07	$l^{-0.5}= 0.33$	2003
Final angular velocity (rpm)	247.90	$l^{-0.5}= 0.33$	748
Energy(J)	421802	$l^4=6561$	64.28

But one cannot take an imaginary one-third time scaling as that may give a different effect on the results.

In the current work, apparent area is used for comparing two scale tests, but in future works other parameters such as mass and time can be used for scaling between two tests adopting effective strategies.

5.2 Dyno and UMT comparison

The comparison is made for the some test sections of Dyno and UMT. The tests are mu green, bedding, fade, pressure series and the characteristic value. In the graphs the black circles indicates the average COF value of the individual test.

5.2.1 Mu green

Low Steel

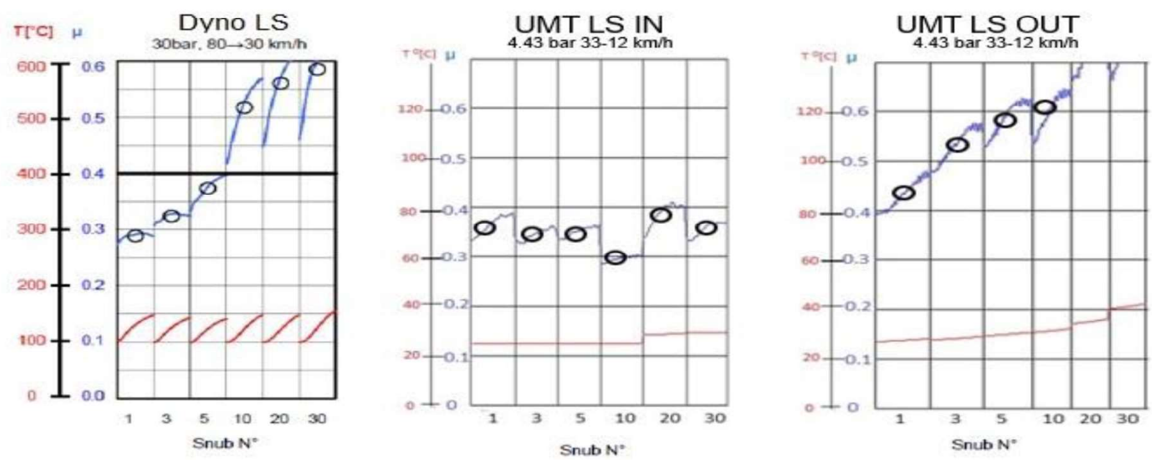


Fig.19 LS mu green dyno vs UMT

NAO

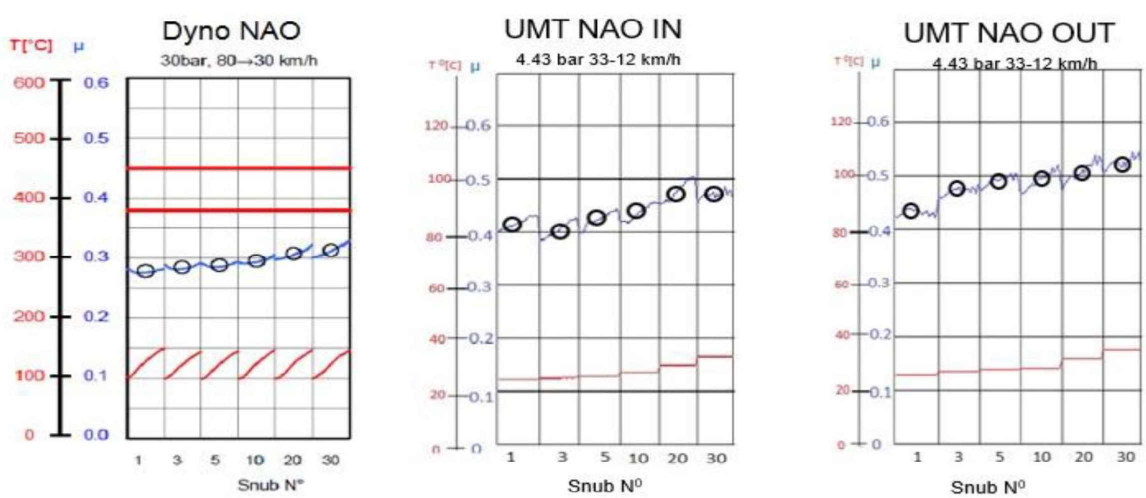


Fig.20 NAO mu green dyno vs UMT

5.2.2 BEDDING

LOW STEEL

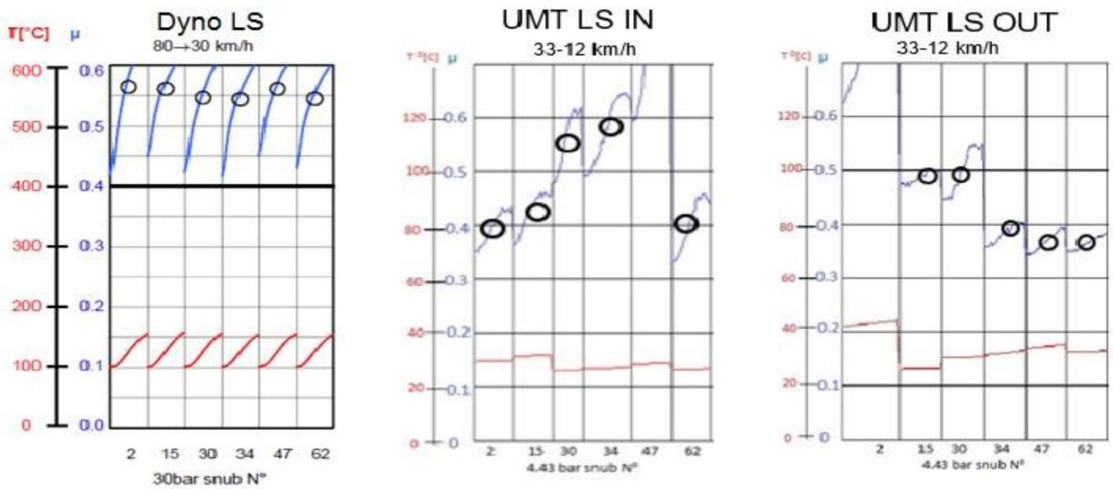


Fig.21 LS Bedding dyno vs UMT

NAO

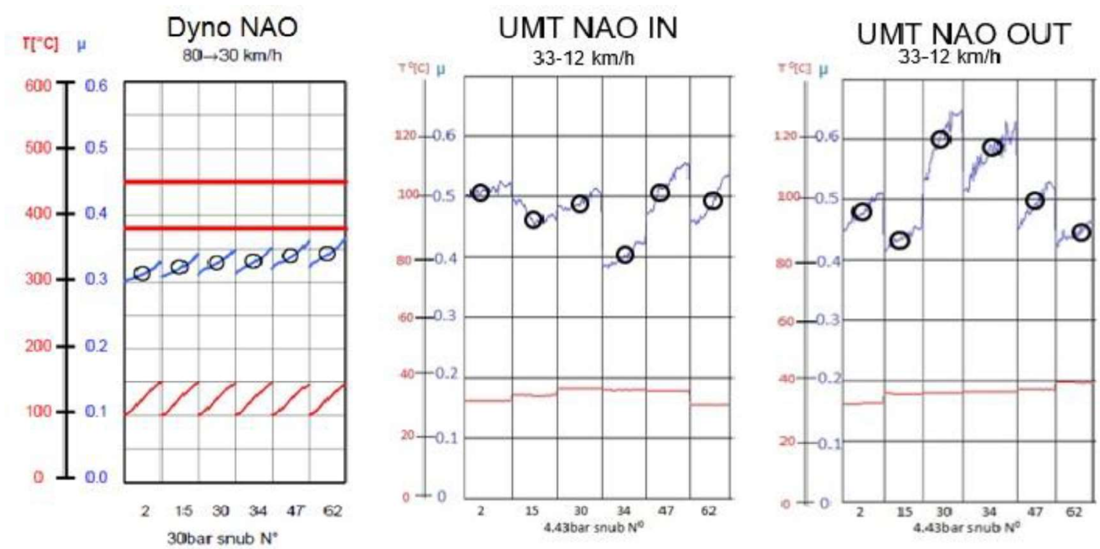


Fig.22 NAO Bedding dyno vs UMT

5.2.3 FADE

LOW STEEL

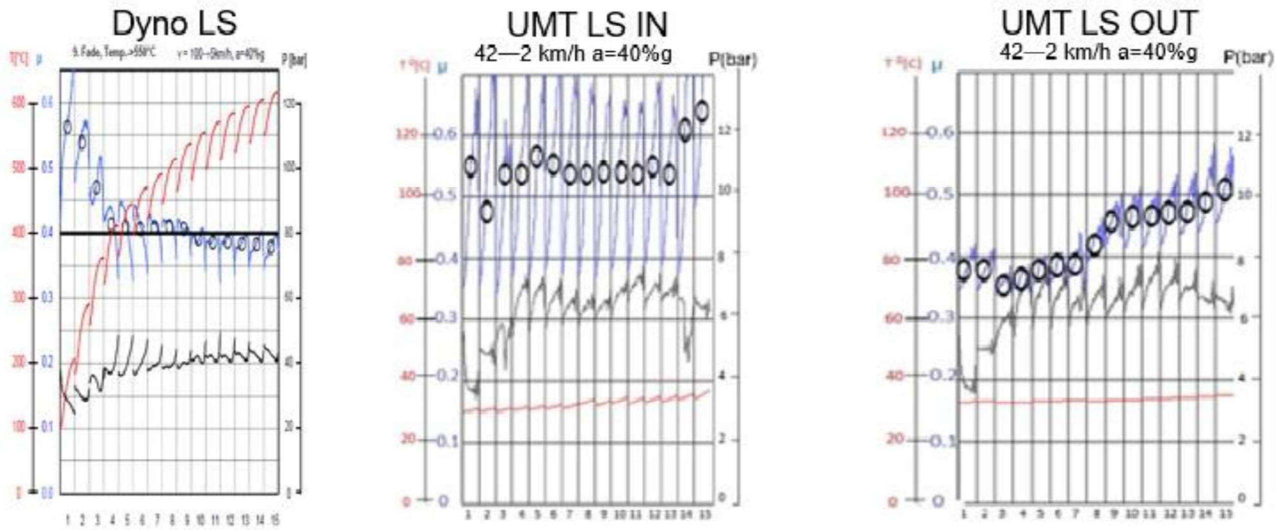


Fig.23 LS fade dyno vs UMT

NAO

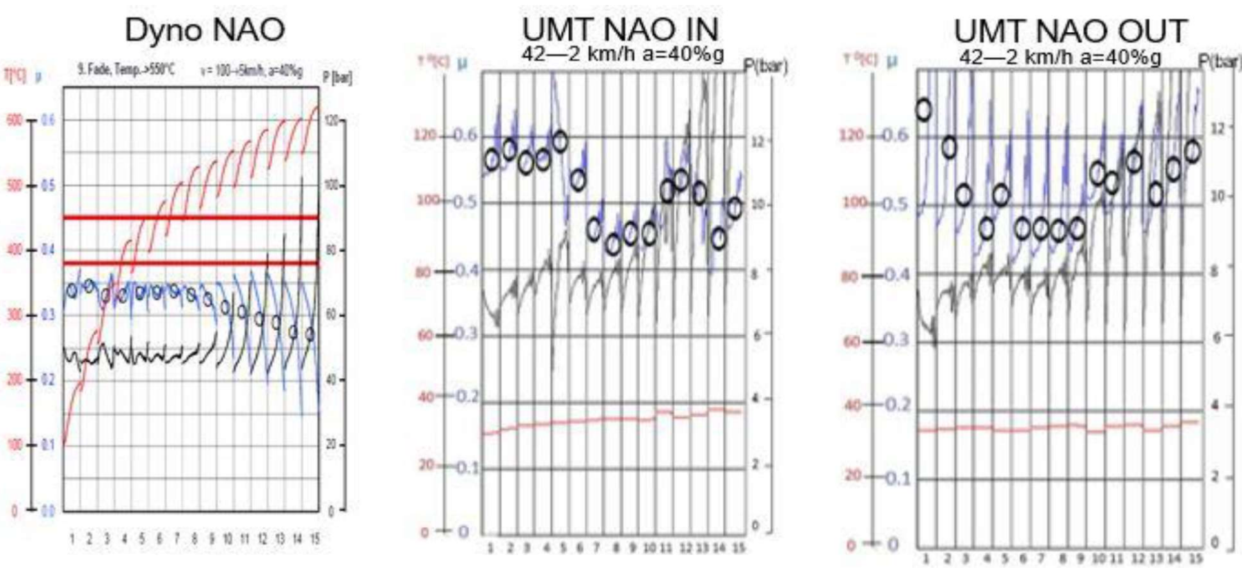


Fig.24 NAO fade dyno vs UMT

5.2.4 PRESSURE SERIES

LOW STEEL

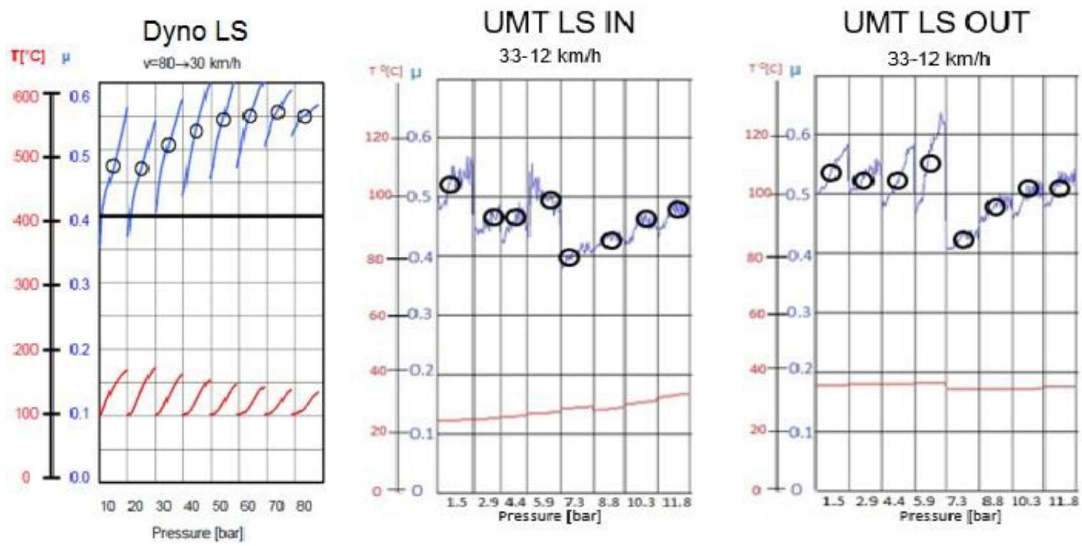


Fig.25 LS Pressure series dyno vs UMT

NAO

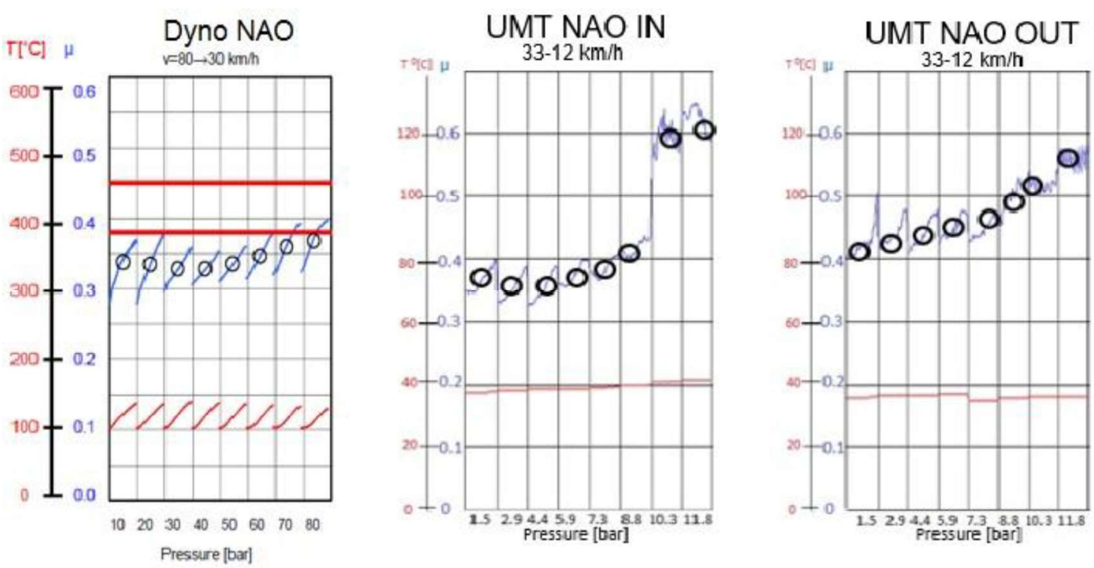


Fig.26 NAO Pressure series dyno vs UMT

5.2.5 CHARACTERISTIC VALUE

Low Steel

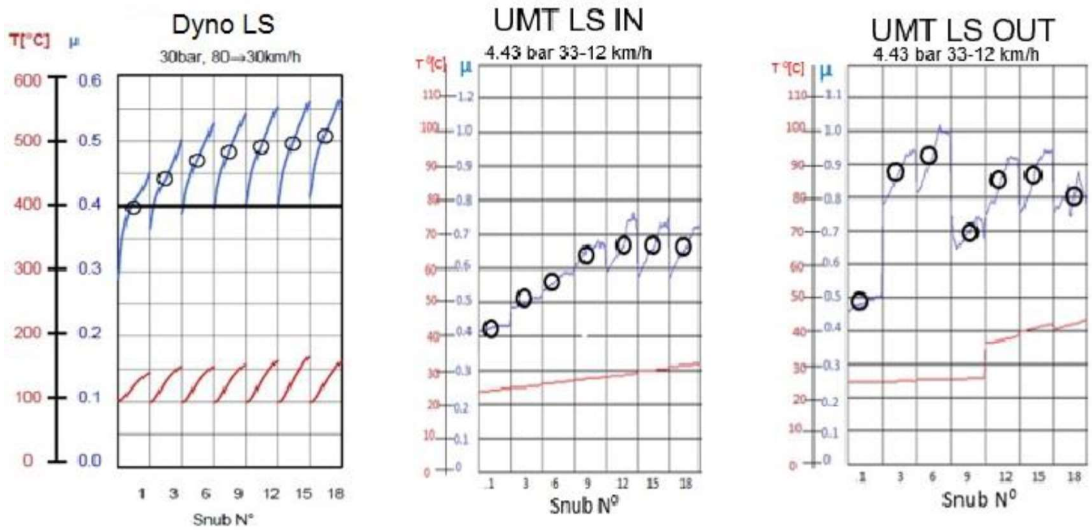


Fig.27 LS Characteristic value dyno vs UMT

NAO

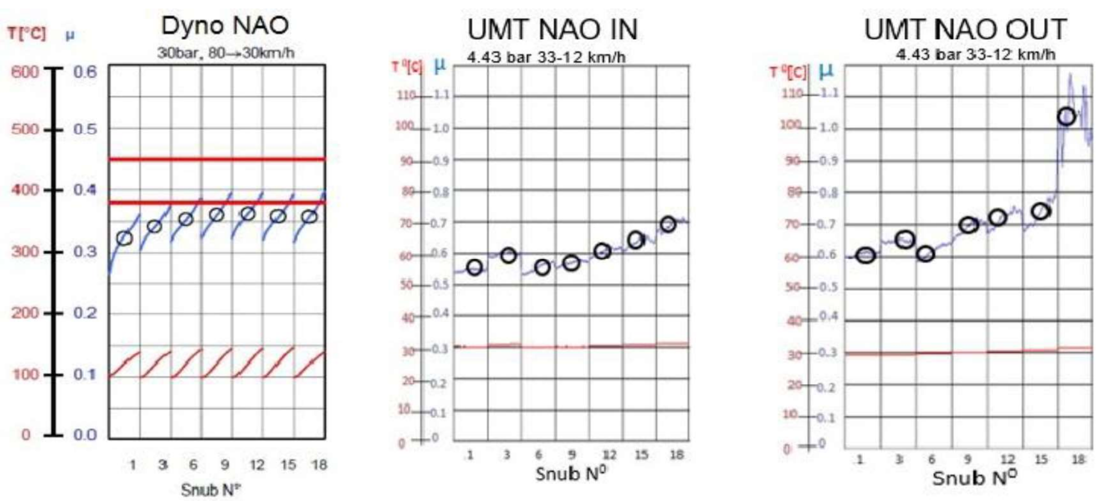


Fig.28 NAO Characteristic value dyno vs UMT

5.3 Average COF graphs

For each individual stops the average COF values are calculated and indicated in the above plots with the black circles. Then the averages of the COF of all the individual stops for each section of tests are calculated for dyno, UMT IN and UMT OUT tests. Then they are tabulated as in the following sections. The averages and standard deviations for all the tests are also calculated and compared.

Low Steel

The graphs below shows the average COF for each tests of Low Steel samples

Table.8 LS average COF

S. No.	Tests	LS DYNO	LS UMT IN	LS UMT OUT
1	Mu green	0.44	0.35	0.59
2	Bedding	0.56	0.52	0.48
3	Fade	0.42	0.54	0.42
4	Pressure	0.52	0.46	0.51
5	Char value	0.47	0.6	0.79
	average	0.482	0.494	0.558
	Std. dev	0.057619	0.094763	0.143422

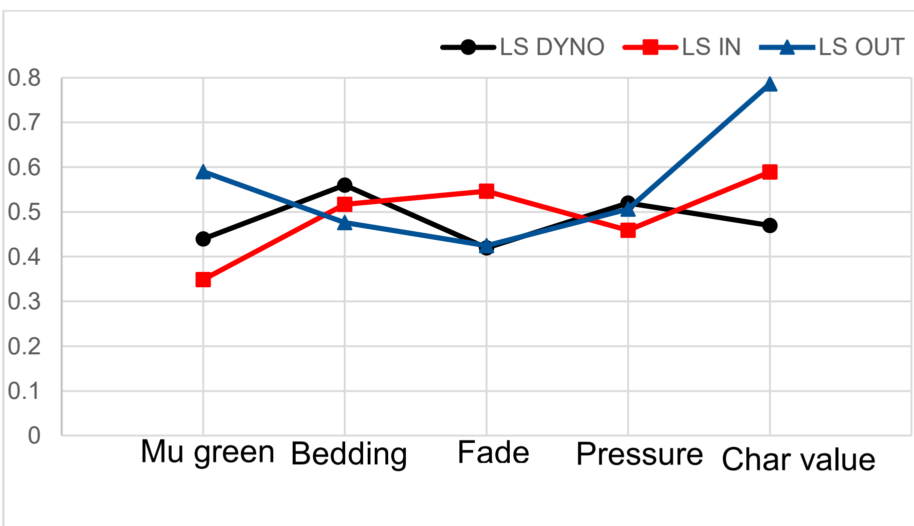


Fig.29 LS average COF

NAO

The graphs below shows the average COF for each tests of NAO samples

Table.9 NAO average COF

S. No.	Tests	NAO DYNO	NAO UMT IN	NAO UMT OUT
1	Mu green	0.29	0.44	0.49
2	Bedding	0.33	0.48	0.5
3	Fade	0.32	0.52	0.53
4	Pressure	0.34	0.44	0.47
5	Char value	0.35	0.6	0.72
	average	0.326	0.496	0.542
	Std. dev	0.023022	0.066933	0.101833

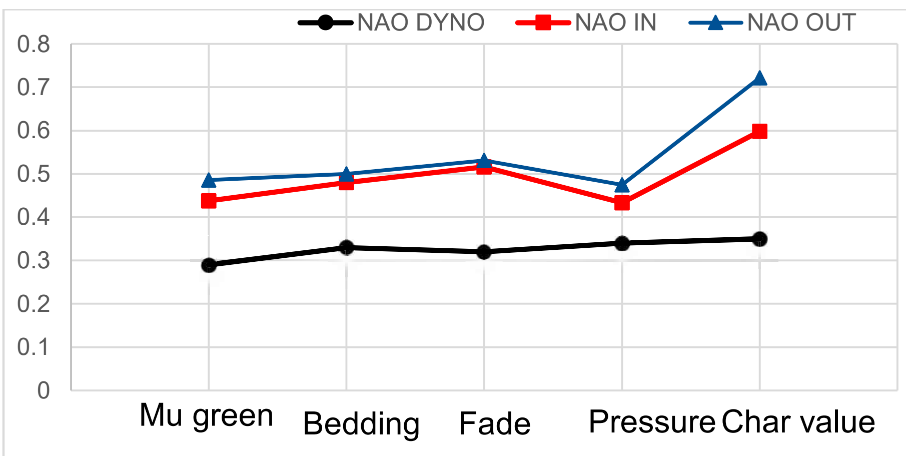


Fig.30 NAO average COF

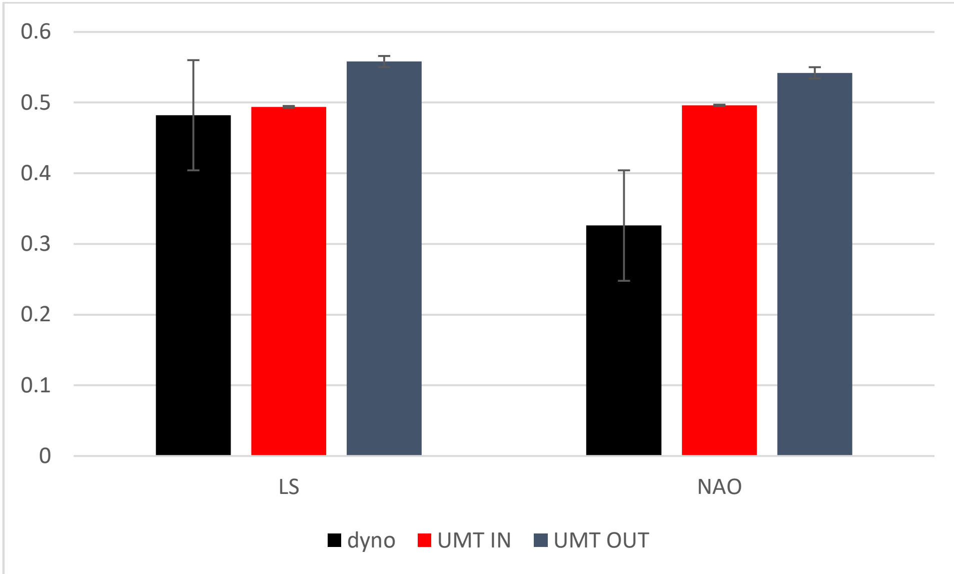


Fig.31 LS and NAO average COF comparison for dyno vs UMT IN vs UMT OUT

From the graph, it can be observed that average COF for a series of tests for NAO samples has same general trend between Dyno and UMT tests but UMT tests shows higher values. Also the dyno tests friction levels are less when compared to the friction levels in UMT tests.

From the graphs it can be understood that there is no general relation between the dyno and UMT samples. In comparison of fade tests between dyno and UMT, the inverse relation of COF vs pressure is observed in dyno whereas in UMT the relation is not observed. This is due to the torque is maintained in dyno tests but in UMT torque cannot be controlled.

There is no general relation between IN and out samples too. IN samples are cut from leading edge and OUT samples are cut from the trailing edge. The pressure acting on the two edges during the contact with the rotor in dyno tests is different. The leading edge may experience higher amount of pressure when compared to the trailing edge. This non uniform pressure distribution wears the brake pads unevenly [20]. So different friction layers are formed on the IN and OUT samples tested in samples. The difference between the IN and OUT samples may be due to this heterogeneity of the brake pads. So for future pads it is important to select the area of the samples for small scale tester from brake pads.

The occurrence of this results can be further explained in detail by conducting the Scanning Electron Microscopy on the dyno, UMT IN and UMT OUT samples.

5.4 Temperature controlled tests

Similar tests with the same conditions are conducted on the LS IN and NAO IN samples in UMT with the temperature control simulating the same temperatures in the AK Masters tests and are compared to the dyno and previously performed UMT tests for the IN samples. The plots are shown below

5.4.1 Mu green

Low steel

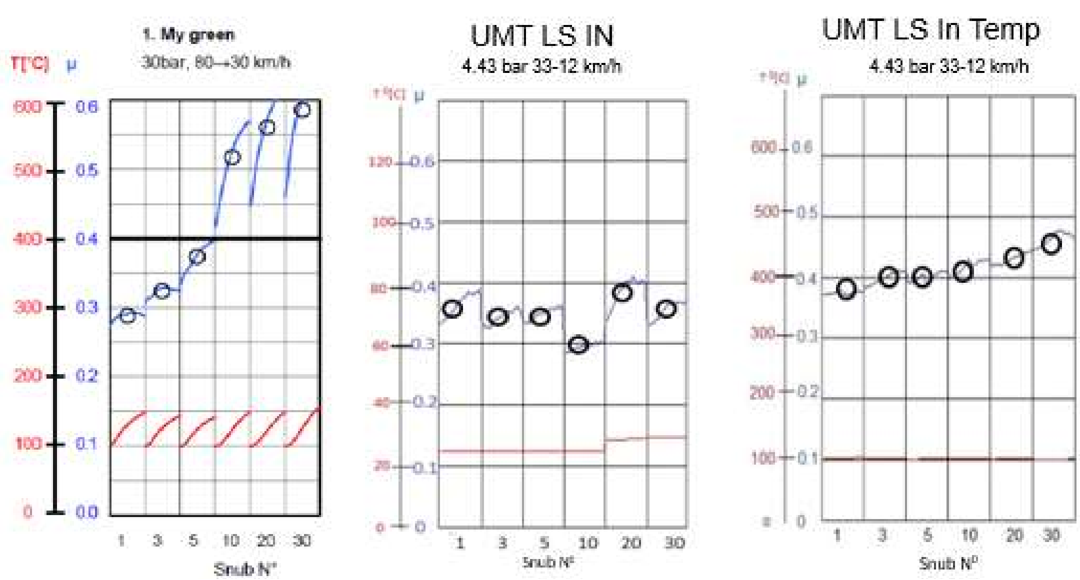


Fig.32 Low Steel mu green tests with T

NAO

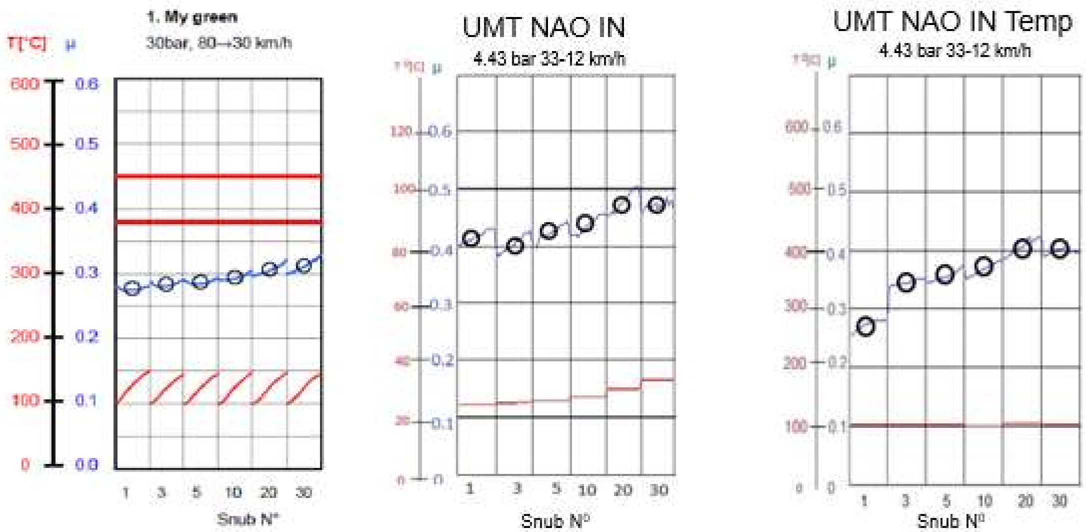


Fig.33 NAO mu green tests with T

5.4.2 Bedding

Low Steel

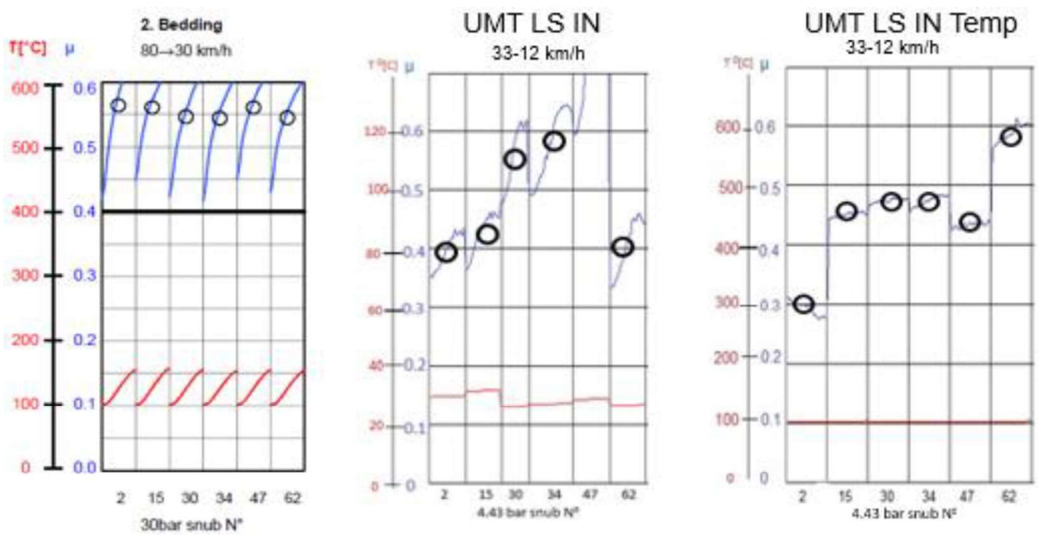


Fig.34 LS bedding tests with T

NAO

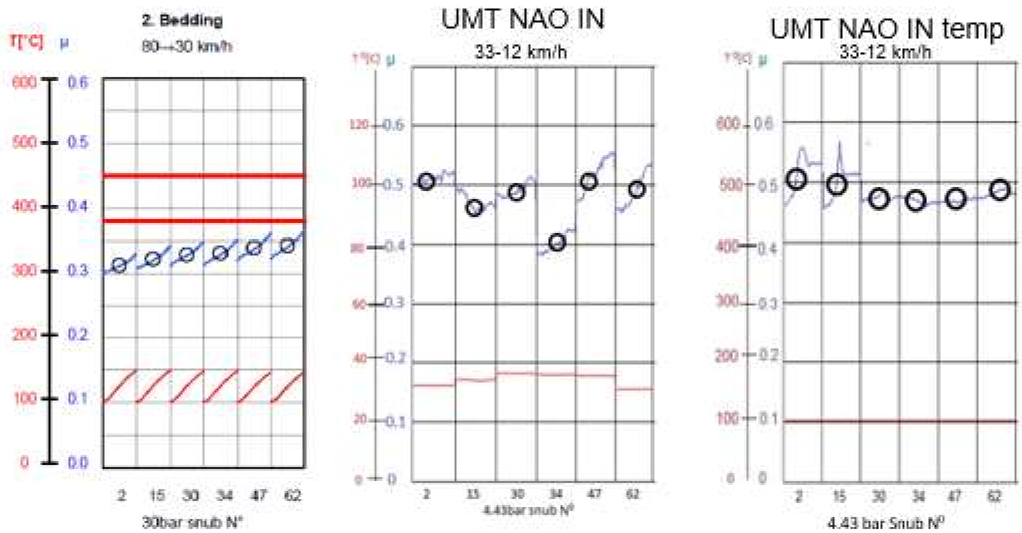


Fig.35 NAO bedding tests with T

5.4.3 Fade

Low steel

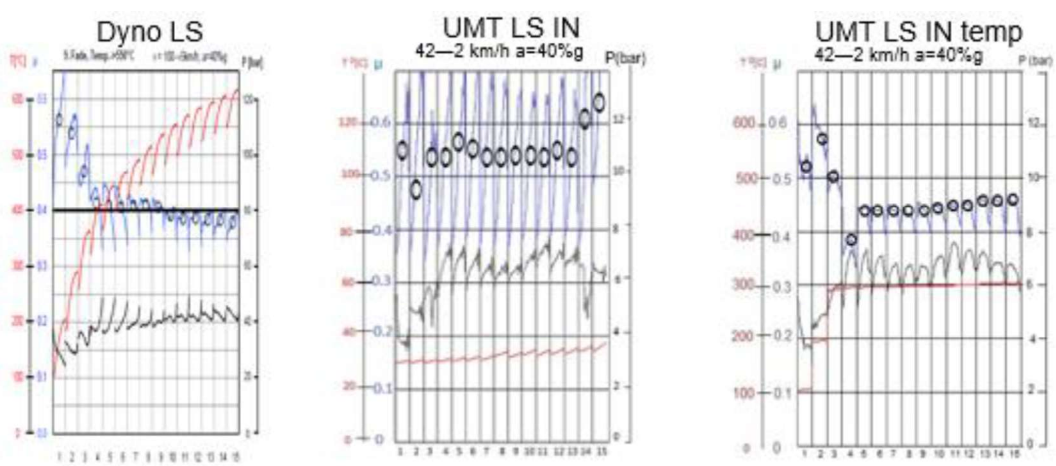


Fig.36 LS fade tests with T

NAO

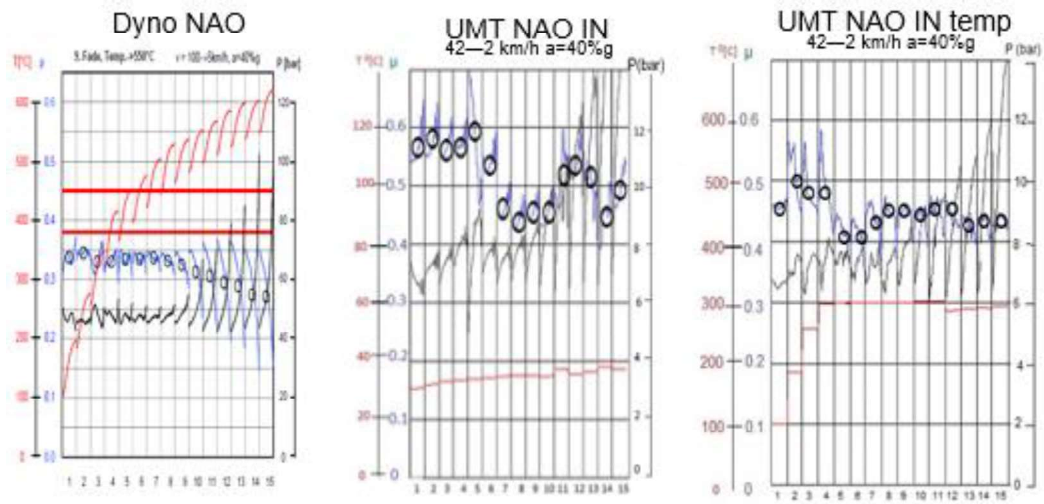


Fig.37 NAO fade tests with T

5.4.4 Pressure series

Low Steel

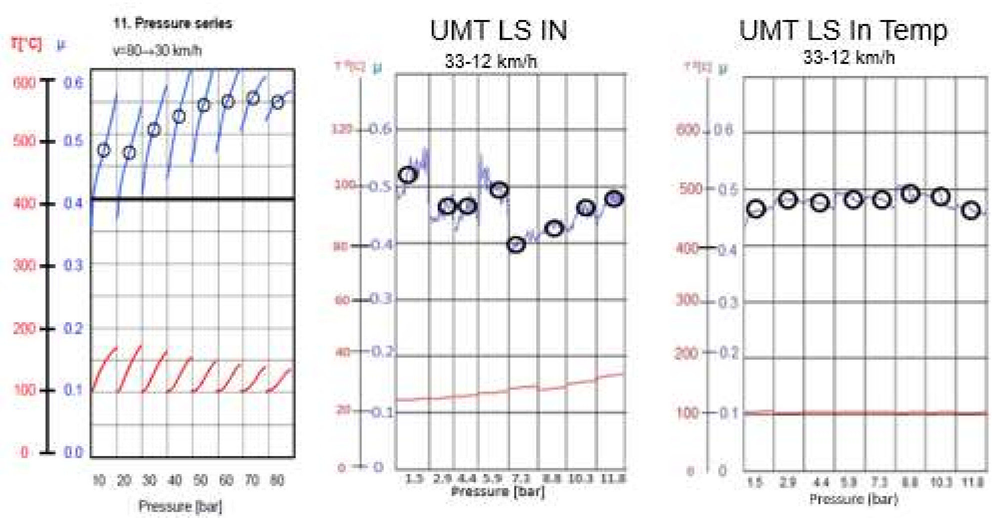


Fig.38 LS pressure series tests with T

NAO

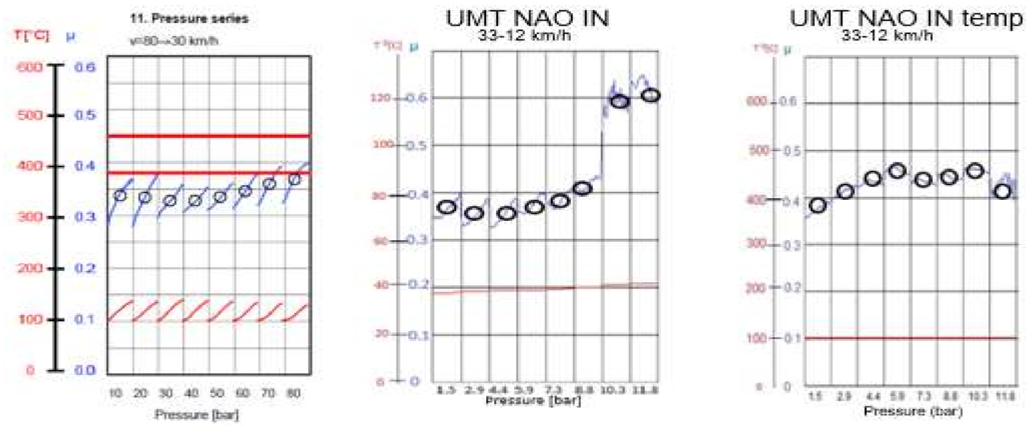


Fig.39 NAO pressure series tests with T

5.4.5 Characteristic value

Low Steel

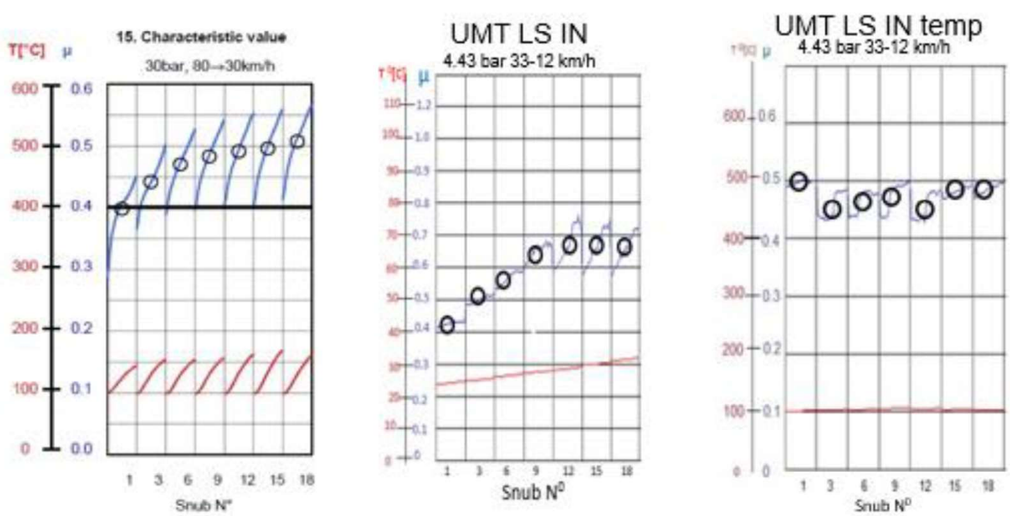


Fig.40 LS characteristic value tests with T

NAO

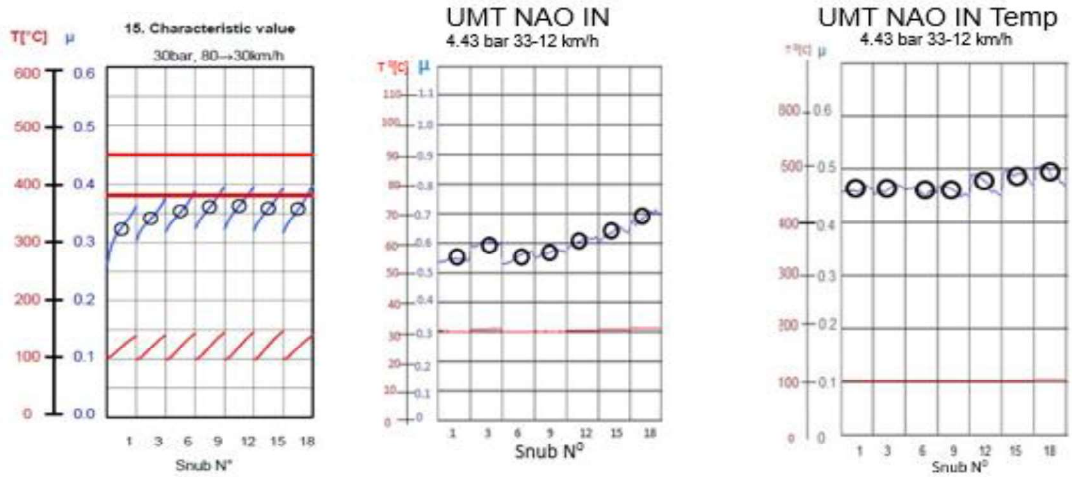


Fig.41 NAO characteristic values tests with T

5.5 Average COF

The averages of the COF values for each section of tests are calculated for dyno, UMT IN and UMT IN temperature control tests for the LS and NAO samples. Then they are tabulated as in the following sections. The averages and standard deviations for all the tests are also calculated and compared.

For Low steel in samples and dyno tests

Table.10 LS average COF with temperature control

S. No.	Tests	LS DYNO	LS IN	LS IN after heater
1	Mu green	0.44	0.35	0.41
2	Bedding	0.56	0.51	0.45
3	Fade	0.42	0.54	0.45
4	Pressure	0.52	0.46	0.48
5	Char value	0.47	0.59	0.47
	average	0.482	0.49	0.452
	Std. deviation	0.057619	0.091378	0.026833

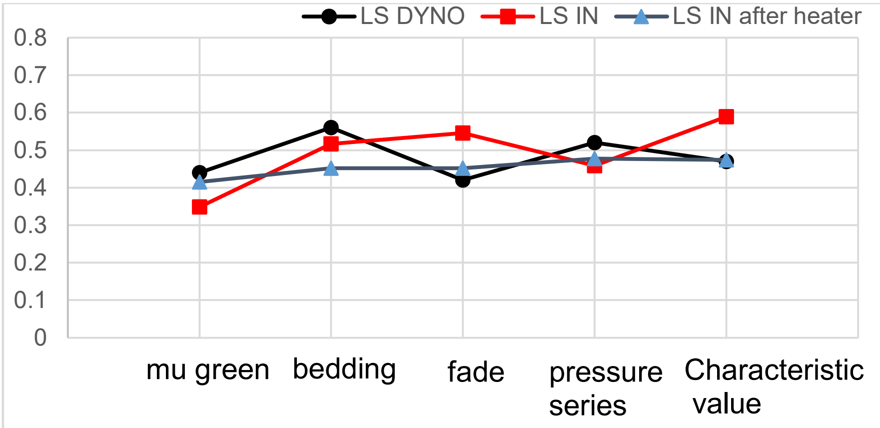


Fig.42 LS average COF with temperature control

For NAO

Table.11 NAO average COF with Temperature control

S. No.	Tests	NAO DYNO	NAO IN	NAO IN Temp
1	Mu green	0.29	0.43	0.36
2	Bedding	0.33	0.48	0.48
3	Fade	0.32	0.51	0.44
4	Pressure	0.34	0.43	0.43
5	Char value	0.35	0.6	0.47
	Average	0.326	0.49	0.436
	Std. deviation	0.023022	0.070356	0.047223

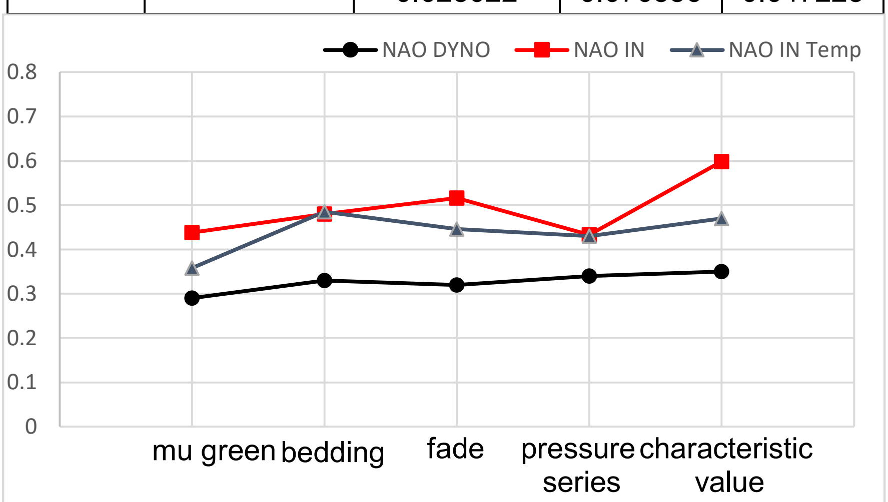


Fig.43 NAO average COF with temperature control

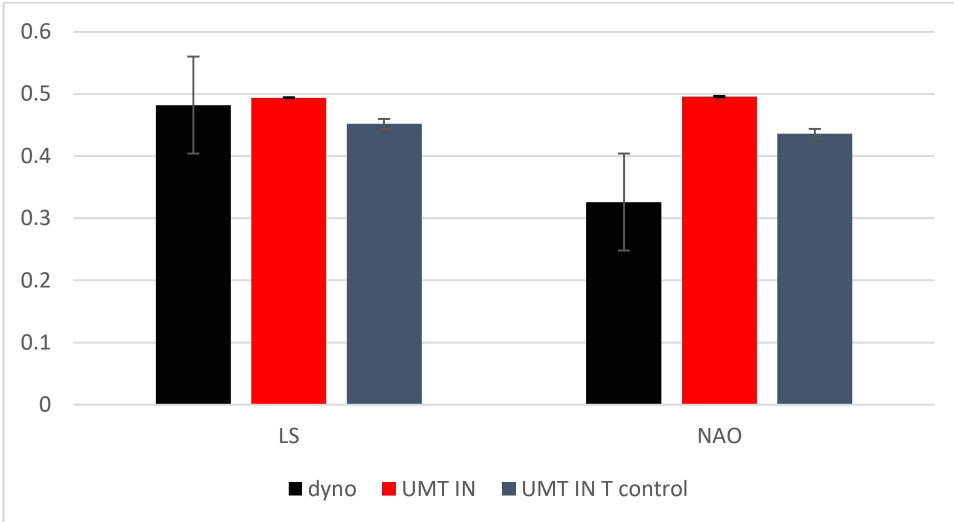


Fig.44 LS and NAO average COF comparison for dyno vs UMT IN vs UMT IN T control

The friction levels after the temperature tests are still different with the dyno and UMT IN samples. The friction levels after the temperature control is somewhat stable when compared to the friction levels of the UMT tests without temperature control. The average friction levels for LS samples with temperature control are between 0.41 and 0.47 and standard deviation is 0.02 whereas for LS IN samples without temperature control the standard deviation is 0.09. For the NAO samples with temperature control COF is between 0.36 and 0.48 with standard deviation of 0.04 and without temperature control the COF is between 0.43 and 0.6 with standard deviation of 0.07.

Especially for the fade tests, as the temperature increases with the temperature control, the friction levels decrease. This is related to the statement by Rudolf L. [20] that friction levels decrease at elevated temperatures near 250 to 315^{0}C .For both the LS and NAO samples the frictions levels are low for the UMT temperature controlled tests at temperature above 250^{0}C when compared to the same tests for LS and NAO samples without temperature increase.

5.6 Wear in dyno and UMT

The wear data is calculated for the dyno brake pad and UMT samples. In dyno the data is taken at 4 points in the trailing area as outer wear and 4 points taken in the leading area of the brake pad as inner wear. In UMT the wear is calculated for the three samples tested before and after the tests using a mitutoyo vernier calipers.

5.6.1 Low steel samples

Dyno

Table.12 Wear in dyno for LS samples

	IN start(mm)	IN end(mm)	wear(mm)	OUT start(mm)	OUT end(mm)	wear(mm)
1	17.11	15.74	1.37	17.18	16.68	0.5
2	17.13	16.08	1.05	17.23	16.65	0.58
3	17.06	16.34	0.72	17.26	16.34	0.92
4	17.09	16.5	0.59	17.3	16.41	0.89
average	17.1	16.17	0.93	17.24	16.52	0.72

UMT

Tabe.13 Wear in UMT for LS samples

	IN start(mm)	IN end(mm)	wear(mm)	OUT start(mm)	OUT end(mm)	wear(mm)
1	5.99	5.88	0.11	6.06	6.04	0.02
2	6.15	6.02	0.13	6.06	5.94	0.12
3	6.08	5.92	0.16	5.95	5.69	0.26
average	6.07	5.94	0.13	6.02	5.89	0.13

5.6.2 NAO samples

Dyno

Table.14 Wear in dyno for NAO samples

	IN start(mm)	IN end(mm)	wear(mm)	OUT start(mm)	OUT end(mm)	wear(mm)
1	17.06	15.86	1.2	16.92	16.09	0.83
2	17.04	15.97	1.07	16.95	16.33	0.62
3	17.03	16.32	0.71	16.97	15.92	1.05
4	17.02	16.48	0.54	16.95	16.2	0.75
average	17.04	16.16	0.88	16.95	16.14	0.81

UMT

Table.15 Wear in UMT for NAO samples

	IN start(mm)	IN end(mm)	wear(mm)	OUT start(mm)	OUT end(mm)	wear(mm)
1	7.07	6.95	0.12	6.98	6.9	0.08
2	7.05	6.88	0.17	6.99	6.92	0.07
3	7.13	7.04	0.09	7.06	7.02	0.04
average	7.08	6.96	0.12	7.01	6.94	0.07

In dyno tests there is more wear for the inner area of the brake pad when compared with the outer area of the brake pad. This proves that there is more applied pressure in the IN samples than the outer samples. This may be an effect to form different friction layers on IN and OUT samples.

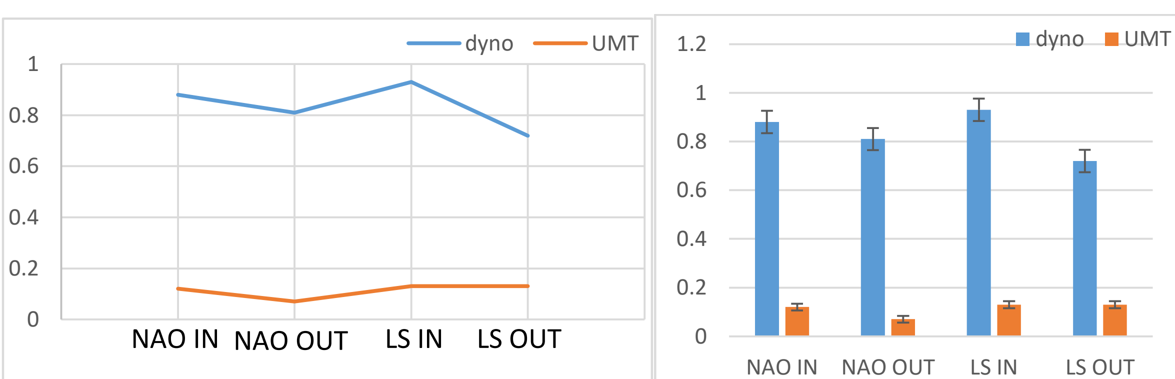


Fig.45 Wear comparison dyno vs UMT

It can be observed that in dyno, the average wear in the LS IN samples is more when compared to the LS OUT samples. But for the LS samples tested in UMT for IN and OUT samples average wear is the same. So the wear in the large scale and small scale tests cannot be compared easily. This prove the point focused on the work done by Jaafar, Selamat and Kasiran [19]. This paper compared the chase and dyno tests and proved that thickness loss in small scale tests cannot be used to predict the thickness loss of large scale tests. From the above results it can be seen that wear in UMT cannot be used to compare wear in dyno.

But UMT have some advantages over dyno. For the fundamental studies, one can study the wear data for every section of tests in UMT. For example if wear data and friction layer analysis in fade section are to be known, one can easily remove the samples from UMT and work on the samples and continue with the tests. But in dyno this facility is not available as all the tests are performed continuously and the temperature effect is high.

5.7 Scanning Electron Microscopy analysis (SEM)

SEM analysis is done for the samples tested in dyno and UMT after the final section of test i.e. characteristic value is performed on the samples. The same samples with size of diameter 11 mm are used in the SEM analysis. The samples are initially kept in an oven at 45^0 c to remove the moisture content. Then they are evaluated in Scanning Electron Microscopy.

5.7.1 Low Steel UMT Surface analysis

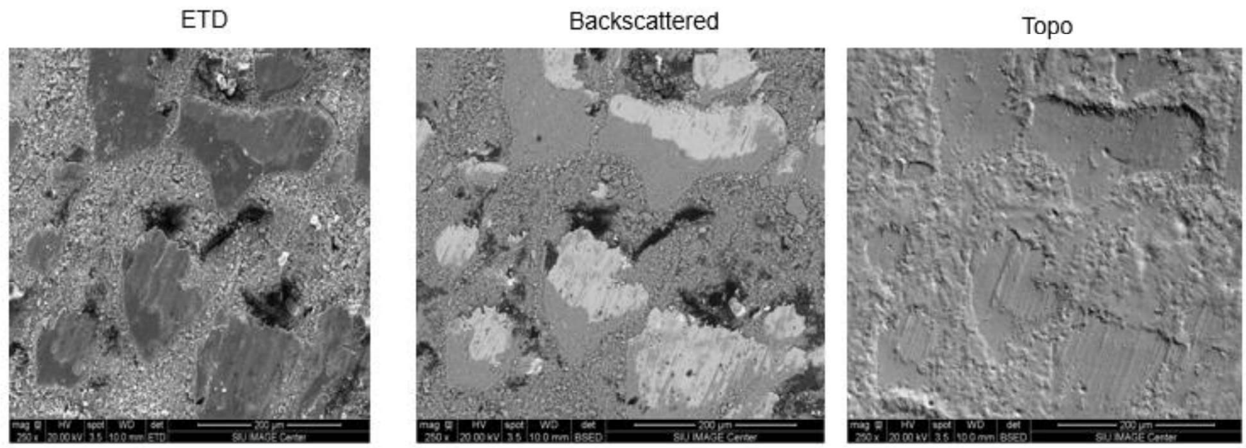


Fig.46 LS UMT surface analysis

From the pictures it can be observed that heavier elements are brighter. Also friction layer is formed on debris but not on steel chips. According to Mikael Erikson [16] friction forms on the primary plateaus having the steel chips but not on secondary plateaus having wear debris. From the current results observed it can be proved that it is not necessary that friction layer occurs only on chips.

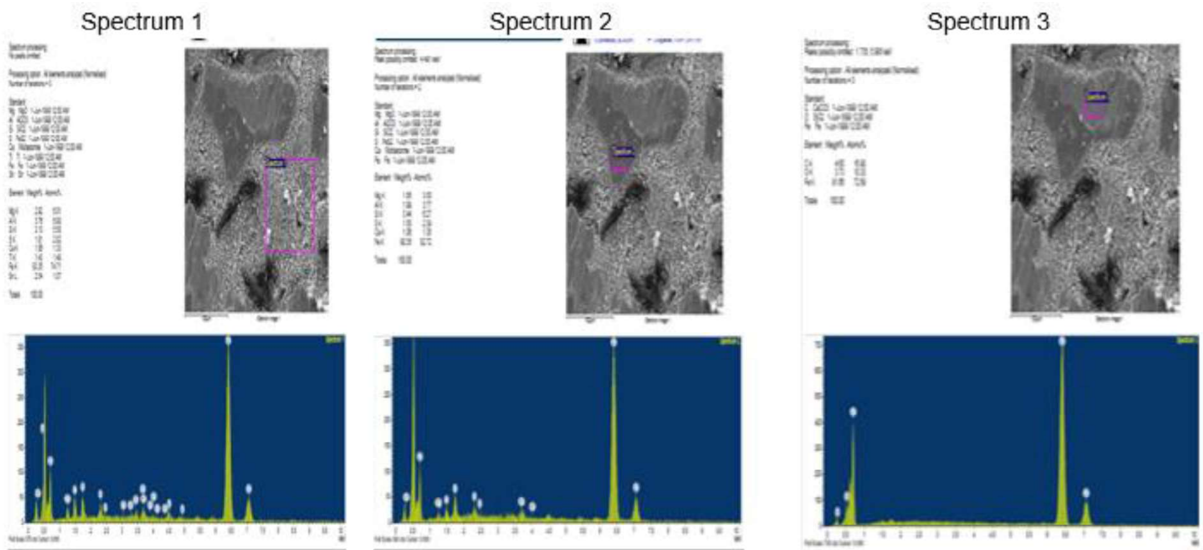


Fig.47 Composition of UMT samples

Spectrum 1 refers the debris where friction layer in UMT is formed. Dominating materials are ferrous oxide and Mg, Al, Ti are additives. Spectrum 2 refers the part of chip which forms the friction layer. This contains more amount of iron when compared to spectrum 1.Spectrum 3 refers the steel chip. This contains mostly iron.

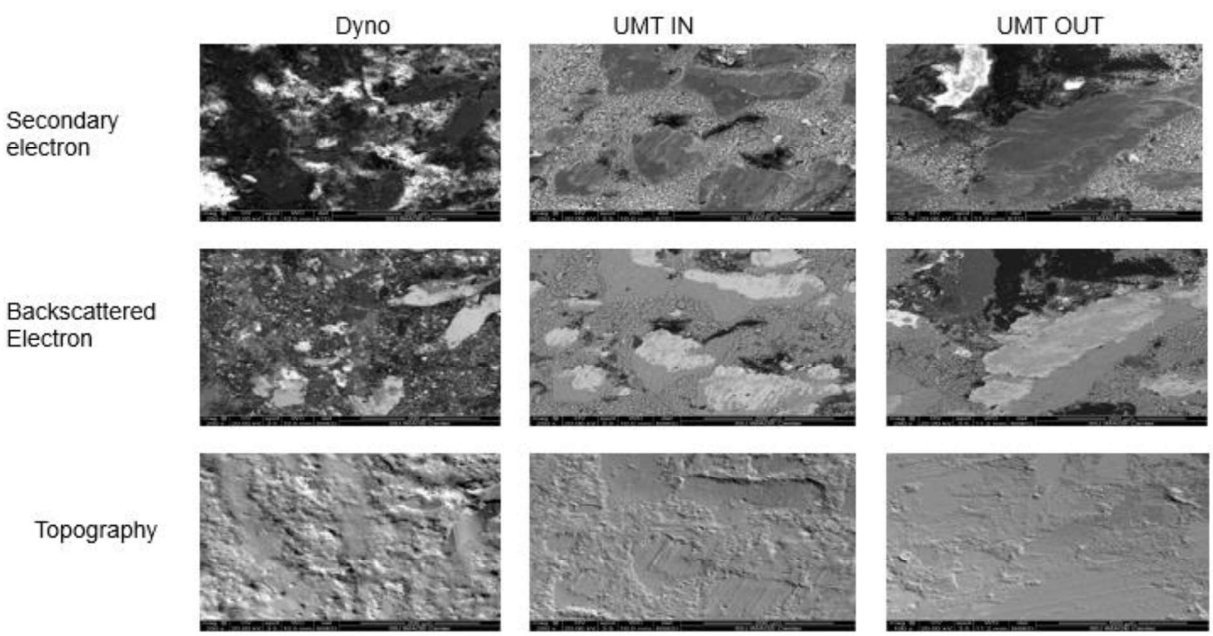


Fig.48 Friction layer analysis comparison dyno vs UMT IN vs UMT OUT

Low Steel IN

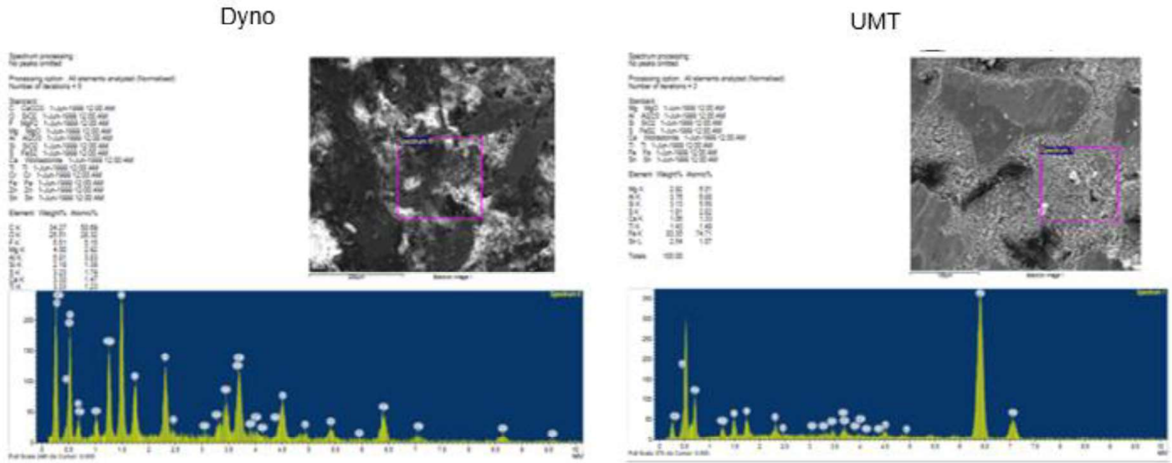


Fig. 49 Chemical composition dyno vs UMT LS samples

The dyno samples have higher amount of carbon where as UMT samples have more iron. As carbon is lubricious, the dyno test has lower average COF values when compared to UMT tests. Similar results are observed for the NAO samples. The chemistry for the samples are different, so the COF values are different in dyno and UMT. In brake dynamometer, the whole brake pad is in contact with the rotor. For UMT the samples are cut from different locations which have different chemistry, so a difference in IN and OUT samples is observed. Brake dynamometer is not sensitive. UMT is suitable in performing sensitive braking applications compared to dyno.

5.7.2 Rotor SEM

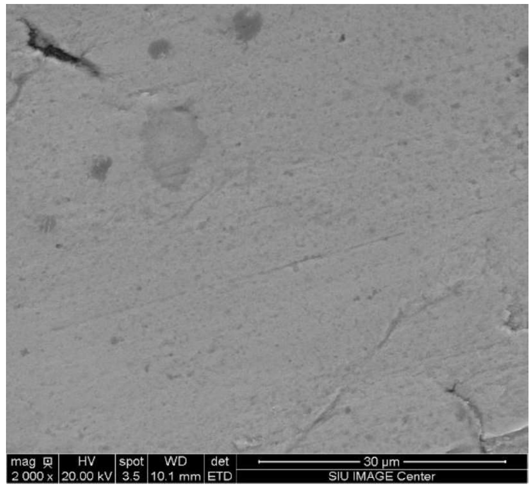


Fig. 50 Cast Iron surface 2kx magnification

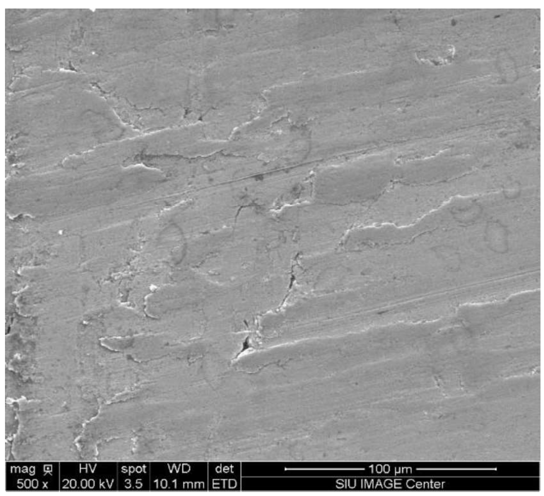


Fig. 51 Cast Iron surface 500x magnification

From the pictures it is observed that there is no full contact of samples on the rotor. There is no perfect full contact track on the surface of the rotor.It is observed there is adhesion between the UMT samples and the cast iron rotor which created a mix of brake pad sample and cast iron layer on the cast iron rotor.

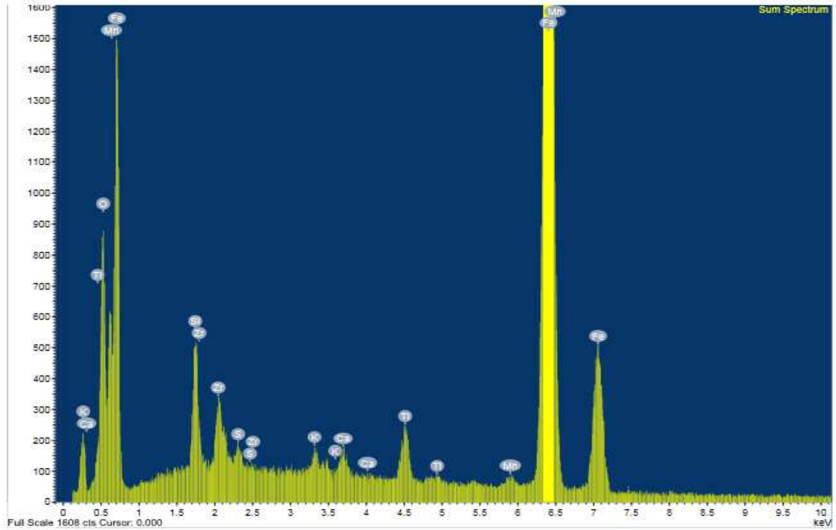


Fig. 52 Cast iron surface chemistry

From the chemistry of the friction layer formed on the cast iron rotor it is observed that friction layer mostly contains the iron oxides. There is a small amount of manganese sulfate. In most of the iron materials at least 0.9% of manganese is used. If manganese is not used then iron reacts with the sulfates and forms iron sulphate which has a low melting point. To avoid this melting a small amount of manganese is used in the iron materials. Potassium titanate is formed by contact with the brake pad.

5.8 Future work

Friction is not a material property, it is a system response. It depends on properties such as surface roughness, surface chemistry, structure and cleanliness, interface lubrication, normal load, sliding velocity and operating temperature, humidity and previous history of surfaces.

The parameters sliding velocity, normal load, braking time are properly scaled using the scaling laws. But there are other things that should be taken care. Considering the previous history of surfaces, the samples tested in dyno are fresh samples. But in UMT the samples tested are already tested in dyno. In fact, considering the SEM analysis, the samples cut from the trailing and leading area of the brake pad tested in dyno have formed different friction layers. So the samples conditions in dyno and UMT are not identical. This may have an effect in the difference in the friction levels between dyno and UMT.

This un-identical nature of the UMT and dyno samples in turn results in the different surface chemistry and surface roughness. This difference in chemistry and roughness is also observed in the SEM analysis composition and topography. Whole together this differences have an effect on the no correlation of the UMT and dyno tests.

So as a future suggestion, one can adopt this scaling strategies more effectively using a new brake pad and samples from the dyno and UMT tests respectively.

As everyone knows the friction and wear are system properties and it is not an easy task to resemble the on field tests using the small scale tests, one can try using this scaling phenomenon with some more basic improvements for better understanding of friction and wear phenomenon and contribute to research and development in this area.

CHAPTER 6

CONCLUSIONS

As friction and wear are system properties, dynamometer and UMT tests showed different performance when scaling laws were adopted. These results are related very probably to the temperature differences during testing in dyno and UMT, respectively. SEM and EDX analyses confirmed formation of different friction layers on surfaces of full scale and small scale samples, respectively; this is related to different conditions applied.

Small scale samples/tests showed different results when samples were “taken” from IN and OUT pad areas , respectively – this could be a result of pads heterogeneity and/or different experienced conditions in two different locations during dyno test – future small-scale tests have to be performed with fresh samples.

In dyno, whole brake pad is tested and due to pads heterogeneity the tests cannot depict the behavior of whole pad composition. But in UMT, the tests performed can show the results of particular composition of brake pad material. So for fundamental research in new formulation of new brake pads, UMT can be used effectively.

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Thesis Paper Title:

Impact of friction test scale on brake friction performance

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