PAVEMENT CONTRIBUTIONS TO WET-WEATHER SKIDDING ACCIDENT REDUCTION

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This paper reviews the state of the art in the United States of the contributions of pavement surface characteristics to the reduction of wet-weather skidding accidents. Although primary emphasis is on road and street pavements, the surface characteristics and wet-weather performance of airfield pavements are also discussed. With regard to roadway pavements, the scope of the paper includes surface characteristics needs in relation to geometrics and traffic, types of surfaces currently being used, and methods for measuring surface characteristics. Current practices and research findings that are considered suitable for implementation are covered. Skid resistance, described as the skid number (SN) measured in accordance with ASTM Method E-274, is the most generally used method to characterize roadway pavements. Texture and surface drainage are becoming increasingly recognized as characteristics to be considered. The method of skid-resistance measurement in widest use in the U.S. uses properly calibrated locked-wheel skid trailers conforming to ASTM Method E-274. No nationally accepted pavement surface characteristics requirements have been established. A SN of 37 measured at 65 km/hr (40 mph) is the most generally recognized surface requirement for main rural highways with a mean traffic speed of 80 km/hr (50 mph.)

Although motor vehicle accidents have decreased in the United States during the past two years, the unpleasant 1975 statistics show that motor vehicle accidents for that year cost $21.2 billion and resulted in 1,800,000 disabling injuries and 46,000 deaths (1). Wet-weather traffic accidents are estimated to be responsible for about 15% of motor-vehicle injuries and fatalities (2). Wet-weather traffic exposure (that percentage of total vehicle-miles exposed to wet pavements) is very difficult to determine on a national scale. One study (3) indicates that wet pavements exist about 6% of the driving time in Central Texas. Another study (4) has found that a rainfall intensity of 0.25 mm/hr (0.01 in./hr) or greater occurs only about 3.5% of the time over the state of Illinois. Use of such figures indicates that wet-weather accident rates are several times dry-pavement rates. At certain high accident sites, the wet-weather accident rate may be 10 to 20 times the dry-pavement rate. For example, 55 accidents were recorded on one curve of the Ohio Turnpike during a 4 1/2-year period. Of these, 37 (67%) were reported as involving skidding on a wet pavement.

With the intent of zeroing in on this important aspect of highway safety, Project 1-H, "Skid Accident Reduction," has been included in the Federally Coordinated Program of Research and Development in Highway Transportation in the U.S. During the past 10 years almost $20 million has been spent or programmed in this area, with the over-all objective of reducing the frequency and severity of accidents associated with skidding and loss of control on wet pavements. The project includes Federal Highway Administration (FHWA) staff studies, direct FHWA contracts, National Cooperative Highway Research Program (NCHRP) projects, and many individual state highway agency studies.

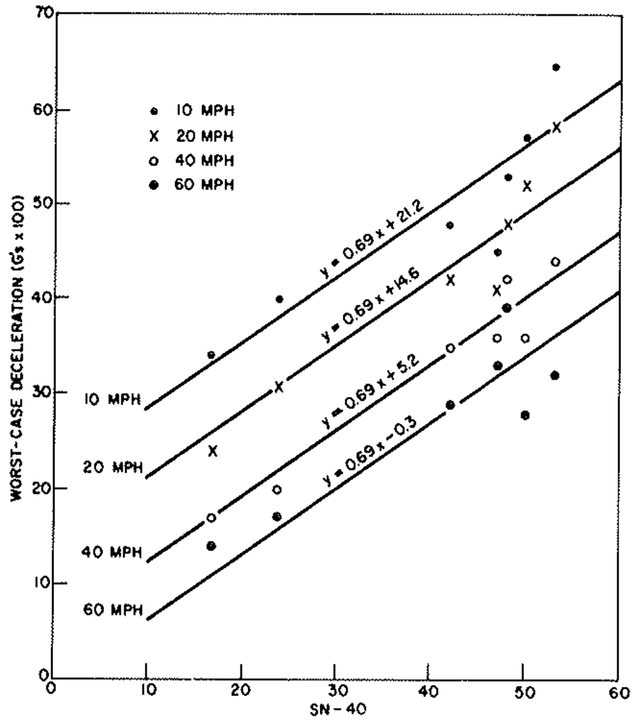
This paper deals with the state of the art in the U.S. of the contributions of pavement surface characteristics to the reduction of wet-weather skidding accidents. It describes current practices and the findings of research considered suitable for implementation. The paper is divided into the specific areas of (a) highway geometrics and the needs of traffic, (b) surface characteristics, (c) measurement of surface characteristics, and (d) airfield pavements.

Highway Geometrics and Traffic Needs

Skidding of a rubber-tired vehicle occurs when the forces developed at the tire-pavement interface exceed the ability of the particular tire and pavement surface, under the existing environmental conditions, to develop frictional resistance. Under dry conditions the friction between the vast majority of pavement surfaces and tires is adequate to accommodate all but the most severe vehicle maneuvers without skidding. However, when wet the ability to develop tire-pavement friction is substantially reduced and becomes much more dependent on the characteristics of both the tires and the pavement surfaces.

Assessment of contributions of pavement surfaces to the reduction of wet-pavement skidding involves driver demands (the intensity of acceleration,

Figure 1. Minimum locked-wheel braking deceleration values as a function of NBS SN_{40}.



braking, and cornering maneuvers) and demands resulting primarily from roadway geometrics (hills, curves, intersections, merging lanes, etc.). Approaches for determining the relative ability of pavement surfaces to make adequate contributions to the needs of traffic have traditionally involved analysis of accident records. This approach combines the influences of driver, vehicle, pavement, and environmental factors on accident experience and identifies locations in obvious need of corrective action. Current recommendations for minimum pavement skid resistance, texture, and other characteristics intended to provide for safe maneuverability during wet weather are generally based on the accident analysis approach.

An alternate approach for determining needed pavement surface characteristics to accommodate the needs of traffic involves measurement or computation of the traffic demand or acceleration forces developed by given sets of conditions (maneuver and roadway geometry) and the correlation of these forces with friction forces developed by anticipated vehicle-tire combinations on various pavement surface types. This approach presents the opportunity for determining the pavement surface characteristics required to accommodate the variability of traffic needs on different sections of roadway. For example, different pavement surface characteristics may be desirable to provide for safe maneuverability of traffic during wet weather on rural tangents, residential streets, urban freeway curves, signalized intersections, merging zones, etc.

Acceleration forces, expressed in units of the gravitational constant, g, may range from practically zero for a vehicle coasting on a straight grade to 1.0 g or more during emergency braking. The latter is beyond the capability of conventional automobile brake systems and thus not realistic as an anticipated tire-pavement force. Research has shown that a majority of drivers develop about 0.2 g during normal driving, with an upper reasonable limit of 0.6 g for emergency stops from 95 km/hr (60 mph) within 60 m (200ft) (5). In addition to braking, acceleration forces are developed during such maneuvers as acceleration from stop, passing, steady-state cornering, combined cornering and acceleration, and combined cornering and braking. These result in various longitudinal and lateral forces that can be computed for given speeds and geometries. For generally accepted speeds and modern design standards, practically all of the resulting acceleration forces are within the 0.2 g to 0.6 g range previously mentioned.

Controlled-skid studies to determine relationships between longitudinal acceleration forces and pavement skid-resistance requirements have been conducted. Seven skid pads of varying surface characteristics and two instrumented automobiles, a 1970 Plymouth Fury and 1971 Ford Mustang, were used. Three sets of tires (conventional bias ply, belted bias ply, and radial) were used on the Plymouth and belted bias ply only on the Ford. All tires were relatively new. For the purpose of developing correlations, the skid resistance of each test pad was measured as skid number (SN) at 32, 65, and 96 km/hr (20, 40, and 60 mph) using a locked-wheel skid tester in conformance with ASTM Method E-274 (5).

It is apparent from analysis of the data that complex interactions exist between pavement surface characteristics, speed, tires, and other vehicle factors. No tire-vehicle combination produced the highest maximum deceleration (negative longitudinal acceleration) for all surfaces and speeds. However, a plot of maximum deceleration versus skid number (Fig. 1) (5, p. 24) was developed in which each point is the worst case from the four tire-vehicle combinations at each of the speeds for each of the given skid pads. Each point represents the average of six skid tests. With measured or computed speed and longitudinal acceleration values for braking sites, the figure can be used to select estimated pavement skid-resistance requirements for braking sites (such as intersections).

Similar studies have been conducted in an attempt to determine relationships between lateral accelerations and pavement characteristics as measured with a locked-wheel tester in conformance with ASTM Method E-274 and with the University of Michigan Mobile Tire Tester that measures cornering slip number (CSN). The limited amount of data available indicates that neither tester characterized pavement surfaces adequately for development of a reasonable correlation with lateral acceleration forces. The difficulty seems to arise from the strong interaction between pavement surfaces and tire-vehicle characteristics. This is supported by another testing program that found good correlation between locked-wheel skid trailer measurements and maximum automobile cornering speed when the same tires were used on both the skid tester and the automobile (6).

Skid Resistance, Surface Drainage, and Texture

The characteristics of a pavement surface that have been identified as influencing the safe maneuverability of rubber-tire vehicles on pavements, particularly when wet, are skid resistance, texture, and surface drainability. Of these, skid resistance has received the greatest amount of attention from the standpoint of both research and operational programs intended to reduce wet-weather skidding. Current practices in the U.S., as well as recent research findings, are discussed for each of these characteristics.

Pavement skid resistance. Tire-pavement friction is the horizontal force developed when a tire that is prevented from rotating slides along a surface. The development of this force involves both the tire and the pavement. In the highway field, pavement skid resistance is the characteristic or capability of the pavement to develop horizontal friction forces on a skidding tire. It is described as the skid number (SN) measured in accordance with ASTM Method E-274, involving the sliding of a locked standard tire at a constant speed along an artificially wetted pavement surface.

NCHRP Report 37, "Tentative Skid-Resistance Requirements for Main Rural Highways," (7) discusses the problem of determining minimum pavement skid resistance and contains a table listing tentative requirements for main rural highways based on data and information available at the time of its preparation. Table 1 (7, p. 54) gives the tentative minimum SN values for various traffic speeds that are generally applicable for the large percentage of rural roadway mileage. Because skid number measurements and accelerations developed by maneuvers are both significantly influenced by speed, the recommended minimum SN_{40} values vary with mean traffic speed. Although there is no nationally accepted minimum pavement skid resistance, the U.S. Department of Transportation Highway Safety Program Manual No. 12, "Highway Design, Construction, and Maintenance," (8) prepared in response to the Highway Safety Act of 1966, contains the table from NCHRP Report 37 as a general guide. In addition, individual state highway agencies have included skid-resistance requirements in state safety programs. For example, Table 2 (9) is from the Louisiana Department of Highways' Skid Accident Reduction Program as the guide for construction of pavement surfaces that will retain adequate skid resistance under traffic in Louisiana.

The ratio of wet-pavement to dry-pavement accidents is useful in determining critical pavement skid resistance values. A study in Kentucky found that the ratio of wet- to dry-pavement accidents on rural two-lane roads decreased rapidly as the SN_{40} value increased to about 40; further increases in skid resistance resulted in only slight reduction in the ratio (10). The average ratio was about 0.25 for pavement with SN_{40} values above 40 and increased to 0.60 as SN_{40} values decreased.

The construction and maintenance of all roadways with wet-pavement skid resistance comparable to dry pavements may not result in the best use of available materials and funds. Meaningful requirements should be based on actual conditions and traffic demands of a site. For example, higher values of skid resistance are needed on approaches to intersections than on rural tangents, particularly in regions of above-average precipitation. From the results of a study of skid-resistance requirements, it appears that a strong general relationship exists between the pattern of braking decelerations at an intersection and pavement skid-resistance needs (5). A reasonable approach to development of pavement skid-resistance requirements may be the determination of requirements for groupings of roadway site types such as (a) level and nearly level tangents, (b) steep grades, (c) long-radius curves, (d) short-radius curves, (e) intersections, and (f) special situations. It should also be recognized that skid resistance is not the only factor that influences the safety or the hazard potential of a site. Traffic volume and speed plus the prospect for wet-pavement conditions all should be considered when determining surface characteristics for safe operation.

Table 1. Recommended minimum interim skid numbers[a].

MEAN TRAFFIC SPEED, V (MPH)	SKID NUMBER	
	SN [b]	SN_{40} [c]
0	60	—
10	50	—
20	40	—
30	36	31
40	33	33
50	32	37
60	31	41
70	31	46
80	31	51

[a] Skid numbers measured in accordance with ASTM E-274 Method of Test.
[b] SN = skid number, measured at mean traffic speeds.
[c] SN_{40} = skid number, measured at 40 mph, including allowance for the skid number reduction with speed using a mean gradient of $G = 0.5$.

Table 2. Guide values for new construction.

ADT per Lane	Minimum SN_{40}
Less than 200	40
200-999	43
1000-5000	45
More than 5000	47

Drainability. Water depth on a pavement surface has a critical influence on the safe operation of vehicles on pavements. Tire hydroplaning is commonly considered to be the adverse effect from excess water. In actuality, complete hydroplaning, even with smooth tires, is probably a rare occurrence. The vast majority of wet-weather skidding accidents undoubtedly occur as the result of water depths well below those needed for complete hydroplaning. This degradation of tire-pavement friction as a consequence of the presence of water is referred to as partial hydroplaning.

The Texas Transportation Institute has conducted a study of wet-weather performance of ten different tire conditions on five different pavements at various water depths and speeds (11). Wheel spin-down (reduction in wheel speed as it is pulled over a wet pavement) was used as a measure of reduction in tire-pavement friction forces. The testing program demonstrated that increasing water depth decreases the speed at which spin-down is initiated. A wheel spin-down of 10% was considered to result in sufficient deterioration of available tire-pavement friction to adversely affect vehicle steering and braking ability.

Research on methods for predicting pavement water depth as a function of rainfall intensity and pavement geometrics has been conducted by the Texas Transportation Institute (TTI), the British Transportation and Road Research Laboratory (TRRL), and the Goodyear Tire and Rubber Co. It is concluded that pavement width (drainage length) and cross slope are the primary roadway factors affecting the drainability of a pavement surface. On a two-lane crowned roadway with a cross slope of 1.5%, a drainage length of 3.65 m (12 ft), a rainfall intensity of 6.4 mm/hr (0.25 in./hr), and using the TRRL formula, the computed maximum water depth would be 0.7 mm (0.028 in.) Using the same cross slope, rainfall intensity, and formula, the computed maximum water depth for a multilane roadway sloped in one direction only, with a drainage length of 10.4 m (34 ft), would be 1.2 mm (0.046 in.) (12).

A study of accident data for the Ohio Turnpike, as given in Table 3 (12, Table 1), indicates that the ratio of wet-pavement to dry-pavement accidents is several times higher for curves of about 1° than for tangent sections. The drainage lengths are 3.65 m (12 ft) on tangents and 10.4 m (34 ft) on superelevated curves. The cross slope is 1.5% for both tangents and 1° curves. There was no indication that pavement skid resistance was significantly different on tangent and curve sections (12).

A Louisiana study of roadway geometry variables on traffic accidents found that of the ten geometric variables considered, pavement cross slope and the number of roadway access points (conflicts) were the two, interacting with traffic volume, having the greatest effect on accident rates (13). It was also found that cross slope had a more significant influence on accident rates during wet weather than during dry weather. These data indicate a rather dramatic relationship between pavement cross slope, water depth, and wet-weather skidding accidents, and thus the importance of provisions for adequate surface drainage.

In addition to cross slope, porous or open-graded asphaltic concrete improves the drainability of pavement surfaces. The concept involves use of a narrowly graded coarse aggregate with sufficiently large void capacity to provide for a high asphalt content for durability and high air void content for internal drainage. This pavement mix can be used as the surface course of a new pavement or as an overlay over existing pavements. When properly designed and constructed, they provide superior skid-resistance characteristics and, more importantly, quite uniform SN values with increases in speed (rather flat SN-speed gradient curve).

Problems that were experienced during the development and early use stages of the open-graded asphaltic concrete pavements have largely been overcome. "Design of Open-Graded Asphalt Friction Courses" published by the Federal Highway Administration (14), contains detailed instructions on mix design and construction control procedures. The recently completed FHWA Demonstration Project, "Improved Skid-Resistance Pavements," resulted in installation of open-graded surfaces in 12 states and technical assistance in the design of mixes in nine additional states. Use of this type of surface is increasing, with their use extending to a majority of the U.S. state highway agencies.

Table 3. Accident experience by surface condition, Ohio Turnpike.

	ACCIDENTS			
		PERCENT		
DEGREE OF CURVATURE	NUMBER	DRY	WET	OTHER*
0°0'	3,317	61.5	18.5	20.0
0°1' to 0°21'	619	56.7	27.6	15.7
0°22' to 0°43'	621	54.4	32.2	13.4
0°44' to 1°5'	616	34.9	53.4	11.7
1°6' to 1°27'	96	60.4	27.1	12.5
1°28' to 1°49'	73	56.2	32.9	11.0
1°50' to 2°11'	78	55.1	21.8	23.1
2°12' to 2°33'	133	47.4	21.8	30.8
All	5,553	56.7	25.4	17.9
GRADE, PERCENT				
+1.5 to +2.4	649	57.5	22.2	20.3
+0.7 to +1.4	547	55.9	23.6	20.5
-0.6 to +0.6	2,879	59.9	24.8	15.2
-1.4 to -0.7	642	52.8	25.7	21.5
-2.4 to -1.5	708	49.4	29.2	21.3
-3.5 to -2.5	83	36.1	49.4	14.5
All	5,553	56.7	25.4	17.9

*Consists largely of snow/ice conditions.

Texture. Texture is a characteristic of pavement surface that is interrelated with skid resistance and drainability in providing for safe maneuverability of motor vehicles during wet-weather conditions. It is usually described as "macrotexture" - the more coarse roughness of the surface formed by the presence of individual particles of aggregate or the texturing of mortar while in a plastic state - and "microtexture" - the fine roughness of the pavement surface attributed to the texture of the individual coarse-aggregate particles or the presence of very fine aggregate in the mortar.

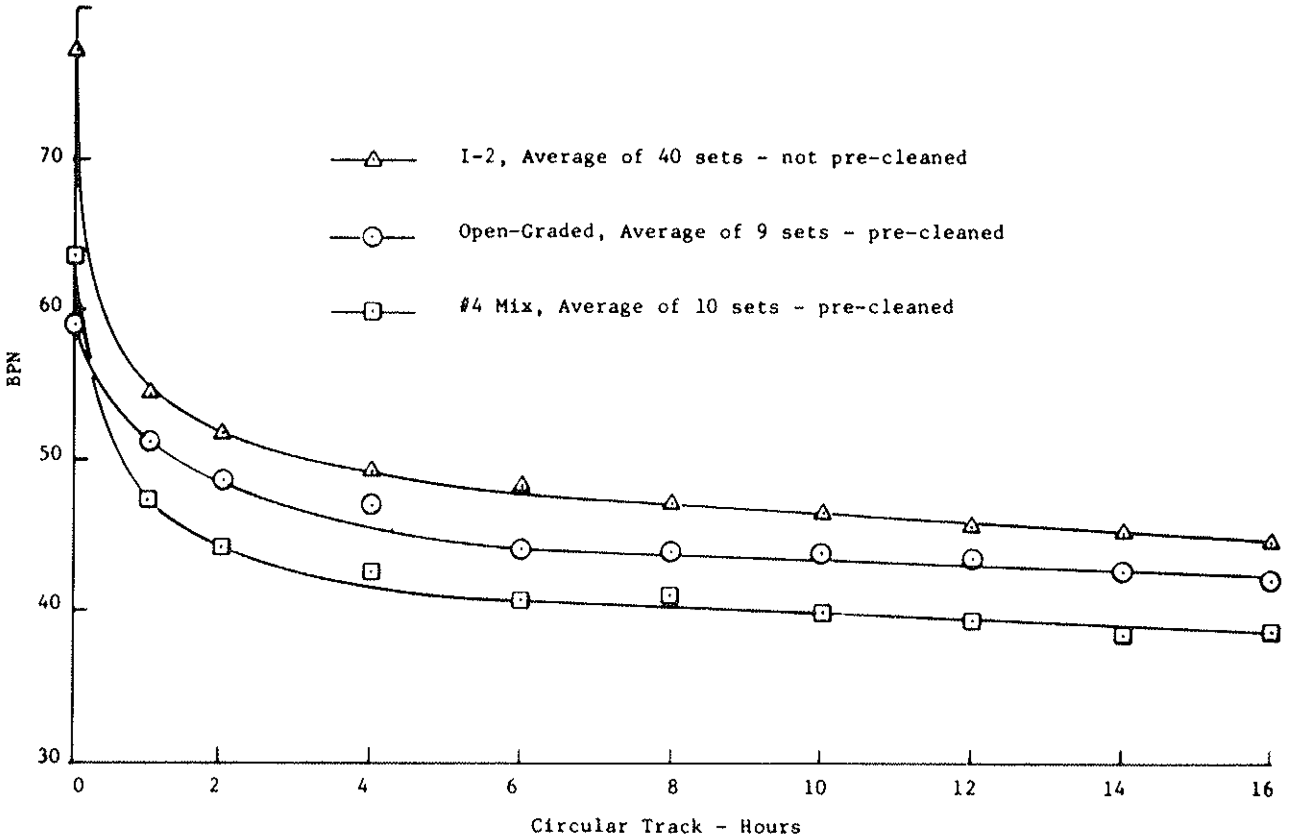
The microtexture of a pavement primarily influences skid resistance at lower speeds. The macrotexture contributes to drainage of water from beneath a tire and thus improves maneuverability at higher speeds and results in a more desirable skid-resistance speed gradient, defined as the slope of the SN-speed curve between the speeds of 50 and 80 km/hr (30 and 50 mph). Texture can be obtained through pavement mix design, size and grading of aggregates, construction procedures, surface finishing methods, and the grooving, etching, or scarifying of hardened surfaces.

In general, the texture of a pavement is at its best level when new or after an initial traffic break-in period. Continuous use by traffic tends to result in a gradual deterioration in the broad categories of polishing or reduction in microtexture and wearing away of macrotexture. In asphaltic concrete the coarse aggregate is primarily subjected to polishing, whereas the fine aggregate and the mortar of portland cement concrete usually becomes polished or worn away. The result is a reduction in skid resistance, particularly in the wheelpaths, consequently deterioration in wet-weather performance.

Because aggregates comprise more than 90% of a pavement mixture, the desirability of selecting wear- and polish-resistant aggregates for pavement surfaces expected to carry relatively high traffic volumes is quite obvious. This involves laboratory evaluation of aggregates and pavement specimens, with the objective of predicting polish-resistance and skid-resistance performance. Laboratory methods found to be useful include circular track devices that simulate field conditions, determination of polished stone value (PSV), and petrographic studies. North Carolina State University has developed methods for determining the polishing properties of aggregates in the laboratory as a step to predicting with reasonable assurance the limits of field polishing of aggregates and pavement mixtures based on the laboratory tests (15). A small-wheel circular track is used to condition laboratory-prepared pavement specimens and friction measurements are made at periodic time intervals using a British portable tester. The British portable numbers (BPN) thus determined have been correlated with skid numbers (SN) measured at 32, 48, 65, and 80 km/hr (20, 30, 40, and 50 mph) with the North Carolina Highway Commission locked-wheel skid trailer. Predictions of the maximum field polishing during the service life of North Carolina pavements can be made. Figure 2 (15, p. 60) shows the relationship between BPN and time of exposure on the circular track for three types of asphaltic pavement mixtures. It appears that an exposure of 6 hr is adequate to establish a polish curve for these North Carolina pavements.

The results of an extensive experimental program

Figure 2. Wide pneumatic tire correlation curves for the standard aggregate.



involving the exposure of 36 pavement sections to simulated traffic of up to 7,000,000 wheel passes on a circular test track generally confirm previous research and experience concerning the importance of aggregate selection to wet-weather performance of pavements. The laboratory test values for each aggregate used in the pavement sections are given in Table 4 (16, Table 3). The Texas polish value was determined in accordance with Texas State Department of Highways and Public Transportation test method Tex-438-A, similar to the British polished stone value test. It was generally found that all pavement sections had high initial skid resistance values, as determined by the British portable tester. The trend was for the skid resistance to drop very rapidly during the first 50,000 wheel passes, continue to reduce at a moderate rate through 1,000,000 wheel passes, and then continue to reduce at a slow rate through the 7,000,000 wheel passes. During this particular test program there did not appear to be a terminal polish level. From a relative standpoint, the skid resistance of the pavement sections was consistent with the polish values of the aggregates used. The other tests did not appear to be helpful in predicting skid resistance (16).

To provide for adequate microtexture of

Table 4. Results of tests on aggregates.

Aggregate	Texas Polish Value	L.A. Abrasion Loss, % 100 rev.	L.A. Abrasion Loss, % 500 rev.	Modified L.A. Abrasion Loss %	Modified L.A. Abrasion Sediment ht., in.	California Durability	Washington Degradation
Crushed trap rock	33	2.5	9.9	9.1	7.4	87	93
Crushed graywacke	46	4	20	18.8	13.9	70	67
Crushed quartzite	34	4.5	19.4	15.9	8.9	96	96
Expanded shale	50	6.6	24.8	---	---	96	87
Calcined bauxite	44	---	---	---	---	100	96
Crushed limestone	22	---	16.6	14.6	8.6	90	84
Typical requirements:	35 min.	10 max.	40 max.	40 max.	13 max.	35 min.	25 min.

Table 5. Tentative recommended polished stone values for various traffic volumes*.

Traffic, Vehicle Passages Per Lane Per Year	Median Polished Stone Value	Range
50,000 to 150,000	28	26.5 - 29.5
150,000 to 600,000	32	30.5 - 33.5
600,000 to 2,500,000	37	35 - 39
2,500,000 to 10,000,000	42	40 - 44
10,000,000 +	47	47 - 49+

*Accelerated Polish Test for Coarse Aggregate TEX 438 (a combination of British Standard 812 and ASTM E 303, The British Wheel and the British Pendulum Tester).

asphaltic concrete pavements, a Texas Transportation Institute study (17) suggests tentative polish values (using Tex-438) for various traffic volumes as shown in Table 5 (17, p. 163).

Pavement macrotexture contributes to wet-weather skid accident reduction from the standpoint of (a) increasing skid resistance and improving maneuverability on wet pavement and (b) improving drainage of water from beneath tires and thus reducing hydroplaning tendency during more intensive rainfalls. The practice of longitudinal and transverse tine finishing of the plastic mortar during construction of portland cement concrete pavements is growing quite rapidly in the U.S. This produces a harsh macrotexture that is somewhat moderated during the first year of traffic exposure, followed generally by quite uniform resistance to wear for many years unless subjected to studded tire or chain wear.

The macrotexture of asphalt pavement is normally developed by the coarse aggregate in asphaltic concrete mixes, precoated aggregate rolled into asphaltic concrete, or use of asphalt seal coats. Performance of these surfaces is influenced by the ability of the asphalt cement to retain the coarse aggregate and by the wear and polish resistance of the particular coarse aggregate used. Open-graded asphaltic concrete is also produced with a rather coarse macrotexture.

Limiting texture values, independent of skid resistance, have not been generally accepted at this time. A study by the Texas Transportation Institute recommends tentative minimum values of 1.0 mm (0.04 in.) for dense pavement surfaces, and 1.3 mm (0.05 in.) for open graded and coarse-textured surfaces, as determined by the modified sand patch method (17). Acceptable noise levels will probably be the limiting factor for maximum macrotexture values. The acceptable noise level in urban areas will generally be lower than in rural areas. For example, asphalt seal coats generate higher noise levels than open-graded surfaces of the same macrotexture. Based on the noisiest pavement type (seal coats), the suggested macrotexture is 3.9 mm (0.15 in.) for rural areas and 2.5 mm (0.10 in.) in urban areas.

The following statement on texturing of plastic portland cement concrete surfaces is from FHWA Notice N 5080.95, September 10, 1976 (18):

> Transverse grooving will provide a pavement surface with good skid-resistance characteristics, will reduce splash and spray and headlight glare from wet roadway surfaces, and will continue to facilitate surface drainage until the depth of the wheelpath ruts exceeds the depth of the grooves. Longitudinal grooving assists vehicle control at curves and sites involving lateral movements. Both types of grooving effectively reduce the hydroplaning potential. The longitudinal grooving of existing pavements, while not necessarily producing an improvement in skid number, has been found to be a very effective means of reducing accidents at sites having high wet-weather accident rates. Although longitudinal grooving may be preferable under some circumstances, transverse grooving is considered to be superior to longitudinal grooving for general use on new construction because of the improved pavement drainage provided.

The notice further states that a burlap or other type of drag finish should not be used as the sole means of providing surface texture on projects with design speeds of 65 km/hr (40 mph) or greater. Metal tines are recommended as being the most practical and dependable method of providing positive texture in plastic portland cement concrete pavements and bridge decks.

Surface Characteristics Measurement

Procedures for determining pavement surface characteristics to accommodate forces developed by traffic are largely empirical at this time. The majority of effort has been directed toward determination of skid resistance as the pavement surface characteristic most closely associated with the prevention of skidding. The method of skid-resistance measurement in widest use in the United States uses a locked-wheel skid trailer conforming to ASTM Method E-274. The pavement skid resistance thus measured is termed the skid number (SN) for the test speed. For example, the SN_{40} value is the pavement skid resistance measured at 65 km/hr (40 mph.). Other pavement surface characteristics important to reduction of wet-pavement skidding are pavement surface drainage, texture, and SN-speed gradient.

Measurement methods, in addition to the locked-wheel type, are described in NCHRP Synthesis 14, "Skid Resistance" (19). Each type of tester measures a different aspect of the friction developed. Even when the same tire or slider is used, speed and modes of operation differ, water film control may not be the same, and other parameters may vary. Therefore, a 1-to-1 correlation between tester results should not be expected.

The results of an extensive research project with the objective being development and verification of methods for improving the ability to measure reliably the skid resistance of wet pavement surfaces with skid testers in conformance with ASTM Method E-274 have recently been published as NCHRP Report 151, "Locked-Wheel Pavement Skid Tester Correlation and Calibration Techniques" (20). The study involved (a) contacts with skid tester owners to collect information on equipment and operating procedures, (b) conduct of laboratory and field experiments to determine the influence of specific parameters, (c) computer simulation studies on the influence of equipment dynamics, (d) conduct of a two-week skid tester correlation program, and (e) preparation of recommendations for reducing variability in skid-resistance measurement.

The reliability of skid-resistance measurement depends on both tester precision and accuracy. Precision is a measure of the repeatability of the results of a single tester and accuracy is a measure of correlation among testers. An analysis of the variance performed on data collected during the correlation program indicates that the precision of skid testers, although not completely satisfactory, is generally better than accuracy. Implementation of recommendations contained in NCHRP Report 151 will aid highway agencies in obtaining more accurate pavement skid-resistance measurements with existing locked-wheel testers and, when combined with operation of the two FHWA-sponsored Field Test and Evaluation Centers for skid testers, will provide a sound basis for calibration of skid testers that will bring about substantial improvement in their correlation nationwide. The two Field Test and Evaluation Centers are located at East Liberty, Ohio, and Bryan, Texas.

Quantitative determination of the drainability and texture characteristics of a pavement is quite complex and no methods are generally accepted in the U.S. at this time. One approach is use of the skid-resistance speed gradient, defined as the slope of the SN-speed curve between the speeds of 50 and 80 km/hr (30 and 50 mph), as a measure of the hydroplaning potential of a pavement. Texture depth is described as the mean thickness of a layer of a given quantity of fine sand or putty spread over a pavement surface. An outflow meter measures the rate of water flow from beneath a rubber gasket placed on the pavement and thus can be an indication of macrotexture and drainability. Stereo photography is also used to identify the textural characteristics of pavements and their relation to skid resistance. This is known as the Schonfeld method and described under ASTM Designation E 559-757, "Tentative Recommended Practice for Classifying Pavement Surface Textures Suitable for Skid-Resistance Photo Interpretation." Pavement surfaces are described in terms of six textural elements and correlations have been developed between the textural numbers and skid trailer SN values.

Airfield Pavements

Airport pavements must have a good textured surface that is designed for anti-hydroplaning during wet or flooded conditions and be clean of contaminants such as rubber deposits accumulated during aircraft landing operations (this is associated with aircraft traffic density). The pavement surface must also have both microtexture and macrotexture, and the aggregate in the pavement mix must be resistant to polish and wear and angular in shape.

The Federal Aviation Administration of U.S. DOT recognizes the importance of providing the aviation community with recommended construction techniques and maintenance procedures to ensure safe aircraft operations during inclement weather conditions. Guidance for design, construction, and maintenance of skid-resistant pavements has been published in an advisory circular (21). It is intended for use by airport operators, engineering consultants, and maintenance personnel.

Much of the guidance given in the circular is based on both experience and research. Although results to date are a considerable improvement in the technology, further work is required before final standardization is adopted. The methods described are acceptable until something better is developed.

The contents of the FAA advisory circular are summarized in the following.

Pavement Construction

When new airfield pavements are being constructed, asphaltic concrete pavements should have a porous friction-course overlay, an aggregate slurry seal, or sawed transverse grooves. Portland cement concrete pavements should receive transverse grooves or wire-comb texturing of the plastic concrete, sawed transverse grooves of the hardened concrete, or a porous friction-course overlay. Before placing either grooves or wire-comb texturing, the plastic concrete must receive a brush, broom, or burlap drag finish. This is required to provide a textured overall surface to increase braking skid resistance.

Pavement Maintenance

After the pavements have been properly constructed, the airport sponsor has the responsibility to maintain them as close to the newly constructed condition as possible. The airport manager can determine the average texture depth and rate of deterioration of friction by conducting surveys using the National Aeronautic and Space Administration grease smear texture test and a continuous friction measuring device, such as the Mu-meter, capable of recording average friction values. The data obtained can then be compared to the following measurement parameters:

Texture - (a) When the average texture depth is equal to or less than 0.5 mm (0.02 in.) for more than 50 percent of the runway surface, improvements should be made to increase the average surface texture to 1.3 mm (0.05 in.). Acceptable improvements can be either grooving or porous friction-course overlays. (b) When the average texture depth is equal to or greater than 1.3 mm (0.05 in.), no texture effort is required.

Contaminants - (a) When the average friction value within the contaminated area is 0.49 or less, for a distance of 150 m (500 ft) or more, the entire contaminated area should be cleaned. (b) When the average friction value within the contaminated area is 0.29 or less, for a distance of 75 m (250 ft) or more, the entire contaminated area should be cleaned. (c) When the difference in friction values either between the uncontaminated and contaminated areas or within the contaminated surface itself is 0.25 or greater, for a distance of 75 m (250 ft) or less, the entire contaminated area should be cleaned.

Paint Marking Areas - When the minimum friction value over the length of the runway marking is 0.25 or less and/or difference in friction values between the unpainted and painted surfaces is 0.25 or greater, the painted areas should be completely removed and repainted (without glass beads) in a striated pattern.

Pavement Abnormalities - When the difference in friction values between the flooded depressed areas and the surrounding pavement surface is 0.25 or greater for distances exceeding 30 m (100 ft), or if there is a repetition of ponded areas, corrective action should be taken. Depending on the extent and circumstances of the depressed areas, minimal normal maintenance to a new overlay may be required.

Over-All Pavement Friction Requirements - After the runway has been cleared of contaminants, the average wet friction value should not be less than 0.50 for any 300-m (1,000 ft) lengths tested for the entire runway length. If any increment does not meet this requirement, the entire runway should be corrected by either grooving or adding a porous friction-course overlay.

Survey Procedures - The above parameters are meaningful only if the airport sponsor is consistent in taking friction measurements. The following are a few basic rules of thumb to follow which will result in data that can be qualitatively analyzed:

1. Preliminary Visual Inspections - A record should be established and maintained by the inspector identifying the rubber deposit limits; areas where ponding occurs during rainfall; any significant cracks; areas of pavement wear; changes in surface texture; or any other deficiencies that may affect the frictional characteristics of the pavement surface.

2. Location of Test Runs - Friction measurements should be made about 3m(10 ft) from the runway center line and should encompass the full length of the runway minus the 150 m (500 ft) required for acceleration/deceleration at the runway ends. The test vehicle should operate at 65 km/hr (40 mph).

3. Test Runs on Dry Pavement - When a friction survey is taken for the first time, a test run of the dry pavement surface should be made before the test run using self-watering equipment. This test will be compared to the wet run to establish the extent of friction loss due to wet pavements. Test runs on dry pavements are not required each time a survey is conducted, but should be made often enough to check the rate of wear of the pavement due to aircraft trafficking.

4. Test Run Self-Watering Equipment - For calibrating the skid resistance of runway pavements, test runs should be made using self-watering equipment that has a controlled flow rate of water to maintain a uniformly distributed water depth of 0.5 mm (0.02 in.) in front of the friction-measuring tires.

5. Test Run During Rainfall - To complete the calibration of the runway, tests should be taken during rainfall, when the surface is flooded and the depressed areas filled with water. Test runs should be taken in the ponded areas and water depths taken. The loss of friction in these areas should be recorded and compared to the parameter given for these conditions. Any remedial action to improve this situation can then be determined.

6. Test Runs on Runway Paint Markings - Test runs over painted areas should be taken using the self-watering equipment to determine their skidding characteristics when wet.

The FAA has provided guidance in an advisory circular whereby airport owners can construct and maintain runway pavement surfaces that will provide anti-hydroplaning and skid resistance for safe aircraft operations. The airport owner should make periodic checks of the pavement surface condition, specifically the texture and contaminants buildup. The latter is significant on airport pavements. Hydroplaning is a worrysome problem for airport personnel. The tire-pavement interface must have escape paths for water or the tire will "ride" on the water, thus causing loss of friction and directional control of the aircraft.

Rubber buildup accumulates more rapidly at the high-density airports. Several methods are available to the airport owner for removing rubber deposits. Chief of these is the high-pressure water technique, in which the equipment is mounted on large trucks and operates at pressures between 35 MPa and 55 MPa (5,000 and 8,000 psi). Friction and texture measurements should be conducted before and after the cleaning operation to determine the improvement or deterioration in the effective friction. Further effort may be required if the friction data do not fall within the established parameters.

Since November 1973 the U.S. Air Force Civil Engineering Center has been measuring the skid-resistance properties on airfields. The program requires friction measurements by both a diagonal braking vehicle (DBV) and a Mu-meter (22) (23). It is felt that the data obtained from these friction measuring devices are complementary, and together they provide the skid resistance of an airfield pavement. It is intended to subject all U.S. Air Force runways in the U.S. and overseas to skid-resistance surveys periodically. There is a strong feeling that well-trained and experienced crews and standardized testing procedures should be used in this program.

Summary

Considerable information on pavement skid resistance is available from the findings of research and experience. Implementation of this knowledge should result in a reduction in wet-weather motor vehicle accidents on highways and safer operation of airfields. Some of the general observations noted are as follows:

1. Wet-weather highway accident rates are several times dry-pavement rates, and at certain sites may be 10 to 20 times greater.

2. The ratio of wet-pavement to dry-pavement highway accidents appears to be a promising approach to determining general pavement skid-resistance requirements for road systems.

3. Braking deceleration patterns may be useful in determining skid-resistance requirements at intersections and other braking sites.

4. Although there is no nationally accepted minimum highway pavement skid-resistance value, an SN_{40} value of 37 seems an appropriate minimum for main rural roadways with a mean traffic speed of 80 km/hr (50 mph) or less.

5. There is increasing recognition of the importance of the macrotexture and surface drainage of pavements to reduce the effects of hydroplaning during wet weather. Use of adequate cross slope, particularly on long-radius curves, open-graded asphaltic concrete surfaces, and grooved or tined portland cement concrete surfaces should result in reductions in wet-weather accidents on highways.

6. There is no generally accepted method for measuring the hydroplaning potential of pavements. However, use of skid-resistance values combined

with the skid-resistance-speed gradient provides the best currently available approach for evaluating the wet-weather performance of highway pavements.

7. The locked-wheel skid trailer conforming to ASTM Method E-274 is the most widely used equipment for measuring highway pavement skid resistance.

8. For airfield pavements, major emphasis is on the design, construction, and maintenance of anti-hydroplaning surfaces by use of grooving and porous friction courses.

9. Rubber buildup on airfield pavements and procedures for its removal are unique problems to airfield pavement maintenance.

10. The Mu-meter and diagonal braking vehicle (DBV) are the most widely used equipment in the U.S. for measuring airfield pavement wet-weather performance.

Questions that appear to be unresolved and in need of further study are:

1. What should be considered reasonably acceptable wet-weather accident rates, proportions of wet-weather to total accidents, and wet- to dry-pavement accident ratios?

2. To what extent should minimum standards for skid resistance and other pavement surface characteristics be established for all road categories (freeways, rural two-lane, residential streets, etc.) and specific site types (intersections, curves, etc.)?

3. Can highway pavement surface characteristic requirements be realistically based on traffic needs at specific locations and sites?

4. How can seasonal variations in highway pavement skid resistance be accommodated in routine inventory programs?

5. Should more economical and simpler equipment be developed for routine measurement of highway pavement skid resistance and hydroplaning potential?

6. Can more economical anti-hydroplaning airfield systems be developed?

Acknowledgments

This paper is the joint effort of a task force of Subcommittee B of the Conference Program Committee. The task force was assigned the responsibility of compiling available information and preparing a state-of-the-art report on pavement contributions to wet-weather skidding accident reduction in the United States. Along with the companion report on providing skid-resistant pavements, it is intended to be an updating of NCHRP Synthesis 14, "Skid Resistance" (19).

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