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VARIATIONS IN FRICTION MATERIAL ELASTIC PROPERTIES RESULTING FROM PERFORMANCE TESTS

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ABSTRACT

The objectives of this paper are to measure the dynamic modulus, its dependence on pre-load, spatial uniformity and temperature dependence for various friction material formulations and platforms. These baseline test results are compared with conventional compressibility test data. A total of 56 pads, five different formulations and six different platforms, are analyzed prior to performance testing. A subset of these pads is then subjected to various performance tests. The performance tests include J2521 as well as more aggressive, TI1160 and DM890 protocols. The characteristics of the same pads are then re-measured to quantify the irreversible changes in modulus as the result of performance testing. The magnitude of the variation in dynamic modulus, pad spatial uniformity, and pre-load dependence as the result of performance tests is quantified.

INTRODUCTION

Dynamic stiffness in friction materials is believed to play an important role in determining the noise performance of braking systems[1-6]. This test data is incorporated into simulation models used to predict NVH performance. Although considerable effort has been devoted to characterizing stiffness prior to testing in the field or on a dynamometer, much less effort has been expended in monitoring the spatial uniformity of the out-of-plane modulus and how the elastic properties are altered by temperature or repeated loading as a consequence of the performance tests. Unlike the various structural components which are comprised of metals, the friction material may evolve and be irreversibly altered with brake application and use. In this study we use ultrasonic methods to determine the dynamic modulus, preload dependence and spatial uniformity of brake pads prior to and after various dynamometer performance tests.

METHODOLOGY

The iETEK instrument is used in this study to determine the dynamic modulus, pre-load dependence and uniformity of brake pads. This method follows directly from the ETEK instrument which has been used for a number of years to destructively measure elastic and engineering constants in friction materials.[8] Overarching advantages of the iETEK method are: 1) the method is non-destructive so that elastic properties can be measured prior to, and after performance tests and 2) the method measures friction material properties directly.

The details of the ultrasonic method used by the ETEK and iETEK have been described previously.[6,7] The ultrasonic technique uses precise timing of shear and longitudinal waves to measure propagation speed of short, high frequency, ultrasonic pulses in the friction material. The ETEK uses vibrations in the low MHz regime, sub-micron strains and zero net stress. Modulus is determined through precise measurements of time-of-flight (ToF) of a propagating ultrasonic wave. ETEK measures both in-plane and out-of-plane Young's and shear modulus, employs pre-load up to 5 MPa and can be operated over a temperature range from ambient to 325°C. The ETEK has been used for a number of years as a destructive test method to measure both the in-plane as well as the out-of-plane elastic properties of anisotropic friction materials.

More recently, ultrasonic methods, based on the ETEK, have also been used to non-destructively measure the uniformity, non-linear properties, and out-of-plane modulus in as-manufactured brake pads. This work has resulted in the development of the iETEK instrument which is specifically designed for rapid measurement of the dynamic modulus in as-manufactured pads. The iETEK method can be used on small samples as well as full-size, as-manufactured components and is commercially available. Figure 1 shows a typical through-transmission ETEK and iETEK configuration used for the out-of-plane dynamic modulus measurement.

a)

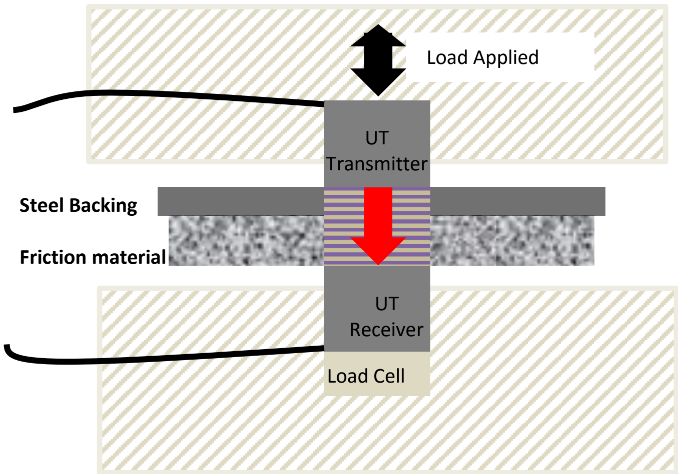


Figure 1. ETEK and iETEK through-transmission configuration for out-of-plane measurement.

Using the iETEK, modulus data is recorded as a function of load and displayed in real-time on the monitor. Samples are subjected to preloads ranging from 100 N to 800 N at a fixed loading rate of 30 N/s. Data can be recorded at a single pre-load or continuously recorded for load-unload cycles so that any hysteresis in the modulus data can be quantified. Measurements are carried out over a region of the pad corresponding to the "footprint" of the sensor which is 15 mm in diameter. Multiple measurements can be made to determine the pad spatial uniformity. Typical iETEK data for three load/unload cycles is shown in Figure 2b. The data is recorded continuously for both the load and unload directions. Hysteresis is sometimes observed with the unload condition generally exhibiting a higher dynamic modulus. Figure 2c shows the spatial variation of the modulus measured at a single load of 800 N for six different measurement positions (see sketch Figure 2d). Figure 2c compares the variation for two different pads of the same formulation.

For the initial phase of this study the dynamic modulus of various friction material formulations have been measured at ambient temperature and at a pre-load of 700N corresponding to pressure ~ 1.7 MPa Subsequently, the previously measured pads are subjected to various performance testing protocols, i.e. TI1160, DM 890, & J2521. The properties of pads are re-measured and compared with the values obtained in the pre-test condition. Additionally, controlled laboratory heating experiments are conducted to measure the variation in modulus on heating.

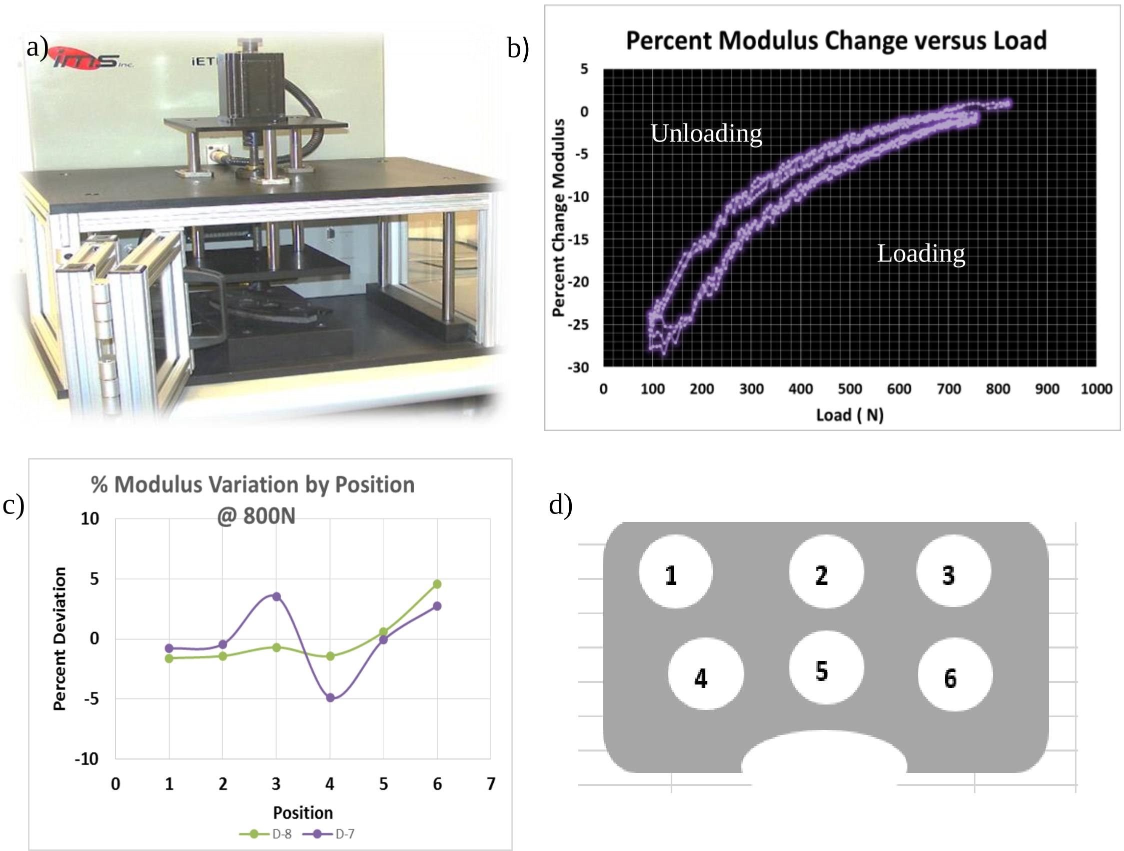


Figure 2a) iETEK; b) typical, out-of-plane modulus data measured as a function of pre-load; c) spatial variation of modulus as a function of position: d) sketch showing the location of the measurements in 2c.

All dynamic modulus data presented in this report measure the properties of the friction material/underlayer combination. The influence of the steel backing and noise shim, if present, have been removed from the data. The iETEK measurement is based upon precise measurement of the ultrasonic propagation speed within the composite brake pad. This involves measurement of the time-of-flight, ToF, through the friction material/underlayer, the steel backing, and the shim. In order to extract the modulus estimate for the friction material/underlayer combination one must correct for the ToF in the steel and the shim. For the steel, the modulus and thus the ultrasonic propagation speed is well controlled so only thickness variations influence the correction factor. Due to the high velocity in the steel, there is only a slight dependence on the steel thickness. A 100 micron error in thickness measurement yields only a 0.5% error in modulus.

For shims there are two contributions to the error, the thickness and the velocity of the shim. Experimentally one can estimate the correction factor by measuring the pad with the shim in place and measuring the same pad after removal of the shim. The difference in propagation time is attributed to the shim. This yields estimates of the shim velocity ranging from 500 m/s to 700 m/s. For those pads where this measurement was possible, this "effective" shim velocity was used to correct the ToF data. Figure 3 shows the sensitivity calculations for the error resulting from variations in shim thickness and shim velocity over a reasonable range. Though the shim is thinner than the steel, owing to its slower velocity, it has a greater influence on the modulus error. A 100 micron thickness variation leads to a 2% modulus error and a 10% variation in shim velocity leads to a 2% error in the modulus measurements.

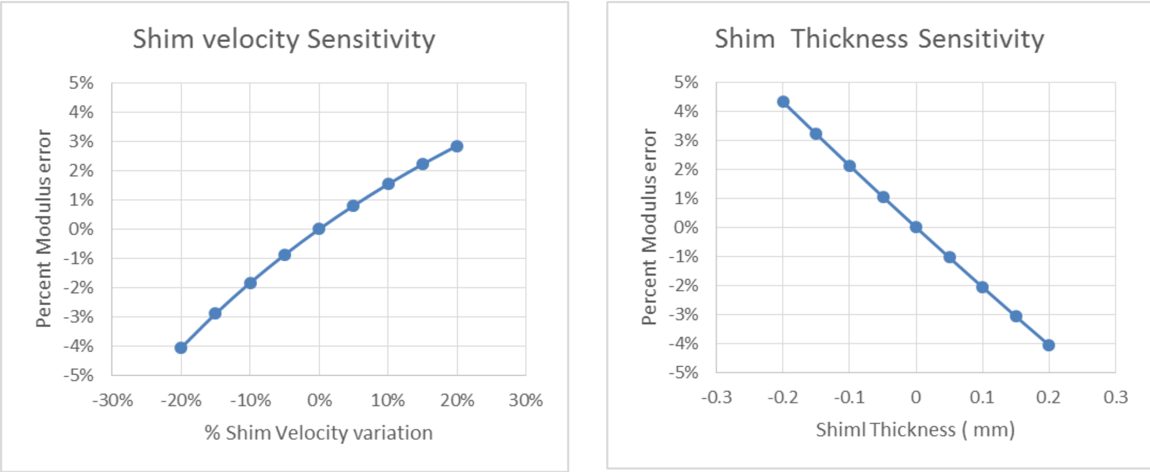


Figure 3 Sensitivity to of i-ETEK modulus measurements to variations in shim thickness and shim velocity.

The performance tests used in this study subject the brake pad to a range of temperatures and pressures. The environment experienced by the brake pad can be broken down into combinations of pressure cycling and temperature history along with mechanical breakdown or wear. With the goal being to assess the impact of usage on subsequent modulus or modulus change, test procedures were chosen that would represent varying levels of pressure history and temperature history. Wear impacts the final geometry of the part and really is only considered in the thickness input for the modulus measurement itself.

Three relatively common brake development dynamometer test procedures were chosen as representative of a range of usage intensity. The mildest test procedure used was the standard SAE J2521 noise test. This procedure does see moderately high ultimate pad temperatures but pressures are generally low and single stop (or drag) energy levels are low. Typical load and rotor temperature measured during a SAE J2521 noise test are illustrated in Figure 4a and Figure 4b. Note that standard fade was included. Figure 4a shows that other than a brief higher temperature excursion during the fade and just a few moderately heavy pressure applies, the bulk of the experience is low pressure (0-3500 kPa) and moderate temperature. Figure 4 shows the rotor temperature, the pad temperature would vary with depth and would be significantly lower than the rotor temperatures particularly with the lower conductivity NAO pads. Of the three test procedures this J2521 would be considered the least aggressive in terms of temperature and loading.

One group of parts, pads from group C, D, E, was only subjected to the aforementioned J2521 test procedure. Modulus measurements were done before and after the test and then those particular pads were finished for the purposes of this study and not used in any further testing.

A second set of parts, Group A and B, was subjected to two different test procedures with modulus measurements taken before and after each dynamometer test. The first procedure of this second group is a BWI TI1160 output performance test which is an adaptation of the SAE J2522 with additional ramp stop sections and FMVSS135 failed power sections. Relative to the J2521 noise test the TI1160 involves a comparatively higher volume of high pressure applies as well as a higher volume of high temperature applies. Many of the stop events are higher energy than the J2521 noise. The second procedure applied to pads from Group A and Group B is a BWI DM890 Thermal Roughness Schedule modelled after a brisk mountain descent schedule. Pressure levels are not as high as the TI1160 but average temperature exposure is the highest of the three test procedures. Five sequences of snubs are performed with each sequence comprised of 15, 120-95 kph or 120-88 kph 3100 kPa snubs run in rapid succession. The loading and rotor temperature profiles for these test procedures are illustrated in Figure 4c and Figure 4d.

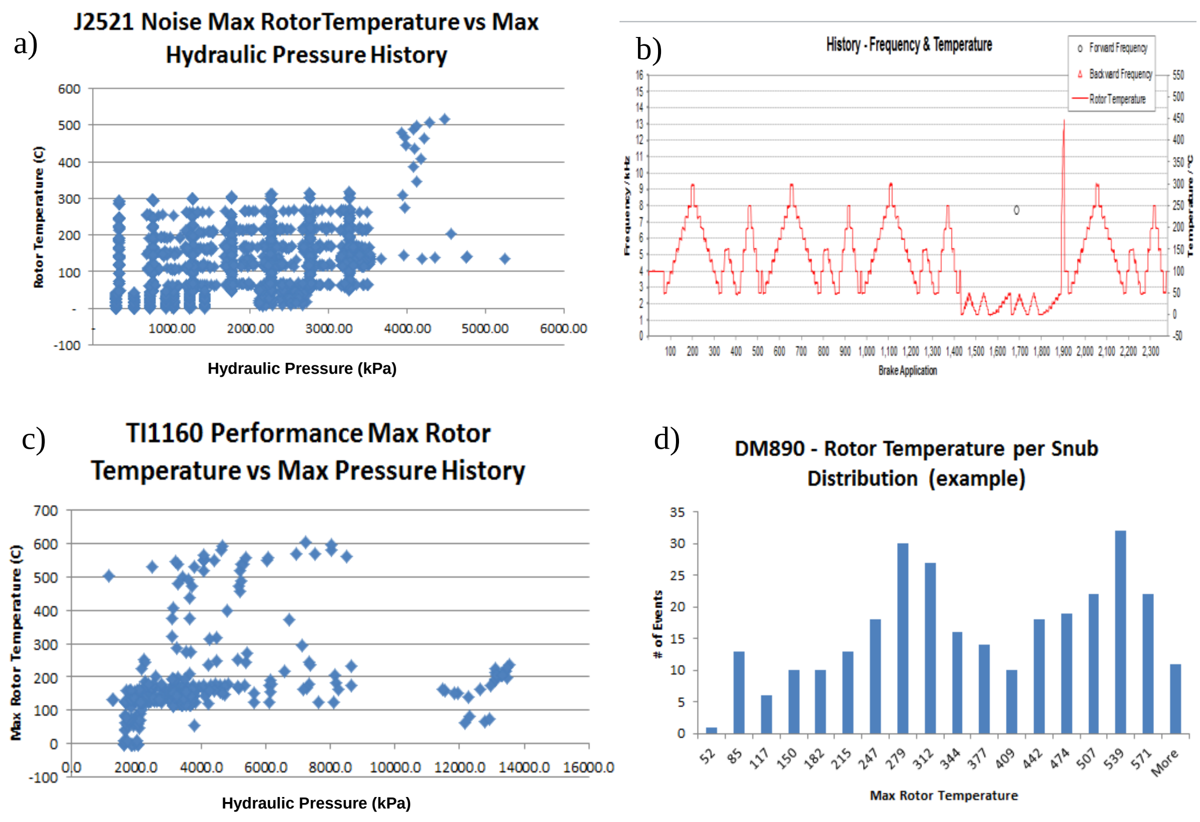


Figure 4. Loading and rotor temperature for three performance tests: a) and b) SAE J2521; c) TI1160; d) DM890.

RESULTS

In this study 11 pad groups, a total of 56 pads, made up of various sizes and formulations were measured on the iETEK. Table I shows an inventory of the pads. In some cases six pads for each material/platform combination were tested. In other cases only four pads were examined. For the smaller pads five positions were measured on the pad while for the larger pads six positions were measured on each pad.

Table I Number of Pads, # of Positions Measured, Platform, and Material

Group	A	B	C	D	E	F	G	H	I	J	K
#Pads	6	6	6	6	6	4	4	6	4	4	4
#Position	5	5	5	5	5	6	5	6	6	6	6
Shims		no							no		
NAO	x	x	x	x		x				x	x
LM					x		x	x	x		
Platform	1x54mm	1x54mm	1x57mm	1x57mm	1x57mm	2x45mm	1x54mm	2x45mm	1x60mm	2x45mm	2x45mm
Material	NAO #1	NAO #2	NAO #1	NAO #2	LM #1	NAO #2	LM# 2	LM# 2m	LM #1	NAO #1	NAO #1

Spatial Uniformity

In addition to monitoring variations in modulus as the result of performance tests it is also of interest to measure spatial uniformity of the pad as it might ultimately influence the NVH performance and may also be an indicator of the uniformity of the manufacturing process. The "footprint" of the ultrasonic sensor is 15 mm in diameter, thus it is possible to make measurements on multiple positions in the pad in order to estimate uniformity. Two templates (5 position or 6 position) were used for the pads depending upon the pad size and location of the spigot holes. Figure 5a shows the 5 position template used on the smaller pads while Figure 5b shows the 6 position template for the larger pads. For the smaller pads, positions 1 and 2 are located on the outer diameter, position 3 in the center of the pad, and position 4 and 5 on the outer diameter. For the six positon template the positions 5 and 6 are on the inner radius of the pad while positions 1 through 4 are on the outer radius with position 2 and 3 located nearer the center of the pad.

a) b)

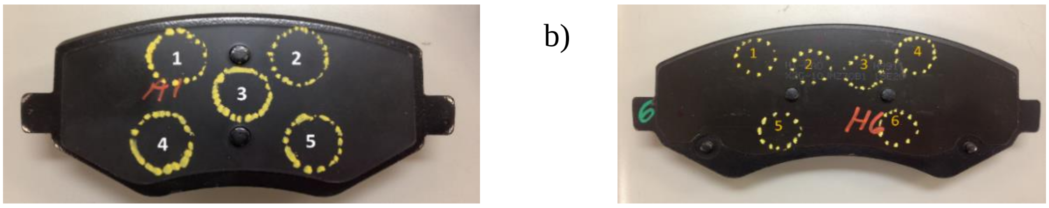


Figure 5. Shows photos of different measurement templates marked on pads with a) 5 or b) 6 measurement positions.

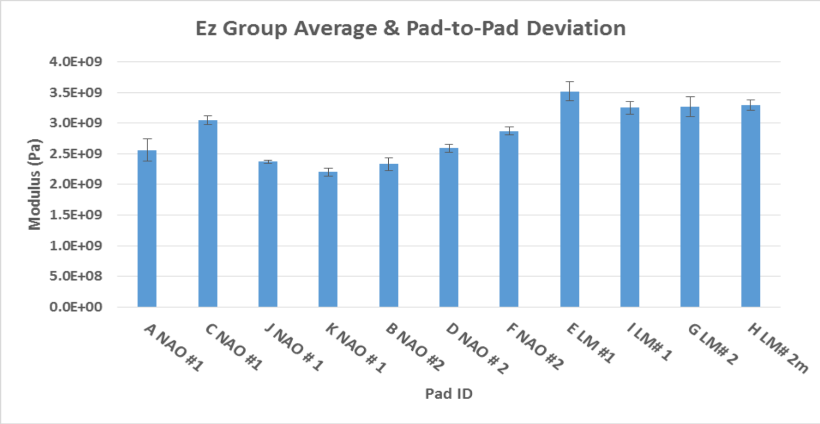
Table II includes the results of the modulus measurements at 700N pre-load on each pad group. In some cases the average is comprised of six pads while in others only four pads were tested. Also listed in Table II are the standard deviation of each pad group and the average of the intra pad variation in modulus.

Table II. Summary of Modulus Data and Variability

Platform	Sample ID	Material	# Pads	Dynamic Ez (Pa)	% Pad to Pad	% intra pad
1x54mm	A	NAO #1	6	2.56E+09	7.22%	6.84%
1x57mm	C	NAO #1	6	3.05E+09	2.35%	3.21%
2x45mm	J	NAO # 1	4	2.37E+09	0.96%	7.57%
2x45mm	K	NAO # 1	4	2.20E+09	3.08%	5.03%
1x54mm	B	NAO #2	6	2.33E+09	4.38%	8.99%
1x57mm	D	NAO # 2	6	2.59E+09	2.41%	4.73%
2x45mm	F	NAO #2	4	2.87E+09	2.20%	13.43%
1x57mm	E	LM #1	6	3.52E+09	4.46%	4.92%
1x60	I	LM# 1	4	3.25E+09	3.14%	3.95%
1x54mm	G	LM# 2	4	3.27E+09	4.85%	7.48%
2x45mm	H	LM# 2m	6	3.29E+09	2.51%	5.36%

As discussed previously, the intra pad variation is comprised of five measurements for the smaller pads and six measurements for the larger pad. In general the intra pad variation exceeds the pad to pad variation. Figure 6 shows the data in Table II in graphical format. For Figure 6a the error bars are the standard deviation of the pad to pad variations while in Figure 6b the error bars are the average intra pad variations for the group. Also shown in Figure 6 are repeat measurements on two of the pad groups, B and D to illustrate the measurement repeatability.

a)



b)

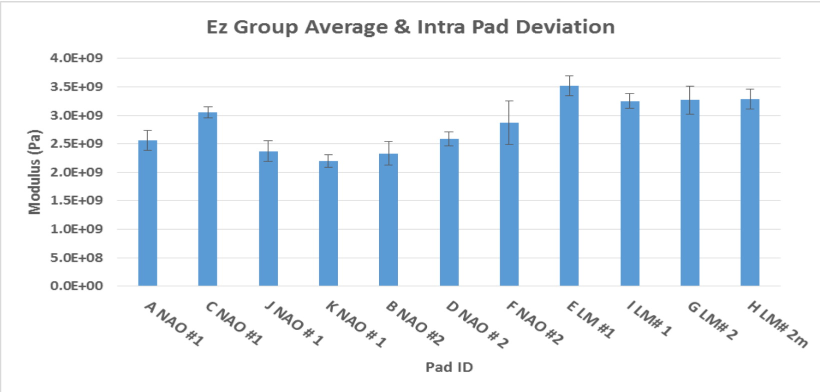


Figure 6 Average Group modulus a) error bars are the standard deviation group average; b) error bars are the average intra pad variation.

For the smaller pads where the measurement template involves measuring two positions on the outer radius, a central position, and two positions on the inner radius, (see Figure 5a) a systematic variation in modulus was observed. Figure 7 shows the average % modulus deviation from the pad mean obtained on all pads from Group B as a function of position. In each case the % modulus variation is normalized to the pad average modulus value. Clearly the central position exhibits a significantly lower modulus for all pads. Figure 8 shows the average trends for pad Groups A, B, C, D, E, and G. All groups except E exhibit lower modulus in the center position.

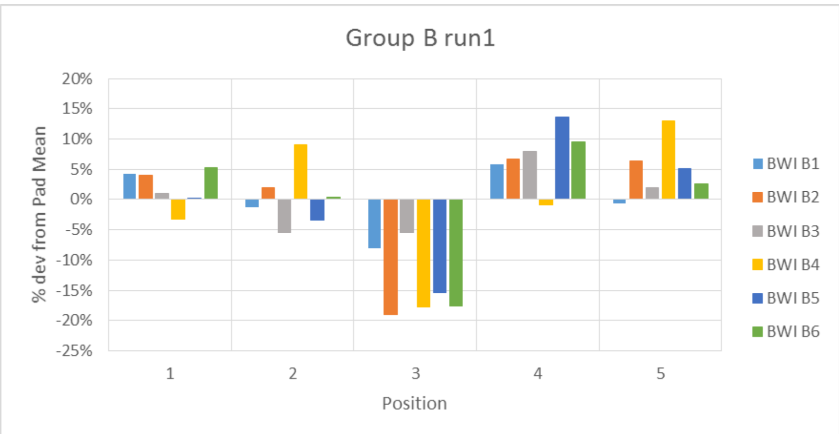


Figure 7. Variation (from Mean) in modulus for six pads in Group B by position

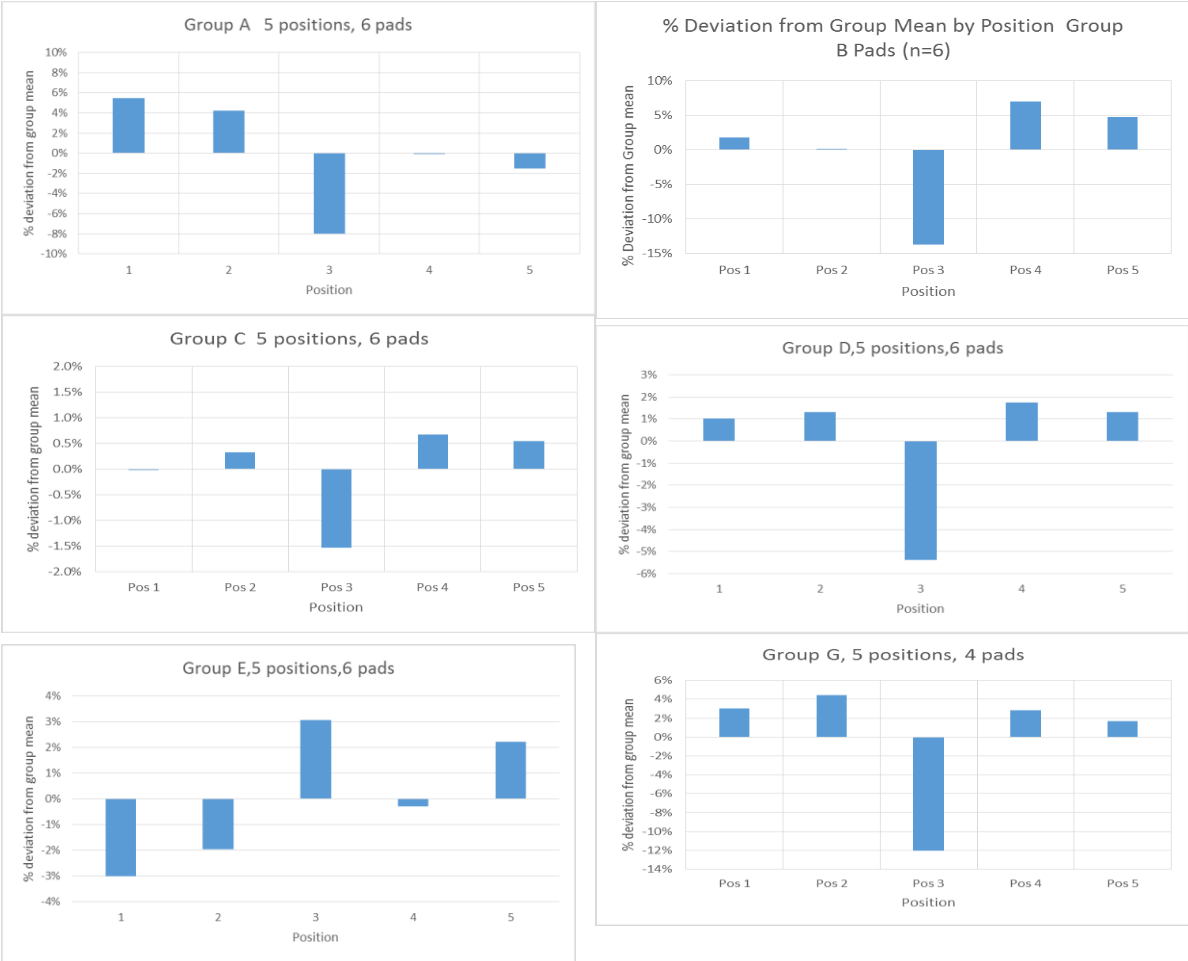


Figure 8. Graphs of variation in modulus versus position for Group A,B,C,D,E and G showing all but one (Group E) having a lower modulus in the center position.

Performance Test Group

The performance tests were only carried out on a subset of the materials analyzed in Table II. For these groups of pads A through H, additional characterization was performed. These tests include the average K6 compressibility data for each group, the dynamic modulus, and density which are group averages. Also shown is the load-dependence of the dynamic modulus and the temperature dependence of the dynamic modulus which were measured on two pads from each group. The load dependence is the % decrease in modulus at 100 N loading relative to the 800 N load. The temperature dependence is the decrease in modulus at 300°C relative to that measured at ambient, 24°C. This temperature dependence was measured on pads which were not subjected to performance testing.

The load-dependence of the all materials in the performance group appears to be comparable. In contrast, there appears to be measureable differences in the temperature dependence for the two different NAO and two LM materials. It is of interest to compare the K6 compressibility values with the dynamic modulus measured on these pads. Figure 9 correlates all the measurements made on each pad. In Figure 9a the K6 is correlated with the dynamic modulus measured at 700 N. In Figure 9b the K6 value is used to extract an effective modulus from the compressibility data. In this case, the line pressure, piston properties, pad thickness, and pad surface area have been used to estimate the modulus from the K6 compressibility data which is correlated with the dynamic modulus measured by iETEK. The correlation is surprisingly good with the modulus derived from K6 data 7.2 times lower than the dynamic modulus data

Table III   Additional characteristics of the Performance Test Group

Sample ID	Material	#	Load Dependence	Temperature Dependence	Dynamic Modulus (Pa)	Compressibility K6 (micron)	Density g/cm³	Perf. Test
A	NAO #1	6	-6.8%	-38.4%	2.56E+09	155.8	2.24	TI1160
C	NAO #1	6	-6.4%	-46.6%	3.05E+09	142.3	2.28	J2521
B	NAO #2	6	-6.3%	-25.2%	2.33E+09	164.2	2.64	TI1160
D	NAO # 2	6	-7.8%	-25.8%	2.59E+09	156.7	2.62	J2521
E	LM #1	6	-5.2%	-44.4%	3.52E+09	132.8	2.63	J2521
H	LM# 2m	6	-7.7%	-30.3%	3.29E+09	110.3	2.82	TBD

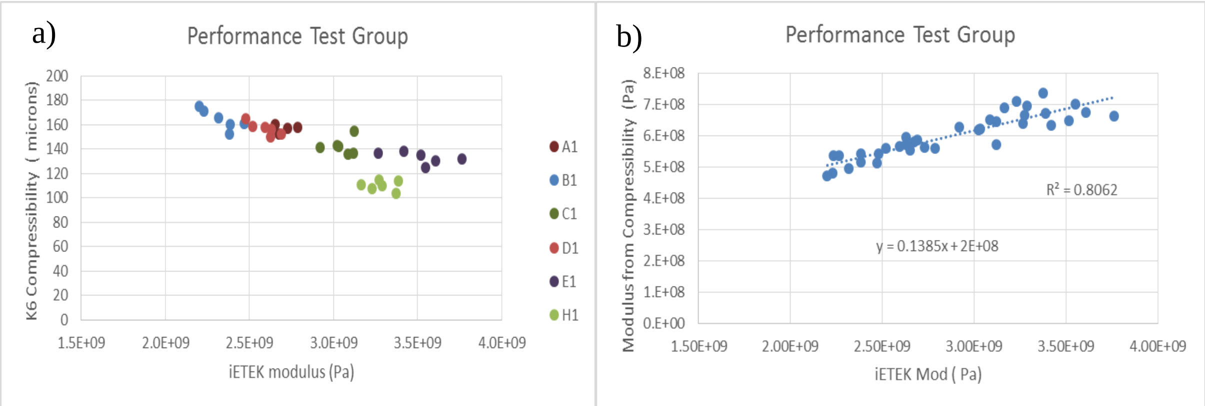


Figure 9a. K6 is correlated with the dynamic modulus measured at 700 N. In Figure 9b the K6 value is used to extract an effective modulus from the compressibility data.

Pre-test/ Post-Test Results

For three pad types, Group C (NAO#1), Group D (NAO#2), and Group E (LM#1) the J2521 noise test has been completed. Table IV summarizes the modulus data obtain both before and after the noise tests on four pads from each group. In each case the iETEK was used to measure the dynamic modulus on five positions in each pad and the average pad value is listed in the Table. The % change column in the table quantifies the magnitude of the irreversible changes in the modulus as the result of the performance test. The average change for the NAO#1 material shows decrease in modulus of 7.89% while the average for the NAO#2 material exhibits a slight increase of 2.64%. The LM#1 materials exhibit the largest irreversible change of 12.17%.

There are two other columns of data listed in Table IV, the preload dependence and the temperature dependence. The dependence on preload is measured on the iETEK by continously monitiring the modulus as the preload is varied from 100N to 800N. The % change relative to the value obtained at 800N is given in the table. In this case only two pads were measured, pad #4 and pad #5 (pad # 5 was not used in the performance tests). The NAO pads show a somewhat greater decrease in modulus with pre-load relative to the LM#1 material. Lastly, the variation in the dynamic modulus, E_z, with temperature was measured in one pad from each group. This measurement was carried out using the laboratory ETEK instrument on pad #5 from each group. Representative temperature test data is shown in Figure 10 for sample D-5 and E-5. The data in the Table is the % variation in modulus measured at 300°C relative to the modulus at 25°C. The variation with temperature is comparable for the NAO#1 and LM#1 pads but is significantly lower for the NAO#2 pad group.

Table IV Pre and Post results obtained on Group A, D, and E pads.

		Initial Modulus Pa	**Post J2521 Noise Modulus Pa**	**% change**	**Pre-Load Dependence (E(800)-E(100))/E(800)**	**Temp Dependence (E(300)-E(25))/E(25)**
NAO #1	C1	3.08E+09	2.77E+09	-10.19%		
NAO #1	C2	3.02E+09	2.84E+09	-6.00%		
NAO #1	C3	2.92E+09	2.69E+09	-7.95%		
NAO #1	C4	3.12E+09	2.89E+09	-7.39%	-6.42%	
NAO #1	C5				**-7.40%**	**-46.61%**
NAO #1	Average	**3.04E+09**	**2.80E+09**	**-7.89%**		
NAO #2	D1	2.59E+09	2.62E+09	1.18%		
NAO #2	D2	2.69E+09	2.81E+09	4.34%		
NAO #2	D3	2.48E+09	2.47E+09	-0.35%		
NAO #2	D4	2.63E+09	2.76E+09	5.15%	-7.82%	
NAO #2	D5				**-9.78%**	**-25.80%**
NAO #2	**Average**	**2.60E+09**	**2.67E+09**	**2.64%**		
LM #1	E1	3.55E+09	3.14E+09	-11.58%		
LM #1	E2	3.42E+09	2.99E+09	-12.43%		
LM #1	E3	3.61E+09	3.28E+09	-9.16%		
LM #1	E4	3.76E+09	3.18E+09	-15.38%	-5.19%	
LM #1	E5				**-4.91%**	**-44.40%**
LM #1	**Average**	**3.58E+09**	**3.15E+09**	**-12.17%**		

Brake pads from Group A (NAO #1) and Group D (NAO#2) have completed the more aggressive TI1180 performance protocol. After this test, the pad modulus was measured on all four pads of the group and then these same pads were subjected to the most aggressive test protocol, DM890. The test results are tabulated in Table V. For Group A, all four pads were measured after the DM890 test. For Group B only two pads were measured after both testing protocols.

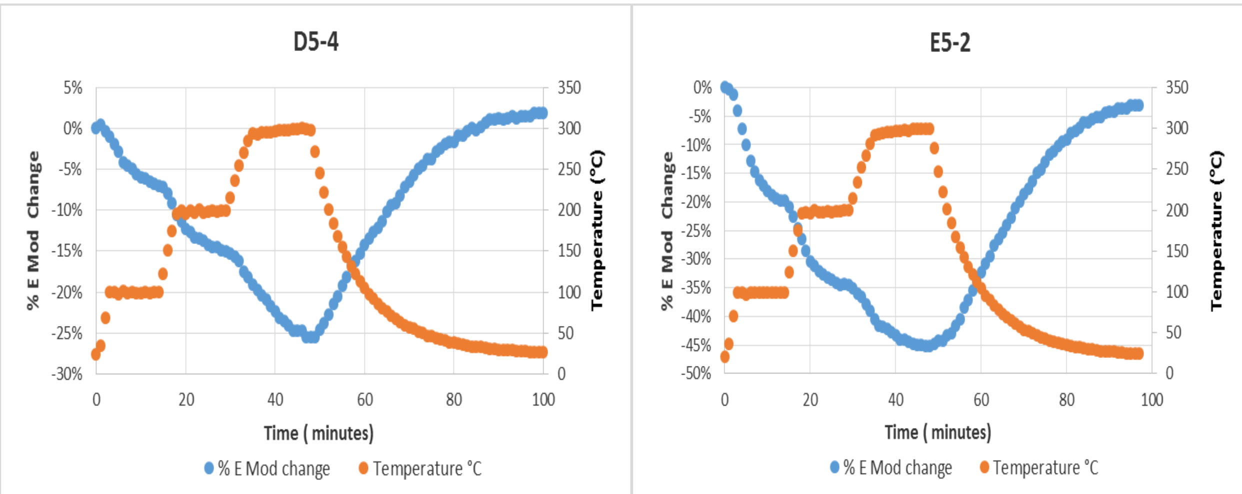


Figure 10. Percent dynamic modulus variation with time and temperature for pad D5 NAO#2 and pad E5 LM#1.

The orange curve shows the stepwise heating profile while the blue curve is the modulus relative to the room temperature value. The combined heating and cooling cycle is 100 minutes.

It is somewhat surprising that the variation in modulus after the TI1160 protocol is quite small. For the Group A, NAO#1 material, the average modulus is reduced only -2.47% as the result of testing. In contrast the same NAO#1 formulation (Group C) showed a modulus reduction of -7.89% as the result for the J2521 noise test. The Group B NAO#2 pads show an average increase in modulus after the TI1160 test but the variability is large ranging from +7.77% to -5.04%. After the DM890 testing the Group A pads experience a significant decrease in modulus with the group average modulus decreasing by -12.06% from the pre-performance test value. The Group B pads also exhibit a decrease as the result of the DM890 test. Although the average modulus reduction is only -4.66% relative to the pre-test condition. The reduction from the post-TI1160 test result is almost -10% for the two pads tested. As in Table IV, we have also included the preload dependence and the temperature dependence of Group A and Group B pads.

Table V. Pre and Post TI1160 and Post DM890 results obtained on Group A and Group B pads.

		Initial Modulus Pa	**IMS Post TI1160 Modulus Pa**	**% change**	**IMS Post DM890 Modulus**	**% change**	**Pre-Load Dependence (E(800)-E(100))/E(800)**	**Temp Dependence (E(300)-E(25))/E(25)**
NAO #1	A1	2.67E+09	2.71E+09	1.21%	2.43E+09	-9.05%		
NAO #1	A2	2.65E+09	2.61E+09	-1.60%	2.29E+09	-13.65%		
NAO #1	A3	2.73E+09	2.69E+09	-1.45%	2.42E+09	-11.39%		
NAO #1	A4	2.79E+09	2.57E+09	-7.83%	2.39E+09	-14.09%	-6.81%	
NAO #1	A5						**-4.95%**	**-38.44%**
NAO #1	**Avg.**	**2.71E+09**	**2.64E+09**	**-2.47%**	**2.38E+09**	**-12.06%**		
NAO #2	B1	2.39E+09	2.57E+09	7.77%	2.32E+09	-2.93%		
NAO #2	B2	2.23E+09	2.30E+09	3.05%	2.09E+09	-6.50%		
NAO #2	B7	2.42E+09	2.26E+09	-6.93%	2.34E+09	-3.52%		
NAO #2	B8	2.63E+09	2.47E+09	-6.13%	2.49E+09	-5.30%	-6.27%	
NAO #2	B5						**-8.39%**	**-25.15%**
NAO #2	**Avg.**	**2.42E+09**	**2.40E+09**	**-0.79%**	**2.31E+09**	**-4.55%**		

CONCLUSION

Dynamic modulus measurements have been made on four different pad formulations from four different platforms on as-manufactured brake pads. The spatial variation in the out-of- plane dynamic modulus is both large and variable. Intra pad variations in the modulus as low as 3.2% and as high as 13.4% have been observed. In some cases the spatial variation in modulus exhibits a specific pattern. Often the center of the pad is more compressible. In addition to measurements of dynamic modulus on each pad, the pre-load dependence and the temperature dependence of modulus has also been measured. For the six pads within the performance test group, the iETEK dynamic modulus data has been correlated with the K6, compressibility data yielding an R^2 value of 0.80.

Testing methods have been formulated that can be used to determine the dynamic modulus both before and after performance tests. Test results obtained before and after J2125 noise testing show that the modulus change is highly dependent upon the formulation. In one NAO material formulation the modulus was reduced by -7.89% while in different NAO formulation the modulus actually increase by +2.5% as the result of testing. It is surprising that the more aggressive testing protocol TI1160 did not lead to larger irreversible modulus variations (relative to J2521). The combined TI1160 and DM890 performance testing protocol appeared to produce the largest decrease in modulus.

It is surprising that significant variation in the dynamic modulus was measured in these studies for the same formulation on different platforms. For example, the "same" NAO#1 formulation was measured for four different platforms and the average group modulus values range from 2.49 GPa to 3.05 GPa. Similarly a second formulation, NAO#2 exhibited a range of values from 2.33 GPa to 2.87 GPa. The reason for this large variation is not known. Although not originally part of this study, methods have been developed to measure the dynamic modulus of as-manufactured brake pads with shims attached. To correct the data for the presence of the shim it is desirable to measure the same pad with and without the shim attached. This provides the necessary time-of-flight correction for the shim. It also provides an estimation of the propagation characteristics of the shim

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