Pavement Friction and Temperature Effects

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The magnitude of friction produced by two bodies in rubbing contact is, among other factors, determined by their material properties. Whenever these properties change, friction will change also. Since rubber is a viscoelastic material, whose elastic and damping properties are strongly affected by temperature, the friction of rubber sliders or skidding tires is likewise affected by temperature.

To better understand the effect that temperature has on pavement friction, the adhesion and hysteresis components are separated and their temperature dependence is studied independently. Whereas the adhesion component may increase or decrease with temperature, depending upon sliding speed, the hysteresis component is usually reduced by temperature. By superposition of the adhesion and hysteresis curves, the temperature dependence of friction can be qualitatively predicted.

Field and laboratory tests made with skid trailers and portable testers confirm this temperature dependence. The experimental results are often difficult to interpret or sometimes ambiguous, however, because the data are influenced by factors other than temperature and reflect the sum of adhesion and hysteresis, both of which are temperature dependent in a different way.

For these reasons correction factors are difficult to obtain ant at present none are available which would permit normalization of friction measurements to a specified temperature within known confidence limits.

•THAT there is some relation between temperature and pavement friction has been known for some time. When Giles and Sabey (1) related the mean monthly air temperatures to the percentage of the total accidents in which skidding on wet pavements occurred, they found that this percentage was changing seasonally and closely paralleling the mean monthly temperatures (Fig. 1). One cannot deduce from these data, however, that temperature is the only factor causing the change in the incidence of skidding accidents. Indeed other data (Fig. 2) show that the frequency of skidding accidents is greater in fall than in spring even though, in first approximation, the mean temperatures in spring and fall should be alike (2, p. 38).

The seasons not only differ in temperature, but there may be other seasonally induced effects which influence accident frequency. Pavement surfaces may change, average tire conditions may differ, driver response to pavement slipperiness may be conditioned by road and weather conditions, etc. To learn whether temperature affects accident frequency via changes in skid resistance a look at how the latter changes during a single day should be informative.

Figure 3 gives the data for a single 24-hr period (3). The skid resistance is higher when the temperature is lower, and vice versa. Although in this case the maxima and

*Deceased.

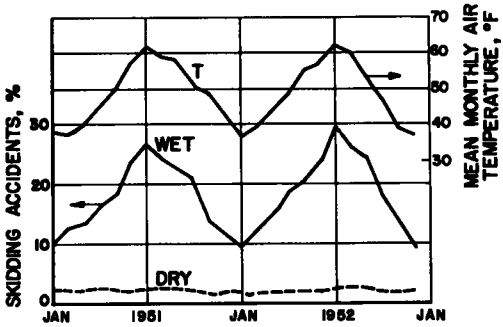

Figure 1. Seasonal variations of the percentage of skidding accidents and of the mean monthly air temperatures in Great Britain (1).

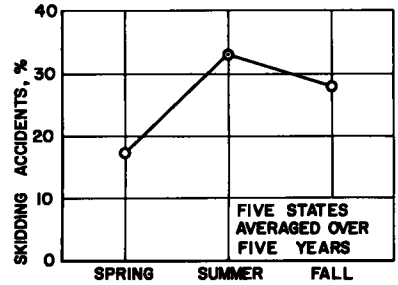

Figure 2. Seasonal variations of the percentage of wet skidding accidents in five states (2).

minima do not exactly coincide there is no doubt that some relation exists between temperature and skid resistance. This is even better illustrated by Figure 4 (4).

Obviously then, in describing the frictional characteristics of pavements, temperature must be taken into account. Since it is not practical to postulate that field tests are to be made at a single temperature, a method for correcting the obtained data to a standard temperature would be extremely helpful if precise comparisons between pavements are to be made. On the other hand, one should also be able to assess the effect of temperature on the frictional performance of commercial tires if reasonable traffic rules and practices are to be postulated or if the accident potential of pavements is to be predicted.

RUBBER FRICTION AS FUNCTION OF TEMPERATURE

In the frictional interplay between wet pavement surface and tire it is primarily the tire which changes characteristics with temperature. In this paper we address ourselves to the problem of how changing tire or rubber temperature affect friction. This is not to say that pavement and water temperatures may be ignored, but they are mostly effective through the manner in which they influence the rubber temperature at the interface.

Wet rubber friction has two principal components: that caused by adhesion (surface friction) and that caused by hysteresis (internal friction), see Figure 5. On any road surface both components are generated, though their relative magnitudes change with the character of the surface. Unless both components respond in the same manner to temperature changes, the friction-temperature relationship will not be the same on

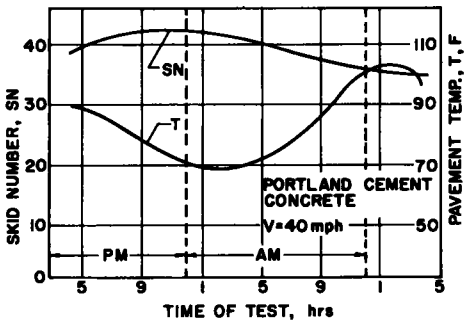

Figure 3. Daily variation of skid resistance and temperature (3): locked-wheel tests with road friction tester.

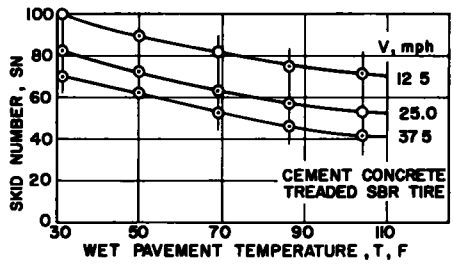

Figure 4. Change of skid resistance with temperature at several speeds: locked-wheel tests with road friction tester.

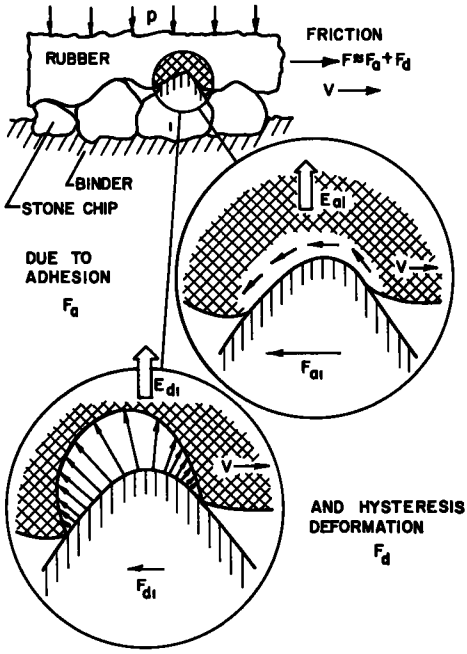

Figure 5. Friction has two principal components: adhesion and hysteresis.

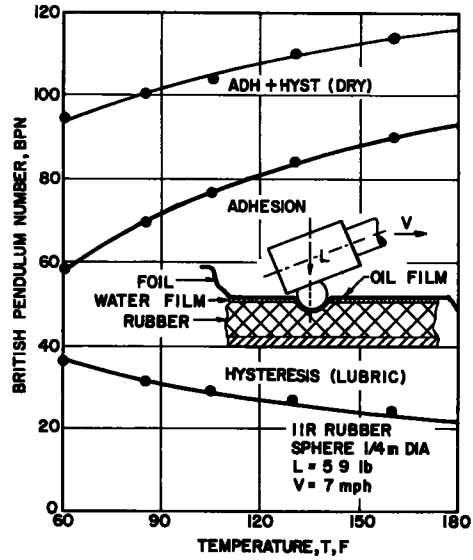

Figure 6. Separation of the friction components by lubricated foil technique (5).

all pavements even though tire or rubber are the same. This mechanism explains at least partially why conflicting data on the effect of temperature are being obtained.

In the laboratory it is possible to separate the two friction components (5). The upper curve of Figure 6 was obtained by sliding a polished steel ball over a dry rubber specimen (the British pendulum tester was modified for this experiment). The lower curve was obtained by placing a thin plastic foil on the rubber and lubricating the foil with a light lubricant. This effectively suppressed most of the adhesion. The difference between the friction values for the two experiments then represents the adhesion component. On wet pavements the adhesion component is of course proportionally much smaller than shown here.

Of interest here is the fact that the adhesion and hysteresis components have different temperature responses, both in sign and in magnitude. The net effect in the present case is a positive temperature-friction gradient. This is in direct opposition to what Figures 3 and 4 show. It must be borne in mind, however, that Figure 6 applies to (a) a particular rubber compound, (b) a particular sliding speed (which is much lower in the case of Fig. 6 than for Figs. 3 and 4), and (c) a particular type of contact (a single steel ball at some arbitrary load vs. the contact patch of a sliding tire on a pavement).

In Figure 7, several rubber compounds were used in the same type of experiment, the plotted results representing total friction in the absence of lubrication. The curves illustrate that not only peak friction values vary, but also that the peak values occur at different temperatures. At a given temperature the friction-temperature gradient for one rubber compound can be positive, while for another it is negative or zero. This means that the relative ranking of the compounds at one temperature is not necessarily the same as at another.

Figure 7 also shows that if one is free to choose the compound and the temperature one can, for a given experiment, achieve insensitivity to small temperature variations. This can be used to improve the precision of routine data acquisition programs when precise temperature control or measurement is impractical. It is, however, necessary to verify the insensitivity to temperature variations over the entire anticipated operating spectrum.

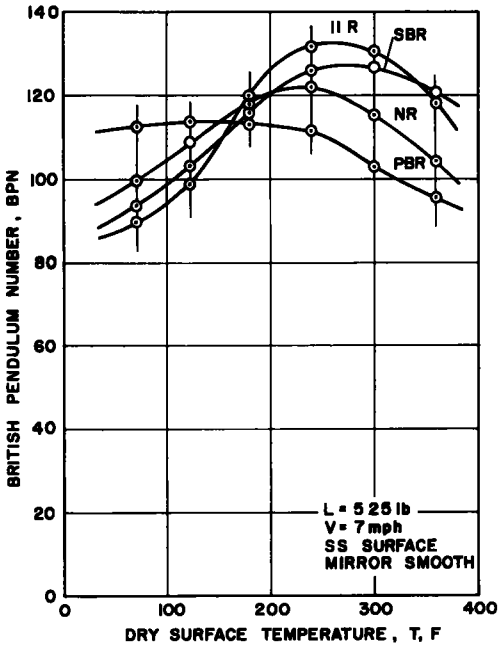

Figure 7. Temperature sensitivity of the friction of four rubber compounds: total dry friction under conditions similar to those of Figure 6.

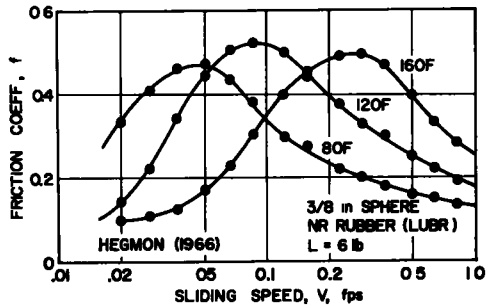

Figure 8. Coefficient of friction as function of low sliding speed at three different temperatures.

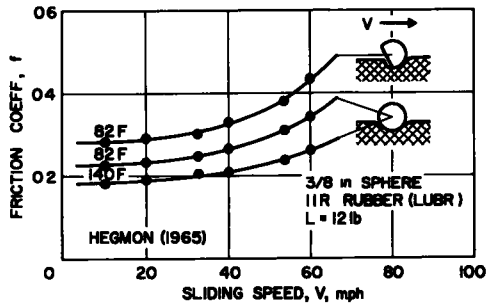

Figure 9. Coefficient of friction at high sliding speed and two temperatures.

For the tests of Figures 6 and 7, the sliding speed was constant. If it is varied, the friction peak will occur at a different temperature. Conversely, if temperature is varied, the friction peak occurs at a different sliding speed (Fig. 8). The data again represent the results obtained with a sliding polished steel ball, but this time in the presence of a lubricant (6, p. 23-25). It should be noted that the sliding speeds for Figure 8 are quite low—even the 160 F peak occurs at only 0.3 fps or 0.2 mph.

As sliding speed is increased friction decreases, but eventually increases again (Fig. 9). The experiments from which the data are taken (7) could not be carried to high enough speeds to reach the second peak. Covering the entire speed range in one continuous experiment results in a curve of the type shown in the upper graph of Figure 10. The solid curve represents the total observed friction, whereas the broken line is that due to hysteresis only, as determined by means of a refined version (6, p. 63-69) of the foil method. The peak at the low sliding speed is almost entirely the result of a maximum of the adhesion component. The high speed peak is caused by the peaking of the hysteresis component since, at least in this case, the adhesion component has completely disappeared (the smooth sphere hydroplanes). It is therefore appropriate to speak of an adhesion and a hysteresis peak, respectively.

As already pointed out, the adhesion peak occurs at very low speeds. A sliding tire always operates to the right of it, but the fact that the peak moves with temperature does concern us here. This is brought out by the lower graph of Figure 10; the normal operating speeds for three types of skid-resistance measuring instruments are shown in relation to friction curves for four different temperatures. From Figure 8 we know that the adhesion peak moves to the right with increasing temperature; consequently T_1, T_2. . ., designate curves for progressively higher temperatures. It can be seen that at ST, the standard speed for skid tests with a road friction tester of the locking wheel type, increased temperature will cause a decreased coefficient of friction to be

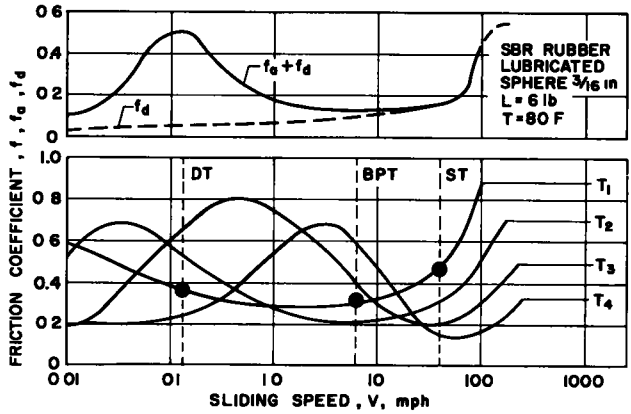

Figure 10. Coefficient of friction over a wide range of sliding speeds—(top) constant temperature, f_a = adhesion coefficient, f_d = deformation (hysteresis) coefficient; (bottom) four temperatures, T_1, T_2,.... DT = Penn State drag tester, BPT = British pendulum tester, ST = skid trailer.

measured. The same is not true, however, if the British pendulum tester (BPT) were used. Here the coefficient would be at a minimum at T_2. Using the Penn State drag tester at very low speed (DT) would place the minimum at T_4, the highest temperature shown.

This example shows why no generalized statement about the temperature-friction relationship can be made even if all variables, except temperature and sliding speed, remain constant. The horizontal shift of the friction vs. speed curves shown in Figures 8 and 10 have been used by Grosch to show that by application of a suitable transform they can be combined into a single master curve. The concept permits substituting a sliding speed change for a temperature change and vice versa. Thus, with the generalized shape of the friction vs. speed curve in mind (top of Fig. 10), it is not difficult to analyze, at least qualitatively, the causes of observed changes of friction with temperature. In practice, obtaining or using such a master curve may encounter certain difficulties because of the superimposition of hydrodynamic effects, problems of measuring or controlling temperatures, self-heating of the rubber at high sliding speeds, etc.

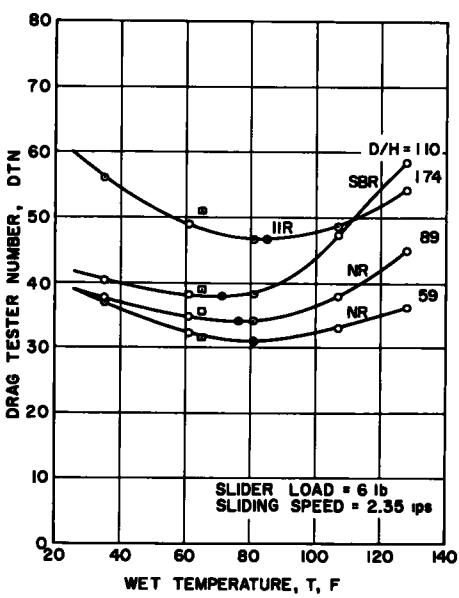

Figure 11. The temperature sensitivity of drag tester sliders: averages of results on several different surfaces—D/H = damping/hardness ratio (Damping determined by rebound method ASTM D1054, Hardness acc. to ASTM D2240).

EXPERIMENTAL EVIDENCE AND ITS INTERPRETATION

In Figure 11, the results of tests performed with the Penn State drag tester are shown. The experiments were carried out to determine the effect of changing the rubber compounds of the slider. The sliding speed (2.35 ips or 0.13 mph) had been selected to obtain minimum sensitivity with SBR rubber over the temperature range normally encountered in the laboratory. It can be seen that the DTN (drag tester number) is virtually constant between 60 and

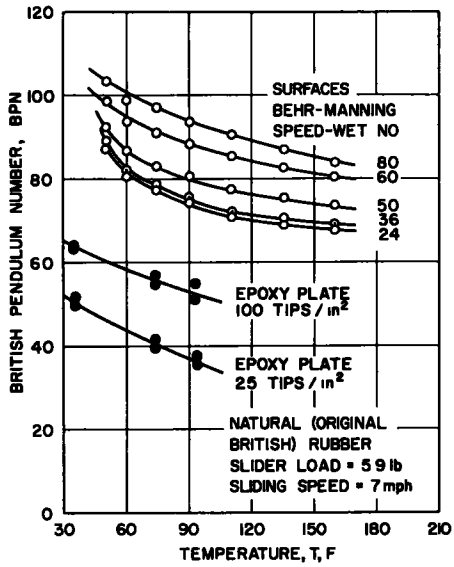

Figure 12. The combined effect of temperature and surface characteristics on friction measured with the British pendulum tester.

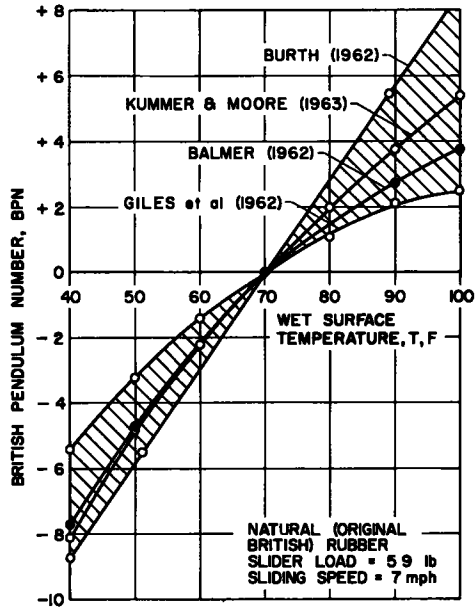

Figure 13. Corrections derived from several sources to normalize British pendulum numbers to 70 F.

80 F. With different compounds the minima (solid dots in Fig. 11), and thus the flat portions of the curves, occur at other temperatures. If the experiments were to have been designed around the use of a compound other than SBR the sliding speed would have had to be lowered in order to move the minimum to 70 F.

This is a practical application of the concepts discussed earlier, but it may be confusing that in the case of Figure 11 minima should occur when earlier only maxima were considered. The occurrence of minima can, however, be explained by reference to Figure 10. As a result of higher temperature, the adhesion component of the friction increases in the region of interest and the hysteresis component decreases. At first the decrease exceeds the increase, so that there is a net decrease in observed friction. With a further temperature increase a point will be reached at which both changes cancel each other: the minimum point of the total friction curve is reached. Further heating will again result in a net rise. (The BPT line in Fig. 10 illustrates such a situation: the coefficient is higher than at T_2 whenever the temperature is either higher or lower than T_2.)

For the curves of Figure 11, the results from six different surfaces have been averaged. Figure 12 shows how different surfaces influence the temperature sensitivity. No minima were reached in this case because the sliding speed was higher than for Figure 11. The shape and the number of asperities per unit area influence not only the general friction level, but also the temperature sensitivity. Whether the latter effect is significant or not cannot be stated generally, if only because not enough data are available and because different applications involve the rubber differently and the range of surface characteristics varies from application to application.

TEMPERATURE CORRECTIONS

If one would attempt to provide a temperature correction to data obtained with the British pendulum tester this does not seem too difficult a task at first. That it is not a simple problem is illustrated by Figure 13. Data reported by several authors have been plotted in terms of the BPN (British pendulum number) which must be added or subtracted to correct the observed BPN to 70 F. At temperatures below 70 F the dif-

ferent sources agree reasonably well, but above 70 F there is considerable spread. Not enough information is available to rule out the possibility that a good part of the spread comes from differences in experimental technique. Another factor is undoubtedly that different surfaces were used for each set of data.

Burth (8) used cement concrete, Kummer and Moore (9) abrasive paper (the raw data are those shown in Fig. 12), Balmer (10) machined epoxy (see also Fig. 12), and Giles et al (11) eight different road surfaces. Precisely what characteristics of the surface must be considered in a correction formula cannot be deduced from the information given in these sources. One might favor the correction suggested by the Giles et al data because they come from actual road surfaces, but before making a choice one would have to know why Burth's data from cement concrete surfaces fall on the opposite side of the range shown in Figure 13.

These complexities are illuminated, though not resolved, if the friction process through which the slider of the British pendulum tester goes is investigated in more detail. In Figure 14, the friction history of three different passes is shown. They differ from the standard pass in that the sliding length is somewhat greater than normal and that the slider was forced to move at constant speed. The dependent variable is therefore not the total energy loss, but the instantaneous coefficient of friction. (It was measured by supporting the test specimen on an air bearing and biasing the specimen against a pressure transducer with a very high spring rate.) The coefficient rises rapidly to a maximum, which corresponds to the adhesion peak of the friction speed curve, and then drops off gradually as the slider edge heats up. Since the test surface was extremely smooth stainless steel, there is little difference between the dry and wet condition. The slider wipes away the water almost completely. Therefore, the friction in this case is almost entirely due to adhesion. When a wetting agent is added to the water the adhesion component is suppressed and only hydrodynamic, viscous and interfacial tension forces remain; even their sum is almost negligible under the conditions of the experiment.

If a less smooth surface had been used the process would have become still more complex. It is therefore not difficult to appreciate that surface characteristics can significantly affect the manner in which temperature influences friction as measured with a pendulum device. According to Figure 14, the initial temperature of the rubber slider should have little influence on the integrated coefficient of friction, but this can be said with certainty only about nearly perfectly smooth surfaces.

It is not surprising that locked-wheel tests with full-scale tires give even less agreement on how to correct for temperature (Fig. 15). Only the Kummer and White data were obtained with the ASTM standard test tire. The rest of the tests employed differing tires and test speeds.

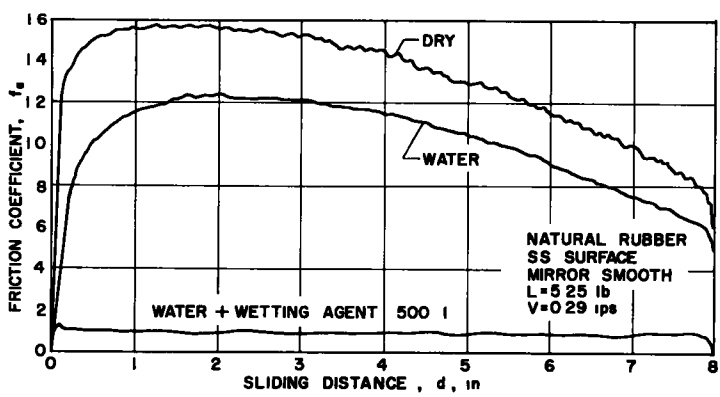

Figure 14. Instantaneous coefficients of friction when the slider from a British pendulum tester passes across a very smooth surface at constant speed.

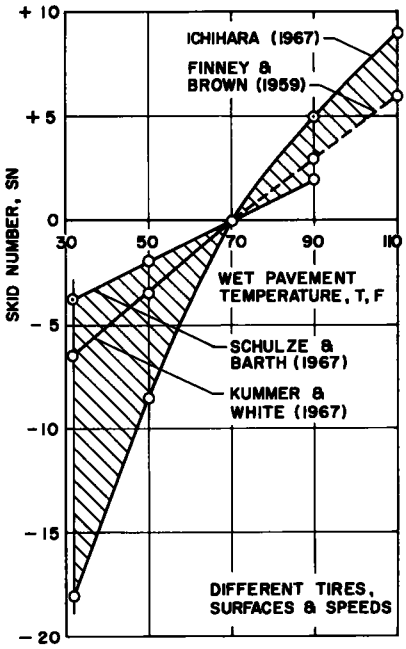

Figure 15. Corrections derived from several sources to normalize skid numbers to 70 F: locked-wheel tests of different tire types at different speeds on unidentified surfaces.

CONCLUSIONS

1. The friction-temperature gradients are in practice always negative for the currently used skid testers. The magnitude of the gradients is, however, still quite uncertain even for the ASTM standard tire and the pendulum tester slider made of either ASTM rubber or British natural rubber.

2. Since different surfaces cause differences in the temperature gradients, compounds which, in the operating range, are least temperature sensitive have advantages. Small gradients result in smaller errors if the surface characteristics are not or cannot be taken into account or if the temperature measurements are not precise.

3. Friction-temperature gradients are a function of surface characteristics because the varying contributions of the adhesion and hysteresi components to the total friction differ. Because the two components have different temperature characteristics the effect of temperature changes is so complex that the effect probably can never be defined quantitatively in a rigorous way except statistically on the basis of a large number of carefully controlled experiments.

4. Although the temperature of the rubber is responsible for the observed temperature dependence of tire or slider-pavement friction the temperature of the pavement and of the water used for wetting it do play a part because of heat transfer across the contact area. In routine tests it is, however, impractical to measure more than one temperature. Without extensive experimentation it cannot be stated how and where this temperature should be measured. Any correction using it would contain a degree of uncertainty. Experiments would have to define the limits of the possible error. The error might be reduced by more rigid test procedures than are now being used.

5. When compliance with a standard must be shown and the observed values are close to the cutoff value it may be necessary to make the compliance tests while the ambient temperature is within specified limits. In conjunction with a tightly controlled test procedure this would eliminate the uncertainties which arise from the complex effects caused by temperature changes.

ACKNOWLEDGMENTS

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This paper was to have been written by H. W. Kummer. He had prepared notes for it, before death put a too early end to his career. The text before the reader was written by W. E. Meyer, with assistance from M. O. Schrock in the interpretation of the Kummer notes.

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