International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

Available at http://inpressco.com/category/ijcet

Research Article

Frictional Characteristics of Brake Pads using Inertia Brake Dynamometer

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Accepted 22 March 2015, Available online 05 April 2015, **Vol.5, No.2 (April 2015)**

Abstract

The conventional disc wears out and brake pollutes the environment. In addition, localized heating occurs in the conventional disc brake. To tackle both of these problems, conventional disc brakes can be replaced with magnetorheological (MR) fluids brakes. MR fluids are materials having shear yield stress as a function of magnetic field. On the application of magnetic field, MR particles get aligned and increase shear resistance between relatively moving surfaces. The friction between stator and rotor increases and fulfils the braking function, which means MR fluids can be used as brake friction materials. Understanding of friction behavior is the key factor of satisfactory & reliable working of the brake system. To characterize the friction behavior of MR brake, there is a need to understand the friction behavior of conventional disc brake system. In this research work, experiments have been done to characterize the frictional characteristics of Volvo disk brake system using full-scale brake inertia dynamometer.

Keywords: *Full scale brake inertia dynamometer, Volvo disk brake, Pressure speed sensitivity, bade-recovery behavior.*

1. Introduction

Magnetorheological (MR) brake (Sarkar and Hirani, 2015), (Sarkar and Hirani, 2013), (Sukhwani, *et al*, 2009), (Sukhwani and Hirani, 2008), (Sukhwani and Hirani, 2008), (Hirani and Manjunatha, 2007), (Sukhwani, *et al*, 2007), (Sukhwani, *et al*, 2006), (Gupta and Hirani, 2011), (Muzakkir and Hirani, 2015), (Muzakkir, *et al*, 2015) is a device, where MR fluids are used as brake friction materials. Successful development of MR brake requires an extensive study of the existing brake technologies, working knowledge of MR fluids, broad practice on existing brake inertia dynamometer and theoretical knowledge of electromagnetic field. Therefore in this research work, experiments on existing brake inertia dynamometer using disk pad brake system have been done. The test set up is fully computerized and it can be programmed for any test schedule. The test setup is equipped with 175 kW variable speed (100 rpm to 1550 rpm) DC motor with a feedback system. To maintain complete safety, there is a provision for emergency pneumatic brake.

A good understanding of friction behavior is the key factor of satisfactory & reliable working of the brake system. FMs (Friction Materials) are required to have certain performance characteristics such as, low fade & high recovery of, good pressure – speed sensitivity characteristics etc., to make these material suitable to automotive application. To ensure the required characteristics, FMs are subjected to laboratory and field tests. While vehicle tests are expensive and time consuming; brake inertia dynamometer tests in the laboratory are faster and economic to verify friction material characteristics. IBD incorporating full-size brakes can simulate vehicle tests reasonably well. These dynamometers consisting of motor, inertial wheels & load measuring device can be tuned to simulate the real-test conditions by using a suitable application software package to control of operating parameters viz. braking pressure, RPM, and temperature as per input schedule (s).

Figure 1 shows a block diagram of a full scale IBD. Simply, it consists of a motor controlled by variable speed drive with suitable application package to vary & count speed-up time and measure torque using load cell arrangement. The analog outputs from the various sensors suitably signal conditioned & fed to the interface card of the computer containing application package, make whole arrangement in close loop control. Tribo-evaluation tests conducted on full scale IBD can be mainly categories into: effectiveness (Pressure-speed sensitivity) & fade-recovery (Temperature sensitivity) studies. The first one measures stopping efficiency of FMs subjected to variable load and speed conditions, while fade-recovery study is related to the loss of braking performance at elevated temperatures and the revival

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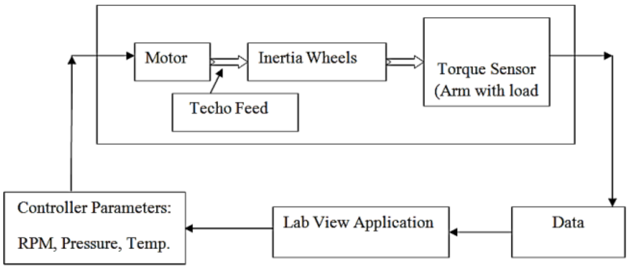

Fig.1 Block diagram of Full scale IBD

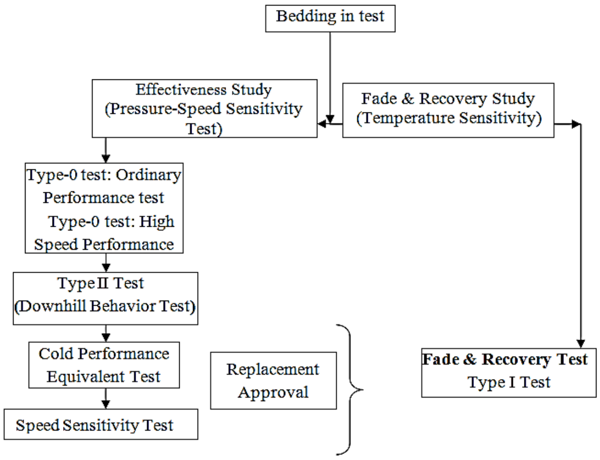

Fig.2 Methodology flow chart

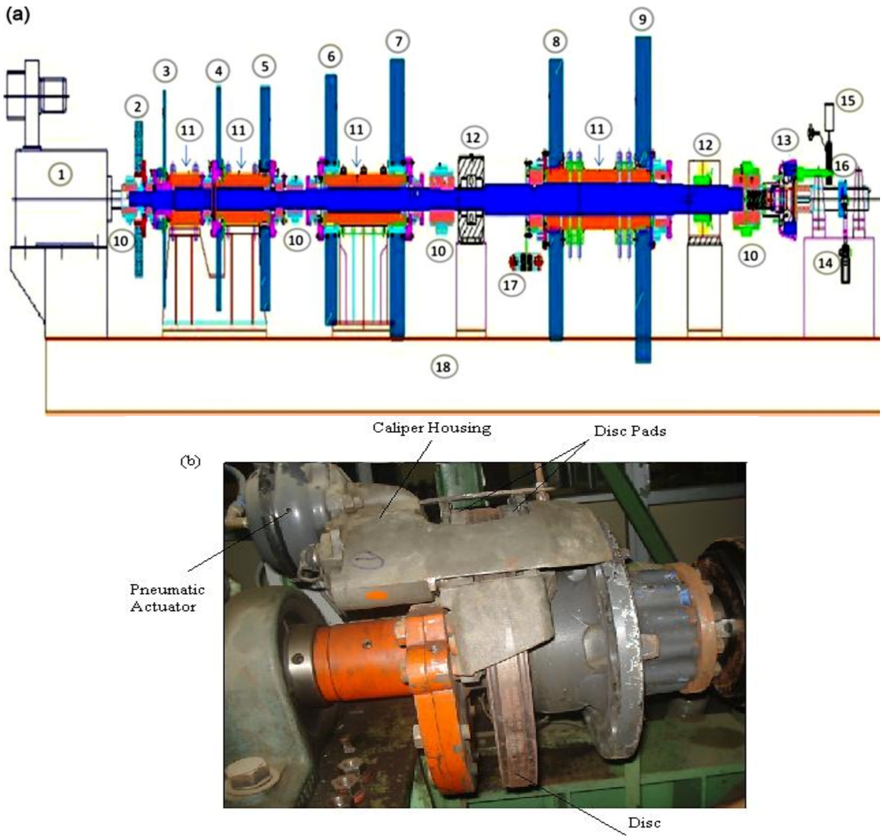

Figure 3 (a) & (b) Schematic of Full scale Inertia Brake Dynamometer :(1) motor, (2) flywheel of 0.5 kg-m sq, (3) flywheel of 2 kg-m sq, (4) flywheel of 4 kg-m sq, (5) flywheel of 8 kg-m sq, (6) flywheel of16 kg-m sq, (7) and (8) flywheel of 32 kg-m sq, (9) flywheel of 64 kg-m sq, (10) couplings, (11) housings, (12) shaft bearings, (13) braking assembly, (14) load cell, (15) air chamber,(16) torque arm, (17) emergency brakes, (18) dyno bed.

Fig.3 Sketch of Inertia Brake Dynamometer (Kumar, *et.al.*, 2009) of the same at lower temperature. A definite methodology is required to evaluate the performance of friction material. Figure 2 illustrates the methodology followed in the present research work. The first step is to bed the brake as per manufacturer's bedding procedure to ensure at least 80% conformal contact area on the disk pads prior to start of ECE R90 test. The bedded brakes are then subjected to effectiveness test (Type-0, II, cold performance & speed sensitivity). Type-0 test is conducted under two different conditions viz. ordinary (low speed) & high speed conditions. In Type II test disk pads are tested to simulate downhill condition of laden vehicle running with 30Kmph on 2.5% down-gradient of 6 Km in gear disengaged condition. Type I test examines fade & recovery (temperature sensitivity) behavior of FMs.

2. Experimental Study on Inertia Dynamometer

An inertia dynamometer (Dyno) setup, shown in Figure 3 is a fully computerized automatic testing machine for four wheelers capable of performing brake test in both hydraulic as well as in air braking mode. The dynamometer applies variable inertial load on the 175 kW motor and measures the braking force, torque and the coefficient of friction through a computer utilizing Lab view(TM)-based software (version 4.0) connected to it. Its main chassis is of ladder type construction & fabricated out of I-section girders of about 300mm height with adequate diagonal members for rigidity. A fully solid state electronic variable speed drive having tachometer feedback is provided to vary motor speed from 100 RPM to 1550 RPM.

The drive motor is fixed on the separate box type bed which is mounted on the main chassis. The main shaft is directly coupled to the motor through gear coupling. There is provision of getting inertia values from 1.5 Kg-m sq to 153.5 Kg -m sq through careful combination of one fixed & ten attachable inertia wheels (Table 1). The temperature of the disk/drum is monitored by a non-contact IR sensor. The analog output from the sensor is suitably signal conditioned & fed to the interface card of the computer to monitor & control the temperature. The wheel temperature can be kept to desired level with a blower & duct arrangement. Table 2 lists the important technical specification of the inertia dynamometer.

The IBD is instrumented for continuous recording of rotational speed, brake torque, pressure in the brake line, braking time & brake rotor temperature, and number of rotations after brake application. Inertia value (as per ECE R90) norm was calculated considering 55% of the gross vehicle weight (GVW). Hence, wheel load of 4455 Kg with tyre rolling radius of 571 mm had given a total of 148.06 kg-sq m inertia value. Bedding tests were performed as per manufacturer's instruction. Table-3(a) and (b) provides important vehicle parameters & bedding schedule respectively. Gear drive coupling is used to engage and disengage the motor to the main shaft. Inertia is the governing parameter to simulate the braking performance as per the real condition, so the required inertia can be achieved with the help of inertia wheels, the inertia wheel can be engaged to the main driving shaft with the help of wheel drive coupling. The description of inertia wheels are shown in Table 1, if required inertia is 50 kgms^2 then by connecting wheels of inertia value 32, 16, 2 kgms^2 required inertia will be achieved.

The required inertia can be calculated as,
Required inertia = (mass on wheel × rolling radius (tyre radius))/gravity
For four wheeler,
Mass on wheel = ¼(Gross vehicle weight)
For two wheeler,
Mass on wheel = ½ (Gross vehicle weight)

Table 1 Inertia Wheels details

Wheel Type	Inertia Value (Kg-m sq.)	Total Number
Fixed	1.5	One
Attachable	0.5	One
	1.0	One
	2.0	One
	4.0	One
	8.0	Two
	16	Two
	32	One
	64	One

Table 2 Technical specification of IITD Full scale inertia dynamometer

Supplier	Pyramid Precision Engineering Pvt Ltd, Chennai, India
Motor	175 KW, 1500 rpm DC motor with external cooling motor
Max Motor torque	1000 kg-m
Base Speed	1400 rpm
Shaft Speed	1500 rpm
Min inertia	1.5 kg-m sq
Max inertia	1570 kg-m sq
No of wheels	11
Max braking torque	1000 kg-m
Max Pressure (Air)	10 Bar
Max Pressure (Hydraulic)	120 Bar
Gross vehicle weight (GVW) range	1000 kg – 16000 kg
Max. dissipated energy	20 MJ

Table 3(a) Vehicle Test Parameters for Volvo bus disc pad B7R Mark-II

Schedule	ECE R90
Gross vehicles weight (GVW)	16200 kg
Vehicle category	M3
Vehicle model	Volvo bus B7R Mark-II
Inertia	148.6 Kg-m sq
Rolling Radius (Tyre radius)	571 mm
Effective radius	172 mm

Table 3(b) Bedding test schedule

Test condition parameter	Value
Start speed	60Kmph
End speed	0
Controller mode	2bar (air-pressure)
Temperature	0-100˚ C
Wet	False
Pause	False
Blower	On

ECE R 90 test schedule was used in the study to test Volvo disk pad lining. Economic Commission for Europe Regulation 90 (ECE R90) is a European standard for brake components that requires brake manufacturers to conform and guarantee the original equipment standards as far as performance and quality is concerned.

Effectiveness studies (Pressure-speed sensitivity)

Effectiveness studies quantify the influence of operating parameters viz. pressure and speed on the braking performance. Type-0 & speed sensitivity test, specified in ECE R90 schedule, were used to measure performance of Volvo disc pad.

Type-0-Test

In type-0 ordinary performance test, Volvo pads were tested for eight brake applications at spaced intervals of line pressure (2-8 bar) at 60 and 40 Kmph respectively. A similar test was performed in Type-0 high performance for three brake applications at line pressure of 6, 6.5 and 7 bar with speed of 90 and 100Kmph respectively. As the severity of the braking increased consequently stopping distance decreased. However, this brought an increase in the average torque needed to stop the vehicle. Experimental design of this test is shown in Table-5.

Table 4 Vehicle categories according to UN ECE RE90

Vehicle Category		Description
Passenger Vehicle	M	4/3 wheeler, max weight < 1Metric ton
	M1	Carriage seats< 8 in addition the driver's seat
	M2	Carriage seats > 8 in addition the driver's seat, max weight< 5 Metric Ton
	M3	Carriage seats > 8 in addition the driver's seat, max weight> 5 Metric Ton
Goods Vehicle	N	4/3 wheeler, max weight > 1 Metric ton
	N1	Max weight < 3.5Metric Ton
	N2	3.5Metric Ton < Max weight < 12Metric Ton
	N3	Max weight > 12Metric Ton
Trailers	O	Trailers (including semi trailers)
	O1	Max. weight < 0.75Metric Ton
	O2	0.75Metric Ton <Max weight <3.5Metric Ton
	O3	0.75Metric Ton < Max weight < 3.5Metric Ton
	O4	Max. weight > 10 Metric Ton

Speed sensitivity test

Speed sensitivity test examines consistency of braking at specified speed (60, 80 & 110 Kmph) and pressure condition. A total of three snub braking operations with nominal release programmed at each test speeds corresponding to a constant braking pressure of 6.5bar. The experimental design for the test is shown in Table-6.

Fade & recovery behavior (Type-I)

Type-I test highlights effect of temperature on. In real life, heat fading occurs in case of constant brake actuation and make brake inefficient if, it can't fully absorb the developed heat. Brake pads & disc used in effectiveness studies were again reused in this study.

Table 5 Experimental design of Effectiveness test (Type-0)

Description	Braking Speed	Release Speed		Pressure		No of Cycles	Blower
	Kmph	rpm	Kmph	rpm	(bar)		
Type-0 Test (Ordinary performance test)	60	420	0	0	2, 3, 4, 5, 6, 6.5, 7 & 8	1 Stop @ Each Pressure	On
	40	280	0	0	2, 3, 4, 5, 6, 6.5, 7 & 8	1 Stop @ Each Pressure	On
Type-0 Test (High speed performance test)	90	630	0	0	6,6.5,7	3 Stop @ Each Pressure	On
	100	700	0	0	6,6.5,7	3 Stop @ Each Pressure	On

The test starts with three braking stops each at speed of 60 & 40Kmph respectively corresponding to a line pressure of 6.5bar. Temperature of the disc was kept within 100deg. using air blower. After this, fade test was carried on using twenty snub braking application with speed of 60 (start) & 30Kmph (end). Temperature of the disk allowed rising freely in this segment by keeping air blower in off condition. Finally, after completion of the fade segment, one full braking stop performed at speed of 60 & 40Kmph each keeping blower still in off condition. Table-7 highlights experimental design of Type-I test.

Definition of required terms used in the Type-I test evaluation have been given below-

μ_{max} (fade)=highest recorded during fade test.

μ_{min} (fade)=lowest recorded during fade test.

% fade ratio= (μ_{min} / μ_{max})* 100

Table 6 Experimental design of speed sensitivity test

Description	Braking Speed		Release Speed		Pressure	No of Cycles	Blower
	Kmph	rpm	Kmph	rpm	(bar)		
Speed Sensitivity Test	60	420	30	210	6.5	3 Stop @ Each Pressure	On
	80	560	60	420	6.5	3 Stop @ Each Pressure	On
	110	770	80	560	6.5	3 Stop @ Each Pressure	On

3. Results and Discussions

Test results obtained in Type-0 & Type-I, were analyzed to extract useful information about friction characteristics of Volvo disc pad material. Effect of operating parameters viz. pressure & speed on μ should be as small as possible otherwise consistent braking performance will not be achieved. Plot of μ with respect to applied braking pressure shows Volvo disc pad sensitivity towards pressure. For an ideal FM, this curve should be straight (parallel to X-axis) with minimum undulation. High slope indicates greater sensitivity of μ with pressure. The difference in μ at selected pressure value indicates its sensitivity towards speed. Higher is the difference; consequently higher is the sensitivity of μ towards the speed variation.

The influence of speed on μ is expressed in terms of speed spread (%) which is calculated from the ratio of the μ at selected speed to that at lower speed. Variation in μ and SS (%) with respect to applied pressure (Type-0, ordinary) were shown in Figure-4(a) and 4(b) respectively. Figure 5(a) and 5(b) show corresponding graph of variation in μ_{Avg} & SS (%) with respect to applied pressure respectively (Type-0, high speed). With increase in pressure & speed μ decreased for all the cases. This happens due to fact that with increase in pressure real area of contact increases excessively & disproportionately as polymeric materials (disc FMs) are visco-elastic.

Table 7 Experimental design of Type-I test

Description		Braking Speed	Release Speed		Pressure		No of Cycles	Blower
		Kmph	rpm	Kmph	rpm	(bar)		
Type-I (Fade & Recovery test)	Cold Performance Test	60 & 40	420 & 280	0	0	6.5	3 Stop @ Each Pressure	On
		60	420	30	210	Corresponding to 0.31 g pressure at 1st stop & maintain in rest of cycles.	3 Stop @ Each Pressure	On
	Hot Performance	110	770	80	560	6.5	3 Stop @ Each Pressure	On

This leads to eventually disproportionately low reduction in pressure on the asperities in spite of increase in load. Hence, μ falls down. However, increase in speed affects μ differently. With increase in speed, μ generally doesn't show fixed trends. The μ value increased slightly, showed maximum followed by a sharp decrease in some cases (as in Figure-5(a)). Furthermore, increase in speed brought more frictional heat which easily caused μ to go down as it was highly temperature sensitive (see Figure 4(a) and 5(a)).

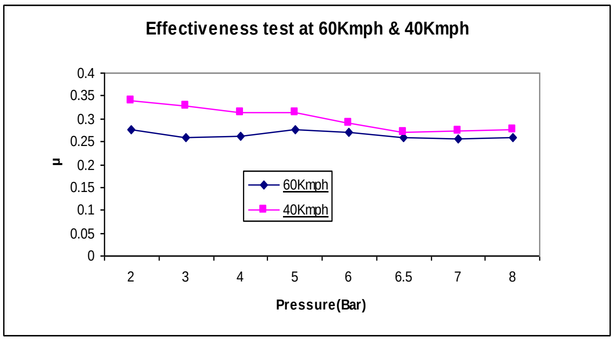

Fig. 4(a) Variation in μ with pressure at 60Kmph & 40Kmph, Type-0 (Ordinary)

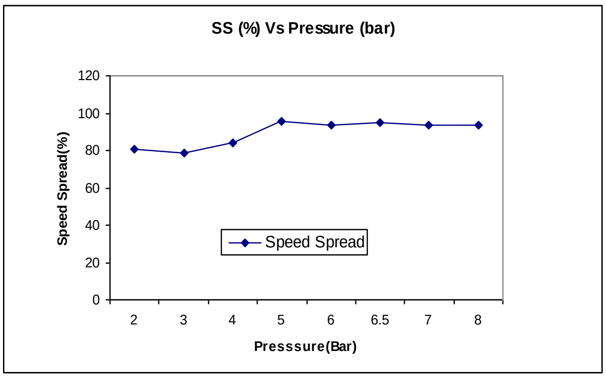

Fig. 4(b) SS (%) with change in pressure from 60 to 40Kmph, Type-0 (Ordinary)

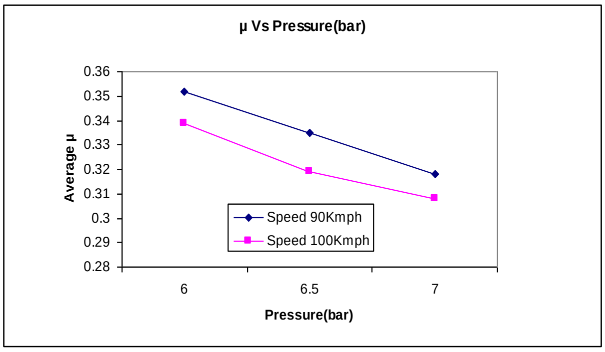

Fig. 5(a) Variation in μ with pressure at 90Kmph& 100Kmph, Type-0 (High performance)

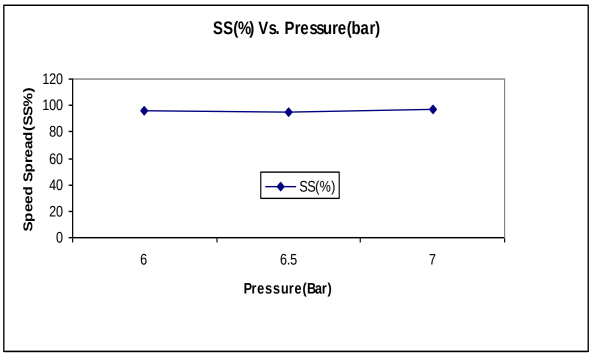

Fig. 5(b) SS (%) with change in pressure from 60 to 40Kmph, Type-0 (High Performance)

Giving a close look on SS (%) Vs pressure graph for both Type-0 tests (ordinary & high performance) brought the fact that stable result obtained at higher pressure region.

Speed Sensitivity Test-

Sensitivity of μ_{Avg} (averaged μ over three brake applications) with respect to speed (Kmph) is shown in Fig-6(a) of Volvo brake pad at test pressure of 6.5 bar. Keeping braking pressure constant (6.5 bar) & varying speed from 60 to 110Kmph brought initially decrement in μ_{Avg} followed by a revival trend. For ideal material, it should be as close to 100 as possible and range should be as small as possible. Variation in SS (%) with speed range was shown in Fig-6(b). a minimum of 86.05% SS drop found which was on good side.

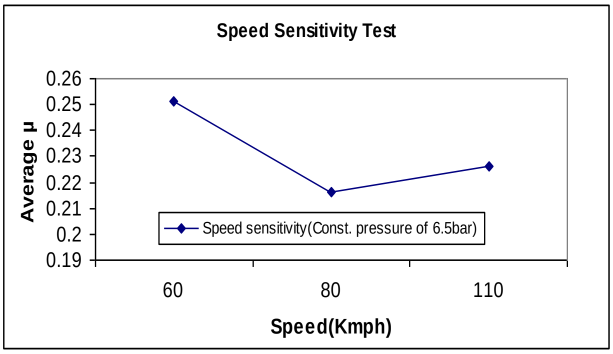

Fig. 6(a) Speed sensitivity of $\mu_{Avg.}$ with respect to speed (Kmph)

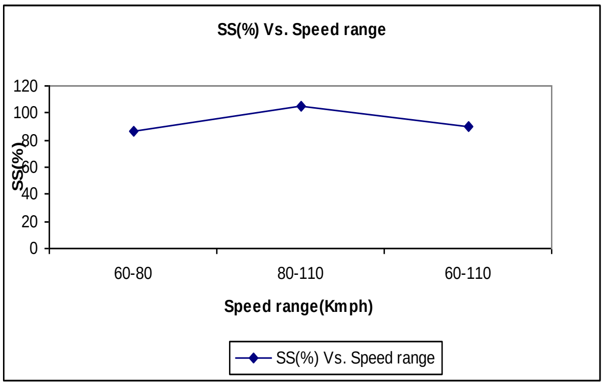

Fig. 6(b) SS (%) Vs. Speed range (Kmph)

Fade behavior study (Type-I)

Figure 7(a) shows fade behavior of Volvo disc pad lining. For an ideal fade curve μ should be in good range (0.3-0.4) and curve should be parallel to X-axis with minimal slope. Performance of FM during fade is decided by a factor called, % fade ratio. That found in this case as 83.43% which was acceptable. Generally fade % ratio in the range of 80-100% are acceptable as per industry norms. The reason behind fade is the thermal decomposition of ingredients due to accumulation of frictional heat. This test condition was achieved by allowing the disk temperature to rise indefinitely (Figure-7(b)) by applying constant snub braking corresponding to fixed (0.3g) deceleration.

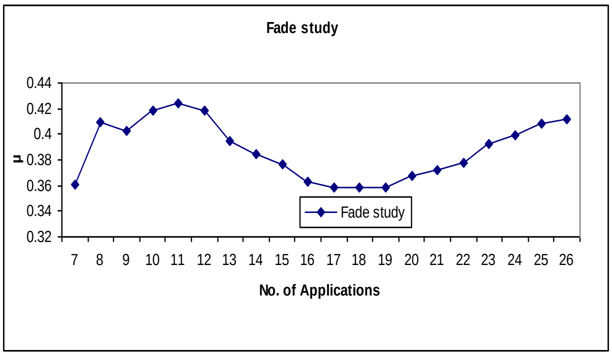

Fig. 7(a) Fade behavior of Volvo disk pad material

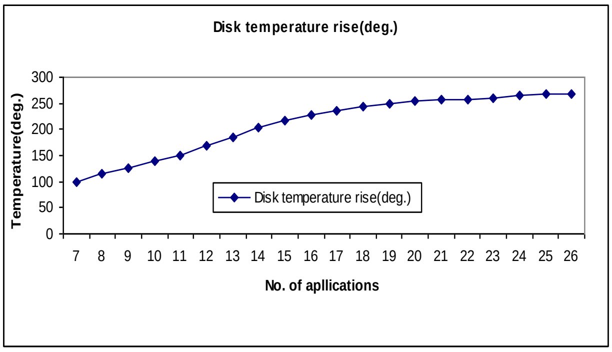

Fig. 7(b) Temperature rise (deg.) in Fade cycle

The experiment on the conventional Volvo brake was performed with the help of standard brake schedule as per the ECE R 90. An ECE R 90 schedule comprises of five major parts viz. bedding in, bedded performance test, high speed performance test, Fade-Recovery test & the speed sensitivity test. The input parameter to the lab view program is test schedule and vehicle parameter e.g., weight of the vehicle, rolling radius and the effective radius of disc brake as shown in the Table 8. The desired inertia can be achieved by connecting the inertia wheel to the main driving shaft with the help of wheel drive coupling. The material of the disc is Pearlitic grey cast iron and for the pad is composite which properties is given in the Table 9.

Table 8 Vehicle test parameters for commercial Volvo bus disk pad

Schedule	ECE R-90
Gross vehicles weight (GVW)	16200 kg
Vehicle model	Volvo bus B7R Mark-II
Inertia	148.6 Kg-m-sec^2
Rolling Radius (Tyre radius)	571 mm
Effective radius (pad on disc sliding radius)	172 mm

Table 9 Physical, chemical and mechanical properties of Volvo bus pads

Parameters	Value
Density (g/cc)	2.24
Acetone extraction (%)	1.25
Hardness ® (ASTM D 785)	95-102
Th. Conductivity (W/m.K) (ASTM-E1461-01)	2.03

Performance test

The performance test examine the behavior of braking torque, stopping distance and disc temperature at average speed with respect to the different applied pressure. The two different speeds (60 Km/hr and 40 Km/hr) and eight different value of pressure (2 to 8 Bar) as per the standard schedule are given below:

Initial speed - 40 and 60 km/hr
Final speed - 0 km/hr
Pressure - 2, 3, 4, 5, 6, 6.5, 7 and 8 bar
No. of cycles - 16 (8 for each initial speed at each operating pressure)
Disc temperature - 100 deg C
Blower - ON

The stopping distance depends upon the braking torque and deceleration rate, higher braking torque and higher deceleration results in lesser the stopping distance. From the Figure 8, it is clear that at the same applied pressure the stopping distance is lesser for the lower speed.

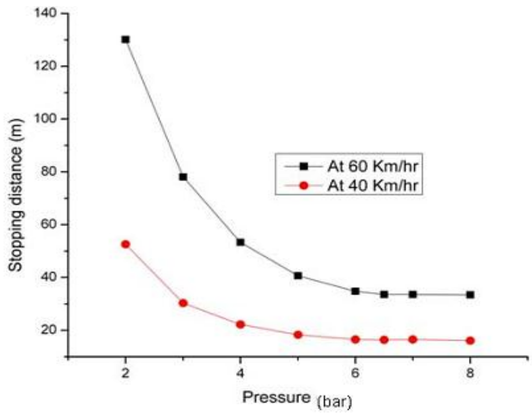

Fig.8 Variation of stopping distance with respect to pressure at different speed

Speed sensitivity test

This test examine the behavior of braking torque, disc temperature and stopping distance when the vehicle is in geared mode and intermediate brake is applied. The final speed of the vehicle is not zero in this test condition, and the test is performed at the operating pressure (6.5 Bar). The test had been performed with the help of standard test schedule which are given below:

Initial speed - 60, 80, 100 km/hr
Final speed - 30, 60, 80 km/hr respectively
Pressure - 6.5 bar for each speed
No. of cycles - 9 (3 cycles at each speed)
Disc temperature - 100 deg C
Blower - ON

Figure 9 shows the behavior of disc temperature and stopping distance at intermediate stopping. The disc temperature is high when the speed of the vehicle is reducing from 110 Km/hr to 80 Km/hr, because more kinetic energy is converted into the heat.

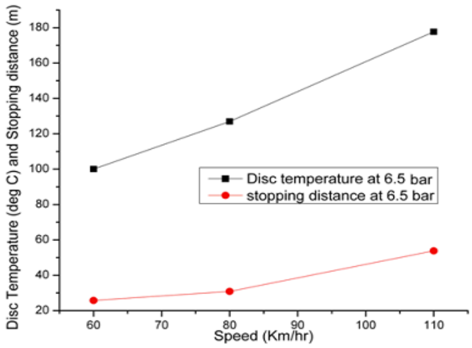

Fig.9 Variation in disc temperature and stopping distance with respect to pressure

High speed performance test

This test examines the behavior of braking torque, disc temperature and the stopping distance with respect to high operating pressure when the vehicle is running at high speed and stop suddenly to zero speed. The test was performed with the help of standard test schedule which is given below:

Initial speed - 90 and 100 km/hr
Final speed - 0 km/hr
Pressure - 6, 6.5 and 7 bar for each speed
No. of cycles - 18 (3 cycles at each pressure corresponding each speed)
Disc temperature - 100 deg C
Blower - ON

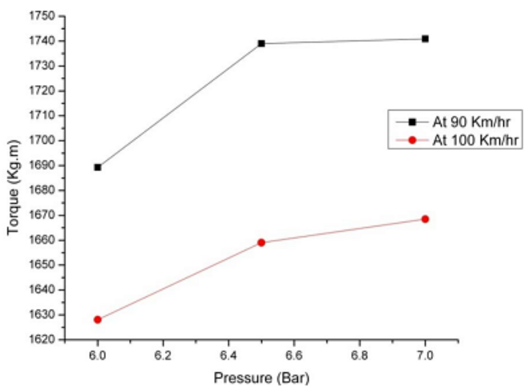

Fig.10 Variation of torque with respect to pressure at high speed

When the speed of the vehicle is constant and operating pressure is increasing then output torque will also increase. At higher speed the output torque is lesser as compare to the lower speed (Figure 10) because at higher speed more heat will generate which reduce the coefficient of friction between disc and pad.

The temperature of the disc will be high at higher speed and higher operating pressure due major loss in kinetic energy. It is clear from the Figure 11 that disc temperature is high at high speed and high pressure.

The stopping distance depends upon the braking torque and braking torque depends upon the applied pressure. It is clear from the Figure 11 that the stopping distance is almost constant with the variation in pressure of 1 bar.

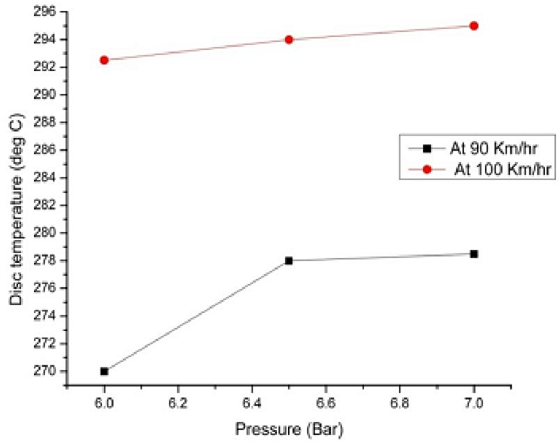

Fig. 11 Variation of disc temperature with respect to pressure at high speed

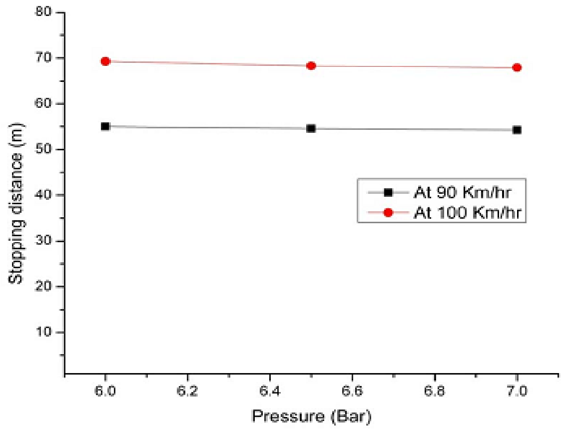

Fig.12 Variation in stopping distance with respect to pressure at high speed

Conclusions

In this research work friction characteristics of Volvo disc brake have been analyzed using Full-scale inertia dynamometer. The following conclusions can be made from this research work.

- The effect of applied braking pressure on coefficient of friction shows Volvo disc pad sensitivity towards pressure.

- With increase in pressure & speed, decreased due to fact that with increase in pressure real area of contact increases excessively and disproportionately as polymeric materials (disc FMs) are visco-elastic.
- Increase in speed brought more frictional heat which easily caused to go down as it was highly temperature sensitive.
- The stopping distance depends upon the braking torque and deceleration rate, higher braking torque and higher deceleration results in lesser the stopping distance.
- The disc temperature is high when the speed of the vehicle is reducing from 110 Km/hr to 80 Km/hr, because more kinetic energy is converted into the heat.
- At higher speed the output torque is lesser as compare to the lower speed because at higher speed more heat will generate which reduce the coefficient of friction between disc and pad.

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