# Factors Affecting Skid Resistance and Safety of Concrete Pavements

B. E. COLLEY, A. P. CHRISTENSEN, and W. J. NOWLEN, Portland Cement Association

The paper discusses the role of the tire and the pavement in reducing motor vehicle accidents resulting from skidding. Consideration is given to the interaction between the tire rubber characteristics of adhesion and hysteresis and the pavement surface characteristics of fine and coarse texture. Data are presented to show the importance of selecting wear-resistant fine aggregate, obtaining a proper mix design, and choosing a finishing method that will produce the desired texture depth. In addition procedures are described for restoring skid resistance to pavements that have become slippery.

•EACH year the highways are being used by more vehicles traveling at increasing speeds. The increased traffic has reduced the average distance between vehicles and this combined with increased speed has reduced alerting time to avoid obstructions. Therefore, every effort must be made to construct vehicles and highways to achieve optimum response to drivers' reactions in order to prevent accidents.

Skidding occurs in many accidents. However, it is sometimes difficult to determine whether the skid was the cause or the effect (1, 2). A report on accidents in which skidding was considered the primary cause was presented by Mills and Shelton (3). A study of these data shows that about 50 percent of the accidents on snowy or dirty pavements, 15 percent of those on clean wet surfaces, and less than 1 percent of those on dry surfaces were caused by skids. More recent data on nation-wide traffic accidents for 1966 (4) show approximately these same percentage groupings for accidents on dry, wet, and snowy-icy conditions. A survey of five states in 1964 showed that the percentage of wet pavement accidents resulting from skidding varied from zero to 23.4 percent with an average value of about 12 percent. Therefore, it is reasonable to assume, on a conservative basis, that about 15 percent of all accidents can be attributed to reduction of tire-pavement friction, and efforts must be made to overcome this fault.

This report is concerned with the role of highway design in the safety program and, in particular, the development of skid-resistant surfaces on concrete pavements to obtain desirable tire-pavement friction forces assuring maximum vehicular control.

New field and laboratory test data are reported together with pertinent findings available in the literature. Some factors affecting the skid resistance and safety of concrete pavements are examined as a part of the overall relationships between vehicles, traffic, and pavement.

## SCOPE AND DEFINITIONS

This investigation is directed toward a study of the skid resistance of pavements as an aid to reducing accident frequency and severity. Of particular concern are methods of obtaining and preserving good skid resistance on concrete pavements.

Terms associated with skidding are sliding, slipping, and cornering. Kummer and Meyer (5) suggested subcategories for skidding to indicate the mode. Specifically, skidding means a sliding motion with locked wheels, and when evaluated with a skid trailer produces a skid number, often loosely called coefficient of friction. If the wheels are not completely locked, but continue to rotate while sliding, the mode is called slipping and the measure of slip resistance is a slip number. Finally, resistance to a cornering skid is cornering resistance, also called cornering force.

Of recent concern is the phenomenon of hydroplaning. When a motor vehicle moves out of control because the tire-surface friction forces provide insufficient restraint, the vehicle is either skidding or hydroplaning. If the tire maintains contact with a firm surface, the movement is generally defined as skidding. If water floats the tire at the prevailing speeds, the movement is called hydroplaning, or in some articles, aquaplaning. Hydroplaning may occur with or without locked wheels.

Moore (6) discussed two conditions of hydroplaning. The velocity that causes hydroplaning with locked wheels is less than that for rotating wheels, and is called the lower limit or sliding limit. The velocity at which an accelerating vehicle will drift out of control on a water film is the upper hydroplaning limit. If brakes are applied during upper limit hydroplaning, no control will be established until the speed has fallen through the lower limit.

## MEASUREMENT OF TIRE-PAVEMENT FRICTION

Many methods and devices have been used to measure skid resistance or pavement wear. These may be grouped into (a) vehicle stopping distance tests, (b) drag of a locked wheel trailer, (c) energy loss of a pendulum, and (d) deceleration of a rotating wheel—and also variations of these principles.

Stopping distance is a measure of the distance required to bring a vehicle to a stop from a specified speed. In the test, a driver attains the desired speed, locks the brakes, and slides to a stop. The friction coefficient or skid number (skid number is the friction coefficient times 100; this term is used in the paper interchangeably with friction coefficient) can be computed from the familiar equation,

$$f = \frac{V^2}{30\,d} \tag{1}$$

where V is vehicle speed in miles per hour at initiation of the skid, and d is the stopping distance in feet.

### Devices

There are a number of locked wheel trailer designs. In all cases, a towing vehicle is driven at the desired speed and water is pumped onto the pavement ahead of the trailer tires when one or both of the trailer wheels are locked. The output of either a torque or a load measuring device is usually traced on an electronic recorder during testing. The stylus displacement is interpreted in terms of the coefficient of friction by reference to a calibration curve.

The British Portable Tester (7, 8, 9) consists of a pendulum with a 1- by 3-in. rubber insert at the end that is set to slide for a distance of 5 in. over the specimen surface. Then for predetermined machine constants, the friction coefficient, f, is approximately

$$f = 0.178\ h$$

where h is the vertical distance of the scale reading below the zero, measured in inches.

A device used to evaluate pavement wear consists of a spinning automotive tire and a means of measuring power requirements to drive the tire against the test surface. Whitehurst and Goodwin (10) have described such a device, and a modified machine using this method was described by Balmer (11).

The PCA skid trailer, British pendulum tester, and a PCA device for evaluating pavement wear are shown in Figure 1.

### Correlation

Correlation studies have been made so that values of skid resistance reported by various agencies would be meaningful. A correlation study (12) of a number of skid

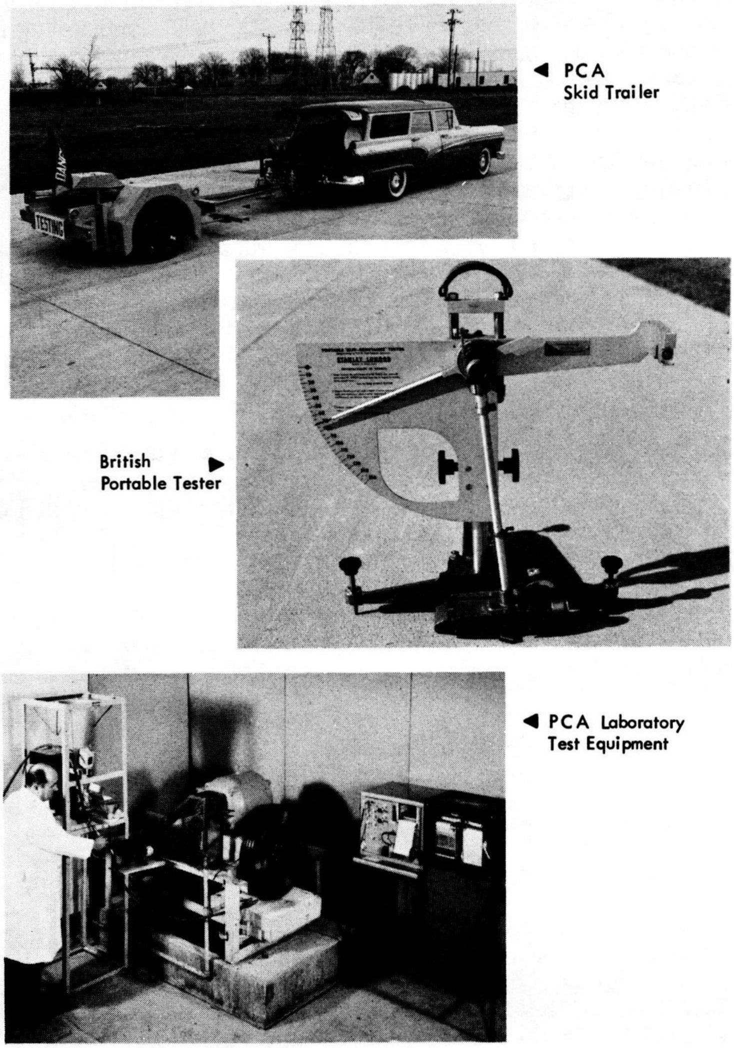



Figure 1. Typical devices for measurement of skid resistance (11).

resistance measuring machines was made at Tappahannock, Va., in 1962. Friction coefficients as determined by eight skid trailers at 50 mph on five surfaces are compared in Figure 2. These were correlated with stopping distances, the British portable tester, the National Crushed Stone Association bicycle wheel and the PDH dragtester. Considerable variation in results is evident among the trailers and similar discrepancies exist among the other devices. Friction coefficients or skid-resistance values must be qualified at present by indicating the test device and method.

## FACTORS AFFECTING TIRE-PAVEMENT FRICTION

A motorist operating his vehicle can speed up, turn, or slow down. The forces at his disposal for implementing these changes are applied parallel to the pavement by means of a friction contact area between the tire and the road. Sufficient friction must develop to permit complete control while accelerating and cornering. The tire also provides a treaded surface which helps minimize the probability of hydroplaning. The

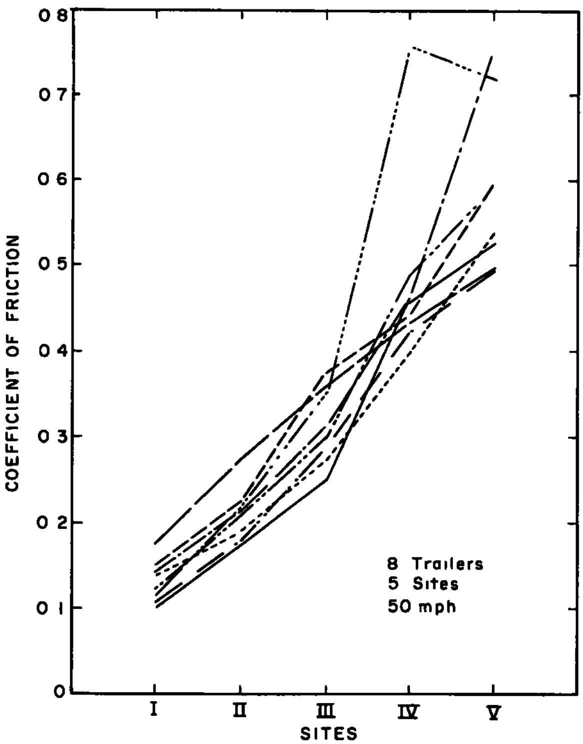



Figure 2. Comparison of trailer test results (12).

role of the pavement surface in skid resistance is to transfer necessary frictional characteristics to the tire and to provide a texture that aids drainage. Thus, frictional forces are functions of both the tire and the pavement surface, and each design should complement the other.

## TIRES

Skid resistance as influenced by the tire is discussed in terms of rubber characteristics and effects of tread composition and design.

### Rubber Characteristics

Adhesion and hysteresis, the two principal components of rubber friction, are indicated in Figure 3, which shows a portion of a tire tread sliding over a rough-textured pavement surface. The adhesion component is a function of the shear forces developed at the tire-pavement interface, whereas the hysteresis component is a function of the energy losses within the rubber as it is deformed by the textured pavement surface. The friction coefficient is the summation of the two components. Adhesion is of primary importance on dry pavements but assumes a lesser role on wet pavements as hysteresis becomes dominant. Maximum values of adhesion and the critical speeds at which they occur are dependent upon the elastic and damping properties of the rubber. On wet pavements, the adhesion coefficient is low and changes only slightly with increased sliding speed. The hysteresis coefficient increases with speed, with the internal damping properties of the rubber, and is practically pressure independent with little sensitivity to contamination and lubrication.

The effect of temperature (13) on the friction components of adhesion and hysteresis is influenced by the type of rubber, sliding speed, and characteristics of the surface. In general hysteresis will decrease at higher temperatures, whereas adhesion is more sensitive to speed changes and may either increase, decrease, or remain unaffected.

The resultant summation of adhesion and hysteresis comprises the coefficient of friction, and the effect of this summation for a locked wheel test on a wet pavement is shown in Figure 4 (14). The coefficient of friction decreased from 0.85 to 0.45 as sliding speed increased from 10 to 50 mph.

### Tread Composition and Design

The selection of the rubber composition of tires is influenced by the tire use. A soft rubber with good friction components does not usually have sufficient tread life on highways to make this composition economically practical. Therefore, the ability to develop good friction in a harder, more durable rubber is obtained by an appropriate tread pattern.

Marick (15) has discussed the role of ribs, grooves, and slots in tire design. He showed that the tire skid number on a smooth pavement was doubled as the number of ribs was increased from 0 to 6. Most of the increase occurred with the addition of the first three ribs, and increasing the number from 6 to 12 did not result in a further significant increase.

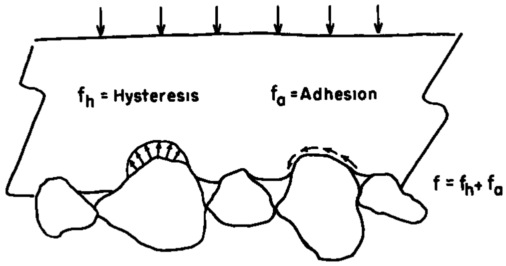



Figure 3. Friction components (13).

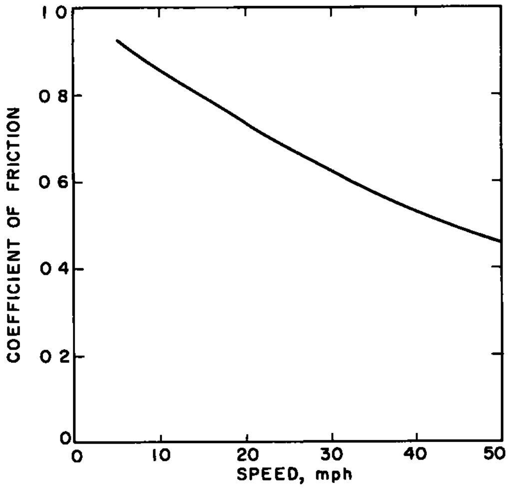



Figure 4. Effect of speed on skid resistance (14)—wet test.

The cutting of slots produces more tread edges and provides a wiping action as well as permitting venting between the ribs. Depending on tread depth, slotting increases the skid number above that of a plain rib design. Figure 5 illustrates how a tire, as it loses tread due to wear, approaches the performance of a plain rib design and eventually that of a smooth tire.

Tread design is not significant on dry pavement surfaces as smooth tires on such surfaces produce good slip or skid resistance. However, when surfaces are tested wet, tire tread gains in importance. This is demonstrated by the data of Goodwin and Whitehurst (14) shown in Figure 6. The friction coefficient values reduced more rapidly for the smooth tire than the treaded tire as speed increased, and at 40 mph the smooth tire would have required twice the stopping distance. Thus it is apparent that tire tread is significant, and that even on a highly skid-resistant surface a driver with smooth tires is a potential hazard.

The type and depth of tire tread as well as the height of pavement surface asperities are important in reducing the dangers of hydroplaning. It is generally conceded that hydroplaning can occur on a film of water if the pavement surface is smooth. For example, bald tires may hydroplane on a smooth pavement surface with a water film 0.1 in. thick, whereas greater water depths are required for treaded tires. Horne and

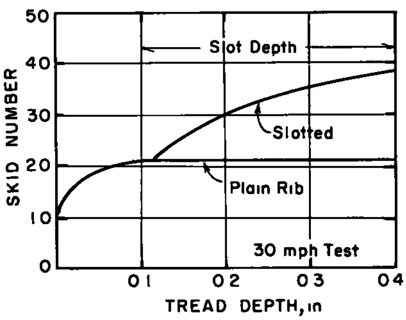



Figure 5. Skid-resistance reduction due to tread wear (15)—wet test.

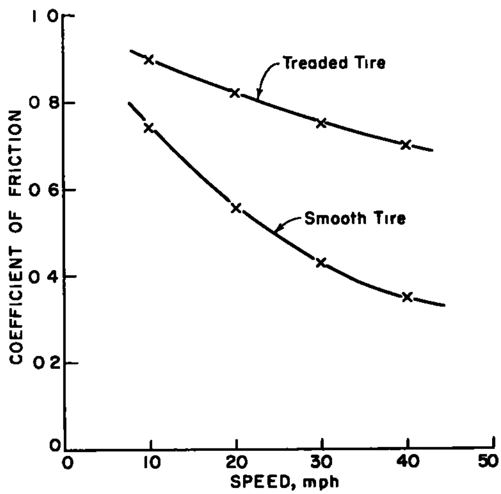



Figure 6. Effect of tire wire on skid resistance (14)—wet test.

Dreher (16) showed that for smooth or rib tread tires, where the fluid depth exceeded the depth of the tread, hydroplaning speed was given by the equation:

$$\text{Hydroplaning speed (mph)} = 10.4\sqrt{\text{tire inflation pressure (psi)}}$$

Based on this equation, hydroplaning speed for the typical passenger vehicle could be reached at 50 to 60 mph.

The effect of water depth on friction coefficients for different speeds is shown by the data of Figure 7, reported by Trant (17). The tires had rib treads and although hydroplaning speed was not reached, there was a large decrease in the friction coefficient as water depth was increased from 0.05 to 0.30 in.

## THE PAVEMENT

To obtain good tire-pavement friction values, the pavement surface must develop good hysteresis and adhesive forces in the tire rubber. In addition, permanence of the skid-resistant properties of a pavement surface is significant. Many surfaces are skid resistant when first placed but lose effectiveness due to wear. The contribution of the pavement to skid resistance is considered by defining: (a) the role and importance of texture, (b) the value of proper mix design, (c) procedures for selecting aggregates to minimize wear, and (d) methods of obtaining a suitable texture during concrete placement.

### Texture

Asperities distributed over a surface form a texture. The nature of the asperities determines the texture classification, i. e., it may be coarse, fine, sharp, dense, etc. It is generally agreed that a pavement surface should have a texture consisting of both fine and coarse asperities. The fine asperities impart the adhesion component in the tire-pavement interaction, whereas the coarse asperities have the dual role of imparting the hysteresis component and providing drainage channels for water.

Texture on a bituminous pavement is created by distributing aggregate particles of various sizes in the mix and then rolling the mixture to form the surface. Thus, both coarse and fine aggregates are generally exposed at the surface. In a concrete pavement, the fine texture results from the sand-cement mortar layer and the coarse texture is formed by the finishing operations while the concrete is still plastic. Thus for concrete, the coarse texture is the ridges of sculptured mortar left by finishing marks; therefore, the coarse aggregate seldom functions as a portion of the surface. This explains why there appears to be a contradiction when a concrete engineer says permanence of skid resistance is primarily controlled by the fine aggregate and the bituminous engineer says the coarse aggregate is the major factor.

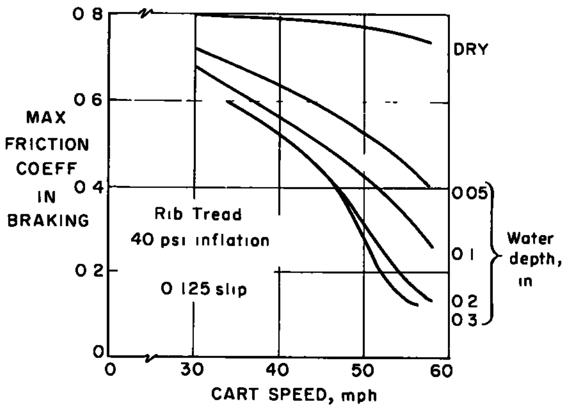



Figure 7. NACA friction-cart trough test (17).

The amount of friction developed by a surface with fine asperities has been related to the "degree of texture" as measured by various test procedures. Some procedures use techniques to obtain a cast reproduction in a plaster or resin, an ink print, or a stereophotographic view of the surface. For example, a "foil-piercing" technique was used by Gillespie (18). Data are shown in Figure 8. Attempts to corroborate these data made by the PCA on new concrete surfaces using a 5-lb weight and 2-in. drop gave impact punctures ranging between 40 to 200 per sq in. for friction coefficients varying from 0.55 to 0.88. These data, although showing considerable scatter, were in fair agreement with

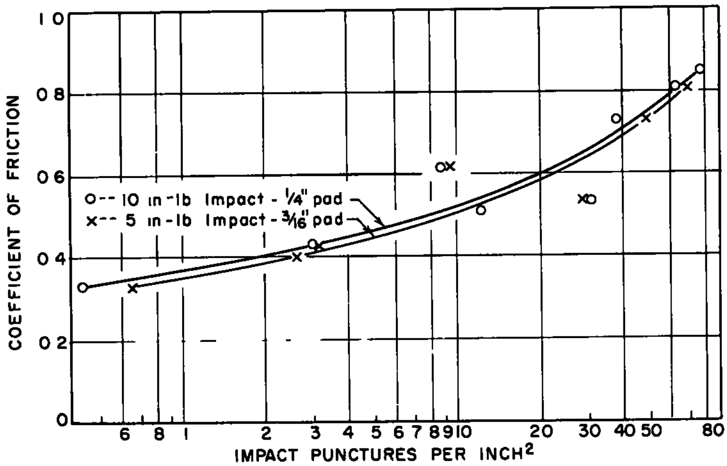



Figure 8. Coefficient of friction (35 mph) vs impact punctures.

the upper portion of the curve (Fig. 8). However on older pavements, this correlation did not exist. For example, some concrete pavements 12 to 15 years old showed no foil punctures, but when tested wet at 40 mph gave friction coefficients ranging from 0.51 to 0.62. Gillespie also reported higher than anticipated skid numbers on concrete surfaces with limited numbers of foil punctures. Thus it appears that this test procedure is not a sufficient criterion for predicting friction coefficients on concrete surfaces. This is not surprising as experience gained during 10 years of field testing with a skid trailer has shown that visual examination and sense of touch are not substitutes for a skid test.

Road contamination resulting from "traffic film" can, when wet, reduce significantly the skid number of a pavement that has fine asperties only. For example, Kummer (5) reports a rise in wet skid number from 11 to 20 for tests made just before and after a rain preceded by a long dry period. Wet skid trailer tests were made on concrete pavements by the PCA following a 0.6-in. rain that was preceded by 20 days with no measurable precipitation. The data showed that 40-mph skid numbers, obtained after the rain, had increased by a greater percentage on pavements that had the lower values prior to the rain. In general, the skid numbers obtained after the rain increased from 6 to 18 percent, with the 18 percent increase occurring on a pavement with a prior to rain value of 40, while only a 6 percent increase was observed for the pavement with an initial value of 60.

Paint is another type of contamination that reduces the skid numbers. Tests obtained by the PCA skid trailer at the Atlanta airport showed that skid numbers in painted areas were reduced from 61 to 29. It is suggested that airport areas requiring painted markings be constructed with colored concrete or with colored aggregates placed in the surface of the concrete.

Large asperities sometimes referred to as macroscopic roughness provide drainage areas under the tires. Macroscopic roughness on a concrete pavement is formed by the mortar and fine aggregates as the surface is sculptured by the finishing operations. Macro-roughness also influences the volume of tire rubber being deformed (hysteresis) and serves to increase the frictional characteristics of the pavement at greater speeds. This action is particularly valuable where conditions are conducive to hydroplaning. Such conditions occur more readily on airport pavements where the combination of relatively slow drainage of large areas and high landing speeds contribute to the problem. On highways, drainage is more readily controlled by the slope of the pavement. Slopes presently used on Interstate highways vary from about 2.25 to 5.75 in. for a 24-ft width. Because concrete pavements retain their shape, these magnitudes of slope generally provide adequate drainage.

Measurements have been made of large-scale asperity roughness using the "sand-patch" (19), "grease-smear" (20), and "drainage meter" (21) methods. Data (Fig. 9) were obtained by Sabey (7) using the sand-patch method on concrete pavements. The braking force coefficient decreased about 15 units as testing speed was increased from 30 to 80 mph. The percentage decrease varied with texture depth and it was concluded that a minimum depth of 0.025 in. was required if the decrease was to be held to 25 percent.

Data (Fig. 10) reported by Poeblikh (22) are shown as a plot of coefficient of friction versus asperity height. The friction value of both the dry and the wet surfaces increased as asperity height increased. For the wet surfaces, the coefficient was more than doubled as asperity height increased from 0.05 mm (0.002 in.) to 4 mm (0.16 in.). However, it should be noted that about 75 percent of the increase was obtained at an asperity height of 2 mm (0.078 in.).

Measurements of texture made by the PCA using the sand-patch method showed asperity heights ranging from 0.014 to 0.075 in. as the method of finish varied from a wood float to a wire brush. More complete data will be presented later when finishing techniques are discussed, but it is apparent that the texture that can be obtained by finishing will provide adequate drainage under the tires. Asperity depths of 0.075 in., although adequate, are not limiting values as even greater depths have been obtained by distributing lightweight aggregates on the surface of the plastic concrete. However it should be recognized that a pavement surface can become so rough that the skid resistance will decrease and operating cost for tires, gasoline, and vehicle maintenance will increase. In addition, rough textures can accumulate rubber deposits and cause lower skid resistance. Wet skid trailer tests made by the PCA at 40 mph on the St. Louis airport showed that rubber deposits lowered the skid number from 60 to 35.

## Concrete Mix Design

Quality concrete is a prerequisite to the retention of pavement skid resistance. An improper mix design or the addition of water to the surface of the plastic concrete can result in a pavement that has a high rate of wear. Under these conditions, the benefits of a good surface texture will be of short duration.

Data obtained by Sawyer (23) demonstrating the effect of variations in cement content and water-cement ratio on concrete wear are shown in Figure 11. For 2-in. slump concrete, after 14 days of moist curing, the wear increased as much as 130 percent as the cement content was decreased. Increased water-cement ratio accompanying a change in slump resulted in an increase of wear of 20 percent.

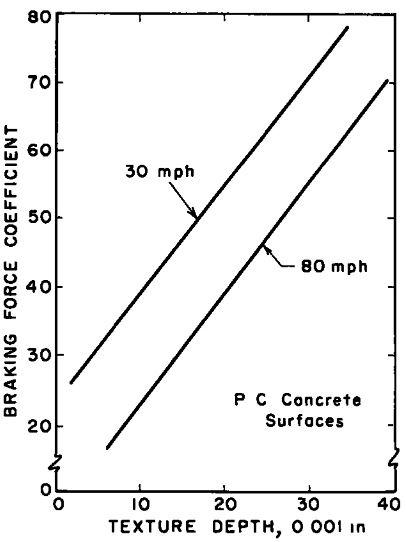



Figure 9. Trends from British data on texture depth effect on friction (7).

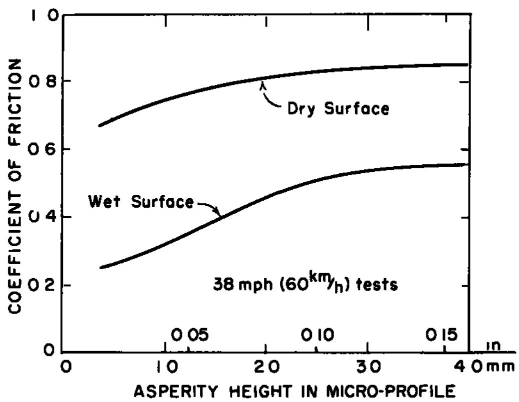



Figure 10. Data trends relating asperity height and friction coefficient (22).

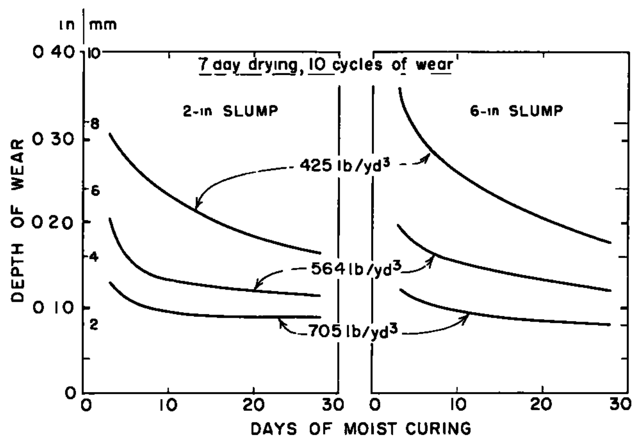



Figure 11. Effect of cement content and cure on concrete wear (23).

Data (Fig. 12) obtained at the PCA Laboratories also show the effect on wear of changes in the water-cement ratio. These tests were made using the rotating wheel equipment described previously (11). For water-cement ratios 0.47 and 0.51, wear increased by about 10 percent. The fine aggregate used in the PCA test contained about 40 percent siliceous material and, and will be shown later, aggregates of this type are less susceptible to wear. Tests were also made to study the effect on wear of changes in the cement content. Data for cement contents of 376 (4.0 bags) and 517 lb (5.5 bags) cement/cu yd were in good agreement with Sawyer's results.

To study the effect on wear of adding water to the concrete surface during finishing operations, duplicate specimens were cast at a water-cement ratio of 0.47, and 25 cu cm of water were sprinkled on the 4-sq ft surface area of the plastic concrete. Wear tests on these specimens showed that initial power requirements needed to drive the rotating wheel were decreased by about 35 percent from the values on specimens without added water, and the final wear values averaged 6. 2 instead of 6. 7.

Results of tests with varied sand content showed that the wear resistance was increased as the percent of sand was increased from 34 to 42 percent. This was probably due to a combination of a larger surface area of wear-resistant fine aggregate at the tire-pavement interface and also an increase in the cement content to maintain a constant water-cement ratio and slump when the percentage of sand was increased. However, it is suggested that PCA recommended procedures (24) be used to determine mix proportions. The amount of sand should be based on the most economical combination of available aggregates that will produce the necessary workability in the fresh concrete and the required qualities in the hardened concrete.

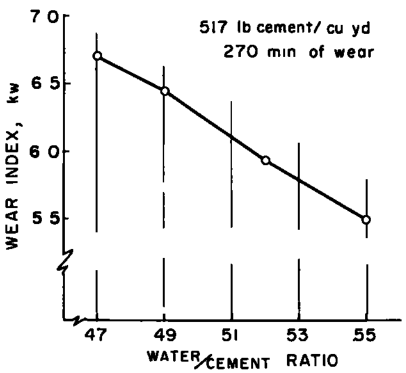



Figure 12. Effect on w/c ratio on wear.

## Wear Resistance and Fine Aggregates

Concrete pavements constructed with numerous aggregate types have retained good skid resistance for many years. The data in Fig. 13 were obtained from a skid trailer survey by Barboza (25) that included 177 concrete surfaces located along approximately 6,500 miles of major highway routes in the United States. Calculations for wear index were based on age of pavement surface, average total daily traffic count, and a correction factor for traffic distribution within the lane. There was a fair degree of correlation between

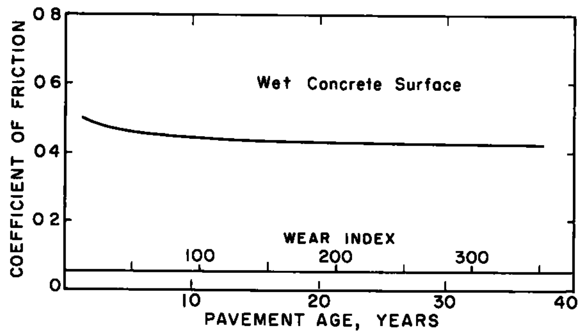



Figure 13. Effect of wear on friction coefficient (25).

wear index and age; therefore, both of these values are shown on the abscissa. The statistical best fit curve shows an average initial friction coefficient of about 0.5 and indicates that the major portion of the wear occurs in the first four or five years of service, with little further reduction as traffic life was extended to 35 years. Many other references can be cited to show similar trends of good performance. However all pavement surfaces wear and some pavements constructed with unsatisfactory materials wear so rapidly that the surfaces may become slippery after only a few years of service. Thus, the purpose of this section is to discuss methods of evaluating wear and to suggest a test procedure for selecting aggregates that will give good performance.

Scholer (26), Maclean (27), Shupe (28) and Whitehurst (29) have investigated the wear of aggregates and concrete. These studies have shown that the wear and hence the skid resistance of pavements depends principally on the mineral composition and hardness of the aggregates.

The equipment (Fig. 1) used by the PCA for evaluating wear of aggregates was described by Balmer (11). In the test, water is fed continuously to an ASTM tire held against a concrete specimen with a normal force of 600 lb while the tire is rotated at a constant speed of 250 rpm (20 mph). After 75 min of wear, a second test phase begins during which a fine Ottawa sand is blown onto the specimen with the stream of water passing between the rotating tire and the concrete. This abrades the specimen and accelerates wear. After two hours of sand abrasion, the test is continued for 75 min without the addition of sand to evaluate the worn pavement. The power in kilowatts required to rotate the wheel against the specimen is referred to as the "wear index" and is considered a comparative measure of the skid resistance.

Early in the PCA investigation, it was determined that the composition of the fine aggregate was the major factor controlling the wear of concrete pavements. Wear tests were made with fine aggregate samples obtained from 20 different sources. As these aggregates had been used to construct concrete pavements, the wear index could be correlated with in-service pavement performance. In addition, the wear index was compared with results from an acid insoluble residue laboratory test pioneered by Gray and Renninger (30).

In the acid insoluble residue test, a representative sample of 2 lb of the fine aggregate is treated with a 6N solution of hydrochloric acid. The acid dissolves the carbonates and leaves the silt, clay, and siliceous material as a residue. It is essential to use an adequate amount of acid to be certain that the action continues until completion. After the action is completed, the solution is filtered and the residue is washed with water, screened on the No. 200 mesh sieve, dried, and weighed. The silt and clay are considered detrimental to the skid resistance and are subtracted from the residue. Thus the siliceous particle content is defined as the residue retained on the 200-mesh sieve expressed as a percentage of the total sample.

The composition of each fine aggregate tested is given in Table 1, together with the siliceous particle content, the laboratory wear index, and the field performance of the pavements constructed with each aggregate. The increase in wear resistance with increasing siliceous particle content suggested that beneficiation of poor aggregates could be obtained by a partial replacement of the fines with a siliceous sand. Laboratory test results that show progressive improvement of several aggregates by beneficiation are given in Table 2. Twenty-five percent replacement was satisfactory for most of the aggregates; however, the acceptable percentages of replacement depended on the siliceous particle content of the blend. Maclean and Shergold (27) have stated

TABLE 1

EFFECT OF AGGREGATE CONSTITUENTS

| Fine Aggregate No. | Principal Constituents (%) | Rating of Field Performance | Wear Index (kw) | Siliceous Particle Content (%) |
|---|---|---|---|---|
| 1 | 90 calcite | Poor | 3.6 | 2 |
| 2 | 70 calcite, 24 dolomite | Poor | 4.4 | 2 |
| 3 | 90 calcite | Poor | 4.0 | 3 |
| 4 | 80 dolomite | Poor | 5.6 | 6 |
| 5 | 75 dolomite | Poor | 5.8 | 9 |
| 6 | 70 dolomite | Poor | 5.4 | 13 |
| 7 | 60 calcite, 16 silt and clay | Poor | 5.3 | 17 |
| 8 | 80 calcite, 15 quartz | Fair | 6.2 | 19 |
| 9 | 65 calcite, 12 dolomite | Poor | 5.9 | 22 |
| 10 | 50 calcite, 33 mica and quartz | Excellent | 6.8 | 33 |
| 11 | 55 dolomite, 39 quartz, quartzite and feldspar | Excellent | 6.8 | 39 |
| 12 | 55 calcite and dolomite, 40 quartz, mica and epidote | Excellent | 6 7 | 40 |
| 13 | 45 calcite, 42 quartz and feldspar | Excellent | 7.3 | 42 |
| 14 | 50 dolomite, 44 quartz | Excellent | 7 0 | 44 |
| 15 | 45 dolomite, 45 quartz | Excellent | 6.8 | 50 |
| 16 | 45 dolomite, 45 quartz | Excellent | 7.2 | 53 |
| 17 | 30 graywacke, 55 quartz | Excellent | 7.0 | 96 |
| 18 | 75 quartz, 17 feldspar | Excellent | 7.3 | 97 |
| 19 | 72 quartz, 20 feldspar | Excellent | 7.2 | 98 |
| 20 | 99 quartz | Excellent | 7.5 | 99 |

that ". . . an important characteristic of rocks that remain rough is the presence of two minerals that have a considerable difference in the resistance to wear." The data presented indicate that this concept can be extended to concrete by the procedure of blending aggregates.

A plot of wear index values as a function of siliceous particle content for the basic field aggregates and laboratory combinations is shown in Figure 14. Although there was no abrupt change in the curve to indicate a separation between poor and excellent field performance, aggregates with a wear index greater than 6.2 were classified excellent. This suggests that a fine aggregate with a siliceous particle content of 25 percent or greater will provide excellent field performance.

Ottawa sand was used to study the influence of particle size on the wear or skid resistance of concrete. This material was selected because it had a greater uniformity of hardness throughout the various particle sizes than could be found in most natural sands. Mortar mixtures with variations in the maximum and minimum particle sizes were used to apply a ½-in. thick resurface to specimens tested previously. Figure 15

TABLE 2

IMPROVEMENT OF SKID RESISTANCE BY BENEFICIATION

| Basic Aggregate No. | Replacement Aggregate No. | Final Blend (%) | | Siliceous Particle Content (%) | Wear Index (kw) |
|---|---|---|---|---|---|
| | | Basic | Replacement | | |
| 1 | 17 | 100 | 0 | 2 | 3.6 |
| | | 75 | 25 | 26 | 5.9 |
| | | 50 | 50 | 49 | 6.5 |
| | | 25 | 75 | 72 | 6.8 |
| | | 0 | 100 | 96 | 7.0 |
| 2 | 19 | 100 | 0 | 2 | 4.4 |
| | | 50 | 50 | 50 | 7.0 |
| | | 25 | 75 | 74 | 7 1 |
| | | 0 | 100 | 98 | 7 2 |
| 4 | 18 | 100 | 0 | 6 | 5.6 |
| | | 75 | 25 | 29 | 6.3 |
| | | 60 | 40 | 42 | 6.6 |
| | | 50 | 50 | 52 | 7.0 |
| | | 0 | 100 | 97 | 7 3 |
| 5 | 11 | 100 | 0 | 9 | 5.8 |
| | | 50 | 50 | 24 | 6.3 |
| | | 0 | 100 | 39 | 6.8 |
| 6 | 18 | 100 | 0 | 13 | 5.4 |
| | | 75 | 25 | 34 | 6.5 |
| | | 50 | 50 | 55 | 7.2 |
| | | 25 | 75 | 76 | 7.7 |
| | | 0 | 100 | 97 | 7.3 |
| 7 | 11 | 100 | 0 | 17 | 5.3 |
| | | 75 | 25 | 22 | 6.4 |
| | | 50 | 50 | 28 | 6.6 |
| | | 25 | 75 | 34 | 6.7 |
| | | 0 | 100 | 39 | 6.8 |
| 10 | 18 | 100 | 0 | 33 | 6.8 |
| | | 75 | 25 | 49 | 7.2 |
| | | 60 | 40 | 59 | 7.4 |
| | | 50 | 50 | 65 | 7.6 |
| | | 0 | 100 | 97 | 7 3 |

shows that better wear values occurred with the larger sand size particles, although it is significant that a specimen containing Ottawa sand graded to include the total range of particle sizes from the No. 20 to 200 mesh sieves gave a wear index of 7.5, which was near the optimum value of 8.2.

In comparison, recent studies by Walz (31) concluded that the mortar surface should be composed of quartz sand well graded below 3 mm (0.12 in.). He indicated also that texture grooves of about 2.5 mm (0.1 in.) width and a low water-cement ratio combined to give good skid resistance for long periods of traffic.

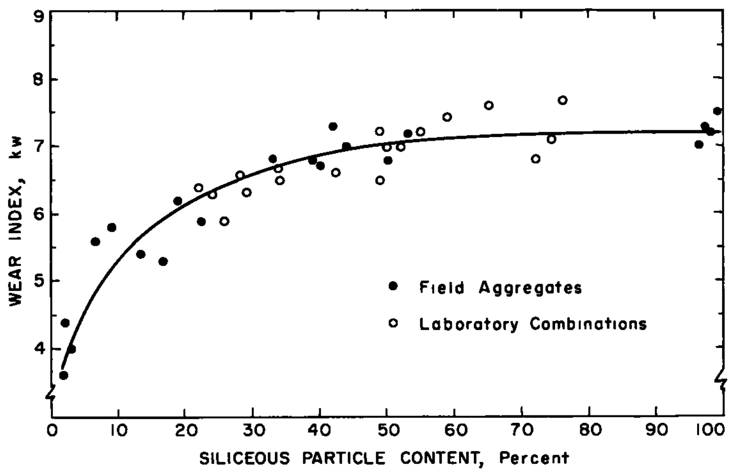



Figure 14. Effect of siliceous particle content on wear index (11).

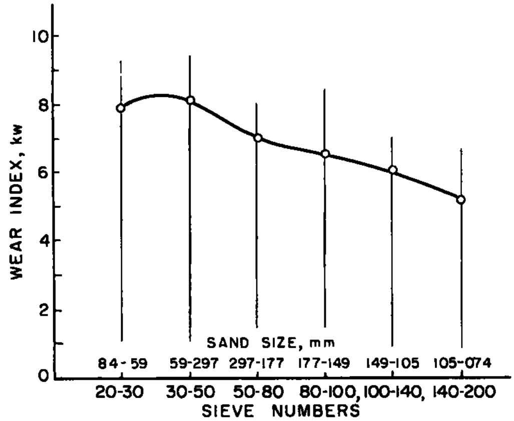



Figure 15. Effect of particle size on skid resistance (11).

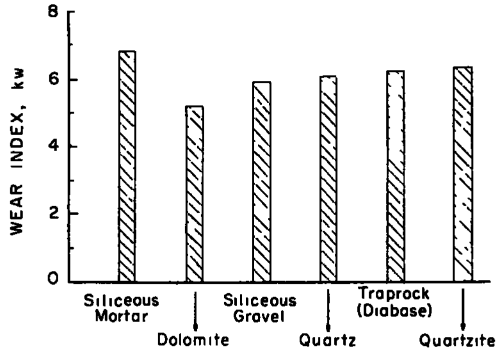



Figure 16. Evaluation of exposed coarse aggregates (11).

Concrete surfaces with exposed 1½ in. maximum size aggregates were tested with the PCA equipment to compare wear resistance with that of a conventional mortar surface. The wear index (Fig. 16) for the mortar surface made with fine aggregate No. 11 (39 percent siliceous particle content) was 6.8 as compared with values that ranged from 5.2 for the coarse exposed dolomite to 6.3 for the coarse exposed quartzite. It is conceivable that an exposed coarse aggregate with an unusually gritty texture could be more skid resistant than a conventional concrete surface; however, these tests demonstrated that a siliceous sand mortar surface was more skid resistant than many of the coarse aggregate surfaces tested.

To obtain superior friction surfaces, abrasives such as aluminum oxide and silicon carbide of 12 grit and smaller were spread over the surface of specimens and floated into the plastic concrete. The data (Fig. 17) showed the 1 lb/sq yd of aluminum oxide increased the wear resistance of a concrete with a siliceous particle content of 39 percent from 6.8 to 8.2 and increased a concrete with only 9 percent siliceous particle content from 5.8 to 7.8. Silicon carbide in the same amount was even more effective and produced values of 10.4 and 8.2. Other tests using ½ lb/sq yd of aluminum oxide yielded 7.2 and 6.4, respectively, and a like amount of silicon carbide produced 8.4 and 6.4. Abrasives in concrete may be advantageous in critical areas such as toll plazas, near busy intersections, or in areas where frequent breaking, traction, or cornering occurs.

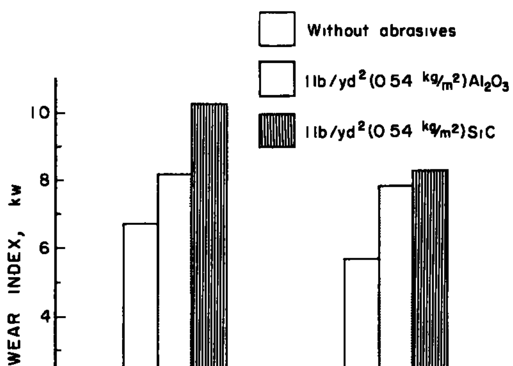


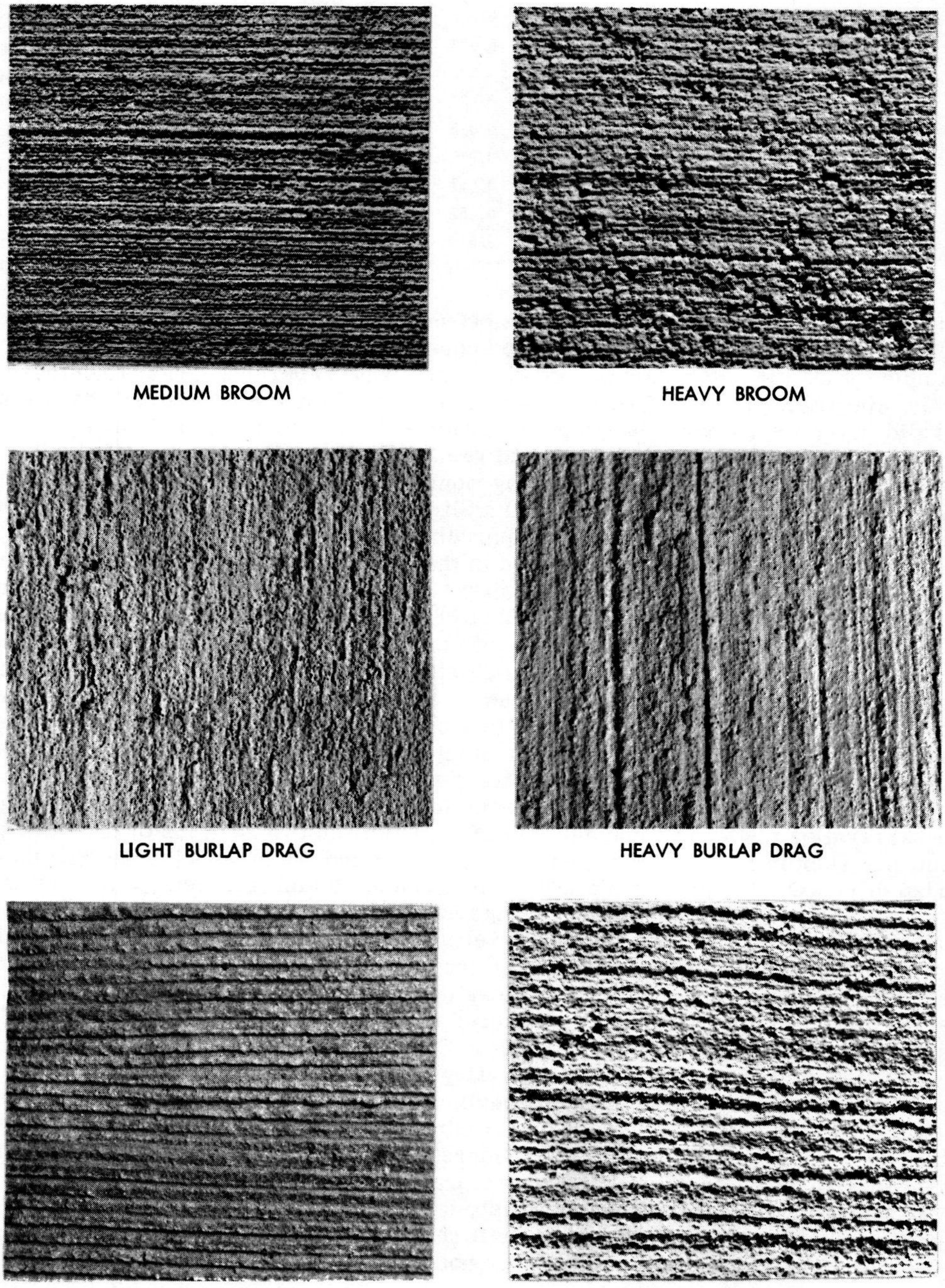

Figure 17. Use of abrasives to develop superior friction surfaces (11).

## Finishing Methods and Texture

Incorporation of a properly selected fine aggregate in a quality concrete mix will provide a gritty fine-textured surface with excellent friction characteristics. Finishing operations add the coarse asperities required to aid drainage between the tires and the pavement surface and reduce the possibility of hydroplaning.

Finishing has generally been accomplished using a burlap drag, a broom, or a belt. In 1963, approximately 60 percent of the highway departments used a burlap drag, 12 percent specified either a burlap drag or a broom, 8 percent a combination of a broom and a burlap drag, 6 percent a belt, 6 percent a broom, and the remainder specified that either a belt or a burlap drag should be used.

To investigate the surface texture produced by these and other finishing methods, specimens were prepared and various finishing devices were used to texture the surface



MEDIUM BROOM · HEAVY BROOM

LIGHT BURLAP DRAG · HEAVY BURLAP DRAG

WIRE DRAG · FLEXIBLE WIRE BRUSH

Figure 18. Examples of surface texture.

TABLE 3

TEXTURE DEPTHS

| Specimens No. | Method of Finish | Texture Depth (in.) |
|---|---|---|
| 1 | Wood float | 0.014 |
| 2 | Light belt | 0.015 |
| 3 | Light burlap drag | 0.017 |
| 4 | Heavy belt | 0.020 |
| 5 | Steel wool | 0.022 |
| 6 | Heavy burlap drag | 0.025 |
| 7 | Wallpaper brush | 0.026 |
| 8 | Medium paving broom | 0.029 |
| 9 | Door mat (cocoa matting) | 0.032 |
| 10 | Wire drag | 0.036 |
| 11 | Heavy paving broom | 0.037 |
| 12 | Flexible wire brush | 0.051 |
| 13 | Stiff wire brush | 0.075 |

30 min after casting. Texture depths measured by the sand-patch method are listed in Table 3 and photographs of the surface texture for specimens 3, 6, 8, 10, 11, and 12 are shown in Figure 18. The largest deviation in depth of any individual specimen in a set of four from the average was only 0.003 in. This indicates that the texture depth for each method of finish was unique for the concrete mix and time interval between casting and finishing. Other data were obtained where the time interval was a variable. In general, only minor differences in texture depth were obtained with a broom for time delays between 30 min and 1½ hr or with a belt for time delays between 30 to 50 min. In contrast, texture depths obtained with a burlap drag varied considerably with the time of finishing. For example, at 20 min after casting, depths were about 25 percent larger than those listed for 30 min after casting. The time delays discussed for the laboratory tests would not be valid in the field where changing temperature, humidity, and wind velocity must be considered. However, the trends should remain the same and one way of obtaining a texture when finishing with a burlap drag would be to make three passes. The first pass should be made while there is still a slight water sheen on the surface and subsequent passes should follow without an appreciable delay between passes.

The texture depths (Table 3) obtained in the laboratory using the belt finish are less than the 0.025 in. found necessary by Sabey (7) to hold the reduction in wet skid number to 25 percent as speed increased from 30 to 80 mph. However, these small depths obtained with a belt are not compatible with the 40-mph wet skid trailer test data obtained by Barboza (25). He showed that existing pavements finished with a belt had greater initial skid numbers and retained skid resistance longer than those finished with either a burlap drag or a broom. Undoubtedly, these data represent accurately the pavements tested; however, it is the opinion of the authors that they may not be representative of what can be achieved as it is believed that only limited attention was given in the past to obtain the best possible finish for each procedure. For example, wet skid trailer tests were made by the PCA in 1967 on two sections of the same pavement, one section finished by transverse brooming and the other with the longitudinal burlap drag. On this project attention was given to obtaining a medium texture with both finishing procedures, and the average 40-mph wet skid number obtained with the burlap drag was 55 as compared to an average value of 66 for the broom finish. It is significant that skid numbers obtained on the broom finish in a direction parallel to the finish marks were about 9 percent less than those obtained transverse to the finish marks. Although these data are considered more representative of what can be done, they should be regarded also as tentative. Experimental sections should be built on new construction by each state incorporating both these and other finishing procedures.

The homemade wire drag used on specimen 10 is shown in Figure 19. Textures obtained using this drag on specimens 45 min. after casting were similar to those obtained by sawing grooves in hardened concrete. Thus a device of this type could be used to finish concrete on projects where drainage is a severe problem.

As all paving materials wear or polish, it is obvious that with other factors being equal, a pavement with a deep texture will retain skid resistance longer than a pavement with a shallow texture. But it does not follow that the texture should be as deep as possible. Instead, the finishing method selected should be compatible with the environment, speed and density of traffic, topography and layout of the pavement, and economics of vehicle operations.

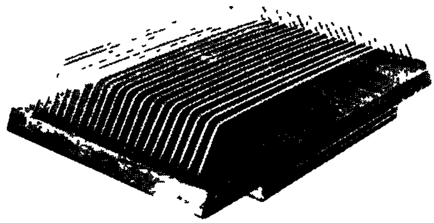


Figure 19. Wire drag.

## METHODS FOR RESTORATION OF SKID RESISTANCE

Although there appears to be a friction coefficient that is optimum for both safety and comfort, it may be necessary to increase this value in particularly hazardous areas. Also, some aggregates polish with wear and the friction coefficient may in time be reduced to an unsafe value. Methods of increasing the skid resistance of surfaces include acid etching, mechanically abrading, sawing, and resurfacing. The choice of method depends on the economics and the end to be accomplished.

### Acid Etching

An improvement in skid resistance of a concrete surface can be achieved with an acid etch. Two acids have been used for this purpose. When it is desired to dissolve the limestone and expose the silicate in the mortar, a common muriatic acid wash is applied. It is followed by a water flush when chemical action is no longer evident. If the reason for low skid resistance was a poor finish, this method is adequate; however, if the fundamental problem was soft aggregate, this treatment must be repeated frequently to assure safe skid resistance.

When it is desired to etch the silicate, a hydrofluoric acid is used. A proprietary preparation of this material is now marketed for this purpose.

### Mechanical Abrading

A smooth concrete surface may be roughened mechanically with a machine with hardened steel cutters rotating on a drum, such as a Tennant machine or, as in England, the roughening may be produced by a flailing action. Depth of cut and spacing may be varied. A disadvantage of these operations is loss of the mortar layer. Also, the grooves have somewhat rounded edges. If the large aggregates are nonpolishing, these treatments may be successful. In areas where hydroplaning is a problem, drainage channels can be produced that will reduce the water film thickness and also provide escape for the water compressed beneath a tire.

### Sawing

A more recent practice in mechanical beneficiation is the cutting of a series of parallel grooves with a bank of diamond or abrasive saw blades. This treatment has been recommended to aid drainage and thus reduce the tendency to hydroplane. Common practice is to groove transversely to reduce stopping distance or to groove longitudinally on curves; however, the Road Research Laboratory has data to indicate that transverse grooving is generally more effective.

Skid numbers measured by the PCA skid trailer before and after sawing a concrete pavement are given in Table 4. Three sections were sawed transversely with ⅛-in. wide by ⅛-in. deep cuts on either ¾-, 1½-, or 3-in. centers. Another section had ⅛-in. wide by ⅛-in. deep cuts sawed longitudinally on ¾-in. centers. The trailer tests were made at 40 mph with water pumped onto the dry pavement ahead of the trailer tires when both of the trailer wheels were locked. The pavement skid numbers were not significantly changed by sawing either transverse or longitudinal grooves. It should be noted that these tests were made on a concrete pavement having an average skid number of 63.

TABLE 4

SKID NUMBERS BEFORE AND AFTER SAWING

| Saw Cut Spacing (in.) | Skid Number | |
|---|---|---|
| | Before Sawing | After Sawing |
| Transverse | | |
| ¾ | 63 | 60 |
| 1½ | 60 | 60 |
| 3 | 66 | 66 |
| Longitudinal | | |
| ¾ | 63 | 63 |

In contrast to these results, tests reported by Horne (32) on flooded pavements representative of poor drainage indicated that both longitudinal and transverse grooves were beneficial in decreasing stopping distance. In addition, data from the California Highway Department (33) indicated that longitudinal grooving on horizontal curves greatly reduced accident rates. For example, in the 12 months before grooving 900 ft of the Santa Ana Freeway, 52 accidents occurred; in the year following, there were only 8 accidents.

From the studies described, it may be concluded that sawing grooves will be of little benefit on well-drained pavements where the maximum speed of traffic is less than approximately 40 mph. For pavements with greater traffic speeds and more surface water than that supplied by a skid trailer, sawing grooves may increase the coefficient of friction as a result of improved drainage and deformation of the tire into the grooves.

### Resurfacing

Concrete overlays are well suited for improvement of skid resistance. A long-lasting surface texture meeting any requirements can be obtained easily by the final finishing operation. A number of airfields have been resurfaced with bonded concrete and performance was reported by Gillette (34). Thick concrete resurfacing without bond has been laid on both concrete and asphalt. Westall (35) reported performance of this construction on airfields in five states. An ACI Committee report (36) presents essentials of overlay design for both bonded thin and unbonded thick resurfacings.

The development of techniques for successful concrete resurfacing has been aided by laboratory studies at the PCA (37, 38). These studies indicated that before resurfacing, the old pavement should be properly prepared to obtain good bond between the new and the old concrete. Any unsound concrete and foreign matter such as oil, asphalt, or soil should be removed. The old concrete should be acid etched or scarified and cleaned. Acid etching is a desirable, economical method of surface preparation for uncontaminated sound concrete, but if the concrete is scaled, scarification is advisable. Heating the coatings of oil and grease by a high-temperature burner immediately followed by scraping has been found to be expedient for heavy contamination. In some cases, oil and grease can be removed by washing and vigorous brushing with strong detergents such as a solution of sodium metasilicate with a resin soap or a solution of trisodium phosphate. After these treatments, the concrete should be thoroughly flushed with water and cleaned. Then a thin layer of mortar or neat cement should be intimately brushed into the clean surface prior to placement of the resurface layer.

Another procedure that has been used to a limited extent is to resurface the pavement with an epoxy resin and abrasives. The surface preparation of concrete for an overlay of a resin is similar to the preparation for resurfacing with concrete, except that no mortar or neat cement layer is placed on the old concrete as a bonding medium. Ordinarily 2.5 to 3 lb/sq yd of epoxy resin (1.4 to 1.6 kg/m$^2$) is sufficient for surfacing.

In a PCA study (11), abrasives such as traprock, granite, expanded slag, and expanded shale were applied at a rate of 1 lb/sq yd to the epoxy resin. The sizes of the abrasives were between the No. 8 and 16 mesh (2.38 to 1.19 mm) sieves. Test results indicated that although initial skid resistance values were excellent, the epoxy resin due to moisture migration in a slab on ground did not provide a long-wearing surface.

## SUMMARY

Skid resistance is an important consideration in safe vehicle operation. From a study of accident reports, it was estimated that about 15 percent of all accidents can be attributed to reduction of tire-pavement friction.

A study of methods of measuring tire-pavement friction indicated that friction coefficients or skid resistance values vary depending on the test method, and variation within methods makes it difficult to establish standard skid numbers.

Skid resistance as influenced by the tire is a function of its rubber characteristics and tread design. Rubber friction is composed principally of adhesion and hysteresis and varies mainly with the conditions of the pavement surface, sliding speed, and rubber temperature. The type and depth of tire tread are important in obtaining good skid resistance on wet pavements and in reducing the dangers of hydroplaning.

To obtain good skid resistance, a concrete pavement surface should have a texture consisting of both fine and coarse asperities. The fine asperities formed by the paste-coated fine aggregate in the mix impart the adhesion component in the tire-pavement interaction whereas, the coarse asperities formed by the sculptured surface of the concrete during finishing operations have the dual role of imparting the hysteresis component and providing drainage channels for water.

Finishing of a concrete pavement has generally been accomplished using a burlap drag, a broom, or a belt. Results of specimens finished in the laboratory indicated that texture depths obtained with a burlap drag varied considerably with the time of finishing compared with finishes obtained with a broom. It is suggested that one way of obtaining a texture when finishing with a burlap drag would be to make three passes, each at a different time interval after casting. It is obvious that with other factors being equal a pavement with a deep texture will retain skid resistance longer than a pavement with a shallow texture; however, the finishing method selected should be compatible with the environment, speed and density of traffic, topography and layout of the pavement, and economics of vehicle operations.

Quality concrete is a prerequisite to the retention of pavement skid resistance. Test data indicated that an increase in the water-cement ratio or the addition of water to the surface of plastic concrete during finishing resulted in an increase in pavement wear and caused the benefits of a good surface texture to be of short duration. A decrease in cement content also decreased wear resistance.

The skid resistance of a concrete pavement is controlled mainly by the fine aggregate in the mortar layer that is textured during finishing rather than the coarse aggregate that seldom functions as a portion of the surface. Test data indicated that a fine aggregate with a siliceous particle content of 25 percent or greater will provide good field performance.

To improve skid resistance at critical areas such as toll plazas or near busy intersections, abrasives such as aluminum oxide or silicon carbide can be spread over the surface and floated into the plastic concrete.

Methods of increasing the skid resistance of old or worn surfaces include acid etching, mechanical abrading, sawing, and resurfacing. The choice of method depends on the economics and the end to be accomplished.

## REFERENCES


1. Penn, H. S. Causes and Characteristics of Single Car Accidents. Highway Research Record 79, p. 1-16, 1965.
2. Allen, T. M. A Factor Analysis of Accident Records. Highway Research Record 79, p. 17-25, 1965.
3. Mills, J. P., and Shelton, W. B. Virginia Accident Information Relating to Skidding. Proc. First International Skid Prevention Conference, Virginia Council of Highway Investigation and Research, Part I, p. 9, 1959.
4. Accident Facts 1967 Edition. National Safety Council, p. 40-50, 1967.
5. Kummer, H. W., and Meyer, W. E. Tentative Skid-Resistance Requirements for Main and Rural Highways. Highway Research Board, NCHRP Report 37, 1967.
6. Moore, D. F. Prediction of Skid-Resistance Gradient and Drainage Characteristics for Pavements. Highway Research Record 131, p. 181-203, 1966.
7. Sabey, B. E. Road Surface Texture and Change in Skidding Resistance with Speed. Road Research Laboratory, Harmondsworth, England, Report 20, 1966.

8. Giles, C. G., Sabey, B. E., and Cardew, K. H. F. Development and Performance of the Portable Skid Resistance Tester. ASTM, Symposium on Skid Resistance, Spec. Tech. Publ. 326, p. 50, 1962.
9. Kummer, H. W., and Moore, D. F. Concept and Use of the British Portable Skid Resistance Tester. Joint Road Friction Program, Pennsylvania Dept. of Highways and Penn. State Univ., Report 6, 1963.
10. Whitehurst, E. A., and Goodwin, W. A. A Device for Determining Relative Potential Slipperiness of Pavement Mixtures. HRB Bull. 186, p. 1-7, 1958.
11. Balmer, G. G., and Colley, B. E. Laboratory Studies of the Skid Resistance of Concrete. Jour. of Materials, ASTM, Vol. 1, No. 3, p. 536-559, September 1966. (PCA Development Dept. Bull. D109).
12. Dillard, J. H., and Mahone, D. C. Measuring Road Surface Slipperiness. ASTM, Spec. Tech. Publ. 366, p. 12, 1963.
13. Kummer, H. W., and Meyer, W. E. Measurement of Skid Resistance. ASTM, Symposium on Skid Resistance, Spec. Tech. Publ. 326, p. 10-11, 1962.
14. Goodwin, W. A., and Whitehurst, E. A. The Maintenance of Variables in Equipment and Techniques for Performing Skid Trailer Tests. ASTM, Symposium on Skid Resistance, Spec. Tech. Publ. 326, p. 36, 1962.
15. Marick, L. The Effect of Tread Design. Proc. First International Skid Prevention Conference, Virginia Council of Highway Investigation and Research, Part I, p. 155-162, 1959.
16. Horne, W. B., and Dreher, R. C. Phenomena of Pneumatic Tire Hydroplaning. NASA TN D-2056, Nov. 1963.
17. Trant, J. P., Jr. NACA Research and Friction Measurements. Proc. First International Skid Prevention Conference, Virginia Council of Highway Investigation and Research, Part I, p. 279, 1959.
18. Gillespie, T. D. Pavement Surface Characteristics and Their Correlation with Skid Resistance. Penn. Dept. Highways-Penn. State Univ. Joint Road Friction Program, Rept. 12, 1965.
19. Instruction for Using the Portable Skid Resistance Tester. Road Note 27, British Road Research Laboratory. HMSO, London, 1960.
20. Horne, W. B. Private Communication. 1965.
21. Moore, D. F. Prediction of Skid Resistance Gradient and Drainage Characteristics for Pavements. Highway Research Record 131, p. 181-203, 1966.
22. Lucas, J., and Malavaille, M. Glissance. Special F, Bulletin de Liaison des Laboratoires Routiers, Ponts et Chaussees, Paris, p. 161-175, 1966.
23. Sawyer, James L. Wear Tests on Concrete Using the German Standard Method of Test and Machine. ASTM, Presentation at 60th Annual Meeting, June 1957.
24. Design and Control of Concrete Mixtures. Eleventh Edition, Portland Cement Assoc., p. 47.
25. Barboza, G., and Close, W. Extended Study of Locked Wheel Friction Coefficient on Wet Road Surfaces. Report No. YM-1372-V-1, Cornell Aeronautical Laboratory, Inc., 1960.
26. Scholer, C. H., and Allen, Harold. Wear Tests of Concrete. Kansas State Agricultural College, Bull. 20, 1928.
27. Maclean, D. J., Shergold, F. A. The Polishing of Roadstone in Relation to the Resistance to Skidding of Bituminous Road Surfacings. Road Research Technical Paper 43, Department of Scientific and Industrial Research, London, 1958.
28. Shupe, J. W., and Lounsbury, R. W. Polishing Characteristics of Mineral Aggregates. First International Skid Prevention Conference, Virginia Council of Highway Investigation and Research, Part II, p. 509-537, 1959.
29. Whitehurst, E. A., and Goodwin, W. A. A Device for Determining Relative Potential Slipperiness of Pavement Mixtures. HRB Bull. 186, p. 1-7, 1958.
30. Gray, J. E., and Renninger, F. A. The Skid Resistant Properties of Carbonate Aggregates. Highway Research Record 120, p. 18-34, 1965.
31. Walz, K. Einfluss der Zussammensetzung und der Oberflachentextur von Strassenbeton auf die Griffigkeit. Beton 17(11), Nov. 1967.

32. Horne, W. B. Private Communication 1968.
33. Accident Award: State and Road Contractor Pay Road-Crash Victim. Engineering News-Record 179 (13), p. 68, Sept. 1967.
34. Gillette, R. W. A 10-Year Report on Performance of Bonded Concrete Resurfacing. Highway Research Record 94, p. 61-76, 1965.
35. Westall, W. G. Concrete Overlays on Asphalt Pavements. Highway Research News 22, Feb. 1966.
36. Subcommittee VIII, ACI 325. Design of Concrete Overlays for Pavements. Jour. ACI 64(8), 1967.
37. Felt, E. J. Resurfacing and Patching Concrete Pavements with Bonded Concrete. HRB Proc. Vol. 35, p. 444-469, 1965. (PCA Development Dept. Bull. D8)
38. Felt, E. J. Repair of Concrete Pavement, Proc. ACI, Vol. 57, p. 139-153, 1960. (PCA Development Dept. Bull. D44)