

THE UNIVERSITY OF MICHIGAN  
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A CORRELATION OF THE FRICTIONAL AND VISCO-ELASTIC  
PROPERTIES OF PLASTICS AND RUBBER

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A CORRELATION OF THE FRICTIONAL  
AND VISCO-ELASTIC PROPERTIES  
OF PLASTICS AND RUBBER

by

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Abstract:

The coefficient of sliding friction of rubber and plastics varies by amounts ranging from 200% to 800% with variations in sliding speed and temperature. These variations are shown to be related to the visco-elastic properties of the plastics and rubbers. A model of the friction mechanism in rubber is presented. In this model it is assumed that for a particular sliding speed the strain rate in the adhesion bonds is much higher than the strain rate in the substrate. Thus, in the equation for friction force  $F = AS$ , the strain rate that controls the shear strength,  $S$ , of the adhesion bonds is much greater than the strain rate that controls the area of contact,  $A$ . A correlation with rubber using values of  $A$  and  $S$  derived from published data shows a variation in  $F$  that very closely approximates experimental results for  $F$ . No correlation was made for plastics but friction data for six plastics are presented, showing large variations in friction with variations in sliding speed and temperature.

Introduction:

The use of plastics as bearing materials has increased greatly in the past decade. There are several reasons for this. Bearings made of plastics can be made at low cost; they are not seriously damaged by neglect, and they do not seize as do metal bearings when lubrication is impossible, such as in the vacuum of outer space or at cryogenic temperatures.

One major difficulty with plastics as bearing materials is that the coefficient of friction varies considerably with variations in temperature or sliding speed. For example, the coefficient of friction of steel on Nylon 6-6 at  $-40^{\circ}$  C varies from 0.42 at a sliding speed of  $10^{-4}$  cm/sec ( $1$  cm/sec  $\approx$  2 ft/min) to 0.26 at 1 cm/sec (Fig. 1). These sliding speeds are not uncommon in control gear of space devices. Again, the coefficient of friction of Teflon varies from 0.06 at  $22^{\circ}$  C to 0.16 at  $-80^{\circ}$  C for a sliding speed of  $10^{-3}$  cm/sec (Fig. 2), nearly a three-fold difference. It is apparent that, where friction forces and the power losses in bearings must be known with great accuracy, plastics cannot be used without considerable information on their frictional characteristics.

The source of these variations in the friction of plastics with changes in sliding speed and temperature is related to the molecular transformations that take place in the plastics. The same variations have been found in rubber. In fact, the most definitive work has been done with rubber, and the conclusions found in this work have been extended to the plastics. Plastics and rubbers are similar in internal structure, and are subdivisions of a class of materials known as solid

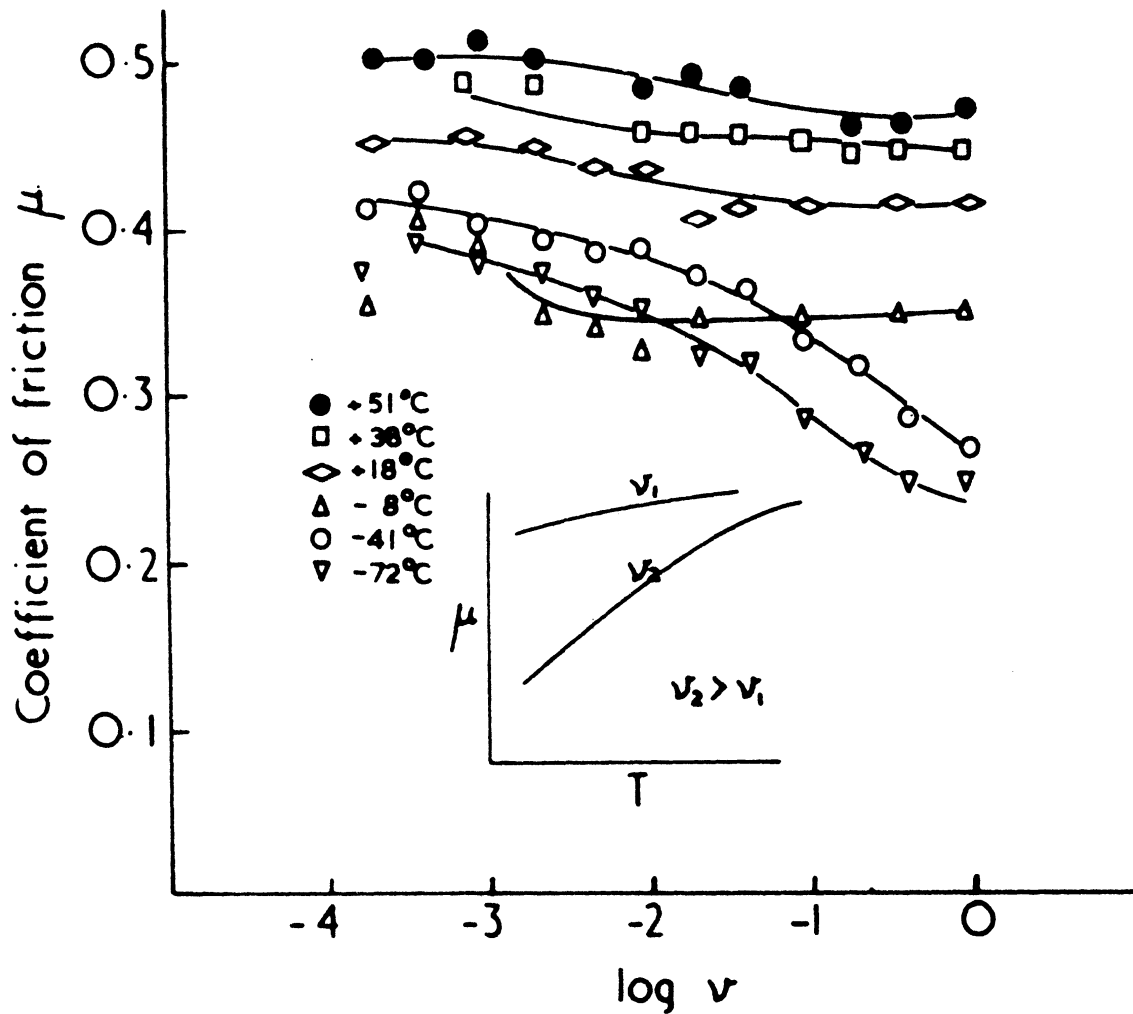


Figure 1. The Coefficient of Friction vs Sliding Speed of Steel on Nylon 6-6. The Applied Load  $W = 900g$ .

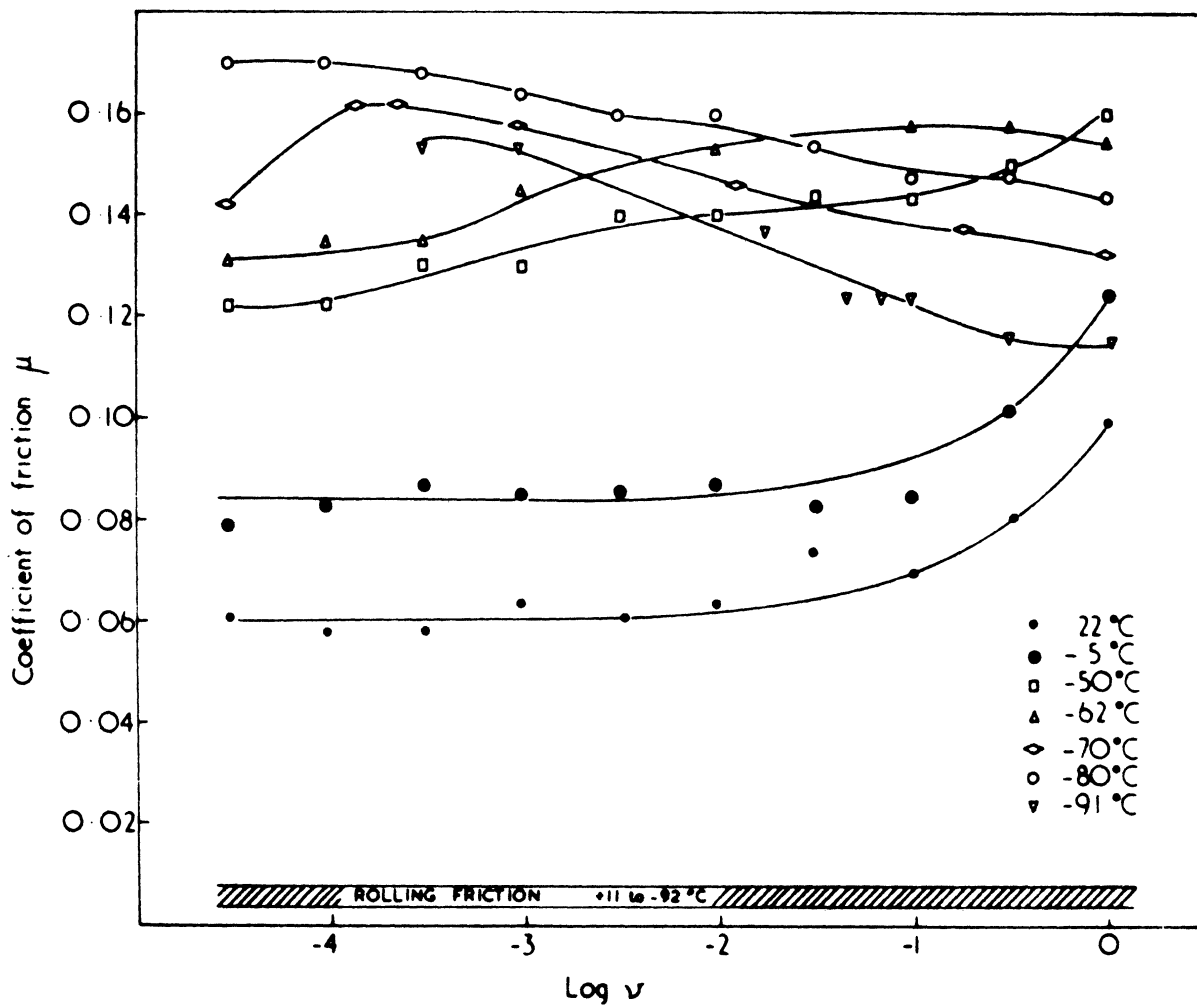


Figure 2. The Coefficient of Friction vs Sliding Speed of Steel on Teflon. The Applied Load  $W = 1800\text{g}$ .

polymers. Certain molecular transformations take place in these polymers which have a drastic effect on the mechanical properties of the polymers. These effects are usually described as visco-elastic properties of the polymers, and sliding friction has been found to be affected by these visco-elastic phenomena.

#### Visco-Elastic Properties of Polymers:

A brief summary of visco-elasticity will aid in understanding the correlation to be discussed. A full and very readable account of visco-elasticity can be found in a book on the subject by Nielsen.<sup>(1)</sup>

Visco-elastic properties are shown in various tests. One type of test is the torsion pendulum test where a torsion pendulum is suspended on a long fiber of the polymer to be tested. Another type of test is the free vibration or the forced oscillation of a "beam" of the polymer. The data from such tests are usually used to calculate an elastic modulus, either the shear modulus  $G$  or the Youngs modulus of elasticity  $E$ , and the internal damping loss of the polymer specimen. These data plotted over a temperature range in the vicinity of the glass-rubber transition in the polymer have the general appearance as shown in Figure 3. The glass transition temperature,  $T_g$ , is the temperature at which a noticeable change occurs in the thermal coefficient of expansion of the polymer, a characteristic temperature for each polymer.

It is usually found that the location of the inflections on the data curves "move" along the temperature axis when the frequency of oscillation of the test is varied. Figure 3 shows the effect of changing the frequency of oscillation from  $f_1$  to  $f_2$ . This frequency (or strain



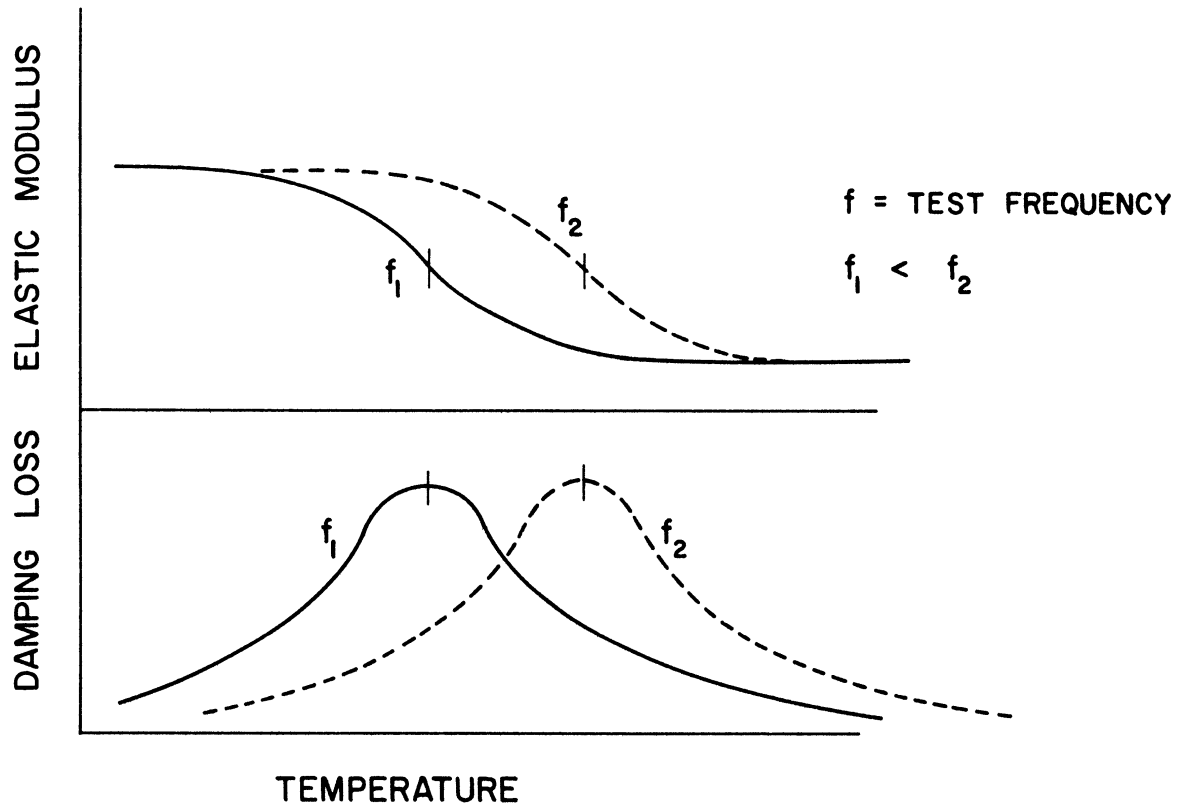


Figure 3. Typical Graphs of Elastic Moduli and Damping Loss versus Temperature.

rate)-temperature interdependence is so regular and general in polymers that a single empirical equation has been found to apply to almost all polymers. This equation is known as the WLF equation<sup>(2)</sup> and is:

$$\log(f_2 - f_1) = \frac{-8.86(T - T_s)}{(101.6 + T - T_s)}$$

where  $T_s$  is  $(T_g + 50^\circ \text{C})$ . A transformation from  $T_1$  to  $T_2$  is accomplished by first setting  $T = T_1$  in the equation to obtain a frequency shift over the temperature range from  $T_1$  to  $T_g$ . The process is repeated by setting  $T = T_2$ . The two frequency shifts are properly added together to get the total frequency shift due to the change of temperature from  $T_1$  to  $T_2$ .

A third type of visco-elastic test was found by Smith.<sup>(12)</sup> He found a visco-elastic effect in the tensile testing of rubbers. He tested the rubbers over a wide range of strain rates and temperatures. For a particular strain rate the fracture tensile stress varies with temperature as shown in Figure 4. Increasing the strain rate moves the transition of the curve to a higher temperature. In fact, Smith found that here again the strain rate and temperature variations are inter-related by the WLF equation.

Visco-elastic test data is not always plotted against temperature. It can also be plotted at one particular temperature over a range of frequency or strain rate. Because of the strain rate-temperature interdependence the data plotted against strain rate will be a mirror image of Figures 3 and 4. Increasing the test temperature will now move the transitions in the curves to higher values of frequency or strain rate.

There are several other manifestations of the visco-elastic

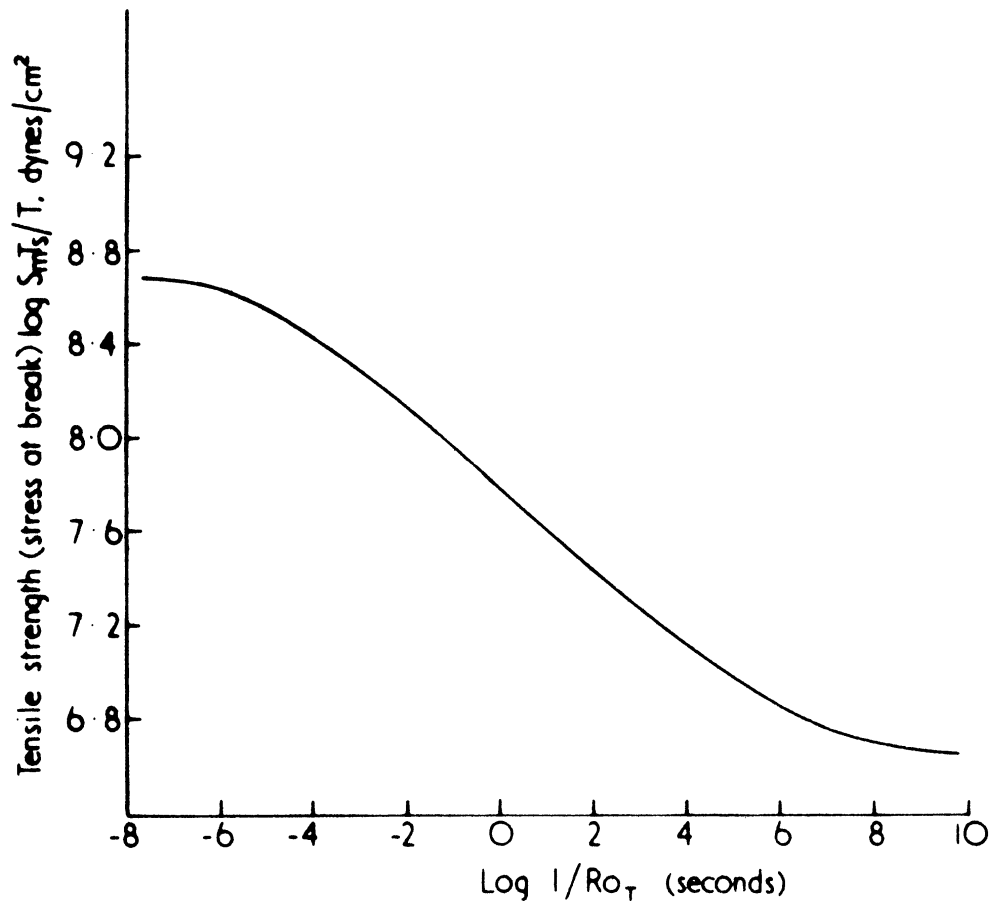


Figure 4. Tensile Fracture Stress versus Tensile Strain Rate for Acrylonitrile Butadiene. (Smith<sup>(12)</sup>)

properties of polymers. However, only the variations in elastic modulus, damping loss, and fracture tensile strength will be referred to in this paper.

In the correlation to follow the most important principle that will be applied is the interdependence of time and temperature. The WLF equation which relates time and temperature in certain mechanical phenomena has been found to apply to most of the polymers. It is presumed that whenever the WLF equation can be used to relate time and temperature in phenomena besides those previously mentioned, such as in friction, then there is evidence of a visco-elastic effect.

#### The Basic Mechanism of Sliding Friction:

Sliding friction usually involves adhesion between relatively small areas of intimate contact between sliding surfaces.<sup>(3)</sup> Sliding of one surface with respect to another requires the tearing apart of the small bonds or areas of adhesion. As bonds in one area break, adhesion occurs at another site. This mechanism predominates in the majority of sliding pairs.

It has been found<sup>(3)</sup> for both metals and for several plastics that the friction force,  $F$ , is directly related to the real area of contact,  $A$ , between the sliding surfaces and a shear strength,  $S$ , which is characteristic of the sliding materials. Thus,  $F = AS$  describes the adhesion component of friction.

In certain cases a part of the sliding frictional resistance may be due to the deformation of one sliding body by the other. The deformation component of friction is equivalent to rolling friction or

well lubricated sliding friction. In these cases adhesion is very small.

The present work was done with a 3/32 inch radius hemispherical ended glass rider sliding on rubber and a 3/32 inch radius hemispherical ended steel rider sliding on plastics. The deformation component of friction might be expected to be significant with these material pairs. To establish the importance of the term some rolling friction results were obtained. The data for Teflon (PTFE) shown in Figure 2 are typical of data found for several polymers. Rolling friction is small as compared with the total friction. Furthermore, variations in rolling frictions with rolling speed and temperature are small as compared with variations in the total friction. This indicates that the large variations with sliding speed and temperature in the total friction are associated with the adhesion component of friction.

#### Visco-Elastic Effects in Rolling Friction:

Even though the deformation component of friction is often small, it should be mentioned that visco-elastic effects appear in rolling friction. Bueche and Flom<sup>(4)</sup> found a visco-elastic effect in the lubricated sliding of steel on polymethyl methacrylate. Later Flom showed a visco-elastic effect in rolling friction of several elastomers<sup>(5)</sup> and thermoplastics<sup>(6)</sup>. Recently, Ludema and Tabor<sup>(7)</sup> have measured the rolling friction of several plastics over a wide range of temperature and applied load. A visco-elastic effect was apparent here as well.

#### Visco-Elastic Effects in the Sliding Friction of Rubber:

Schallamach<sup>(8)</sup> was the first to recognize the visco-elastic effect in sliding friction. He slid rubber on glass surfaces and on

abrasive paper at various speeds and temperatures. He suggested that the frictional sliding of rubber is a rate process based on an activation mechanism. He later expanded on this theory<sup>(9)</sup>, but he did not arrive at a point in his theory that will allow the friction variations to be deduced directly from any mechanical property of the rubber.

The most thorough work showing the relation between sliding friction and visco-elastic properties of rubber was that of Grosch.<sup>(10)</sup> He worked with five rubbers sliding on wavy glass and on abrasive paper. The composite of his original friction vs sliding speed data at 20° C for acrylonitrile butadiene is reproduced in Figure 5. We have verified Grosch's experimental results with the same rubber.

Figure 5 has the same appearance as the visco-elastic loss modulus data. The loss modulus is related to the damping loss, and has the same general shape of curve in the rubbers used in these tests. Grosch found that the friction "peak" for all five rubbers can be translated along the temperature axis by changing the sliding speed from  $V_1$  to  $V_2$ . In fact, the WLF equation can be used here if  $(f_2 - f_1)$  is replaced by  $(V_2 - V_1)$ .

Grosch derived a very interesting relationship from his work. At 20° C the sliding velocity at which friction is the greatest can be taken to be  $V_s$ . Also at 20° C in a vibratory visco-elastic test there is a maximum value of loss modulus which occurs at  $f_v$ . For four of the five rubbers the ratio  $\frac{V_s}{f_v} = 6 \times 10^{-7}$  cm. Grosch takes this ratio to mean that a vibration is associated with sliding, and there is a sequence of adhesional bonds between the sliding surfaces, the rubber jumping locally a small distance before a new bond is formed. Presumably, the

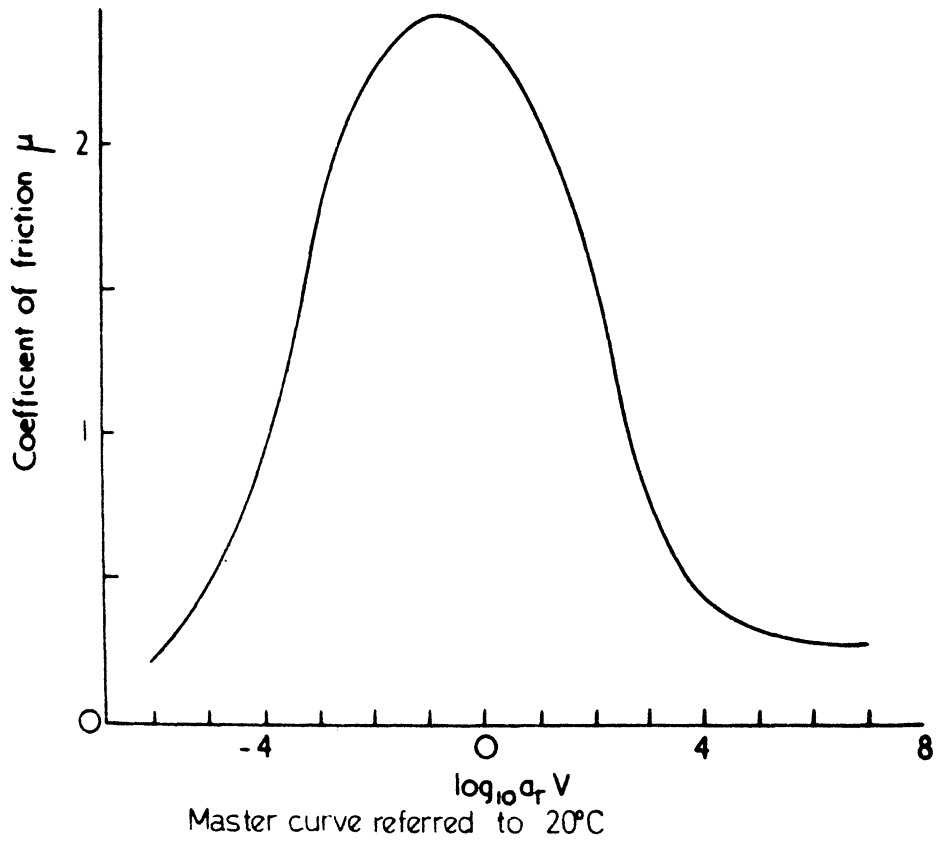


Figure 5. Composite Curve of the Coefficient of Friction versus Sliding Speed for Acrylonitrile Butadiene. (Grosch<sup>(10)</sup>).

bond formation and the release of the bonds are controlled by the activation mechanism of Schallamach.

Bartenev and El'kin<sup>(11)</sup> have also found that the principle of time-temperature equivalence applies to the frictional properties of rubber. They conclude that the existence of the friction peak such as shown in Figure 5 is due to a combination of two mechanisms. At low temperature the friction is controlled by the area of contact. As the temperature increases, the modulus of elasticity of the polymer decreases and the area of contact increases. At higher temperatures the process is controlled by an "adhesion molecular-kinetic" mechanism, which is similar to the activation mechanism of Schallamach. In the theory of Bartenev and El'kin both mechanisms are apparently time and temperature dependent to the same approximate extent. Thus, there exists a friction peak over a wide range of sliding speed and temperature.

#### The Adhesion Theory and Rubber Friction:

The adhesion theory of friction can be applied to polymers as well as to metals. The adhesion theory of friction is described by  $F = AS$  as shown previously. For use with polymers the equation should reflect the large visco-elastic effects in the material in order to account for the large variations in friction.

Both terms A and S can be related to visco-elastic properties of materials. It is only necessary that these visco-elastic terms be properly treated so as to produce the product,  $AS = F$ , where F will have the appearance of Figure 5. This will be the general outline of the argument below.



From the contact stress equations of Hertz it can be shown that the contact area for a hard sphere on a soft flat plate,  $A$ , is proportional to  $\frac{1}{E_c^m}$  where  $E_c$  is a complex elastic modulus of the soft flat plate. In elastic materials such as rubber,  $m = \frac{2}{3}$ . It has already been seen in Figure 3 that the elastic moduli vary with strain rate and temperature. Thus, the quantity,  $A$ , will also vary with strain rate and temperature, but in an inverse manner. Bartenev and El'kin have in effect applied this principle as part of their theory of rubber friction.

The exact nature of the quantity,  $S$ , is less definite, but it is probably related to the shear strength of the polymer. This assumption is not difficult to justify in the case of steel sliding on plastics, for example. It is usually found that a film of the plastic adheres to the steel and thereafter sliding takes place between two plastic surfaces. For glass sliding on rubber there is no direct evidence of a film of rubber on the glass. On the other hand, there is little doubt that the friction of rubber is caused by adhesion. The exact nature of this adhesion is not known. It is therefore assumed that this surface adhesion mechanism is equivalent to the internal bonding mechanism in the rubber. Finally, the nature of the internal bonding of the rubber is reflected in the shear strength and tensile strength of the rubber.

As mentioned previously Smith<sup>(12)</sup> has found a visco-elastic transition in the tensile fracture strength,  $\sigma_F$ , of rubber. According to the above assumption there would then be a visco-elastic transition in the quantity,  $S$ .

The product,  $AS$ , can now be examined qualitatively. Figure 6 is a graph of the two visco-elastic functions,  $A$  and  $S$ , with frequency or

strain rate as abscissa. The curve for A is the inverse of E. When plotted against temperature, the curve for E has the shape shown in Figure 3. When plotted against frequency or strain rate the curve for E is the mirror image of Figure 3. Finally, the curve for A is the mirror image of the curve for E with a height on the log scale two-thirds that of the curve for E. Since the transition in E for rubber often covers three orders of ten, the transition in A will cover two orders of ten.

The curve for S is taken to be parallel with the curve for  $\sigma_F$ . Here the shape will be the mirror image of Figure 4. The data for  $\sigma_F$  from Smith shows that the transition in  $\sigma_F$  covers a factor of one hundred.

Ordinarily, it would be expected that all visco-elastic functions would change simultaneously. Thus, the increase in S would coincide with the decrease in A as shown in Figure 6. Accordingly, the product, AS, is shown as a straight line and the visco-elastic effect is not apparent in the friction force.

A more reasonable assumption is that changes in A and S are not coincident. An essential feature of the mechanism of friction introduced here is that the quantities, A and S, are each affected by different strain rate. The quantity, S, is taken to be a property of the adhesion bonds which are the primary cause of sliding friction. Since the bonds are very small the strain rate in the vicinity of the bonds for a particular sliding speed,  $V'$ , must be very high. Therefore,  $V'$ , corresponds with a value of S at a high strain rate. On the other hand, the quantity, A, is controlled by the mechanical properties of the substrate and not by the bond strength. For a particular sliding speed  $V'$  the strain rate in the substrate is small relative to the strain rate in the

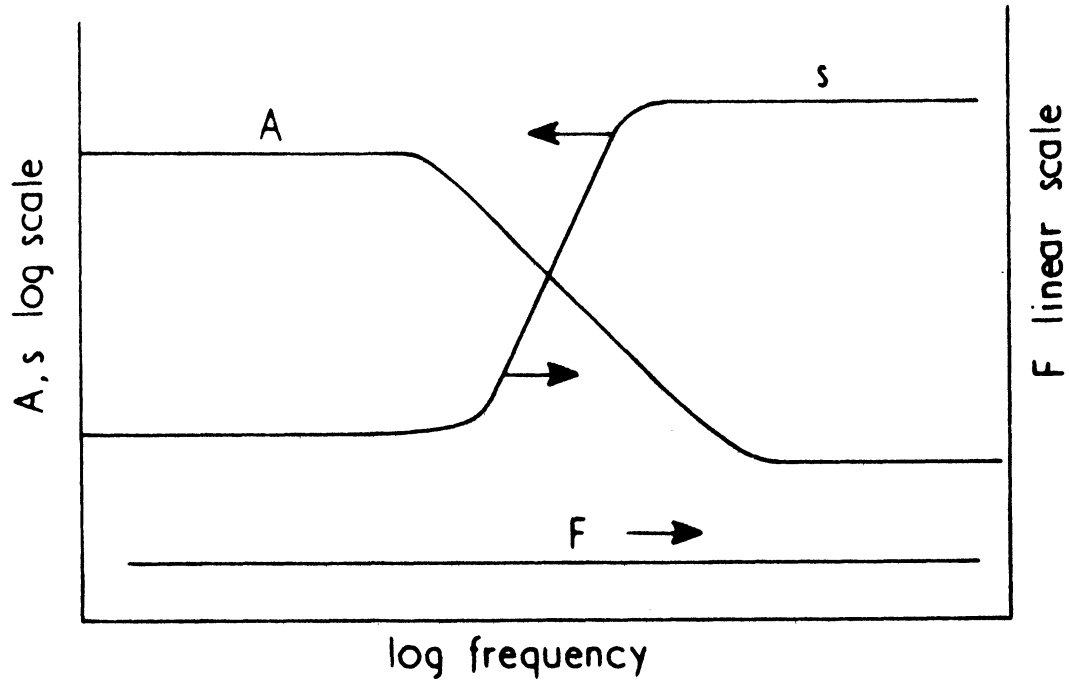


Figure 6. Graph of the Equation  $F = AS$  Where the Transitions in the Curves for A and S are Coincident.

adhesion bonds. Thus,  $V'$  corresponds with a low strain rate value of A.

Figure 7 shows the visco-elastic functions, S and A, plotted with respect to sliding speed. The quantity  $V'$  corresponds with a high strain rate value of S and a low strain rate value of A. The produce, AS, in this case is shown to increase to a high value and decrease again with increasing sliding speed just as Grosch and others have found.

Sufficient data have been found to make one semiquantitative correlation. The material is styrene-butadiene rubber and the curves are shown in Figure 8. The quantity, A, was assumed to be proportional to  $\frac{1}{E^{2/3}}$ . The data for E were taken from Fletcher and Gent<sup>(13)</sup> and from Nielsen<sup>(1)</sup>, pp. 163. The friction data, F, are due to Grosch<sup>(10)</sup>, Figure 7. At 20° C the friction peak occurs at near 5 cm/s, and transforming the data to correspond with the temperature of the data for E(0° C) moves the friction peak to 0.5 cm/s. Then we can adjust the relative positions of the friction curve and the curve for E by using the correlation of Bueche and Flom<sup>(4)</sup>. They found in lubricated sliding which is primarily a measure of indentation or deformation losses that 1 cm/s sliding speed corresponds with 25 c/s in the dynamic visco-elastic test. There is no way of determining whether the position of the transition in the curve for  $\sigma_F$  is properly located. The precise position and the exact shape will depend upon the geometry of the adhesion bonds. However, it is obvious that the curve for  $\sigma_F$  (i.e., S) is shifted with respect to the curve for E (i.e., A) as is also indicated in Figure 7.

#### The Mechanism of Rubber Friction:

Data were available for a correlation for only the one material.

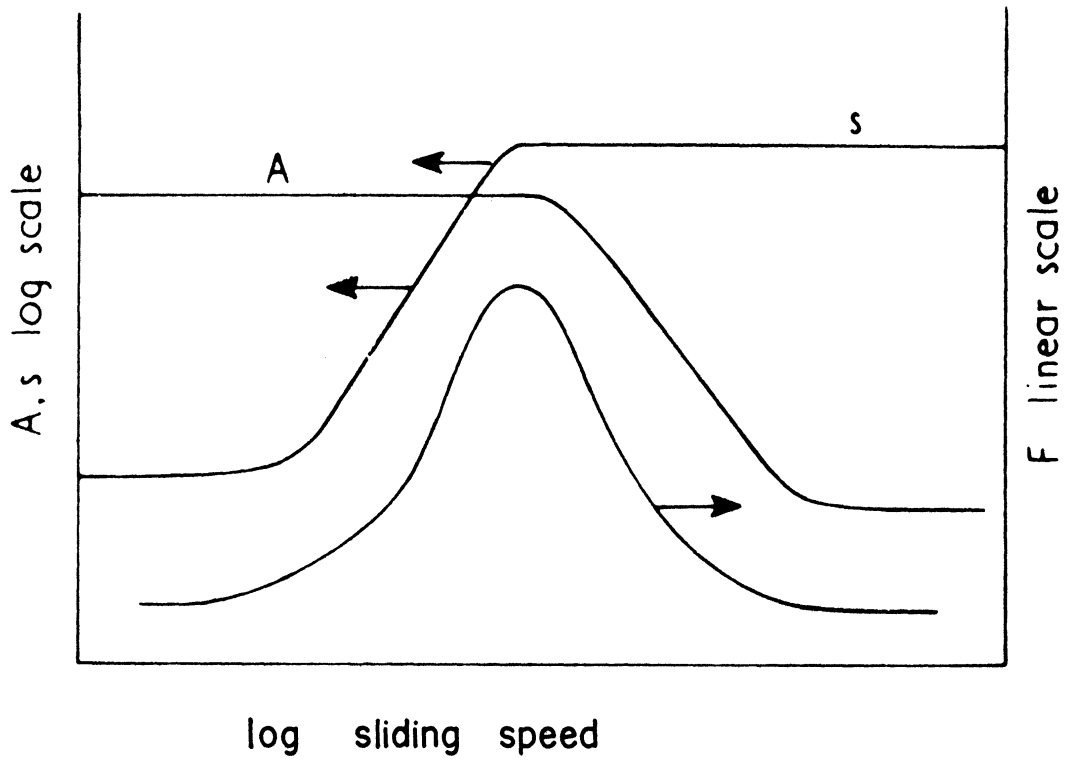


Figure 7. Graph of the Equation  $F = AS$  Where the Transitions in the Curves for A and S Are Not Coincident.

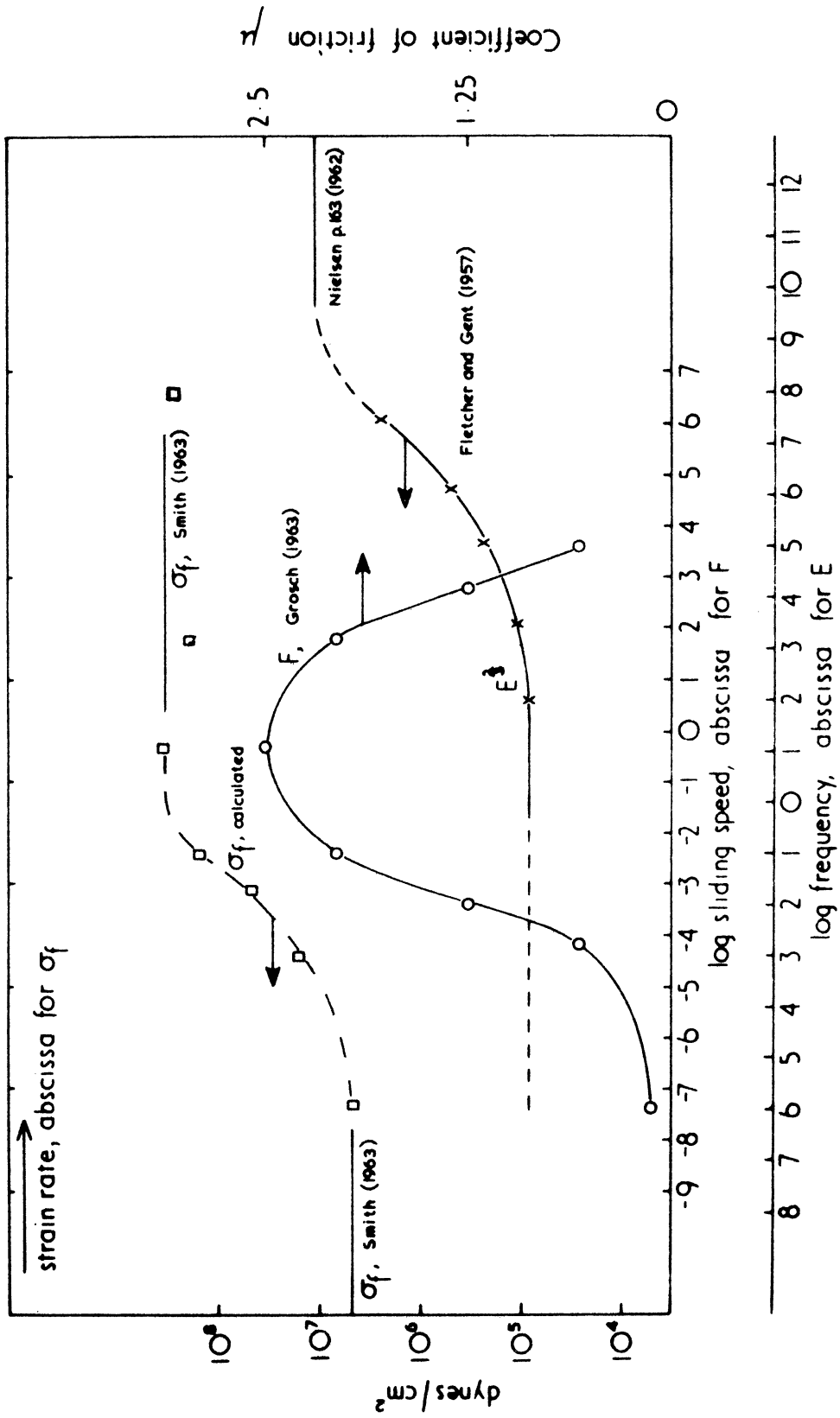


Figure 8. Construction of  $\sigma_f$  from Published Values of F and E.

But the main feature of the mechanism of rubber friction appears. As sliding speed increases the strength of the bonds increases and friction increases. At a still higher speed the area of contact decreases due to an increasing modulus of elasticity of the substrate and friction again decreases. Ordinarily, it would be expected that all visco-elastic transitions would occur at the same time. But in the case of sliding friction the greater strain rate in the fracturing bonds increases  $S$  before the slower strain rate due to indentation brings about a decrease in the area of contact.

#### The Friction of Plastics:

Large variations are seen in the friction of plastics as shown in Figures 1, 2, 9, 10, 11, and 12. Figures 1, 2, and 9 show the coefficient of sliding friction over a range of sliding speed at several temperatures. Figures 10, 11, and 12 are friction data plotted against temperature at two different sliding speeds.

The main feature of all of these data is that a sliding speed-temperature interdependence appears in plastics as well as in rubber. Unfortunately, there are not sufficient data for a correlation as was done with rubber. However, the sliding speed-temperature interdependence can be checked in an approximate manner. For example, take the data for polyethylene in Figure 9. The curve for the test conducted at 60° C can be thought of as being the same data as the curve for 40° C only the curve for 60° C is located at a higher sliding speed than is the curve for 40° C. Also the 40° C curve can be seen to be shifted to the right of the 19° C curve, etc. Or again in the data for poly-cyclohexyl- $\alpha$ -

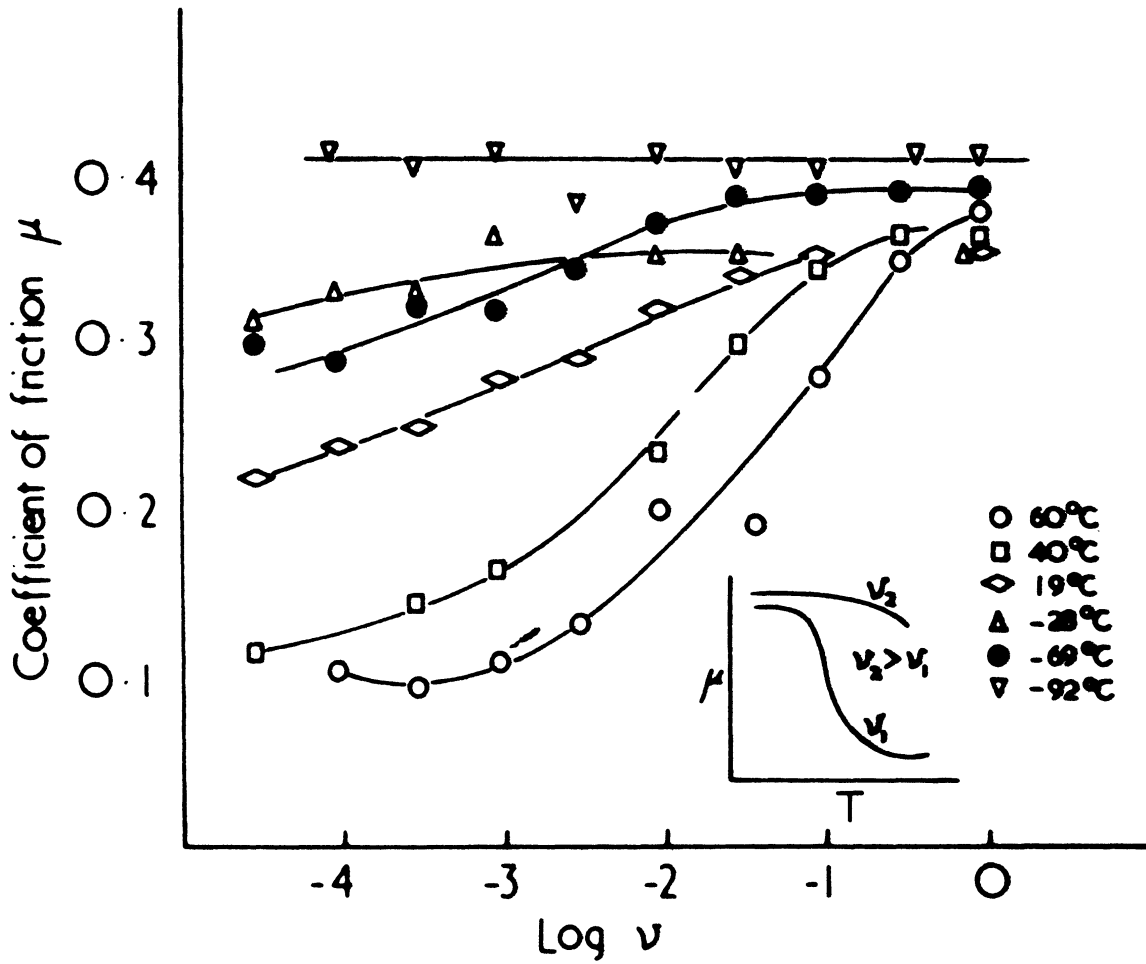


Figure 9. The Coefficient of Friction versus Sliding Speed of Steel on Polyethylene. The Applied Load  $W = 900g$ .



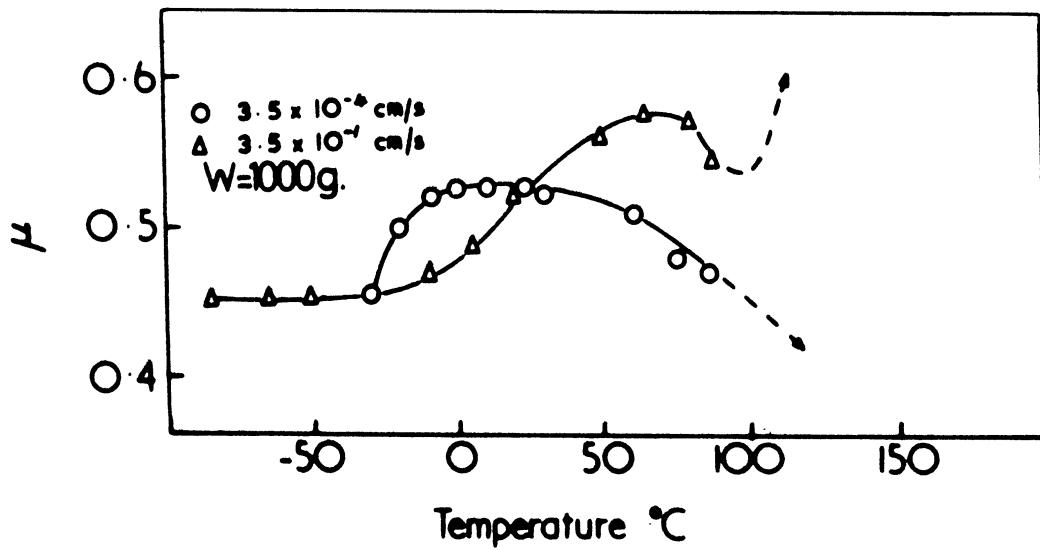


Figure 10. The Coefficient of Friction versus Temperature of Steel on Polycyclohexyl- $\alpha$ -Chloroacrylate. The Applied Load  $W = 1000$ g.

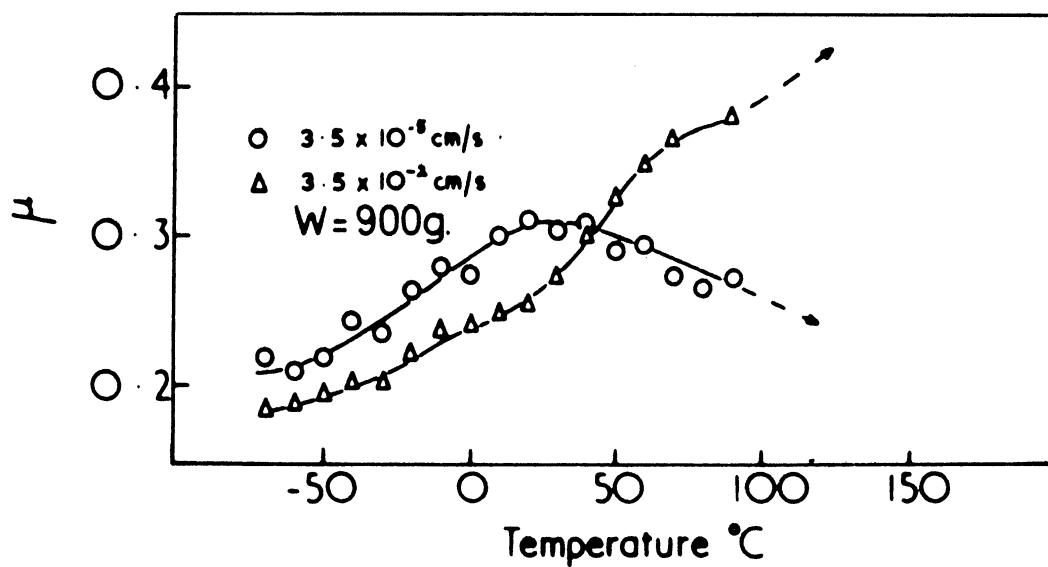


Figure 11. The Coefficient of Friction versus Temperature of Steel on Kel-F. The Applied Load  $W = 900$ g.

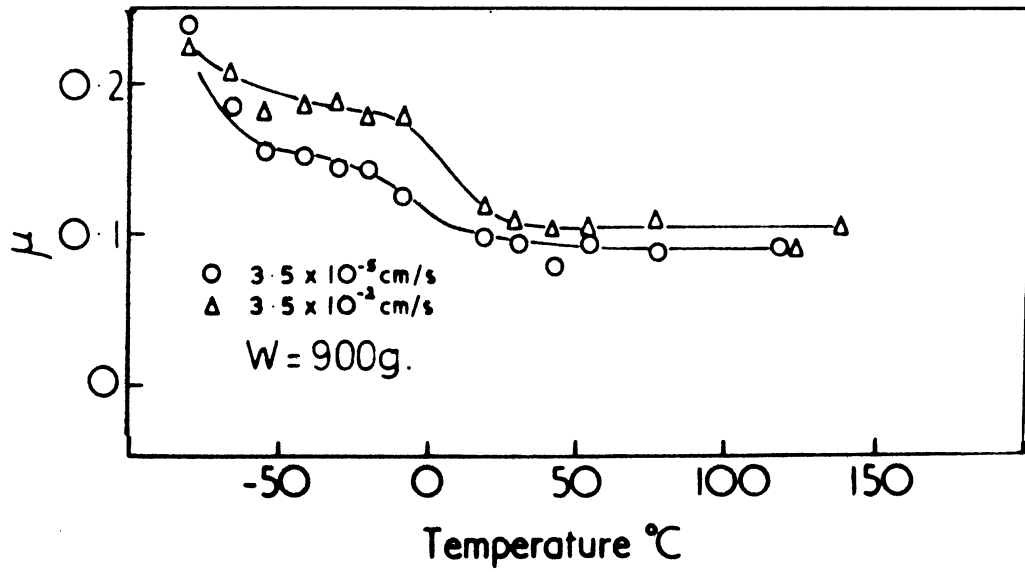


Figure 12. The Coefficient of Friction versus Temperature of Steel on Poly-Oxy-Methylene. The Applied Load  $W = 900g$ .

chloroacrylate in Figure 10 the peak of the higher sliding speed curve is located at a higher temperature than is the peak of the curve for the lower sliding speed test.

In both of these cases higher sliding speed appears to coincide with higher temperatures. Indeed the same direction of shift is noted with all of the plastics. The magnitude of the horizontal shift is difficult to determine since a vertical shift may also be present in some cases.

The observed horizontal shift is consistent with the direction of shift which can be calculated with the use of the WLF equation. Thus, there is some evidence that a visco-elastic effect appears in the friction of plastics as well as in the rubbers.

Stronger evidence will not be available until certain experimental difficulties are overcome. Friction data should be obtained at a lower temperature. Friction data should also be obtained at a higher temperature. Unfortunately, at the temperatures above  $T_g$  the plastics become viscous liquids. In essence this means that the area of contact,  $A$ , will become uncontrollably large and obliterate any transition in the quantity,  $S$ . This is not a problem with rubber since above  $T_g$  rubber is solid and the quantity,  $A$ , is limited by the visco-elastic properties of the rubber. Work is continuing in this area.

#### Conclusions:

There is considerable evidence for a visco-elastic effect in the friction of polymers. The sliding speed-temperature interdependence in sliding friction can be described by the same WLF equation that

describes the frequency-temperature interdependence in conventional visco-elastic tests.

In view of a possible visco-elastic effect in friction it should not be surprising to find large variations in friction with sliding speed and temperature. Variations in the coefficient of friction are a source of considerable concern to users of polymers. It is often assumed by engineers and often implied in tables of coefficient of friction that the coefficient of friction for any material can be taken to be constant. Another approximation often seen is that the variations in the coefficient of friction over all standard conditions are not large. Such assumptions are not sound.

In the absence of reliable polymer friction values in handbooks a tempting assumption is that the coefficient of friction varies monotonically and in a linear manner. This would be especially useful for obtaining analytical solutions to problems involving friction, but again not valid.

Experimental results seem to indicate a rather complex frictional behavior of polymers. It has been shown that sliding speed and temperature are important variables in the study of the friction of polymers. By extension from the work in conventional visco-elasticity it can be expected that additional significant variables might be the applied load, thermal history of the polymer, additives and fillers in the polymer, and absorbed moisture content. Since the properties of polymers cannot easily be predicted, it is apparent that extrapolation of polymer friction values from one condition to another is highly unreliable.

A final conclusion has to do with the fundamental mechanism of

friction. It appears that the friction of polymers can be described by the simple equation  $F = AS$ . The large variations in  $F$  can be accounted for by treating  $A$  and  $S$  as visco-elastic properties of the polymer. An important point here is that for a particular sliding speed the strain rate in the adhesion bonds is greater than the strain rate in the polymer substrate. Thus, the strain rate that controls  $S$  is greater than the strain rate that controls  $A$ . This concept should be useful in further study of the friction of polymers.

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