# Unpublished Load and Temperature Dependence of Friction Material Stiffness

Dynamic stiffness in friction materials is believed to play an important role in determining the noise performance of braking systems. It is now recognized that dynamic stiffness is influenced by a host of factors including temperature, pre-load, strain rate and strain/thermal history. These properties may evolve and be irreversibly altered with brake application and use. Considerable effort has been devoted to characterizing pad stiffness prior to testing in the field or on a dynamometer. Much less effort has been expended in monitoring how the stiffness is altered by temperature or repeat loading. Furthermore, the relative contributions of temperature and preload on brake stiffness is often difficult to measure and track with brake use. In this report we use ultrasonic techniques to measure the dynamic stiffness as a function of temperature and preload for several different friction materials.

In order to demonstrate the measurement method on a known material we conduct a series of experiments using a 12 mm thick section of a polycarbonate polymer (tradename Lexan). Lexan is chosen because it has a modulus in the range found in friction materials and has linear, isotropic elastic properties. Measurements are made by sandwiching the Lexan sample between two ultrasonic sensors and continuously recording the variation in the time-of-flight, ToF from the sending transducer through the Lexan plate to the receiver. For elevated temperature work, quartz buffers are used to thermally isolate the sensors from elevated temperature. The Lexan is placed in a small heated stage. The coupling load is applied through the sensor/quartz buffer combination which can be varied between 0.25 MPa and 5.5 MPa.

The typical measurement configuration is shown in Figure 1. In this case the sample is embedded in dry ice and the time-of-flight of ultrasound is monitored continuously as the sample is cooled from ambient to -30°C. In this case, the experiment is carried out in a “pitch-catch” through transmission configuration with sensor located above and below the sample. The ultrasonic sensors are attached to quartz buffers which serve to convey the ultrasound to the cooled sample. Quartz is used because it has excellent ultrasonic transmission characteristics and near zero thermal expansion and velocity variations with temperature. The same configuration can be used up to a temperature of 300°C.

Figure 2 shows the data obtained on the Lexan sample when heated to 100°C. This graphic is somewhat complex but provides a nice way of displaying the combination of temperature sensitivity and the preload sensitivity (i.e. coupling pressure). The temperature profile is indicated by the plot in red which shows a rapid heating of the stage from ambient to 100°C, followed by a hold at 100°C for 1000 seconds and then a slow cool-down to ambient temperature. The blue curve shows the longitudinal modulus. This modulus is calculated using the measured ultrasonic velocity derived from the ToF and the sample density. The longitudinal modulus is defined as:

$$C_{33} = \rho V_L^2$$

Where $\rho$ is the density and $V_L$ is the longitudinal velocity. The longitudinal modulus is related to the Young’s modulus, $E_{33}$ but depends upon the Poisson’s ratio. For Lexan the Poisson’s ratio is ~ 0.39 so for isotropic material such as Lexan, the Young’s Modulus, $E_{33}$, should be approximately 0.50*$C_{33}$. The “book value for the Young’s modulus obtained from static tests is 2.37 GPa. This can be compared with the

Young's modulus determined from the $C_{33}$ value of 2.90 GPa measured at a frequency of 1 MHz. The difference is attributed to the viscoelastic properties of the Lexan.

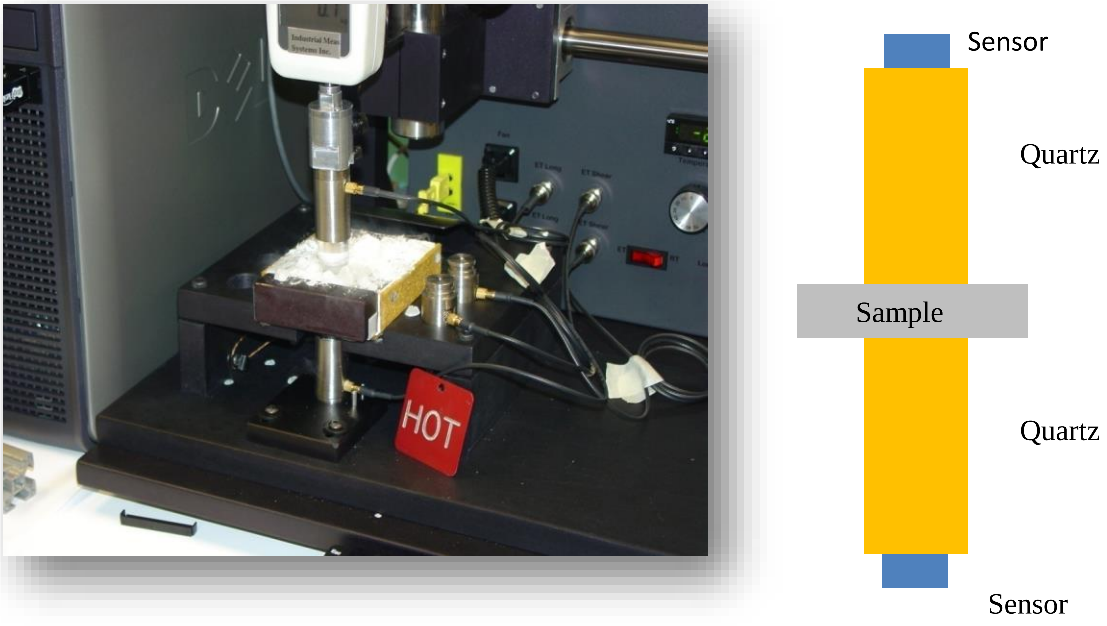


Figure 1 Measurement configuration for measuring ultrasonic velocity over temperature range from -40°C to 300°C.

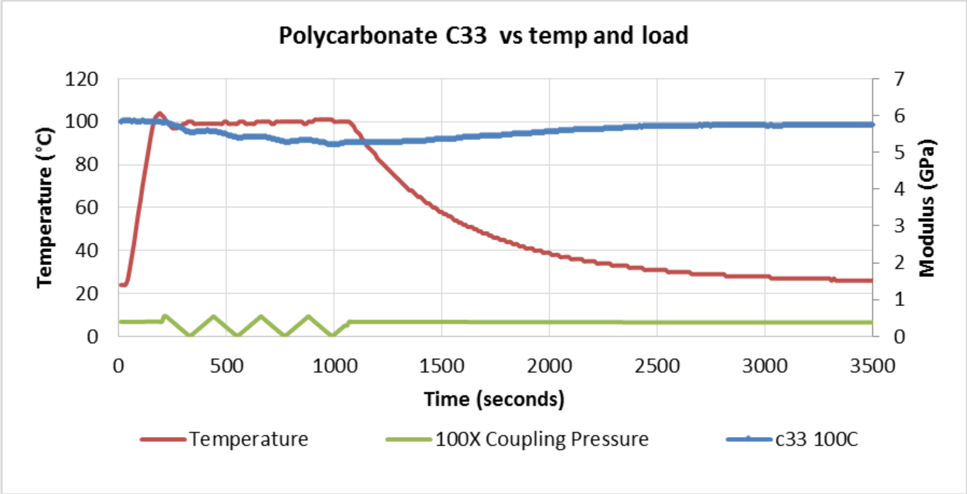


Figure 2. Longitudinal modulus, temperature, and coupling pressure for Lexan plotted as a function of clock time. In each case data is recorded every 10 seconds.

In this Figure, the coupling pressure has been multiplied by 100 so that it can be plotted on the modulus scale. The pressure is held constant at 4 MPa then varied from 0.25 MPa to 5.5 MPa when the temperature is 100°C and then returned to 4 MPa during the cooling. There is a slight monotonic drop in the modulus as the temperature is held at 100°C. This is attributed to the fact that the thermal transport in the Lexan is poor and much time is needed for the sample to equilibrate with the heater. There is also a slight oscillation of the modulus with coupling pressure. This is illustrated more clearly in Figure 2 where we have expanded the modulus scale. The overall variation in modulus with temperature at a fixed coupling pressure of 4 Mpa is 10%. The small modulus variation with coupling pressure (0.5 MPa to 4.0 MPa) at the elevated temperature is on the order of a few percent. The variation in modulus with coupling pressure occurs primarily at loads less than 2 MPa. This small oscillation may be attributed to a variation in the coupling and not a true modulus change in the material.

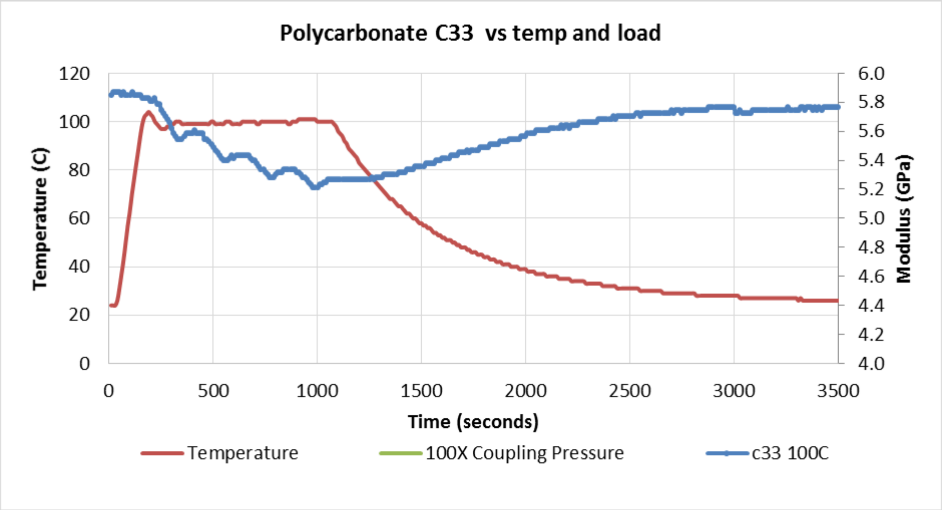


Figure 3. Same as Figure 2 with expanded Modulus scale.

Figure 4 shows a more detailed plot of the modulus of Lexan as a function of coupling pressure obtained in a separate experiment at ambient temperature. As can be seen the variation of modulus with pre-load (coupling pressure) is quite small.

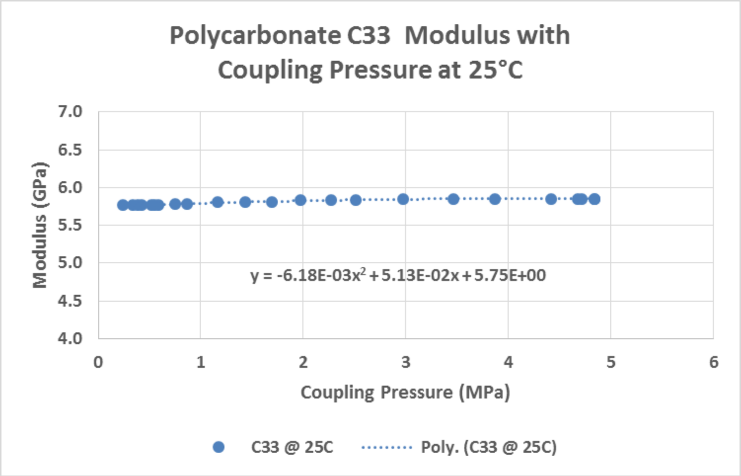


Figure 4 Variation in $C_{33}$ vs. coupling pressure for polycarbonate (LEXAN) at room temperature

These same test methods have been applied to a semi-met friction material. A test piece, 19 mm X 15 mm X 11.2 mm was acquired from a production pad. The steel backing and the underlayer portion has been removed. Ultrasound was propagated through the sample thickness, 11.2 mm, which is the out-of-plane direction in the pad. At ambient temperature and a pre-load (coupling pressure) of 4 MPa, the ToF was 12.19 microseconds. Figure 5 shows the test data plotted in the same format as that shown in Figure 2 for the Lexan sample. In this case, a pre-load of 4 MPa was maintained on the sample while it was heated to 300°C and held for ~ 1000 seconds. After equilibrating at 300°C a loading cycle from 4 MPa to 5.5 MPa to 0.5 MPa to 5.5 MPa to 4.0 MPa was applied. The loading cycle is shown in the blue plot at the bottom of the graph. As before, this is the loading pressure multiplied by 100 in order to appear on the modulus scale. In this experiment, values of temperature, modulus, and preload is plotted as a function of clock time every 15 seconds.

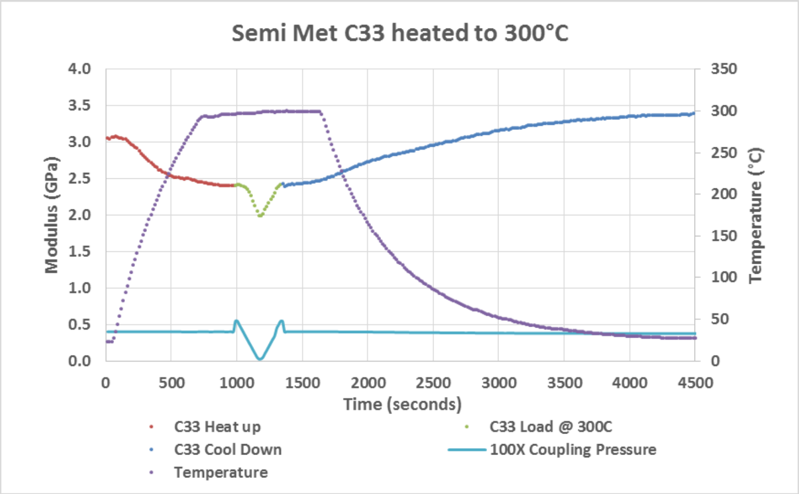


Figure 5 Time history of longitudinal modulus, $C_{33}$, temperature, and pre-load (coupling pressure) for semi-met friction material.

Figure 5 contains information about the variation in modulus with both temperature and pre-load. The plot of the $C_{33}$ modulus data is divided into 3 sections. The red points show the heating portion of the cycle; the green portion in the result of application of the pre-load at 300°C; the blue is the cool down. The pre-load or coupling pressure is plotted in blue at the bottom of the graph. For the heating portion the pre-load is held at 4 MPa while the temperature is changed from 23°C to 300°C. The modulus is reduced by 21.4% going from 3.06 GPa to 2.41 GPa. At 300°C the load is varied from 5.5 MPa to 0.5 MPa. At this temperature the modulus is reduced further to a low of 2.05 GPa at 0.5 MPa. (33% less than the value at ambient temperature). After cycling the pre-load the coupling pressure is restored to 4 MPa and the sample is allowed to cool. Note that the modulus does not return to its original value but has returned to a higher value, 3.39 MPa (10% higher than the original value). The sample has been irreversibly altered by the temperature cycle. A summary of the measurements is shown in Table 1.

Table 1 Summary of the time history of the modulus variations for semi-met sample

| Time | Coupling | Temp | Modulus | |
|---|---|---|---|---|
| s | MPa | °C | GPa | %Dev |
| 0 | 4.00 | 23 | 3.06 | 0.0% |
| 945 | 4.00 | 296 | 2.41 | -21.4% |
| 1155 | 0.51 | 298 | 2.05 | -32.9% |
| 4560 | 3.74 | 27 | 3.39 | 10.7% |

Figure 6 compares the load dependence of the modulus, $C_{33}$, at three different times in the history of the sample. The red curve shows the values obtained initially prior to any heating of the sample. The blue curve shows the load dependence measured at 300°C. The green curve shows the variation measured at 22°C after the heating event at 300°C.

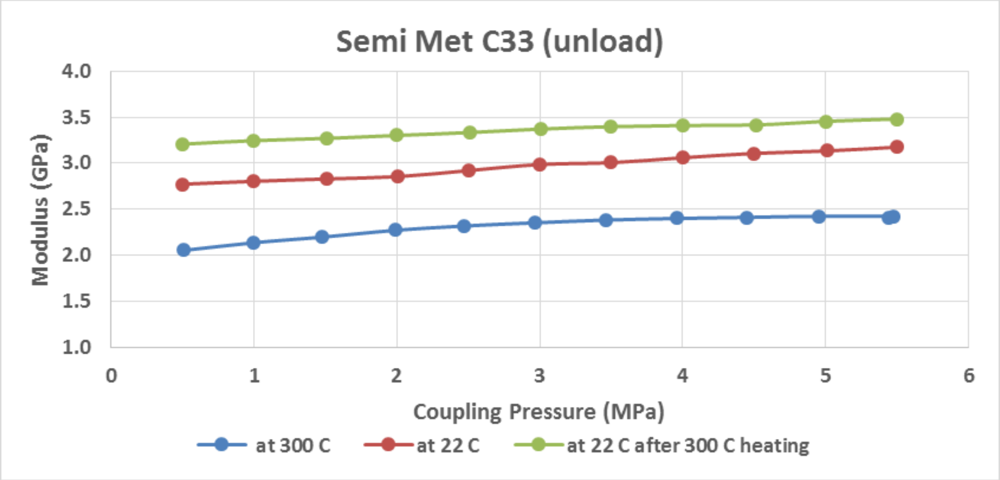


Figure 6 Load dependence of the modulus, $C_{33}$, at three different times in the history of the sample.

Remember that longitudinal modulus, $C_{33}$ is one of the diagonal elements of the elastic constant matrix. It is not identical to the Young's modulus,$E_{33}$, in the thickness direction but should exhibit similar trends with temperature and load.

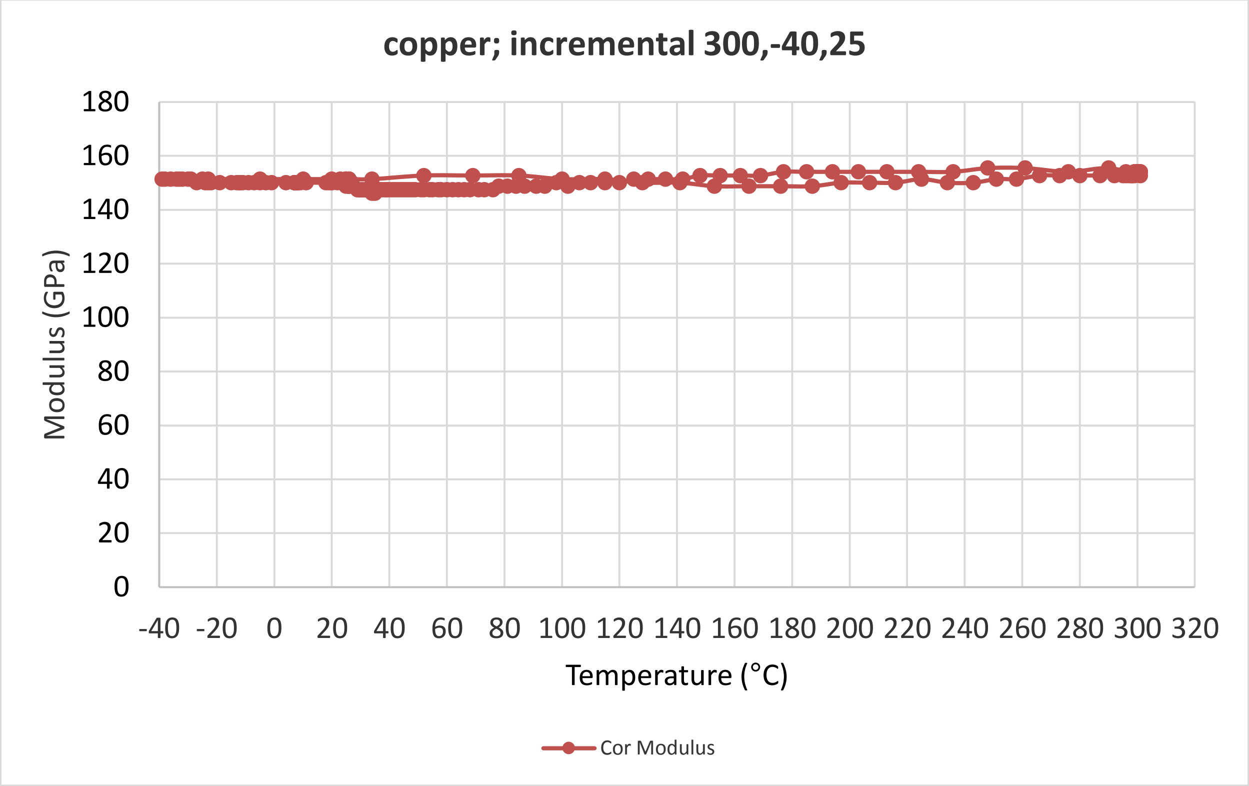
The longitudinal modulus is defined as:

$$C_{33} = \rho V_L^2$$

Where $\rho$ is the density and $V_L$ is the longitudinal velocity. This is related to the Young's modulus, $E_{33}$ but depends upon the Poisson's ratio. For this semi-met friction material the Young's Modulus and the longitudinal modulus are quite similar. $E_{33} \sim .95*C_{33}$.

# Ultrasonic measurements over extended temperature range

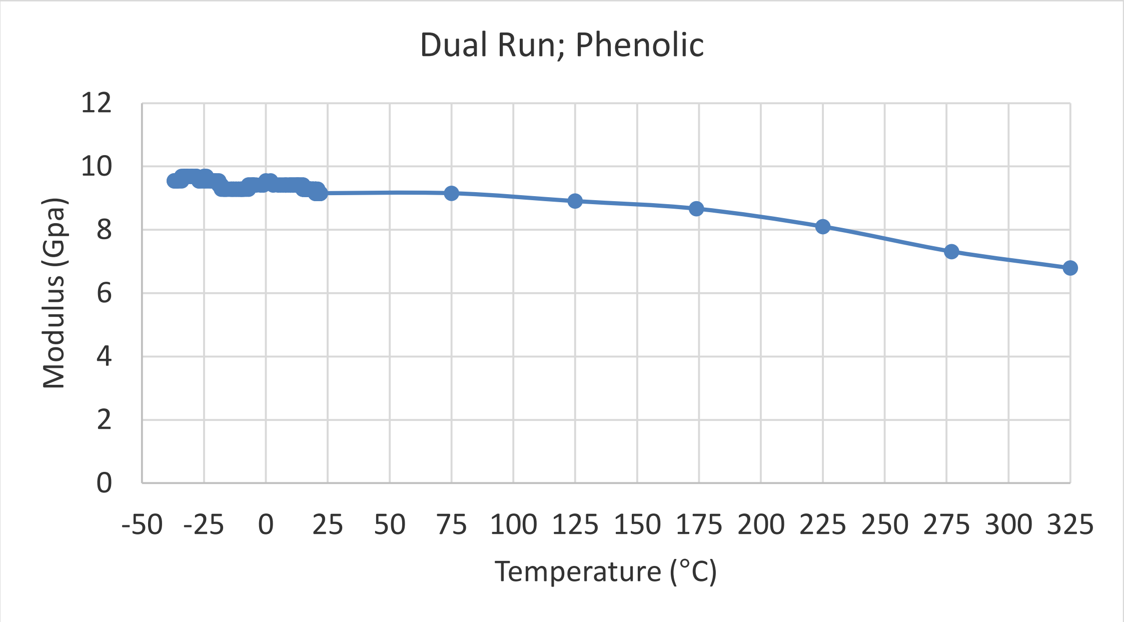
## Unpublished data



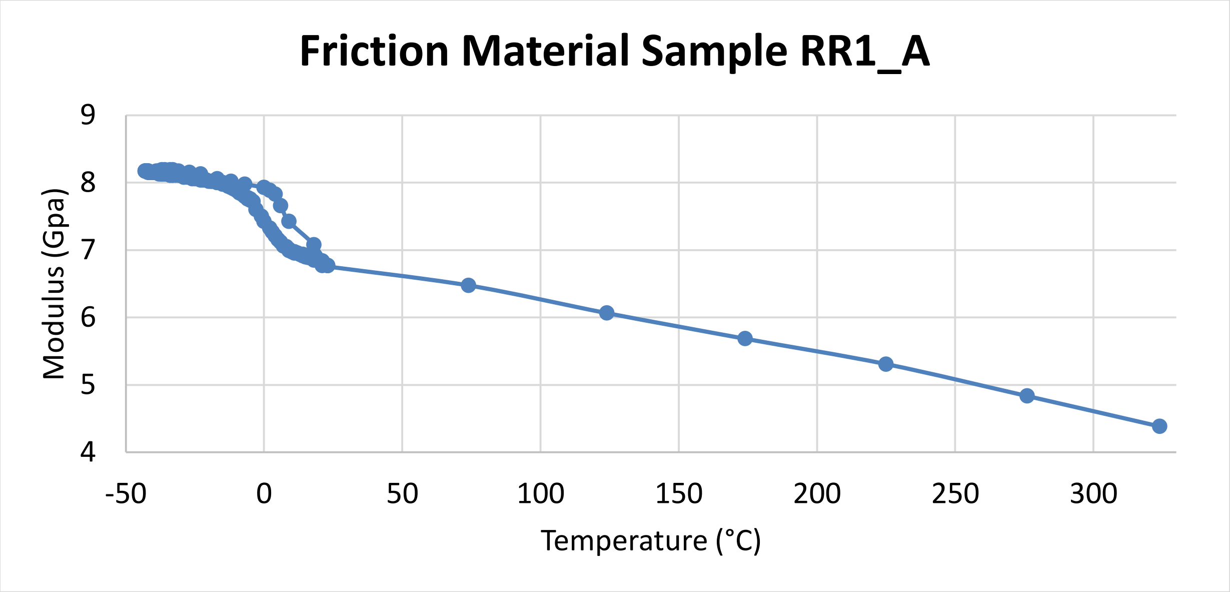
**Measurement of the temperature dependence of modulus of copper sample over the temperature range for -40°C to 300°C. The longitudinal velocity was measured in two steps. Sample was heated from 20°C to 300°C and allowed to cool to 20°C. The sample was then cooled using dry ice to -40°C and monitored during its return to ambient temperature. For copper we expect little variation in modulus over this temperature range. This data is presented to show the stability of the system.**

**The longitudinal modulus is defined as:**

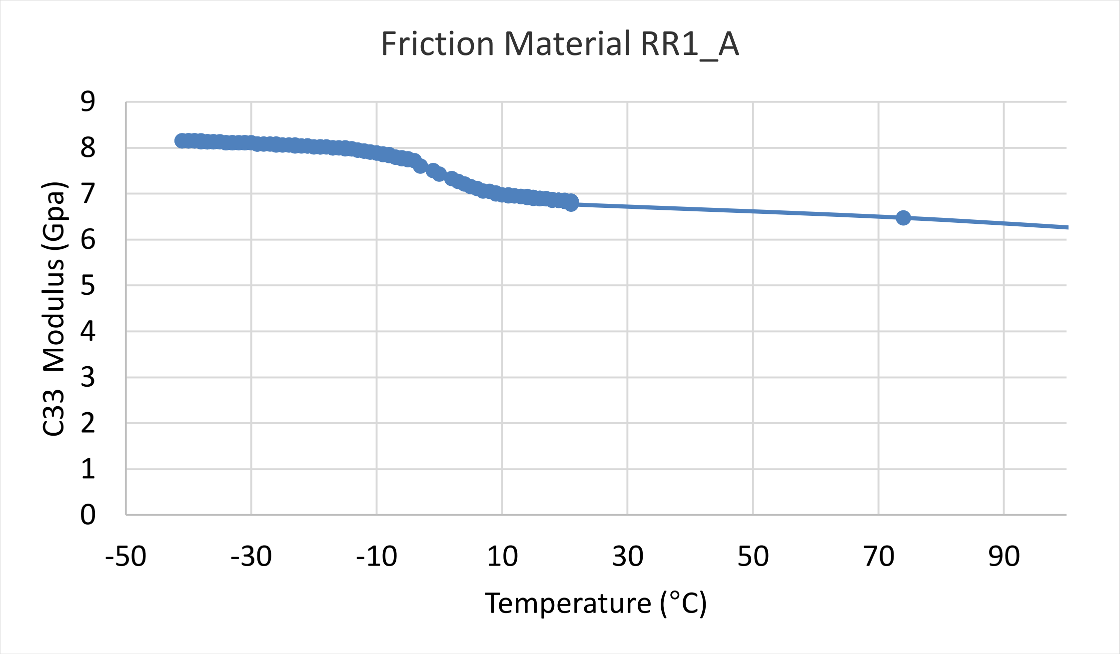
$$C_{33} = \rho V_L^2$$



**Measurement of the temperature dependence of the longitudinal modulus of “neat-resin” phenolic sample over the temperature range for -40°C to 325°C. The sample was first cooled to -40°C. The variation in the longitudinal velocity was monitored continuously (30 second intervals) as the sample warmed to 20°C. Upon reaching 20°C, the sample is heated in a step-wise fashion with set points at 75°C, 125°C, 175°C, 220°C, 275°C and 325°C with a hold time of 200 seconds at each point.**



**Longitudinal modulus of friction material (density 3.18 g/cc). The longitudinal velocity is monitored continuously at 30 second intervals during cool down to -40°C and subsequent warming to 20°C. The data is double-valued in this region because the sample is not equilibrated on cooling but is equilibrated on warming from -40°C. Upon reaching 20°C, the sample is heated in a step-wise fashion with set points at 75°C, 125°C, 175°C, 220°C, 275°C and 325°C with a hold time of 200 seconds at each point.**



**Expanded view of the lower temperature region shown in the previous Figure. The non-equilibrated data has been removed and only the warm-up portion of the data is shown in the range from -40°C to 25°C. In this region data is recorded every 30 seconds. Upon reaching 20°C, the sample is heated in a step-wise fashion with set points at 75°C, 125°C, 175°C, 220°C, 275°C and 325°C with a hold time of 200 seconds at each point.**