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REVIEW OF CAUSES AND ALLEVIATION OF LOW TIRE TRACTION ON WET RUNWAYS

by Walter B. Horne, Thomas J. Yager, and Glenn R. Taylor

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CONTENTS

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SUMMARY

Three main factors which cause loss of tire traction on wet runways, namely, dynamic hydroplaning, viscous hydroplaning, and tire tread rubber reversion are reviewed. Consideration is given to the interaction of certain variables such as pavement surface texture, runway water depth, tire tread design, vertical tire load, and tire inflation pressure with these factors. A method for measuring average texture depth of a runway surface is described and appears promising as a means of classifying runway surfaces as to their slipperiness when wet. Finally, two promising methods for increasing tire traction on wet runways are discussed; namely, air jets placed in front of tires and pavement grooving.

INTRODUCTION

Extreme loss of tire braking and lateral traction sometimes occurs during landings of aircraft on wet and flooded runways and is of utmost importance to safe operations. The term hydroplaning, or aquaplaning, is usually used to describe this drastic loss in traction, especially when it occurs under flooded runway conditions. Although few statistics are available to indicate the frequency of occurrence of hydroplaning, personnel of two large U.S. airlines have estimated that 5 percent of their landings each year are made on wet runways. Their experience also indicates that in one of every 500 wet landings hydroplaning was encountered to some degree and that the attendant loss of tire traction contributed to a tendency for the aircraft to depart sideways (crosswind) from the runway in some cases and to overrun the runway in other cases. Fortunately, most of the occurrences involving loss of traction did not lead to accidents but were incidents in which the pilot was able to keep the aircraft within the confines of the runway during landing. It should be noted, however, that the margin between an accident where damage or injuries

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[1] Formerly presented at AIAA/RAeS/JSASS, Aircraft Design and Technology Meeting, Los Angeles, California, November 1965 (AIAA Paper 65-749).

are suffered and an incident where no aircraft damage or passenger injuries occur is very small. The possibility of the aircraft tires' losing traction as often as once every 500 wet landings demonstrates the urgent need for developing some method or device, either on the runway or on the aircraft, that will alleviate the drastic loss in traction during take-off and landing and thus will increase safety of flight.

Since 1960, the Langley landing-loads track of the NASA has been extensively used in the study of tire traction (refs. 1 to 19). This research allowed two types of loss of traction on wet surfaces to be separated and defined; namely, dynamic and viscous hydroplaning. It was found that for complete dynamic hydroplaning (where the water lifts the tire completely off the surface) to occur for a given airplane landing condition, the runway must be flooded beyond a critical fluid depth, and the aircraft must be traveling at a speed which is in excess of a critical ground speed (referred to as the dynamic hydroplaning speed) and which is dependent upon the square root of the tire inflation pressure used on the aircraft. It was found, on the other hand, that a viscous hydroplaning which requires only a thin-fluid film to be present on a smooth runway may also occur. This type of hydroplaning can occur at much lower ground speeds than dynamic hydroplaning. Fortunately, the texture existing on most runway surfaces is sufficient to break up and dissipate the thin viscous film which leads to this type of hydroplaning.

Studies of accidents and incidents of aircraft skidding sideways off the runway and overrunning landing strips have disclosed a significant number of cases that could not be fully explained by either the dynamic or the viscous types of hydroplaning. These studies also disclosed that, in most of these cases, white streaks were developed in the tire paths on the wet runway and that the tires showed evidences of a "reversion" of the tread rubber to an uncured form in the skid patches developed on the tread surface.

In a recent research program at the Langley landing-loads track, a series of tests were made with the aircraft tire locked to prevent rotation so that the tire was forced to skid along the wet and flooded test surfaces at different ground speeds. During these tests, the tires developed tread rubber reversion in the skidding footprint region, and extremely low friction coefficients were measured down to speeds as low as 25 knots.

The purpose of this paper is to illustrate the effects of dynamic and viscous hydroplaning on tire traction performance, to describe the effects of prolonged tire skids and tread rubber reversion on aircraft braking and direction control, to suggest methods for improving aircraft tire traction on wet runways, and to discuss a method of measuring the average depth of texture as a means of classifying runway surfaces as to their slipperiness when wet.

SYMBOLS

Measurements referred to in this paper were taken in U.S. Customary Units and equivalent values are indicated herein in the International System of Units (SI). Details concerning the use of SI, together with physical constants and conversion factors, are given in reference 20.

F_Z	vertical load, lb (newtons)
p	inflation pressure, lb/in^2 (newtons per centimeter^2)
s_1	slip ratio (ratio of relative skidding velocity to horizontal velocity of axle)
V_p	dynamic hydroplaning speed, knots
μ	instantaneous tire-ground friction coefficient
μ_{AV}	average friction coefficient between slip ratios of 0.10 and 0.50
μ_{EFF}	effective friction coefficient (average μ developed by aircraft as modified by pilot braking or antiskid system
μ_{MAX}	maximum friction coefficient
μ_r	rolling resistance coefficient for unbraked wheel and tire
μ_{SKID}	skidding friction coefficient (friction coefficient at slip ratio of 1)
μ_{STATIC}	friction coefficient obtained at ground speeds < 2 knots

FACTORS AFFECTING TIRE BRAKING TRACTION ON DRY RUNWAYS

An understanding of braking traction of tires on dry surfaces is needed to provide background information and also to serve as a basis of comparison for the traction results obtained on wet surfaces.

Slip Ratio

When rolling tires are forced by braking action to slow rotation from a free-roll condition to a locked or full-skid condition, the friction coefficient developed between tire and ground varies with slip ratio in the manner shown schematically in figure 1. Slip ratio may be defined as follows: The difference between the peripheral velocity of the wheel and the horizontal velocity of the wheel axle is defined as the relative skidding velocity occurring between the tire and the ground. The ratio of this relative skidding velocity to the horizontal velocity of the axle is defined as the slip ratio s_1. With no braking (slip ratio zero), the lower limit of the friction coefficient μ_r is determined by the resistance of the rolling tire, wheel bearings, and unloaded brake. Under normal tire operating conditions, μ_r usually falls within the range 0.02 to 0.05. As braking torque is applied to the wheel, the friction coefficient rises until it reaches a maximum value referred to as μ_{MAX}. It should be mentioned that up to this point practically no sliding or slipping occurs between the tire footprint and the ground.

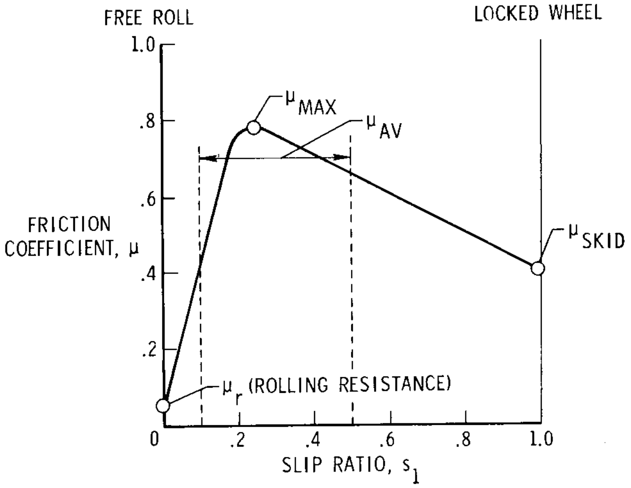

Figure 1.- Friction-coefficient variation with slip ratio.

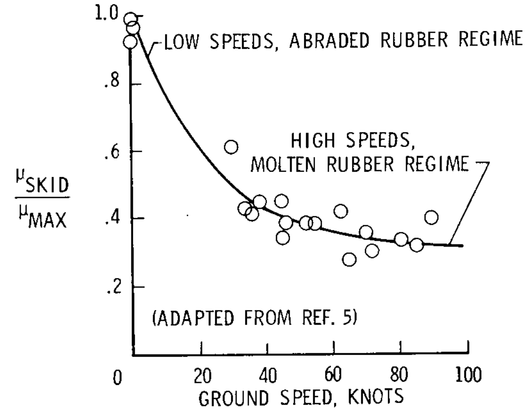

Figure 2.- Effect of speed on full skid friction coefficient on dry runway.

The apparent slip shown up to the region of μ_{MAX} in figure 1 is due to elastic deformation of the tire. After μ_{MAX} is attained, unless the brake torque is rapidly decreased, the wheel quickly locks at a friction coefficient μ_{SKID} usually considerably lower than μ_{MAX} as indicated in figure 1 and as is shown by data in figure 2 (from ref. 5). The locked wheel skid is a highly undesirable condition for the tire at high speeds on dry runways. Shown in figure 3 is a tire which blew out after sliding only 60 feet (18.3 meters) at a ground speed of 100 knots on a dry concrete runway under a vertical load of 10 000 pounds (44.5 kilonewtons). Calculations show that while the tire was sliding, the contact patch of the tire, with an area of approximately 40 inches^2 (258.0 centimeters^2), was absorbing 460 horsepower (343.0 kilowatts). During this time, 1 inch (2.5 cm) of tread rubber and carcass cord was melted and eroded away in less than 0.36 second, the duration of the locked wheel skid in this case. One way to avoid such situations of

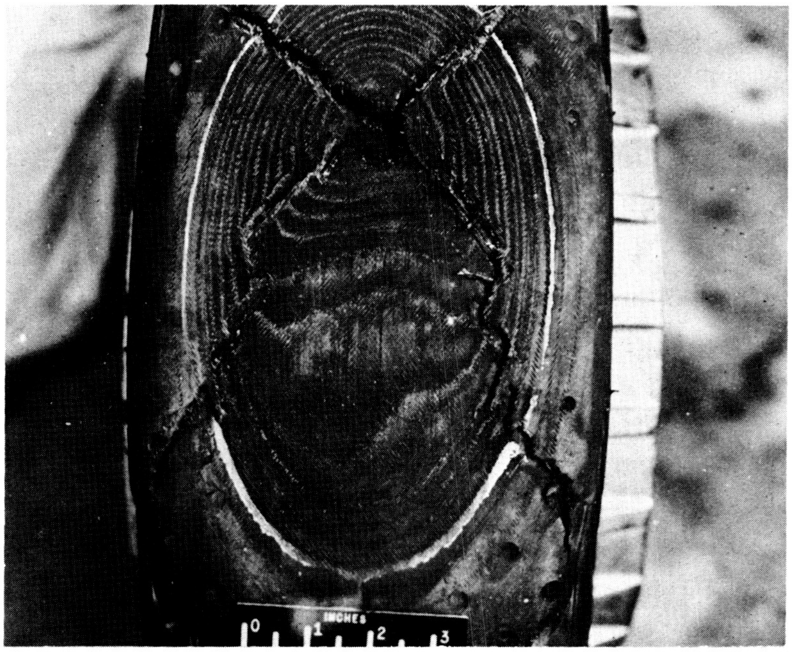

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Figure 3.- Blowout with 32 × 8.8 aircraft tire after skidding 60 feet (18.3 meters) on dry concrete at ground speed of 100 knots.

excessive tire wear is to provide an antiskid system which prohibits wheel lockup and simultaneously forces the tire to brake under conditions of favorable slip ratio.

Inflation Pressure and Vertical Load

Data given in reference 19 indicate that the maximum tire-ground friction coefficient obtained at very low ground speeds (hereinafter called μ_{STATIC}) tends to decrease with increasing tire-ground bearing pressure on a dry runway. The data shown in figure 4 illustrate this trend. The tire inflation pressure represents a reasonable approximation of the average bearing pressure developed between tire and ground although tire carcass stiffness and tread effects introduce some small differences. These data taken from reference 19 were obtained at extremely low ground speeds ranging from 0.008 to 1.7 knots. These data, representing many airplane tire sizes, also show that μ_{STATIC} may be approximately predicted for the range shown by the empirical equation:

$$\mu_{\text{STATIC}} = 0.93 - 0.0011p \tag{1}$$

The effect of vertical load changes on friction coefficients on dry surfaces is negligible since the tire acts as an elastic body and the footprint area increases with the load with little change in tire pressure. The effect of the small rise in tire inflation pressure which does occur as the tire deflects under increasing vertical load is small. For example, the pressure rise due to loading a tire from zero to rated deflection (rated load) is approximately 2 to 3 percent of the initial inflation pressure. As can be seen from figure 4, this pressure change will not modify the friction coefficient to any great extent.

Speed and Pavement Surface Texture

The influence of pavement surface texture and speed on dry runway braking effectiveness is shown in figure 5. These data indicate that the pavement surface texture and the material used affected the friction coefficient very little. However, the effect of increasing ground speed was to decrease the braking effectiveness. It is believed that the trend of μ_{AV} to decrease with speed is primarily due to inertia effects acting on the deflecting tire as it rolls through the ground contact zone. These inertia effects tend to reduce the tire-ground contact area as speed increases and thus create a higher bearing pressure and hence, as shown in figure 4, a lower friction coefficient. Tire tread temperature and other as yet unknown effects may also contribute to this decrease. It should be mentioned that somewhat lower dry friction values are obtained for very smooth surfaces than for the textured surfaces shown in figure 5. Also shown in figure 5, by the horizontal dashed lines, are the predicted values of μ_{STATIC} obtained from equation (1). The data show that the calculated values agree well with the experimental μ_{AV} values obtained at low ground speed for these tests.

Figure 5 also presents rolling resistance values (μ_r) obtained from reference 17. These data indicate that the aircraft tire free rolling resistance, in contrast to μ_{AV}, tends to increase with increasing ground speed.

Tire Braking Performance

The braking performance of aircraft tires on dry runways may be summarized as follows:

(1) Maximum braking is achieved over a slip ratio range from about 0.1 to 0.3. Operation at lesser slip ratios reduces the braking action but has the advantage of having all the stopping energy being absorbed by the brake and hence very little tire tread wear develops. Operation at greater slip ratios than 0.1 to 0.3 also results in reduced braking action, but increases tire tread wear since the energy absorbed in stopping is now divided between the brake and the partially skidding tire. Operation at full skid condition or slip ratio 1 results in no energy being absorbed by the brake, reduced braking action, and intolerable tire tread wear.

(2) Next to slip ratio, the tire inflation pressure has the largest effect on braking friction coefficient, with increasing pressure tending to decrease the maximum attainable values. For example, doubling the tire pressure from 100 to 200 pounds per square inch (69.0 to 137.9 newtons/centimeter^2) results in μ_{STATIC} decreasing from about 0.82 to 0.71 (fig. 4). Increasing ground speed also tends to reduce the dry braking effectiveness.

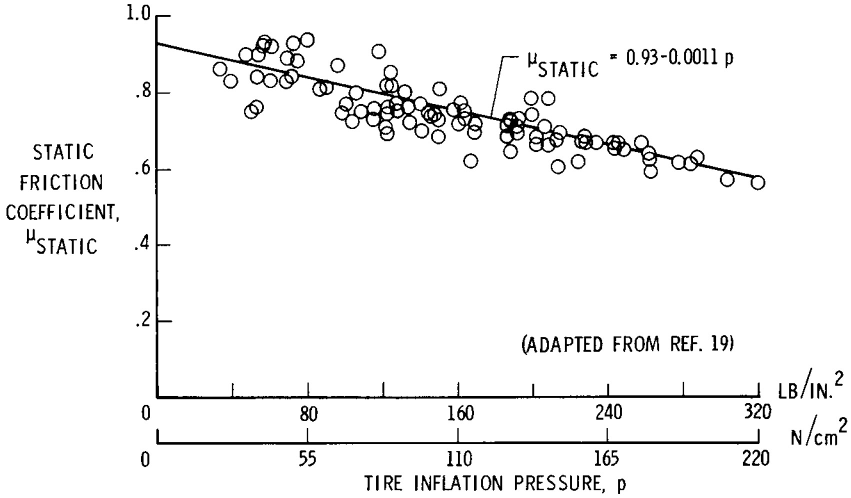


Figure 4.- Static-friction-coefficient variation with inflation pressure. Dry concrete; Ground speed = 0.008 to 1.7 knots.

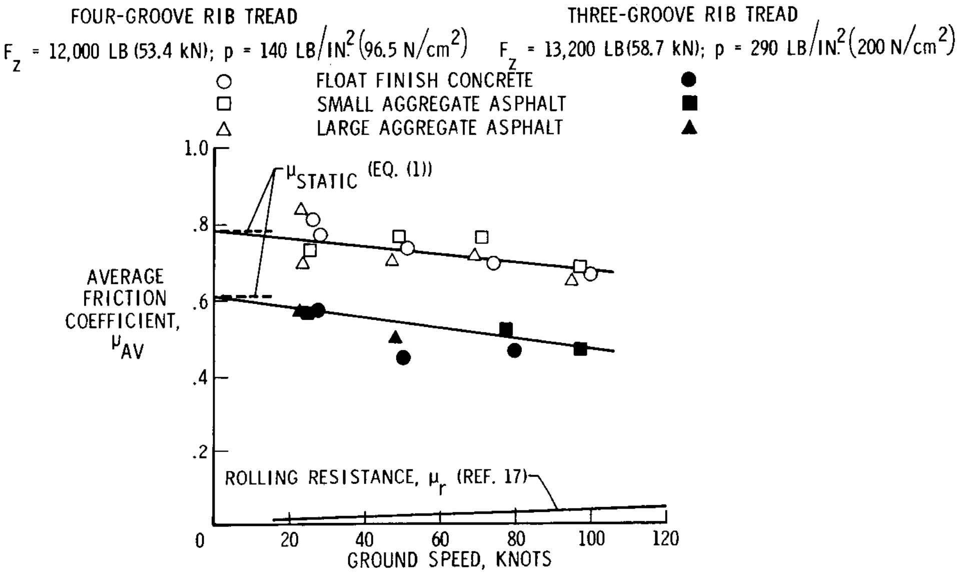


Figure 5.- Surface texture and speed effects on dry runway braking effectiveness. 32 × 8.8 type VII aircraft tire.

Increasing speed from 30 knots to 100 knots (fig. 5) results in μ_{AV} dropping from 0.77 to 0.68, a 13-percent reduction. Elevating the temperature of the tread rubber also has a pronounced effect on reducing braking effectiveness (fig. 2), but the fall-off in braking friction with rubber temperature is not known for tires operating under full-scale conditions.

(3) For the conditions of load and pressure studied, the results indicate that pavement surface texture and tire tread design have little effect on dry runway braking effectiveness.

FACTORS AFFECTING TIRE BRAKING TRACTION ON WET OR FLOODED RUNWAYS

The three main factors which, acting separately or in combination, can degrade tire braking traction to extremely low values on wet surfaces are now discussed. These factors are dynamic hydroplaning, viscous hydroplaning, and phenomena associated with tire tread rubber reversion.

Dynamic and Viscous Hydroplaning

Considerable research has been carried out on both dynamic and viscous hydroplaning in recent years. (See refs. 1 to 18.) Essentially, hydroplaning may be defined as the condition under which the tire footprint is progressively lifted off the runway surface by the action of fluid pressure as speed increases and then rides on a fluid film of some finite thickness. Since fluids cannot develop shear forces of a magnitude comparable with the forces developed during dry tire-pavement contact, tire traction under this condition drops to negligible values. Water pressures developed on the surface of the tire footprint and on the ground surface beneath the footprint have been measured during a recent investigation at the landing-loads track (ref. 16). This research showed that it was possible for this water-pressure buildup under the tire footprint to originate from the effects of either fluid density or fluid viscosity, depending upon conditions; hence the classification of hydroplaning into two types, namely dynamic or viscous.

Both types of hydroplaning are illustrated in figures 6 to 8. Also shown are the effects of vertical load, inflation pressure, fluid depth, and pavement texture on hydroplaning. The data shown in these figures were obtained during a recent investigation at the landing-loads track where five pavement surfaces were placed in line. The test tire was braked in succession from a free roll to a locked wheel and was then allowed to return to the free-roll condition on each of these surfaces as the test carriage proceeded down the track. The first test surface encountered was a smooth, steel-troweled, concrete surface having an average texture depth of 0.04 millimeter. The next

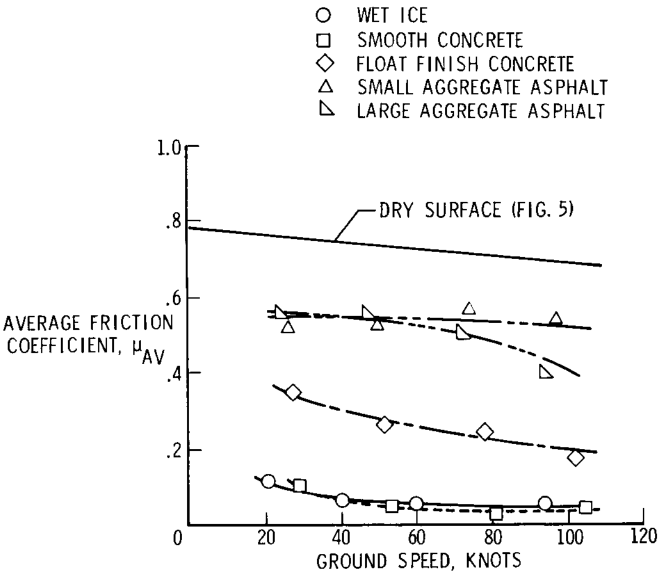


Figure 6.- Damp runway braking effectiveness. 32 × 8.8 smooth tread; F_z = 12 000 lb (53.4 kN); p = 140 lb/in^2 (96.5 N/cm^2).

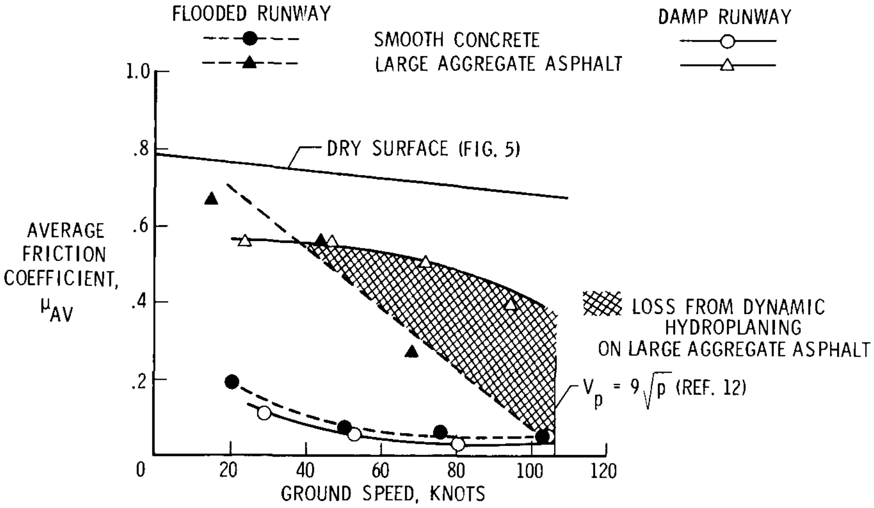


Figure 7.- Comparison of damp and flooded runway braking effectiveness. 32 × 8.8 smooth tread; F_z = 12 000 lb (53.4 kN); p = 140 lb/in^2 (96.5 N/cm^2).

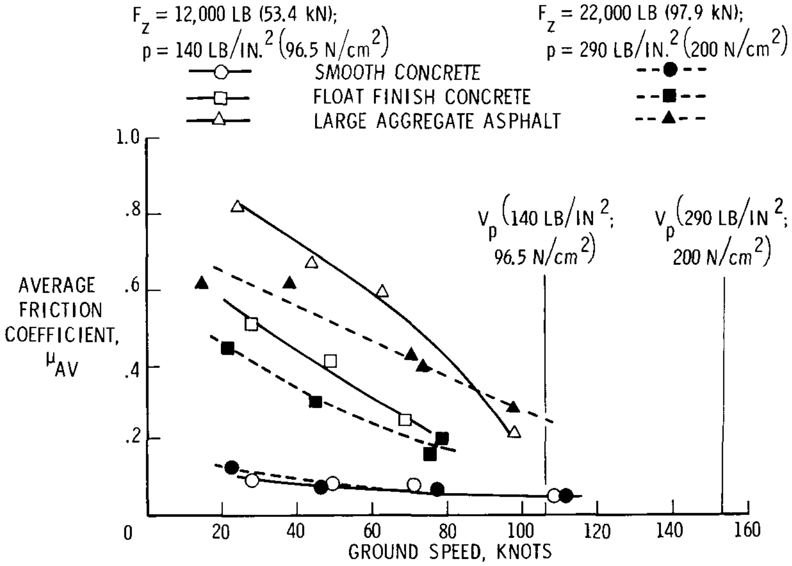


Figure 8.- Inflation pressure and vertical load effects on flooded runway. 32 × 8.8 smooth tread; Water depth = 0.1 to 0.2 in. (0.2 to 0.5 cm).

surface was a more textured float-finish concrete having an average texture depth of 0.19 millimeter. The next two test surfaces were asphalt. The first of these used a small aggregate to produce an average texture depth of 0.34 mm. The second asphalt surface was classified as large aggregate and had an average texture depth of 0.56 mm. The fifth and final surface was smooth wet ice. To obtain this surface, a 200-foot (61.0-meter) length of the track was refrigerated and water was placed on this surface and frozen. At the time of testing, the ice surface was lightly sprayed with water to produce a water film on the ice surface.

Damp runways.- A series of smooth-tread braking tests were made on the five test surfaces just described under the following condition of wetness. All test surfaces except ice were flooded with water to a depth of 0.1 to 0.2 inch (0.2 to 0.5 centimeter).

The water was then allowed to stand until the surfaces were thoroughly saturated. Just before the test runs were made, the standing water was removed from each of the test surfaces by means of stiff bristle brooms. This action left each of the test surfaces without any standing water, but damp to the touch and discolored in appearance (from dry condition). The damp surface condition was selected to minimize dynamic fluid pressure buildup. Any traction loss suffered by the test tires under this damp condition would therefore be primarily due to viscous type hydroplaning. The results from this study are shown in figure 6.

Also shown in figure 6 is the dry traction curve (from fig. 5) obtained for the same load and inflation pressure conditions. These data indicate that the water film present on the damp smooth concrete surface was sufficient to produce viscous hydroplaning, down to very low ground speeds. It can be seen that the values obtained on damp smooth concrete are essentially as low as those obtained on wet ice. The effect of pavement texture in reducing viscous hydroplaning effects is strikingly illustrated by noting the decrease in traction loss encountered by the textured pavement surfaces under damp conditions.

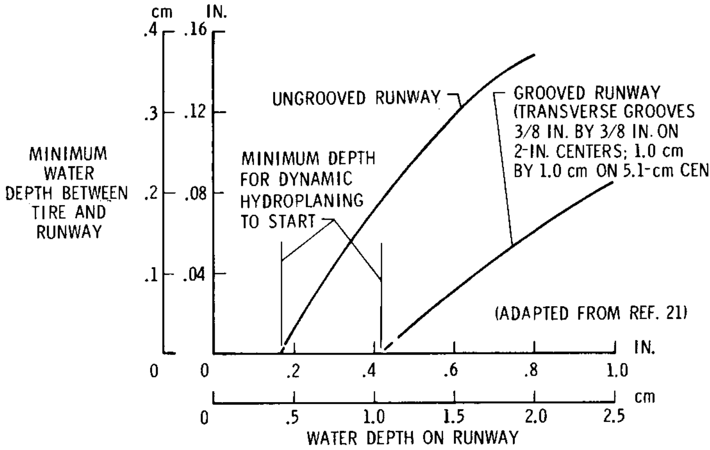
Flooded runways.- The effect of flooding the test surfaces on smooth tire braking effectiveness is noted and compared with damp surface data in figure 7. This figure shows only the results obtained on the smooth concrete and large aggregate asphalt test surfaces. The data obtained for the other test surfaces were omitted for clarity, but showed similar trends according to the degree of texture of the test surface. In this instance (fig. 7), the test runways were flooded to a depth of 0.1 to 0.2 inch (0.2 to 0.5 centimeter) and the test runs were performed immediately upon reaching this depth. The data show that for the large aggregate asphalt surface, this flooding resulted in a large loss in traction as compared with the results for damp surfaces at the higher ground speeds. They also indicate a total traction loss at about 106 knots which corresponds to the predicted hydroplaning speed from dynamic hydroplaning theory (ref. 12). The hatched area in this figure indicates the loss attributed to dynamic hydroplaning for the large aggregate asphalt surface. The smooth concrete results show that flooding this surface resulted in increasing the friction coefficients slightly over those obtained on the damp surface. This increase is attributed to the larger fluid drag created by the tire displacing water from the tire path under the condition of greater water depth. The data also show that the friction coefficients for smooth tires on damp smooth surfaces are essentially equivalent to the coefficients attained during complete dynamic hydroplaning.

Vertical load and tire inflation pressure.- Reference 16 states that viscous hydroplaning is not greatly affected by changes in tire vertical load and inflation pressure. This conclusion is supported by the data shown in figure 8 for the flooded smooth concrete surface. The data in this figure indicate that for this smooth surface, approximately doubling the vertical load from 12 000 to 22 000 pounds (53.4 to

97.9 kilonewtons) and tire inflation pressure from 140 to 290 pounds per square inch (96.5 to 200.0 newtons/centimeter^2) affected μ_{AV} only slightly for this surface.

As further stated in reference 16, dynamic hydroplaning was also insensitive to vertical load changes but was greatly affected by the tire inflation pressure. This conclusion is also verified by the data of figure 8 obtained on the textured pavements. It can be seen that the data for $p = 140$ pounds per square inch (96.5 newtons/centimeter^2) tend toward minimal values at its critical dynamic hydroplaning speed value of 106 knots while the data for $p = 290$ pounds per square inch (200.0 newtons/centimeter^2) tend toward its minimal value of 153 knots. It should also be noted that although raising the inflation pressure on wet surfaces increases the traction at high speeds, it reduces the traction at low speeds. This effect results from decreases in μ_{STATIC} (fig. 4) as inflation pressure increases. If one seeks to increase tire traction at high speeds on flooded runways by raising the tire inflation pressure, one must also accept reduced traction values at lower speeds on flooded runways, as well as reduced traction values at all speeds on dry runways.

Pavement surface texture.- The data shown in figures 6 to 8 have demonstrated the necessity of providing an adequate texture to pavement surfaces so as to minimize traction losses from viscous hydroplaning. The results of reference 16 indicate that open-textured type pavement surfaces also help to alleviate traction losses from dynamic hydroplaning by providing escape paths for the water trapped between the tire footprint and the ground. Pavement grooving provides similar dynamic fluid pressure alleviation as shown in figure 9, adapted from reference 21. Some viscous fluid pressure alleviation should also be provided by the sharp edges of the grooves when contacting the tire tread surface. The data shown in figure 9 indicate that the 3/8-inch (1.0-centimeter) by 3/8-inch (1.0-centimeter) transverse grooves located on 2-inch (5.1-centimeter) centers more than doubled the water depth required for dynamic hydroplaning to take place. The probability of hydroplaning occurring on such a grooved surface is low because of the extremely high rainfall rates required to deposit and maintain a water depth of over 0.4 inch (1.0 centimeter) on the runway surface.



(ADAPTED FROM REF. 21)

Figure 9.- Effect of transverse grooves on critical hydroplaning water depth.

Measurement of pavement texture depth.- As can be inferred from the discussions thus far, pavement slipperiness is related directly to the pavement surface texture and its ability or inability to alleviate dynamic and viscous fluid pressure buildup. It thus follows that pavement slipperiness can be possibly correlated with some characteristic of the physical makeup of the texture such as size, shape, and number of asperities per square inch. Research along these lines, for example, is being conducted by D. F. Moore (Cornell Aeronautical Laboratory), H. W. Kummer and W. E. Meyer (Pennsylvania State University), and Robert Sugg (British Ministry of Aviation).

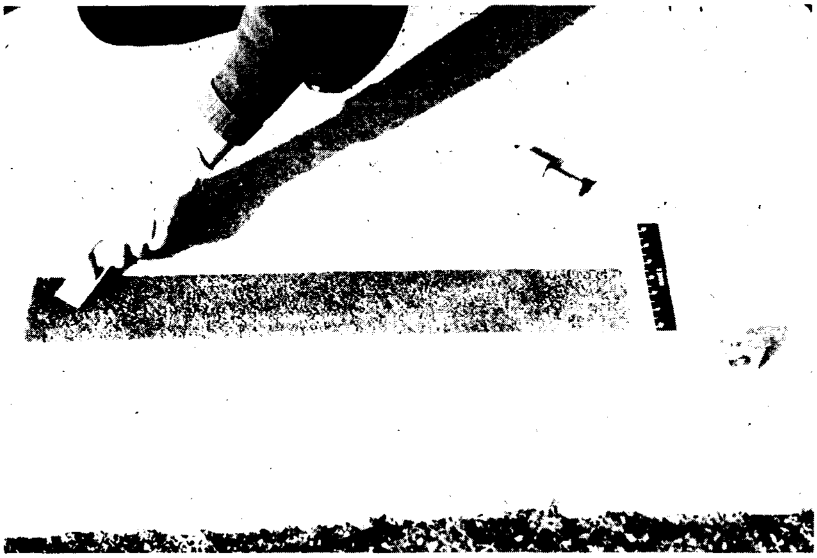


Figure 10.- Method of measuring runway surface texture. L-2551-10

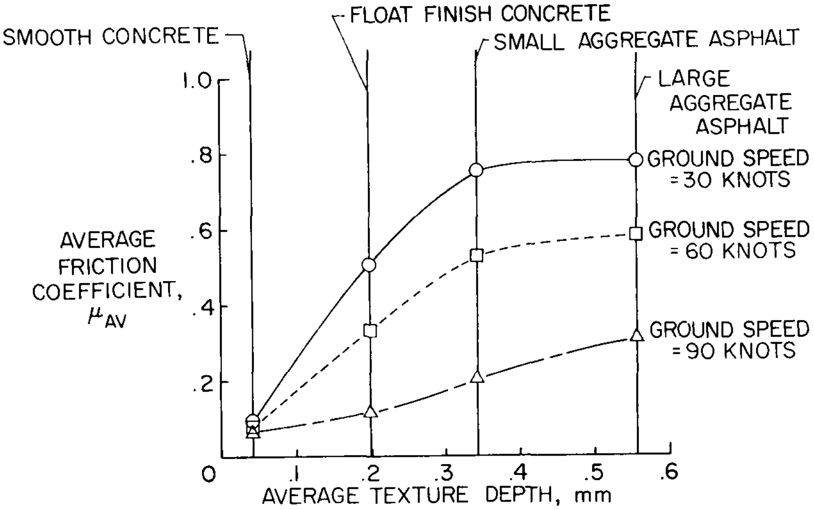


Figure 11.- Correlation of braking friction coefficient with average texture depth. 32 × 8.8 smooth tread aircraft tire; F_z = 12 000 lb (53.4 kN); p = 140 lb/in.^{2} (96.5 N/cm^2); flooded runway; Water depth = 0.1 to 0.2 inch (0.2 to 0.5 cm).

The Langley Research Center (ref. 18) has developed a simple technique to determine the average texture depth of a pavement surface. This method involves spreading a known quantity of grease on the pavement surface with a rubber squeegee to fill the runway pores. The average texture depth for the surface is then obtained by dividing the surface area covered into the volume of grease used. An illustration of this procedure is given in figure 10. The correlation of average texture depth with braking traction for the test runway surfaces at the track is given in figure 11. It is noted that, for a given speed, increasing the surface texture increases braking traction up to some level after which no further increase in traction is obtained. The results indicate that a greater depth of texture is required to develop maximum tire friction coefficient at the higher speeds. Photographs of the surfaces are shown in figure 12. Additional correlations of braking traction with average texture depth on actual operational pavement surfaces are needed to clarify the usefulness of this technique.

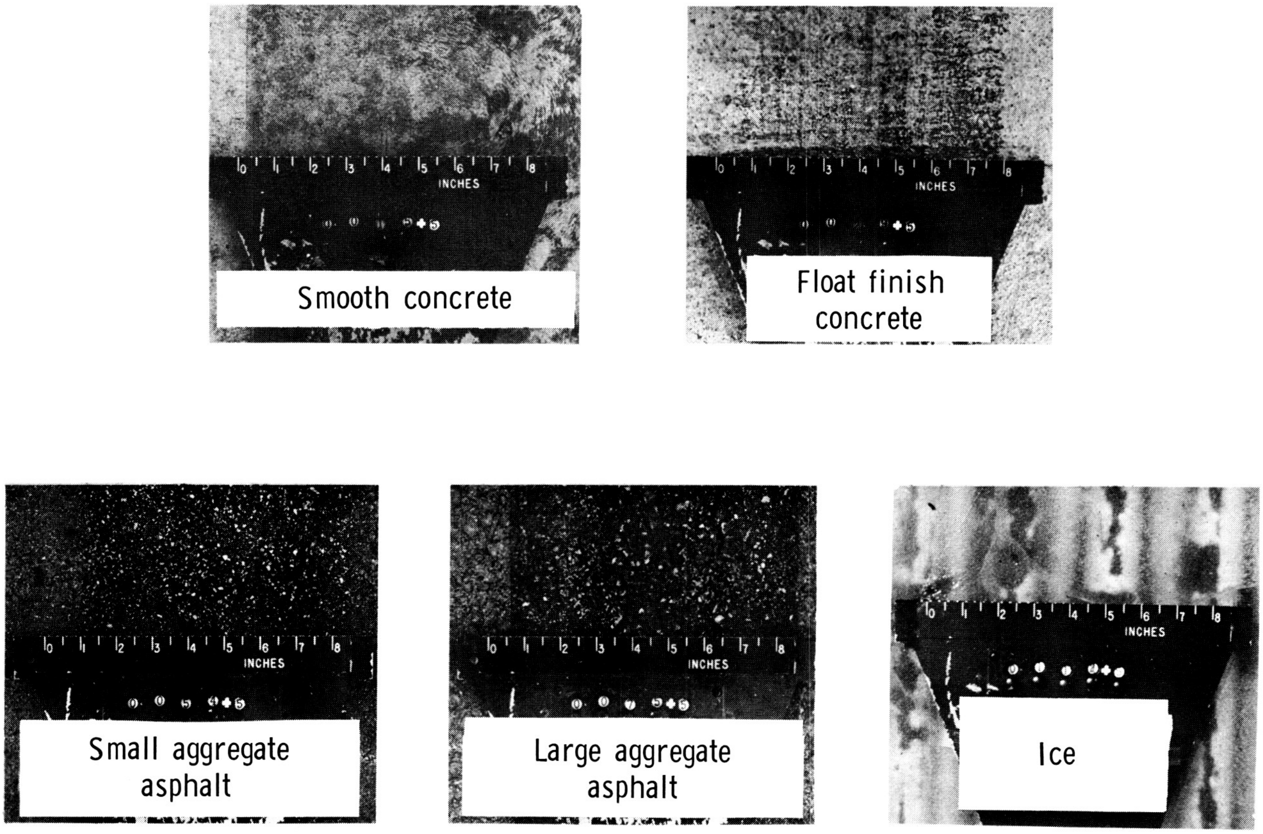


Figure 12.- Test runway surfaces at landing-loads track. L-2551-12

The use of techniques, such as that previously described, is needed to define minimum standards of runway texture for safe operations on wet surfaces. Such standards would provide a capability for quickly determining when a pavement surface needs to be repaired or replaced as a result of its poor braking traction qualities when wet or flooded.

Tire-tread design – wet runways.- Braking performance of smooth tread aircraft tires on most wet or flooded runway surfaces is greatly improved by cutting or molding a series of circumferential grooves into the tire tread. The resulting traction improvement on wet surfaces with grooved tires over that with smooth tread tires is due to two effects. First, the low pressure channels formed in the tire footprint by the tread grooves and runway surface tremendously facilitate water drainage from the footprint area even under deeply flooded runway conditions. This effect disappears, however, as the critical dynamic hydroplaning speed is neared or exceeded as shown in figure 13. For shallow water depths where the grooves do not become choked, total dynamic hydroplaning is delayed to a higher speed as shown in figure 14. As a result of the better drainage, traction performance of the grooved tire is also greatly improved over that of the smooth tire at sub-hydroplaning speeds. The data presented in figures 13 and 14 show that this benefit is lost as the tire tread wears, or as the groove depth decreases.

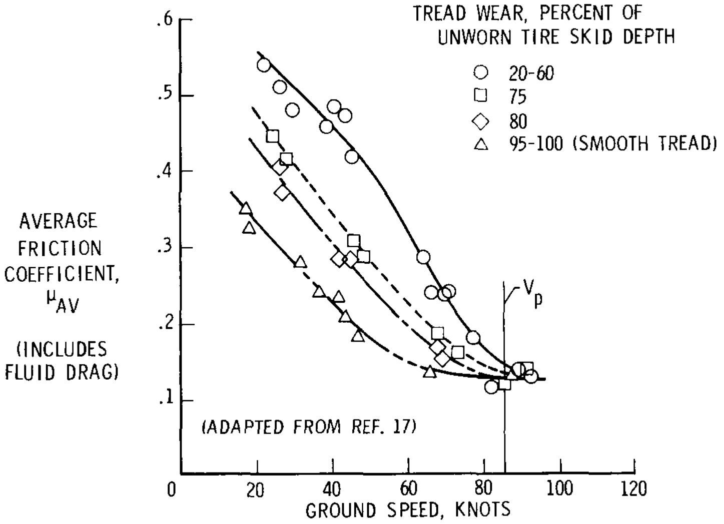


Figure 13.- Effect of tread wear on flooded concrete runway. Five-groove rib tread; F_z = 10 500 lb (46.7 kN); p = 90 lb/in^2 (62.1 N/cm^2); Water depth = 1.0 in. (2.5 cm); Initial tread skid depth = 0.25 in. (0.6 cm).

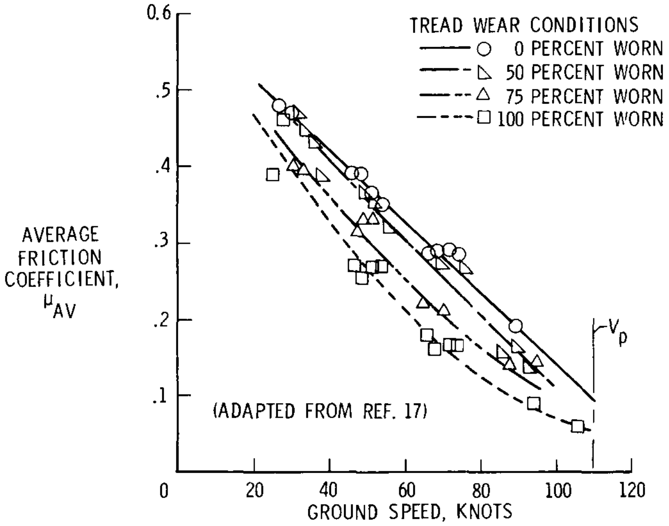


Figure 14.- Effect of tread wear on wet concrete runway. Five-groove rib tread; F_z = 10 500 lb (46.7 kN); p = 150 lb/in^2 (103.4 N/cm^2); Water depth = 0.1 to 0.3 in. (0.2 to 0.8 cm).

The second effect to be discussed is the ability of the sharp edges or corners of the tread grooves to penetrate and displace the viscous fluid film separating the tire from the pavement. Adhesion between tire and ground is thus regained along the line of pavement contact of the groove edges, which increases traction of grooved tires over that of smooth tread tires on the smoother wet pavements. Automobile tire manufacturers have found that the addition of closely spaced sipes or small knife cuts in the rib areas of circumferentially grooved tires increases traction on wet smooth surfaces to a much greater extent than simple grooving. Up to the present time, this feature has not been provided in high performance aircraft tires because of tread chunking or tread retention problems; however, because of the substantial benefits which might accrue from tire siping, this procedure should be reexamined for application to aircraft.

Tire-tread design – ice-covered runways.- For a number of years, tire manufacturers have been requested to provide aircraft operators with "ice-grip" tires. These special tires have thousands of chopped up pieces of small diameter wire molded into the tire tread that become exposed as the tread surface wears. This feature was designed to increase the grip of the tire on icy pavements. Three ice-grip tires having different wire content were tested on the ice-covered runway of the Langley landing-loads track, and the results obtained are shown in figure 15.

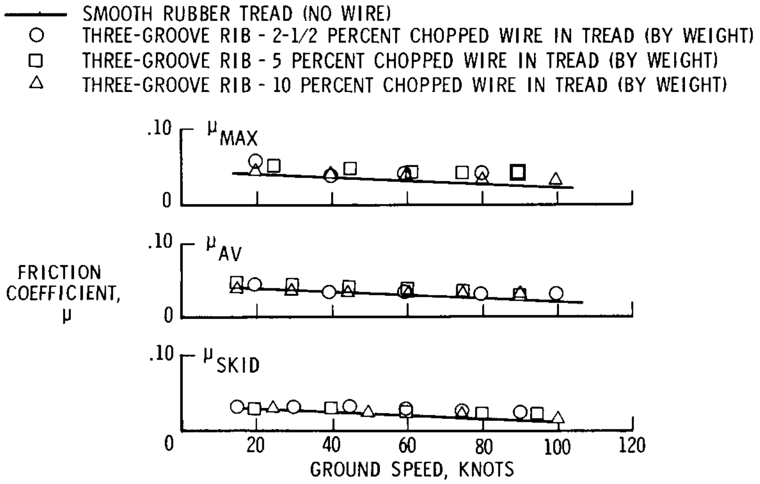


Figure 15.- Ice-grip tire-braking effectiveness on wet ice. 32 × 8.8 aircraft tire; F_z = 13 200 lb (58.7 kN); p = 290 lb/in^2 (200 N/cm^2).

No significant improvement in traction was apparent on the wet ice surface with the ice-grip tires than with a smooth tread tire (without the wire). It is not known at this time whether the minor improvements obtained were the result of the ice-grip feature or of the three grooves in the tread design of the ice-grip tire. In fact, the friction coefficients measured for all the tires tested on ice differed only slightly from the values shown in figure 5 for free rolling. The four tires tested under both conditions were constructed by using the same mold shape and rubber compounds, and only the wire content and groove design were varied.

Fluid viscosity and slush.- Data presented in reference 16 demonstrated that increasing fluid viscosity increased the fluid pressures developed between tire and ground at a given speed and, hence, enhanced the possibility of viscous hydroplaning. The data in figure 16 (from ref. 11) show that traction loss at low speeds (where dynamic effects are unimportant) is much greater on the more viscous slush than on the water-covered runway. These tests were conducted on a moderately textured concrete runway and it is believed, on the basis of data presented in reference 16, that these losses could be decreased by increasing the texture of the surface. The effective friction coefficient used in figure 16 is the mean value of the friction coefficient developed at the tire-ground interface using antiskid braking.

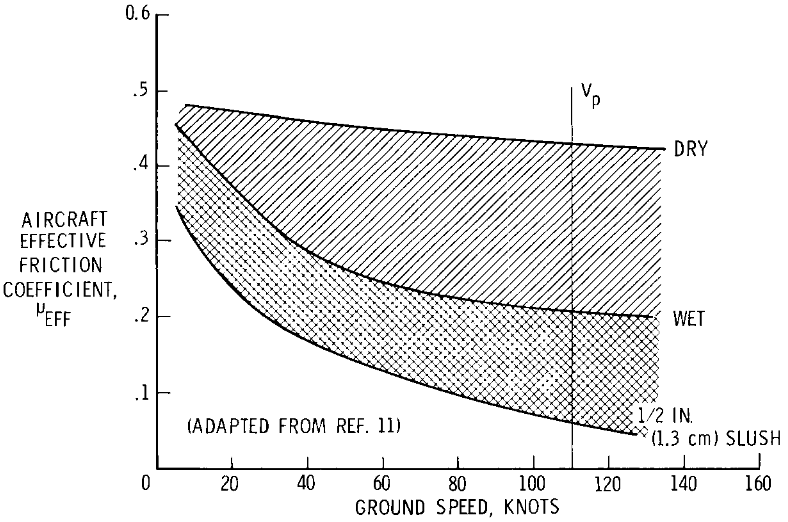
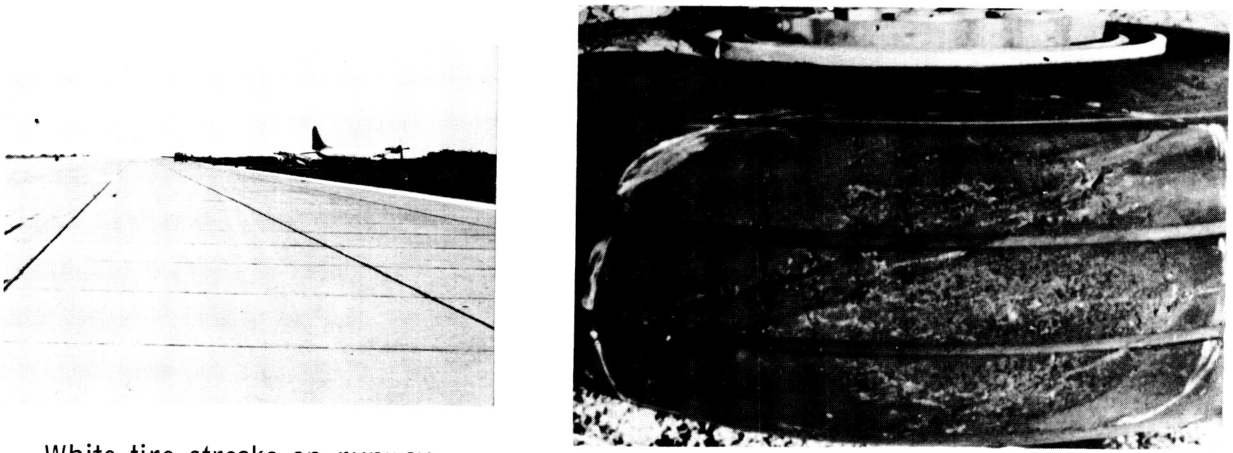


Figure 16.- Braking effectiveness on jet transport. Full antiskid braking; $p = 150$ lb/in^2 (103.4 N/cm^2).

Tread Reversion

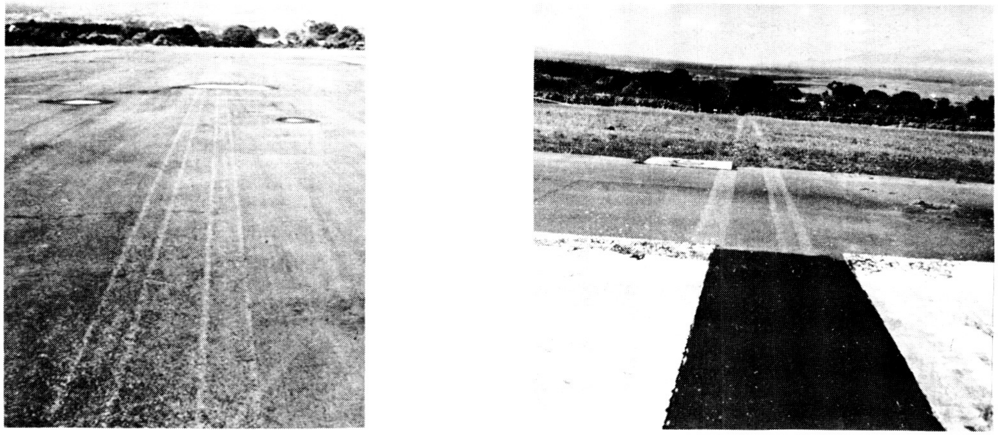
Evidence from skidding accidents.- A recent survey of conditions that prevailed during landing accidents on wet runways showed a very interesting correlation. In numerous documented cases on wet runways involving aircraft departure off the side of the runway or in an overrun (both types of accidents indicate drastic loss of tire traction), the runway surface was found to have developed white streaks in the tire paths. The aircraft tires showed evidences of prolonged locked wheel skids with indications that the rubber in the skid patches had reverted to an uncured state. Examples of the two types of accidents made available to NASA are shown in figures 17 and 18. In figure 18, where effects of an overrun accident are shown, the white streaks persisted down to the point that the aircraft stopped.



White tire streaks on runway

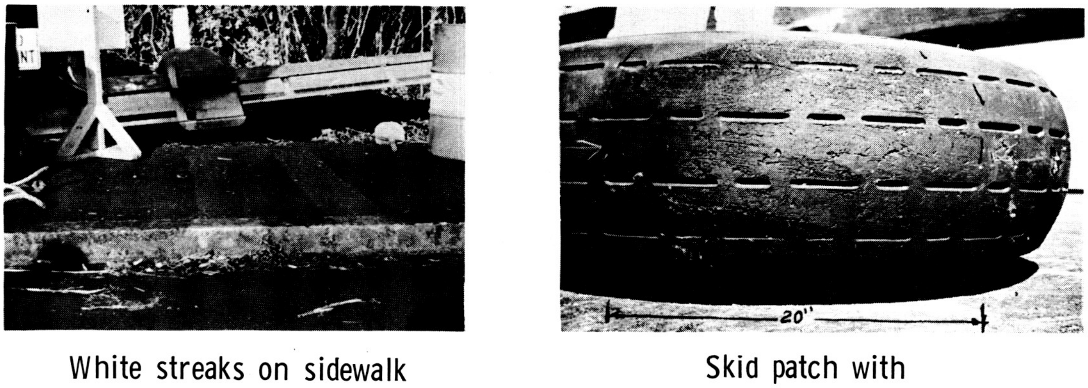
Reverted-rubber skid patch

Figure 17.- Hydroplaning accident with four-engine prop jet on flooded runway during heavy crosswind. L-2551-17



White streaks on runway
≈70 knots

White streaks on over-run
≈5-10 knots



White streaks on sidewalk
≈5 knots

Skid patch with
reverted rubber

Figure 18.- Hydroplaning accident on flooded runway with twin-engine transport aircraft. L-2551-18

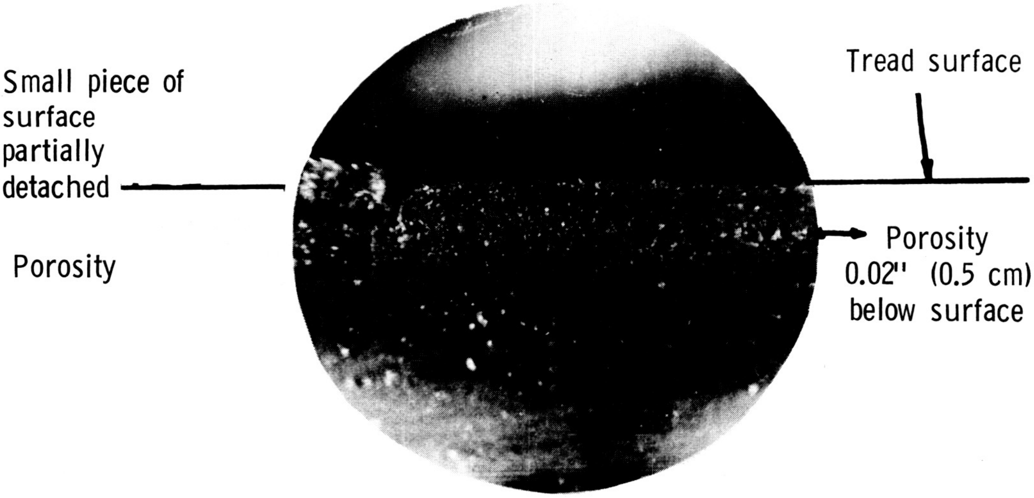
In contrast, if the wheels lock on dry runways at speed, black streaks from molten rubber eroding from the tire are immediately deposited in the tire paths. Although friction decreases under this condition, at least one-third of the maximum dry friction coefficient is still available for stopping the aircraft, as was illustrated in figure 2. It thus appears that some mechanism other than viscous or dynamic hydroplaning must be at work to prevent the skidding tire from developing traction on wet textured pavements even at very low ground speeds as indicated in figure 18.

Reverted rubber in skidding footprints.- The tread condition known as reverted rubber was pointed out as early as 1943 in an unpublished memorandum by J. H. Hardman and V. E. Gough of Dunlop Rubber Ltd., England. In this case, the reverted rubber developed during locked wheel skids on wet grass. (See fig. 19.) Hardman and Gough stated that their examination of the tread blisters revealed that the deterioration was of a fine porosity in a thin layer parallel to and just below (about 0.02 inch; 0.05 centimeter) the original tread surface and that this porosity resembled overheating of the rubber due to attainment of local temperatures around 392° F (473.15° K). The tread surface itself was, however, unaltered and showed the original surface cracks and fine abrasion marks. This film, which was about 0.01 inch (0.03 centimeter) thick, showed no trace at all of any effects of high temperature. This surface film was, however, torn away in places having a "scabby" appearance (as shown in fig. 19). The porosity extended under all adhering pieces of surface film and was noted to be quite tacky when the latter was torn off. Hardman and Gough further stated that puffs of steam or white smoke were visible at points along the whole length of the "slide" (about 200 or 300 yards; 182.9 or 274.3 meters) after touchdown.

Further examples of tread reversion made available to NASA are shown in figures 17, 18, 20, 21, and 22. These examples show the tacky porous reverted rubber mentioned by Hardman and Gough but do not show the undamaged surface layer that they mentioned. It perhaps was destroyed during the low-speed ranges of the skids. Because the examples cited cover such a large range of aircraft types, it is suspected that most aircraft can suffer or experience this phenomenon during prolonged wheel skids on wet or flooded runways.

Duplication of reverted rubber during track tests.- A series of tests was made at the Langley landing-loads track with tires locked to prevent rotation on dry, wet, and flooded runways at speeds ranging from about 25 to 100 knots. A typical footprint of a smooth-tread tire after a 467-foot (142.3-meter) skid on a flooded runway at 78 knots ground speed is shown in figure 23. In this particular test, the tire was allowed to skid first along 62 feet (18.9 meters) of a dry, smooth concrete runway to produce molten or reverted rubber in the tread; the rest of the skid took place on the runway flooded to a depth of 0.1 to 0.2 inch (0.2 to 0.5 centimeter). Other tests were made where the skid was initiated on either damp or flooded smooth concrete, and also for an alternately wet

(a) General view.



(b) Photomicrograph.

L-2551-19

Figure 19.- Reverted-rubber skid patch obtained during locked wheel skid at high speed on wet grass. Photograph from Hardman and Gough, Dunlop Rubber Ltd., 1943.

and puddled runway condition. Under all conditions of the tests, if reverted rubber developed in the footprint, the traction values fell to very low values in comparison with those obtained with the tire under normal rubber tread conditions. (See figs. 24, 25, and 26.) As shown in figure 27, the reverted rubber condition tends to make all runway surfaces smooth acting. Pavement surface texture, which (as discussed previously) has such a large effect on traction losses from dynamic and viscous hydroplaning (normal rubber curves), has but little effect for the reverted rubber condition for the texture-depth range shown.

Formation of reverted rubber in skidding footprint.- Data regarding the formation of reverted rubber in the skidding footprint on wet runways are very limited, and the effects of pavement texture, wetness, and ground speed are as yet unknown. However, some facts are known about the process. A reverted-rubber state has been obtained at Langley on dry pavement by skidding the tire a short distance, which suggests that the process can be initiated at touchdown on drained sections of wet runways prior to wheel spin-up.

Figure 20.- Reverted-rubber skid patch obtained with four-engine jet transport on wet runway. L-2551-20

Generation of steam in the skidding tire footprint, first discussed by Obertop (ref. 22), offers an explanation for the reverted rubber and the reduced traction that may be developed by tires at very low speeds on textured and untextured surfaces. It may be noted that the steam pressure in the footprint, if developed, must closely equal the tire-ground bearing pressure at all speeds. Moreover, if steam is formed, then it must be superheated steam, and for tire-inflation-pressure ranges of aircraft, this temperature is sufficiently high to melt the rubber tread surface. In this concept, once the reverted condition starts, it is possible to have a steam pump established in the footprint, and the

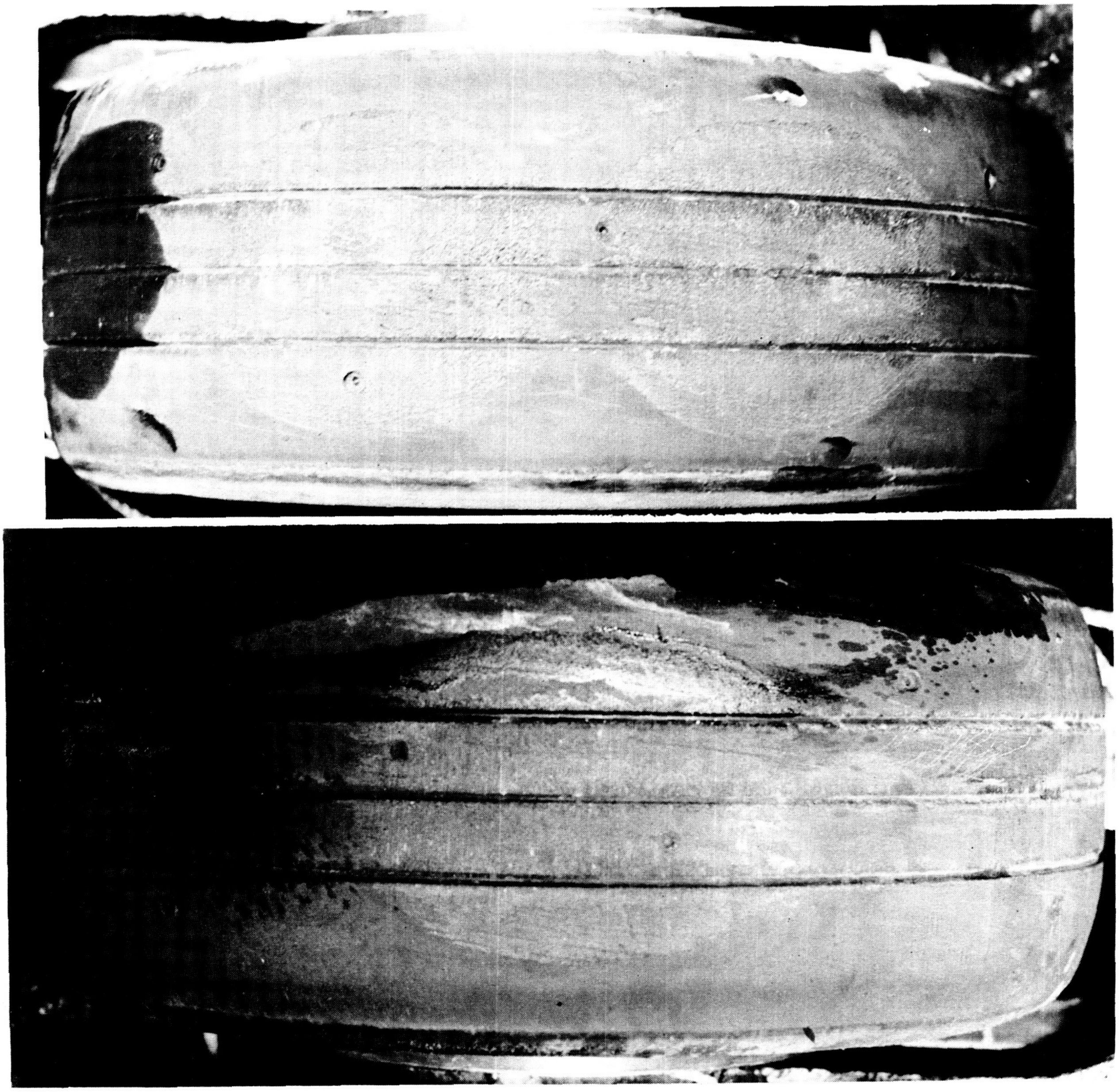
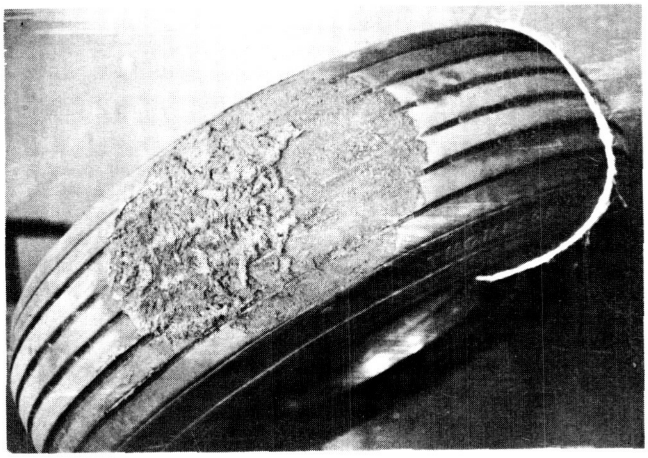
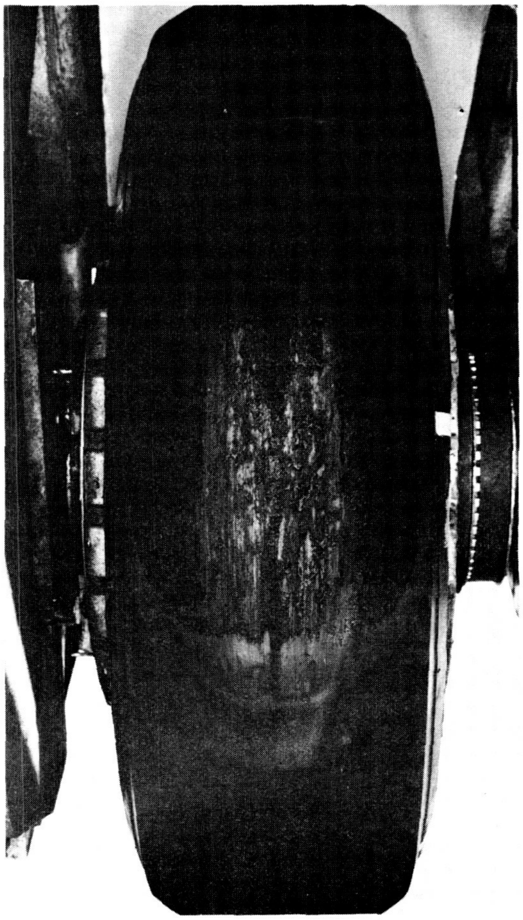


Figure 21.- Reverted-rubber skid patches. Hydroplaning accident with supersonic fighter on wet runway with isolated puddles. L-2551-21



L-2551-22
Figure 22.- Reverted-rubber skid patch obtained with four-engine prop jet on wet runway.



L-2551-23
Figure 23.- Reverted-rubber skid patch from tests at landing-loads track. 32 × 8.8 smooth tread aircraft tire; F_Z = 16 000 lb (71.2 kN); p = 250 lb/in^2 (172.4 N/cm^2).

reverted rubber formed may act to effect an efficient seal, which permits high steam pressures to persist right down to a stop on the runway. The steam pressure would tend to lift the tire away from the pavement surface and thus reduce traction on wet surfaces in a manner similar to the fluid pressure buildup from viscous and dynamic hydroplaning effects. The steam concept also offers an explanation for white streaks developed in the tire paths in that the paths would be cleared of dirt and other contaminants by high pressure superheated steam.

With reference to the question of temperature buildup in the footprint, a few preliminary tests were made. A 32 × 8.8 aircraft tire was equipped with thermocouples (fig. 28) and tested at the Langley track. The peak temperatures experienced by this aircraft tire at the end of an approximately 65-foot (19.8-meter) skid at a ground speed of 77 knots on a damp, smooth concrete surface are shown in figure 29. The results show that the peak temperature decreases as the tire inflation pressure decreases, which perhaps explains the lower automobile tread temperatures reported in reference 16 where an attempt was also made to investigate the steam hypothesis at much lower tire pressures. The data show that the temperature buildup on the tread surface of a skidding tire on wet surfaces is related to the unit pressure the tire develops in the skid patch on the pavement, is higher near the center of the skid patch, and varies with pavement texture (fig. 30).

In summary, the results of the limited studies made at Langley indicate that reverted rubber may form and possibly provide better sealing around the periphery of the footprint (see fig. 23) than normal rubber, thus allowing a very thin film of water to be trapped in the footprint, heated up, and converted to steam. The steam cushion generated could support the tire off the surface and produce the low friction coefficients measured. It could also provide the mechanics for scouring the runway and producing the white streaks which have been observed after numerous aircraft skidding incidents.

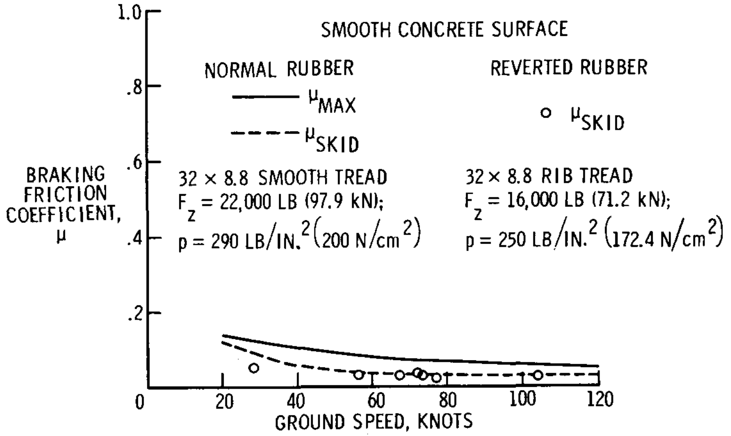


Figure 24.- Effect of reverted-rubber footprint on braking friction. Flooded runway.

Multiple reverted rubber skid patches.- Numerous instances have been observed where multiple reverted rubber skid patches such as those shown in figure 21 develop around the tire circumference. For these cases, it is believed that intermittent wheel lockups from braking, actuated either by the pilot or by antiskid devices, cause the multiple patches. This explanation is borne out by the film sequences (ref. 23) of the action of an antiskid-equipped bogie landing gear of a supersonic bomber during wet landings. These sequences show wheel lockups for as long as 21 seconds and successive wheel lockups before the wheels have regained free-roll rotational velocity. Thus, the antiskid system appears to permit the tires to operate (for this low tire-ground friction coefficient regime) on the back side of the curve of friction coefficient as a function of slip ratio in figure 1.

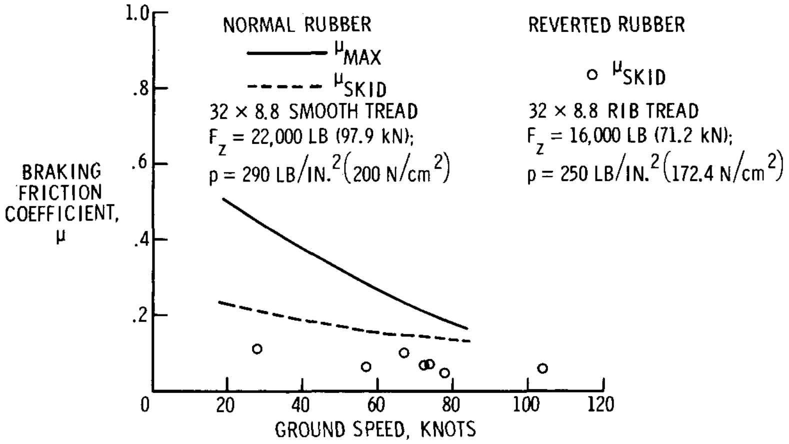


Figure 25.- Effect of reverted-rubber footprint on braking friction. Flooded runway; float finish concrete surface.

Discussion of Tire Braking Performance on Wet or Flooded Runways

The preceding sections of the paper have attempted to show that viscous hydroplaning, dynamic hydroplaning, and tire-tread reversion all can, depending upon conditions,

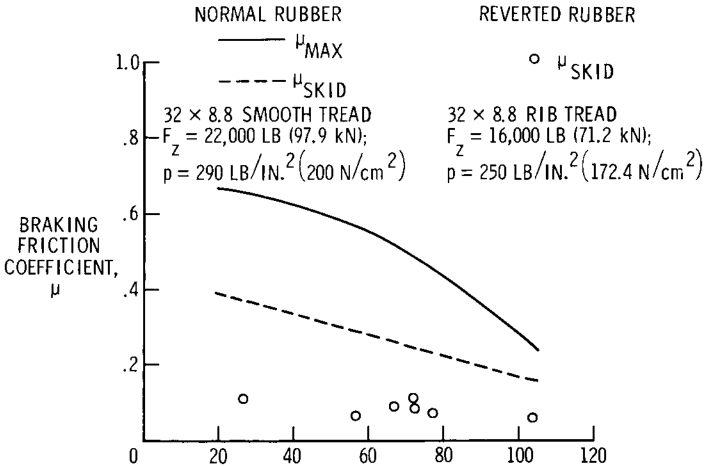


Figure 26.- Effect of reverted-rubber footprint on braking friction. Flooded runway; small aggregate asphalt surface.

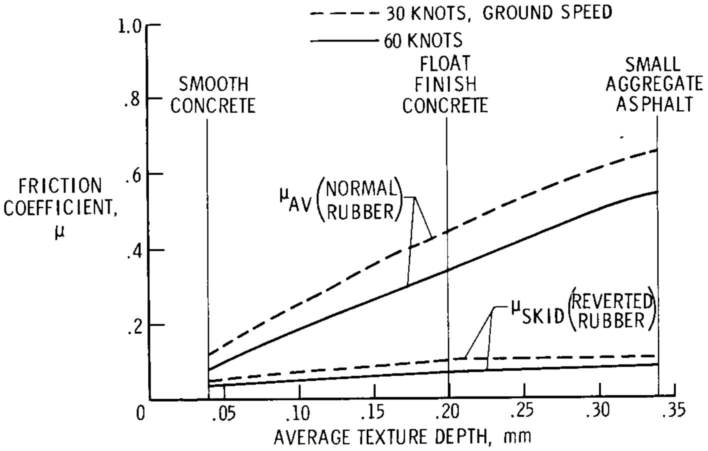


Figure 27.- Effect of surface texture on braking friction. Flooded runway.

create total loss of tire traction on fluid-covered pavements. Fortunately, the critical conditions required of the tire, pavement, or aircraft to achieve almost total loss of traction for each of these phenomena are different. This makes possible certain avenues of approach to combat and alleviate each hydroplaning type. For example, the critical parameter for viscous hydroplaning is pavement surface texture. If an adequate texture is provided on the runway surface, viscous losses are greatly alleviated over all ranges of operating speed, inflation pressure, and tire tread condition ranges.

On the other hand, the critical requirement for dynamic hydroplaning to occur is fluid depth on the pavement. Removing the fluid from the tire paths, by air jets or otherwise, eliminates dynamic hydroplaning as a problem. Fluid removal can be accomplished by satisfactory tire tread designs up to a certain critical ground speed dependent upon inflation pressure and fluid depth conditions. Once this critical ground speed is exceeded, total traction loss occurs until either the speed or the fluid depth is reduced.

The condition of tire-tread reversion is potentially the gravest problem because its occurrence requires only that the pavement be smooth and damp. The prevention of tread reversion can be simply stated: Prevent the wheel from locking during landing runout.

The alleviation of traction losses on wet runways not only by viscous and dynamic hydroplaning but also by tire-tread reversion has been the subject of recent and continuing research at the landing-loads track. Some of the more promising means of alleviation that have been studied are discussed in the following section of the paper.

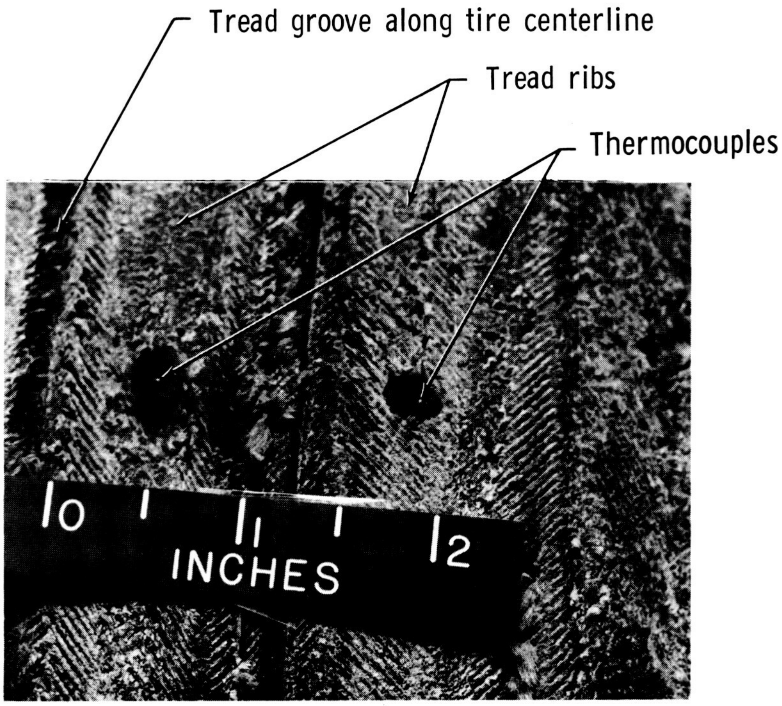


Figure 28.- Thermocouple installation on rib-tread tire. L-2551-28

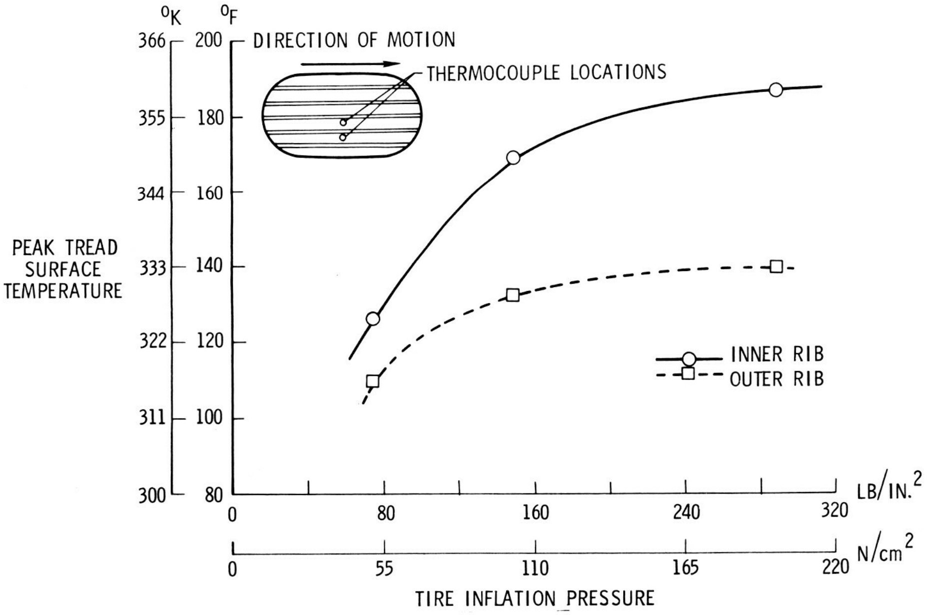


Figure 29.- Tread-surface temperature rise after 65-ft (19.8-m) skid on damp smooth concrete. Ambient temperature = 82° F (301° K).

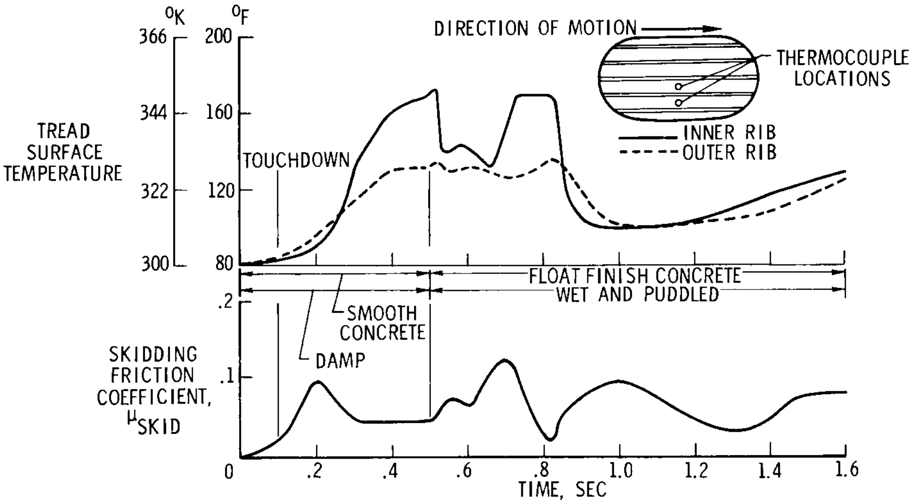
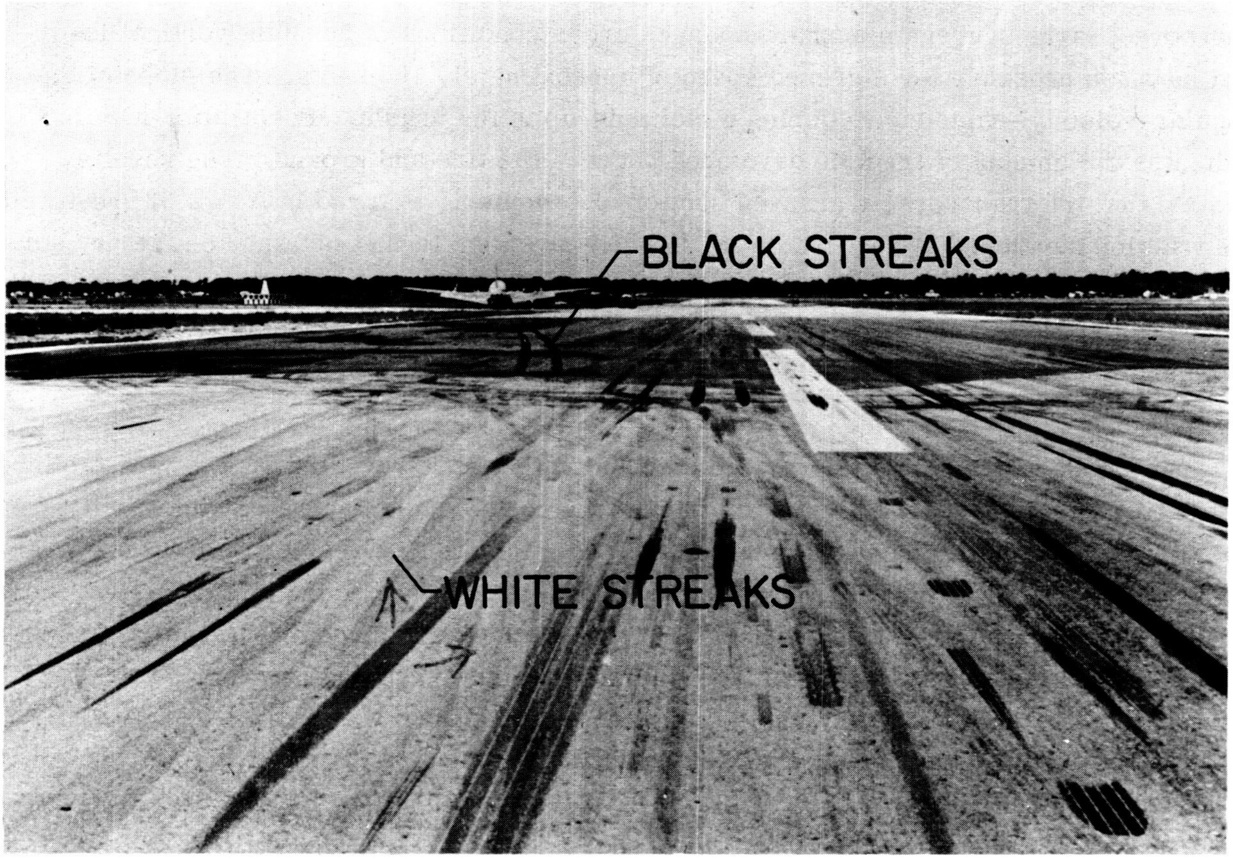


Figure 30.- Time histories of tread-surface temperature and full-skid friction coefficient. Locked wheel skid at 77 knots ground speed; F_Z = 10 000 lb (44.5 kN); p = 150 lb/in^2 (103.4 N/cm^2).

WAYS OF IMPROVING TIRE TRACTION ON WET SURFACES

Pavement Surface Texture

The paramount importance of pavement surface texture in alleviating viscous traction losses has been discussed in this paper. It is important, for definition and classification of surface traction characteristics, to be able to describe quantitatively the relative slipperiness of pavements in terms of some easily measured pavement surface parameters such as the average texture depth described earlier. Other researchers such as those previously mentioned, Moore (Cornell Aeronautical Laboratory), Kummer and Meyer (Pennsylvania State University), and Sugg (British Ministry of Aviation) have suggested alternate methods. Additional data, obtained by these or other techniques, are needed to correlate appropriately pavement texture with tire traction under wet conditions. In the accumulation of such data, particular care should be exercised to account for such factors as tire pressure, test speed, and tread design to assure that the data obtained are representative of aircraft operational conditions on wet runways. For example, a significant point can be drawn from the photograph of figure 31 where the skidding aircraft tire left white tire streaks on the runway up to the point where the pavement was resurfaced. The new surface, having a rougher texture, shows black skid marks, indicative of higher friction coefficients.



Note! Deposited rubber in skid marks occur during change in runway surface texture

L-2551-31

Figure 31.- Hydroplaning accident with four-engine piston transport. Large areas of runway covered with water during landing.

Pavement Grooving

Pavement grooving shows great promise as a means of alleviating all forms of tire traction loss on wet runways. It was initiated by Judge (ref. 24) in England and first applied there to military airfields in 1956. The following discussion attempts to describe some beneficial aspects as well as to pose some possible problems associated with pavement grooving.

The work of Gray (ref. 21 and fig. 9) demonstrated that transverse grooves can greatly increase the critical water depth on the runway required for dynamic hydroplaning to occur, and thus reduce (because of the higher rainfall precipitation rates required) the probability of aircraft encountering dynamic hydroplaning. The increased traction due to transverse grooving of a flooded runway is illustrated by the wheel spin-up time histories measured at the Langley track and presented in figure 32. In this figure are presented wheel spin-ups from a locked-wheel skid condition on dry and flooded, grooved and ungrooved, large aggregate asphalt surfaces under conditions of constant vertical load and inflation pressure for a ground speed of approximately 100 knots. The slope of the angular-velocity—time curve during wheel spin-up is the angular acceleration and thus indicates the amount of traction developed between the tire and ground. The results showed that the transversely grooved section of pavement, pictured in figure 33, restored the traction developed by the tire on the flooded pavement to that obtained on the dry surface. This result indicates, for example, that the installation of transverse grooves in the touchdown areas of runways might prevent prolonged skids from developing on aircraft tires and thus prevent the dangerous development of reverted rubber in the tire skid patch.

It has been shown in the previous discussion that once reverted rubber is established in the tire footprint, extremely low friction coefficients develop on wet pavements down to very low ground speeds. Because the friction coefficients that result are as low or even lower, in some cases, than the tire free-rolling resistance coefficient μ_r, the tire has a tendency to remain in the locked wheel condition for long distances on the runway. Tests at the landing-loads track show that transverse pavement grooving can remove the reverted rubber in the tire footprint as the tire slides across the grooves and restore tire traction capability to normal rubber conditions. This result is shown in figure 33.

The results presented show that transverse grooves on runways can effectively restore normal braking action to tires operating in the reverted rubber mode. It may not be necessary for the runway to be completely grooved to obtain this beneficial effect. Consider that only the middle third of a runway is transversely grooved, and assume that an aircraft touches down off runway center line with one main landing wheel operating on the grooved runway and the other wheel outside the grooved area. When wheel braking commences, a higher braking force should be developed by the landing-gear tire(s) operating on the grooves than the tire(s) off the grooves. This situation should produce a large moment about the aircraft center of gravity, so that the aircraft tends to return to the center of the runway. This effect would also be beneficial during crosswind landings on wet runways.

The effects of pavement transverse grooving on the runway life, on aircraft vibrations, and on tire-tread wear are as yet unknown and further assessment of potential problems is required. However, the very promising results obtained from limited tests made on grooved runways indicate that further full-scale research on actual runways is needed to evolve both beneficial and adverse effects encountered during operational usage. On the basis of present available information, grooving of complete runways cannot be recommended at this time but installing transverse grooves in paved runway overrun areas appears justifiable. In times of emergency, the grooves in overrun areas would be available to help stop the aircraft, yet the grooved surface would not interfere with

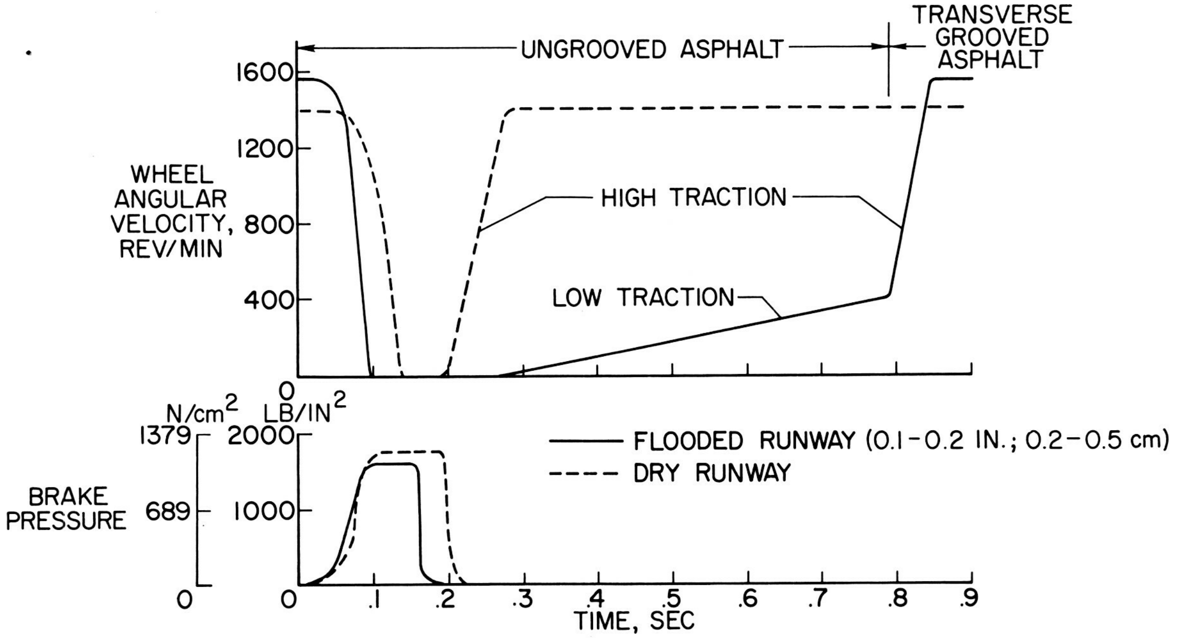


Figure 32.- Effect of transverse grooves on wheel spin-up. Ground speed ≈ 100 knots; F_Z = 12 000 lb (53.4 kN); p = 140 lb/in^2 (96.5 N/cm^2).

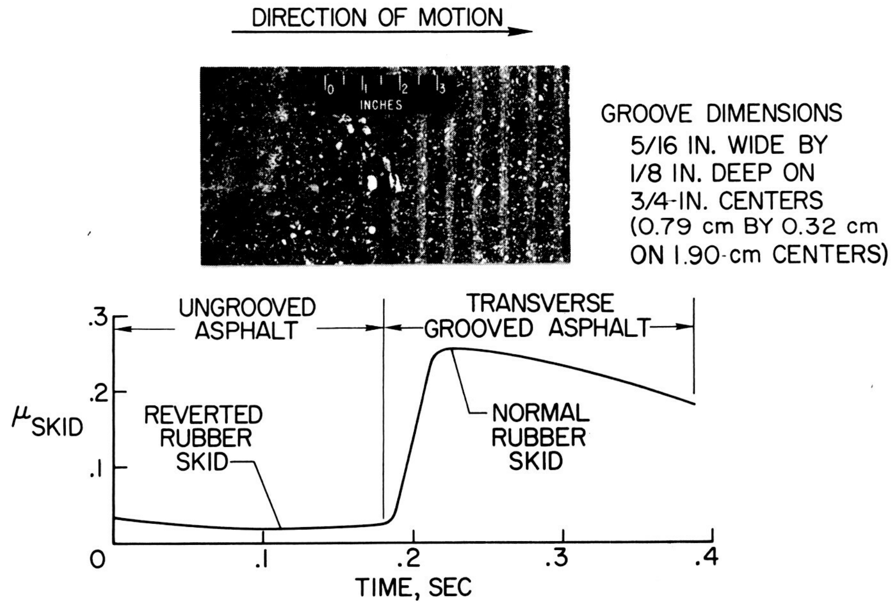


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Figure 33.- Effect of transverse grooves on reverted rubber skid. 32 × 8.8 aircraft tire; Ground speed = 77 knots; F_Z = 16 000 lb (71.2 kN); p = 250 lb/in^2 (172.4 N/cm^2); Water depth = 0.1 to 0.2 in. (0.2 to 0.5 cm).

operations in normal landing areas. Also, some experience on pavement deterioration through weathering effects of the grooving could be established.

Some track tests were also conducted with longitudinal runway grooves, but the results were inconclusive and are not presented.

Air Jets

Air jet research to improve tire traction was first performed at the Langley Research Center in 1958; the results of this initial work, performed on a small wheel and belt arrangement, are reported in reference 25. Air jet research at Langley was resumed at the landing-loads track in 1964, and some of the results obtained during this investigation (refs. 15, 16, and 18) are summarized in the following paragraphs.

Figure 34 shows a view of the test fixture and air jets used in the current test program. The test tire was a regular 6.50 – 13 automobile tire inflated to a pressure of 27 pounds per square inch (18.6 newtons/centimeter^2). Both a smooth-tread and a 4-groove ribbed-tread tire were tested. Essentially, the air jet arrangement, as shown, was a tandem-nozzle arrangement with the trailing nozzle located about 7.5 inches (19.0 centimeters) behind the front nozzle and about 10 inches (25.4 centimeters) in front of the tire. The tire in this figure is resting on a glass plate which was located flush with the concrete surface in the test runway. From beneath this glass plate, photographs of the tire footprint were taken as the tire traveled across the plate. The water over the

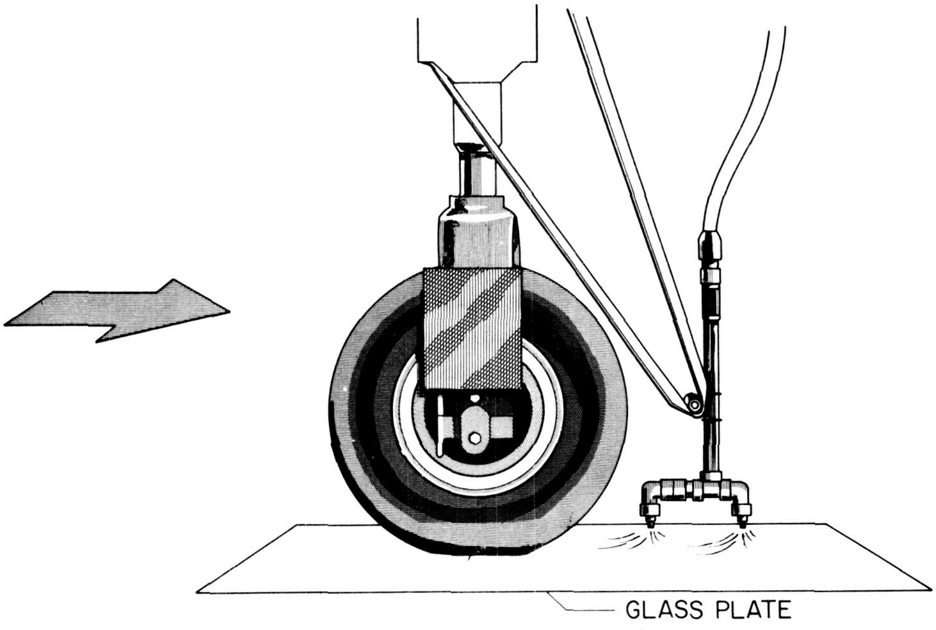
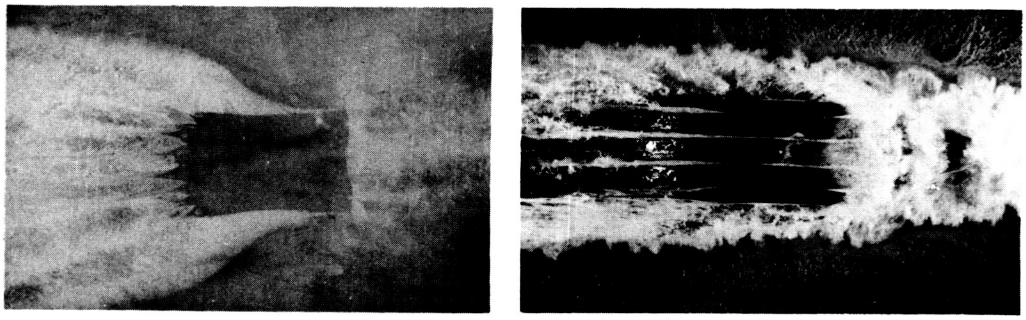


Figure 34.- Arrangement of air jets. Airflow ≈ 2.7 lb/sec (12 N/sec); Nozzle pressure ≈ 390 lb/in^2 (269 N/cm^2). 10/20-22/65

glass plate was colored with a green sea-marker dye to give better contrast. These photographs showed the very beneficial effect which can be obtained by completely clearing water from the footprint (fig. 35). The left portion of the figure, without air jets, shows the tire in a completely hydroplaning condition when traveling at a speed of 54 knots. The right portion of the figure, with air jets, shows the good contact of the tire with the runway when the tire is traveling at a speed of 87 knots. In this test, hydroplaning was alleviated.



Without air jets
(Ground speed = 54 knots)

With air jets
(Ground speed = 87 knots)

L-2551-33

Figure 35.- Path-clearing effectiveness of tandem air jets (adapted from ref. 18). Water depth = 0.3 in. (0.8 cm).

The surface of the test runway shown schematically in figure 36 was very smooth except for a 52-foot (15.8-meter) section in the middle which was sandblasted in order to have a surface texture somewhat more representative of highways and runways in use today. The beginning of the sandblasted concrete surface had an average texture depth of 0.104 millimeter as measured by the grease technique described earlier (fig. 10). This value is about half the texture depth of the float finished concrete surface also described earlier. (See fig. 11.)

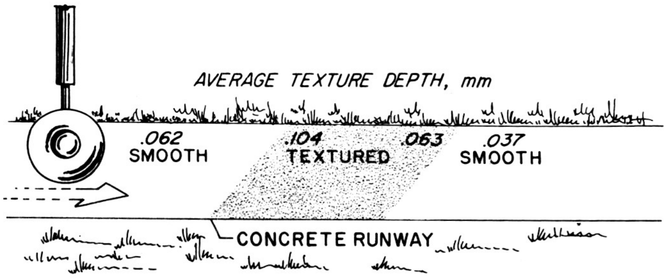


Figure 36.- Schematic of level runway surfaces (adapted from ref. 18).

Figure 37 presents values of locked wheel friction coefficient and hydrodynamic pressure plotted against runway distance for one run. These values were obtained at a carriage speed of 90 knots, almost twice the hydroplaning speed of 47 knots, with the ribbed-tread tire and a runway water depth of 0.3 inch (0.7 centimeter). The runway surface condition is noted in figure 37; there were three sections, a smooth concrete section, the sandblasted textured concrete section, and another smooth concrete section. The

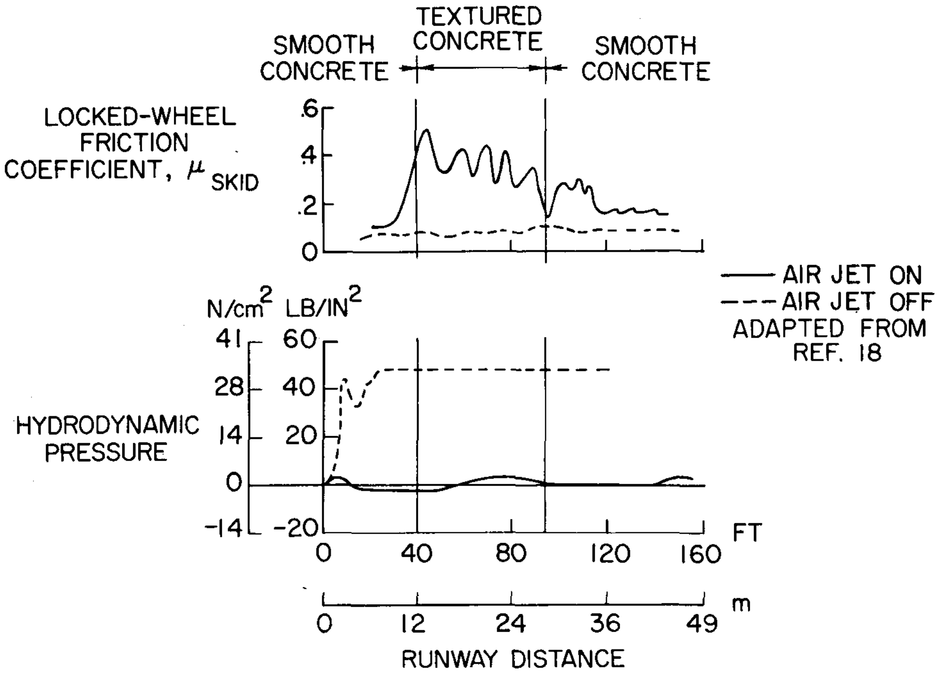


Figure 37.- Effect of air jets on braking traction. Water depth = 0.3 in. (0.8 cm); Ground speed = 90 knots.

results with the air jet off show that hydrodynamic pressures above 40 pounds per square inch (27.6 newtons/centimeter^2) were developed on the tire footprint and that very low values of μ_{SKID} were obtained. With the air jet on, hydrodynamic pressure was reduced to near zero on the tire surface and μ_{SKID} was substantially increased, especially on the textured concrete section where the friction coefficient is greater than 0.4. The gradual decrease in μ_{SKID} shown as the tire traveled over the sandblasted runway section is due to a nonuniform texture achieved during sandblasting as indicated in figure 36.

Figure 38 presents wet runway cornering force data as a percent of dry runway values plotted against the same runway distance as in figure 37. The yaw angle was 5^o, the water depth was 0.3 inch (0.7 centimeter), and the speed was 77 knots, which was greater than the critical hydroplaning speed. With the air jet off, less than 5 percent of the dry runway cornering force is achieved; but, with the air jet on, more than 50 percent of the smooth tire dry runway cornering force is obtained in the textured concrete section.

Figure 39 summarizes results obtained with the locked wheel, the 4-groove ribbed-tread tire, and 0.3 inch (0.7 centimeter) of runway surface water. The values of μ_{SKID} on both smooth and textured runway surfaces are plotted against forward speed. On the smooth concrete surface, there is a relatively small difference between the results obtained with the air jet off and the air jet on because of the inability of the air jet to remove the very thin fluid film which adheres to the smooth surface. On the textured

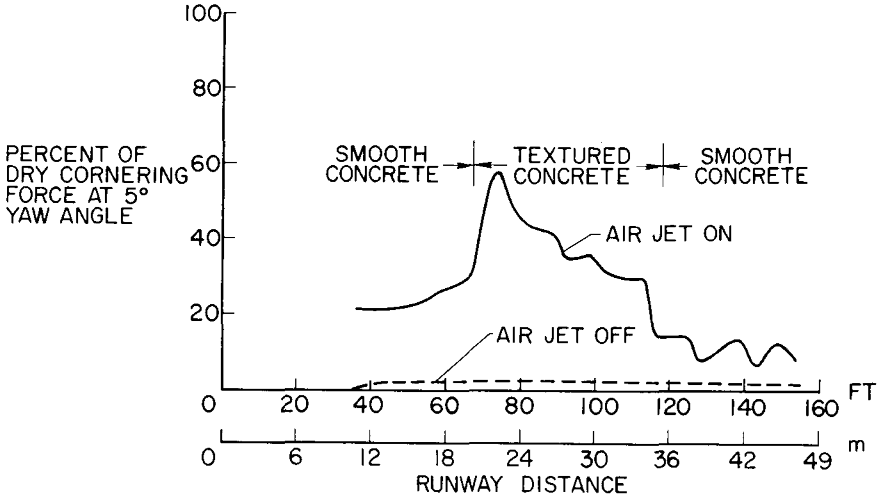


Figure 38.- Effect of air jets on cornering force. Water depth = 0.3 in. (0.8 cm); Ground speed = 77 knots.

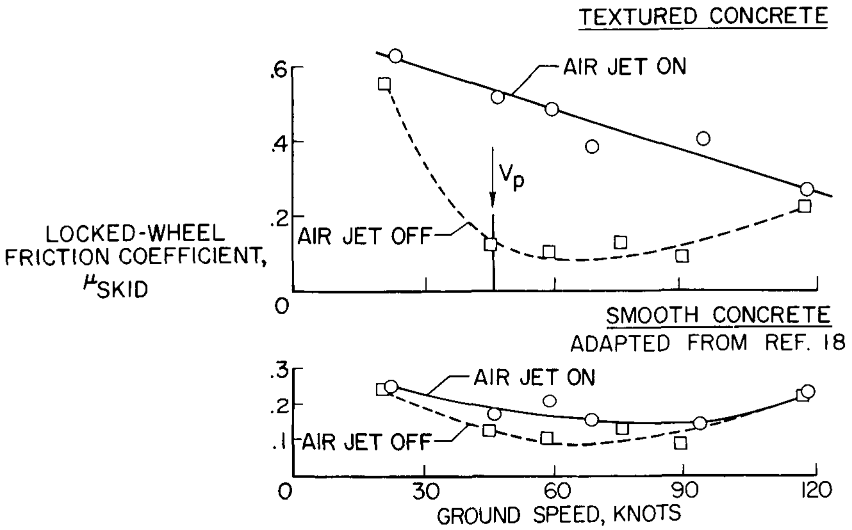


Figure 39.- Effect of ground speed on air-jet performance in improving braking traction. Water depth = 0.3 in. (0.8 cm).

surface, however, the many surface irregularities puncture this thin surface film, and much higher values of μ_{SKID} are obtained with the air jet on than with the air jet off.

CONCLUDING REMARKS

The purpose of this review has been to enumerate and evaluate the principal factors involved in tire traction losses that develop during aircraft operation on wet or flooded runways in the light of available research results. The results have shown that the hazards to aircraft ground operation because of dynamic and viscous hydroplaning and rubber tread reversion are significant and can lead to conditions of low traction more frequently than was previously realized.

Future landing operations may introduce more difficulties than in the past because the number of high performance jet aircraft in operation is increasing at a rapid rate. Also, many more airports with shorter runways are expected to accommodate these jet aircraft. These contingencies emphasize the need for expanding research on pavement slipperiness and aircraft braking systems, especially in the promising areas associated with pavement surface texture, pavement grooving, and air jet development.

Langley Research Center,
National Aeronautics and Space Administration,
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126-61-05-01-23.

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