EFFECTS OF PAVEMENT SURFACE CHARACTERISTICS AND TEXTURES ON SKID RESISTANCE

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DISCLAIMER

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Texas Highway Department or the Federal Highway Administration.

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ABSTRACT

Data are presented relating the various pavement surface characteristics, operating modes of tires, and field methods of measuring skid numbers for different pavement surfaces. Void areas were determined for 41 pavement surfaces and correlated with the reduction in skid numbers caused by an increase in speed from 20 to 60 mph. The correlation coefficients were statistically significant. Void areas of highway surfaces can be increased by increasing the macro-textures of the surface to obtain small decreases in skid number with increased speed. Microscopic textures and small-scale macroscopic textures (in terms of centerline average heights) are also significantly correlated with the skid number measured by a skid trailer equipped with a standard E-17 test tire.

Equations are provided to permit predictions of the skid numbers at 20 mph from the texture parameters of pavement surfaces. Reduction in the skid number due to increasing speed may also be predicted by equations involving the void areas at the tire-pavement interface. Thus, the data presented offer a means of pre-evaluation of the expected skid characteristics of pavements.

SUMMARY

The research reported includes a literature review and an experimental program conducted under Research Study 2-8-68-138, "Vehicle-Pavement Interaction." The purpose of the research was to determine the relationships between skid numbers and small-scale pavement textures combined with macrotexture paremeters.

By means of multiple regression analyses, skid numbers were related to independent variables consisting of small-scale textures, macrotextures, and aggregate size. The equipment consisted of a locked wheel trailer conforming essentially to ASTM E-274 and standard skid test tires (ASTM E-249) both with and without tread. In general, pavement surfaces with rounded aggregates can be characterized by surfaces with hemispherical protrusions; surfaces with crushed aggregates can be characterized by surfaces with pyramidical protrusions.

Microtextures and small-scale macrotextures (in terms of centerline average height up to 1000 microinches were significantly correlated with 20 mph skid numbers measured with a standard skid trailer. Macrotextures and aggregate particle size factors improve the correlation coefficients. A correlation coefficient of 0.867 was obtained by relating the skid number at 20 mph to a combined independent variable consisting of: 1) the small-scale textures measured on aggregate particles by the Clevite BL-185 Surfindicator, 2) macrotexture measured by the Texas Highway Department Profilograph, and 3) the weighted particle-size factor.

Equations, used to estimate the skid numbers at 20 mph from the values of pavement surface textures and aggregate sizes are given in the conclusions. Similar equations for total void areas are given to estimate the decrease in skid number from 20 to 60 mph.

IMPLEMENTATION

The results of this research stress the importance to driver safety of the microtextures and the small-scale macrotextures of aggregate particles exposed on pavement surfaces. These textures together with the macrotextures as measured by the Profilograph and the distribution of the aggregate size have a decided influence on the skid number measured by a locked-wheel trailer and hence on driver control. The results also show that low values of macrotextures are indicative of poor drainage from the tire-pavement interface. Low values of void areas result in large reductions in skid numbers as the skidding speed increases.

Some Texas pavement surfaces have sufficient macrotextures to provide decreases in skid numbers below ten percent; however, many of the pavement surfaces have low values of macrotexture. Certain types of aggregates retain the microtextures better than others. Hence, for prolonged high skid resistant pavements, maintenance efforts should be directed toward the construction of pavements with ample surface macrotexture and the coarse aggregates in these surfaces should wear or abrade in such a manner as to provide adequate microtexture.

KEY WORDS

Friction Coefficient, Brake-Slip Number, Skid Number, Cornering Slip Number, Stopping-Distance Number, Deceleration Coefficient, Macrotexture, Microtexture, Skid Number Decrease, Void Area, Water Drainage.

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INTRODUCTION

Improvements in highway design have permitted increased volumes of traffic at higher speeds on our highways. Unfortunately, the high volumes have also resulted in increased numbers of highway accidents. Many of the accidents on wet highways have been attributed to slippery conditions or lack of sufficient forces between tires and pavement to properly decelerate, corner, or accelerate the vehicles (1). Some of the factors that influence the forces between the tire and pavement are: 1) the design and composition of the tire, 2) the operating mode of the tire, 3) the pavement surface texture, and 4) the thickness of water film on the pavement (2). The effects of pavement surface texture on skid number have been investigated mainly by researchers of paving materials, highway design, highway construction, and highway safety to better understand the tire-pavement interactions.

Various methods have been developed to measure the texture of pavement surfaces, and efforts have been made to correlate the textural properties with the skid resistance parameters. The large-scale macroscopic texture which affects the value of the void area between the tire tread and pavement is reported to be related to the decrease in skid number as speed increased, while the small-scale macroscopic texture and the microscopic texture to a lesser extent are related to the skid number (3). The need for information relating the decrease in skid number and the void area for water drainage from the tire contact area seems logical. A high rate of water drainage means a low hydrodynamic lift pressure against the tire and better contact of the tire with the pavement surface. Thus, there is less opportunity for the tire to hydroplane on a pavement with good drainage than on a pavement with poor drainage (4).

This important relationship has been investigated on six different types of pavement surfaces (5). However, further investigation involving a broad range of types of pavement surfaces is needed to reinforce the correlation between skid number and macrotexture. Similarly, more data are needed to reinforce the correlation between skid numbers and a combination of small-scale macroscopic textures and microscopic textures.

Highway pavement surfaces must have the proper surface properties to provide sufficent friction forces during all operating modes of vehicle tires. The operating modes are the free-rolling, slipping, and the skidding modes. Sufficient friction forces under all operating modes will lead to fewer skidding accidents and to safer highways.

Various types of equipment and methods have been developed for measuring friction coefficients of highway pavements. The three most widely used field methods include the stopping-distance method, deceleration method, and the skid-trailer method. Information may be found on other skid measuring devices. In addition, various studies on the correlation of the skid testers have been conducted and advantages and disadvantages of the various methods have been noted (2, 3, 4).

The texture of a pavement surface can be characterized by a face profile consisting of a series of rather abrupt changes in elevation. Variations in textures can result from the different sizes of aggregates on the surface and from various pavement finishing operations. The textures resulting from construction can be altered by the effects of traffic wear and environmental factors. In general, the textures can be categorized into three groups (3): 1) large-scale macroscopic texture, 2) small-scale macroscopic texture, and 3) microscopic texture. The large-scale macroscopic texture describes the average spacing of the surface peaks and (neglecting internal drainage) determines, in large measure, the water drainage properties of the pavement surface. The small-scale macroscopic texture is the "grittiness" of the surface caused by cemented sand-sized particles or by sharp projections on the larger aggregates. This macroscopic texture largely determines the friction properties at any given speed (3). The microscopic texture, which also influences the friction properties, is the minute (microinch range) surface characteristic of aggregates. Accurate methods of measuring pavement surface textures and a knowledge of the effects of the macrotextures and microtextures would be helpful in determining the friction coefficients of pavement surfaces. One method of converting pavement surface texture to an equivalent skid number has been introduced by Schonfeld (26).

METHODS OF MEASURING TEXTURE

The literature search indicated that various agencies in this country and abroad are engaged in developing methods for measuring pavement surface textures. The interest stems from the theory that the surface texture is related to the skid resistance of a tire-pavement combination during braking, cornering, or acceleration of the vehicle. Detailed descriptions of surface texture measuring methods are found in the literature. Some of the methods described are results of developments in the wood and metal fabricating industries where the surface finishes of the products are very important. Descriptions of texture measuring methods pertinent to this work can be found in earlier reports (8, 9) associated with this study.

Related studies in the field of texture measuring methods will furnish valuable background for those interested in the details of this interesting subject (10...26); however, space limitations do not permit the inclusion of descriptive details.

EXPERIMENTAL PROGRAM

Skid Tests and Texture Measurements

An experimental program involving skid tests and texture measurements on six of the 36 highway pavement surfaces and on the five Research Annex test surfaces was conducted during the Spring of 1970. The purpose of the experiments was to determine the correlation between skid numbers and small-scale textures in terms of centerline average heights up to 0.001 inches and small-scale textures combined with macrotexture parameters. Descriptions of the test equipment, pavement surfaces, and the test procedures used in the experimental program are provided in the subsequent sections.

Test Equipment

The test equipment consisted of the THD research skid trailer, the Clevite Model BL-185 Surfindicator, the THD Profilograph, the modified sand apparatus, and the putty impression apparatus.

THD research skid trailer. The THD research skid trailer shown in Figure 1 conforms substantially to the requirements of ASTM E 274-65T. The test tire with four circumferential grooves, was designated as the standard E-17 tire. In addition, duplicate tests were conducted with a bald or smooth tread E-17 tire. The smooth tread condition was obtained by grinding the tread from the standard E-17 tire. All tests were conducted at 24-psi inflation pressure. A water film thickness of approximately 0.020-inch was applied by the self-watering system of the skid trailer to the pavement surfaces. Details of the development and calibration of the skid trailer can be found in a THD report (30).

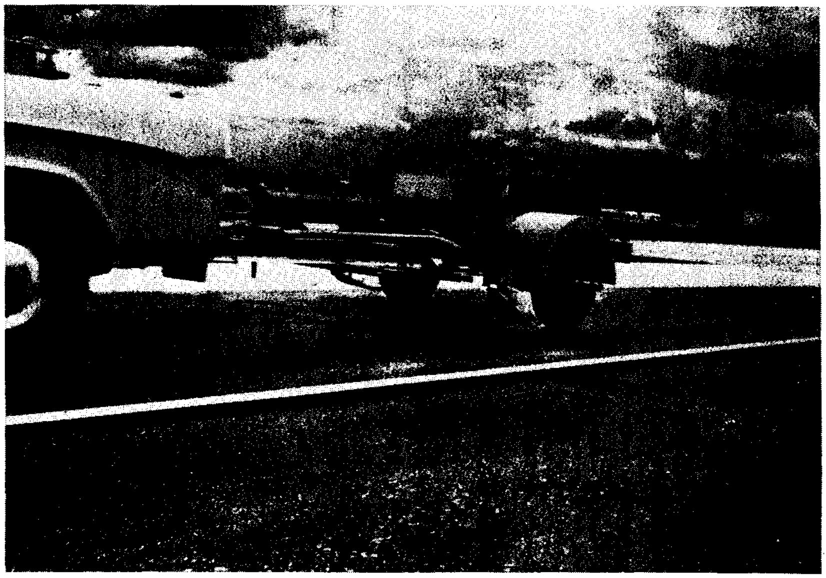

Figure 1. Texas Highway Department research skid trailer.

Figure 2. Celvite Model BL-185 Surfindicator.

Clevite Model BL-185 Surfindicator. A proprietary device called the Surfindicator (Figure 2) is an example of a stylus tracer method with an electrical system of transferring the stylus response to an averaging device. Various models of this device are manufactured by the Clevite Corporation, 4601 North Arden Drive, El Monte, California 91731. The device is generally used to measure the uniform textures of machined surfaces such as those on metallic products.

The Surfindicator Model BL-185 obtained by the Texas Highway Department was used in the experimental program described in the subsequent section. This model consists of a surface datum pickup with a stylus, some associated electronics, and a dial gauge for displaying the H_{CLA} or H_{RMS} readings from one to 1,000 microinches (16). The stylus has a conical diamond tip with a radius of 0.0005 inch. A maximum movement of the stylus of approximately 1/16-inch is permitted with respect to a shoe near the stylus. Thus, it appears that small-scale macrotextures as well as microtextures can be "sensed" by the stylus. The BL-185 is a potential-generating device, and consequently, a variation in readings is caused by changes in the speed of traversing the stylus. However, a limited compensation is provided in the electronics to minimize this variation (16). Three peak-to-peak spacing cutoffs of 0.003-, 0.010-, and 0.030-inch are provided for the purpose of accuracy of measurements. A setting on any one of these cutoffs eliminates the signals from the peak-to-peak spacings on the surface above the cutoff value. Thus, the setting of the device on the 0.030 inch takes into consideration signals from all peak-to-peak spacings on the surface up to a maximum of 0.030 inch.

In calibrating the Surfindicator, the procedure consists of providing a brief period of equipment warmup followed by zeroing and balancing and selecting a peak-to-peak spacing cutoff value (0.030 inch is generally used). A standard calibration block with a H_{CLA} value of 125 microinches is used to calibrate the device. The pickup with the stylus is moved by hand in a steady, oscillating motion on the surface of the block with a speed estimated to be from 1/8- to 1/4-inch per second. No mechanical means of measuring the traverse speed was available, and the operator had to rely on his judgement. Adjustment of the calibration screw is made until a reading of 125 microinches is displayed on the dial gauge, and a deliberate increase in the speed of tracing results in a minimum increase in the reading from the 125 microinches. In testing, the pickup is moved on the surface with the same steady motion and speed.

One change was made on the Surfindicator concerning the surface-datum pickup. The shoe adjacent to the stylus was removed, and a holder was fabricated so that the pickup will sense the texture from a true-datum line. The holder was merely a rectangular aluminum block with a hole drilled in one end and a slot machined from this hole to one side of the block. Both the hole and the slot were approximately 2 inches in length. When the pickup was inserted in the hole with the styles extending out of the slot, the tip of the stylus protruded 0.076 inches from the side of the holder.

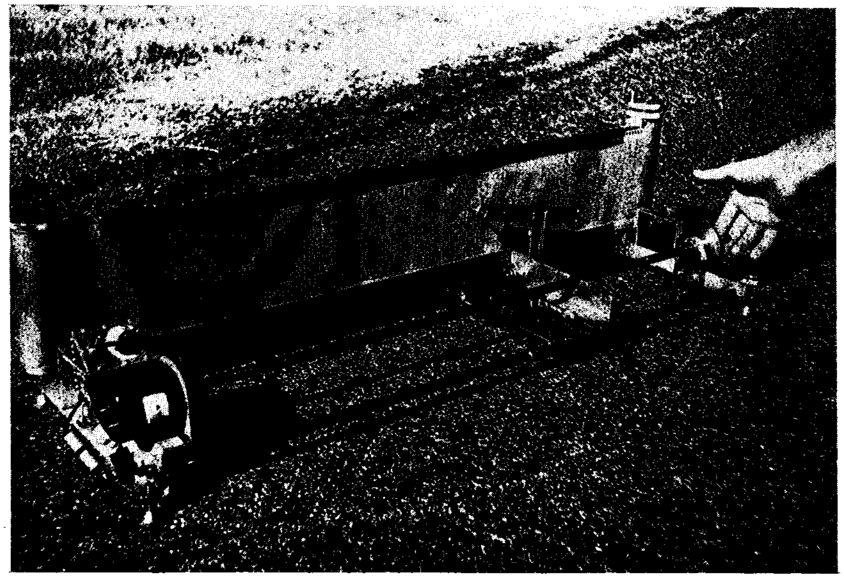

Figure 3. Texas Highway Department Profilograph.

Figure 4. Putty impression texture apparatus.

THD Profilograph. The Profilograph (Figure 3) developed by the Texas Highway Department is an example of stylus tracer method (13, 14) with a mechanical linkage system and a true-datum pickup (15). The mechanical linkage system magnifies the vertical movement of the stylus, and the resulting profile is recorded on a chart. In addition, the upward vertical excursions are recorded on a counter as the cumulative vertical peak heights of the surface texture through the length traversed by the stylus. A reading of 29 digits on this counter represents an inch of cumulative vertical movement of the stylus. The average peak height of the asperities in inches is obtained by dividing 29 times the number of peaks into the counter reading. A peak has been arbitrarily defined as any magnified asperity with a minimum height of 1/16-inch and a maximum base length of 1/4-inch or any multiple set of these dimensions. Any asperity with less than the minimum dimension is omitted.

Putty impression apparatus. The putty impression method (Figure 4) was initially developed as a means of providing surface texture correction factors for nuclear density measurements of asphalt concrete pavements (18). A 6-inch diameter by 1-inch thick metal plate and 15.90 grams of silicone putty, commonly called "Silly Putty", are the two items necessary in this method. One side of the metal plate has a 4-inch diameter by 1/16-inch deep recess.

The silicone putty is formed into an approximate sphere and is placed on the pavement surface. The recess in the plate is centered over the putty and the plate is pressed down in firm contact with the surface. An alternate method is to stick the sphere on the center of the recess in the plate and to press the plate firmly against the surface. When tested

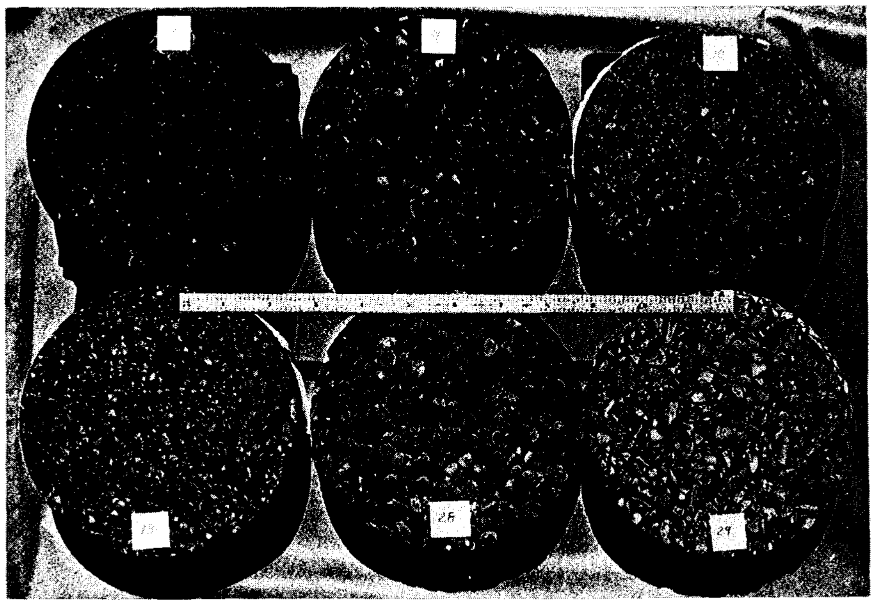

Figure 5. Surfaces of highway pavements.

on a smooth, flat surface that has no texture, the 15.90-gram sphere will completely fill the 4-inch by 1/16-inch recess. A decrease in the diameter of the putty is associated with an increase in the texture depth of the pavement surface. An average texture depth based on volume per unit area is determined from an average of four diameter measurements by

$$T_p = \frac{1}{D^2} - 0.0625$$

where

T_p = average texture depth, and

D = average diameter of the putty.

Pavement Surfaces

The highway pavement surface numbers 3, 4, 10, 13, 28, and 29 were selected from the list of 36 highway surfaces in the experimental program reported by Gallaway and Rose (9). These selections include surface courses and surface treatments with rounded gravels and crushed aggregates. Figure 5 shows the surfaces of cored specimens obtained from the pavement surfaces. The five experimental surfaces at the Research Annex were also included in the program; these surfaces were designated as T-1 thorugh T-5.

Test Section and Test Locations

A typical test section layout for each of the highway surfaces is shown in Figure 10 with some approximate dimensions. The purpose of selecting the test path as a diagonal across the highway was to obtain an indication of the differences in the skid number and the texture values among the OWP (outer wheel path), BWP (between wheel path), IWP (inner wheel path), and the centerline of the highway. These skid test locations were numbered as shown in Figure 6. A 6-inch core specimen was obtained from each location for texture measurements with the putty impression method and with the Clevite BL-185 Surfindicator.

For the Research Annex surfaces, the entire surface length of 600 feet was considered as the test section. The two rows of four test locations selected for the experimental program conducted in Summer of 1969 were used. Each test location, measuring approximately one foot by two feet, was appropriately marked off for the skid tests and for the Surfindicator measurements. No cores were obtained from these experimental surfaces.

Test Procedures

Skid Tests. In conducting the skid tests on the highway pavement section, the skid trailer was towed along the test path shown in Figure 6. The test wheel was locked and released for location 1 on the shoulder and locked again just before location 2 and not released until passing location 8. No excessive heating of the tire was observed. The same sequence in reverse order was followed for the other diagonal path. The self-watering system was used throughout the tests. Duplicate tests were conducted with the trailer going in the reverse direction. Test speeds of 20- and 40-mph with the standard E-17 test tire and with the smooth tread tire were used in the experiments. Thus, a total of eight tests were conducted on each of the test locations.

Skid tests on the Research Annex test sections were conducted in accordance with the procedure in ASTM E 274-65T. The test wheel was locked

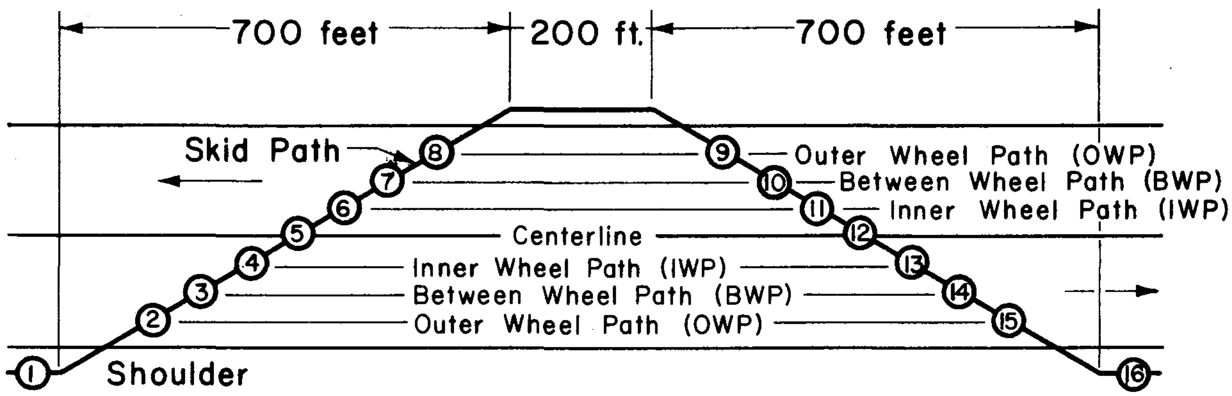

Figure 6. Skid test layout for highway pavement section.

separately at each of the eight test locations. Duplicate tests were conducted with the skid trailer going in the reverse direction. The test speeds, types of tire tread, and the total number of tests at a location were the same as for a highway test location.

Macrotexture measurements. Two macrotexture measurements of the pavement surfaces were obtained at each of the test locations with the THD Profilograph. In keeping with standard practice the Profilograph was oriented so that the traverse of the stylus would be in the direction of traffic and parallel to the centerline of the highway.

In testing a surface, the stylus assembly was placed in the proper position for testing, the counter was zeroed, and an unused section of the recording chart was rolled on the chart table. When the motor was started, the stylus assembly moved horizontally over a distance of approximately 28 inches. A magnified trace of the surface profile was recorded, and the total upward vertical excursion was displayed on the counter. No Profilograph measurements were made on the Research Annex surfaces. The values obtained during the previous experimental program and reported by Gallaway and Rose (9) were considered valid, since no traffic was applied on these surfaces to effect any appreciable changes in the macrotexture characteristics of the surfaces.

Macrotexture measurements determined by the putty impression method were taken on the surfaces of two of the four cores obtained from the OWP, BWP, and the IWP of a selected test section. One of the two cores from the highway centerline was selected for the measurement. The selection of the cores was made after careful observations and after testing to see if the test place rested evenly on the surface. In measuring the texture by the putty impression method, 15.90 grams of silicone putty was formed into a spherical shape and was adhered to the center of surface of the recess in the plate. The putty was squeezed by pressing the plate against the surface of the core. When the face of the plate contacted the surface of the core, the plate was removed. The average diameter determined from four diameter measurements was recorded.

Macrotexture data on the Research Annex surfaces were obtained from an earlier report by Gallaway and Rose (9).

Texture Measurements with Surfindicator. Texture measurements with the Clevite BL-185 Surfindicator were taken on the surfaces of all the 6-inch cores obtained from the highway pavement section, except those taken from the shoulders. After calibrating the Surfindicator as described previously, the pickup inserted in the holder was placed on the surface and was moved in a steady oscillating motion. The traversing speed was estimated to be from 1/8-inch to 1/4-inch per second, and the stroke was approximately 3/4-inch. An average H_{CLA} value from the dial gauge was read while moving the pickup. A total of 24 measurements was made on the surface of each core. The locations and directions of the 24 traverse lines were randomly selected. However, areas with large holes or other unusual surface features were not considered typical and were therefore avoided. An additional 12 measurements were taken on individual coarse aggregate particles, if such particles were exposed on the surface. For these additional measurements of the stroke of the stylus movement varied and was limited by the size of the exposed aggregates.

For the Research Annex surfaces, 12 surface measurements were obtained at each test location. Twelve additional measurements were taken on exposed aggregate particles of the surfaces.

Test Data

Table 1 shows the average skid numbers measured with the THD skid trailer using the E-17 tire and the smooth tread tire at speeds of 20- and 40 mph. The macrotexture data obtained with the Profilograph and the putty impression method together with the average Surfindicator textures are also shown in Table 1. Friction forces measured with the skid trailer were converted to skid numbers. Temperature corrections based on the work by Giles, Sabey, and Cardew (31) were applied to the skid numbers shown in Table 1. The average peak height was determined by following the procedure described previously for obtaining the Profilograph texture. The average diameter of the putty patch was used to determine the average texture depth for the putty impression method. Although the methods used in obtaining the Profilograph texture and the putty texture differ, the two results are comparable.

The Surfindicator texture values shown in Table 1 are averages of the dial readings in microinches. Some of the highway surfaces and Research Annex surfaces had no coarse aggregate particles exposed on the surfaces. Highway surface number 28, a farm-to-market road, had neither paved shoulders nor a distinguishable centerline. The stylus of the Surfindicator had a tendency to bind on the extremely rough surfaces of cores taken from the shoulders. Thus, no Surfindicator measurements were obtained on these surfaces.

TABLE 1

SKID NUMBER, SURFINDICATOR TEXTURE, MACROTEXTURE, AND AGGREGATE SIZE FACTORS FOR PAVEMENT SURFACES

Surface Number	Location	Skid Number: E-17 Tire 20 mph	Skid Number: E-17 Tire 40 mph	Skid Number: Smooth Tire 20 mph	Skid Number: Smooth Tire 40 mph	Surfindicator Texture (microinches): Surface	Surfindicator Texture (microinches): Aggregate	Macrotexture (inch): Profilograph	Macrotexture (inch): Putty Impression	Aggregate Size Factors: Top Size Factor (Inch)	Aggregate Size Factors: Weighted Particle-Size Factor (Inch)
	OWP	58.50	39.75	36.25	23.38	420.21	—	0.0000	0.0141		
3	BWP	52.75	39.75	37.13	24.13	437.40	—	0.0000	0.0194	.3750	.3111
	IWP	50.63	38.25	35.88	21.38	430.10	—	0.0345	0.0105		
	℄	59.25	47.00	44.25	30.50	438.33	—	0.0000	0.0117		
	OWP	38.75	29.50	33.88	23.50	363.44	136.15	0.0851	0.0288		
4	BWP	41.75	32.13	36.75	25.25	363.75	133.85	0.1409	0.0215	.5000	.3441
	IWP	38.75	29.50	34.38	22.38	360.78	127.29	0.0663	0.0479		
	℄	46.50	34.75	41.50	26.50	373.13	143.54	0.0865	0.0505		
	OWP	41.88	31.25	36.25	21.00	380.21	129.17	0.0894	0.0338		
10	BWP	43.50	31.75	38.63	19.25	373.54	126.46	0.0618	0.0207	.3750	.2640
	IWP	43.25	32.75	38.63	20.38	372.55	118.13	0.0666	0.0208		
	℄	55.75	41.50	53.00	29.50	371.67	135.42	0.0829	0.0216		
	OWP	67.55	50.75	61.63	43.38	433.96	228.13	0.0589	0.0223		
13	BWP	68.00	50.25	62.25	45.50	437.50	217.92	0.0238	0.0146	.3759	.2496
	IWP	70.75	52.00	59.38	43.63	436.02	228.96	0.0376	0.0278		
	℄	73.00	56.75	70.25	46.75	436.04	236.25	0.0858	0.0296		
	OWP	43.50	40.88	41.50	37.88	302.08	128.13	0.0904	0.0786		
28	BWP	41.13	40.00	38.38	34.75	311.88	118.33	0.0774	0.0667	.5000	.5000
	IWP	35.25	32.75	37.00	30.50	307.71	120.21	0.0613	0.0950		
	OWP	42.00	65.75	39.50	31.25	335.52	178.96	0.0506	0.0375		
29	BWP	45.75	41.38	42.63	36.88	356.15	190.52	0.0619	0.0548	.5000	.5000
	IWP	44.63	39.00	40.13	32.75	345.10	177.50	0.0539	0.0466		
	℄	59.50	57.00	52.75	46.50	348.13	188.96	0.0683	0.0854		
T-1	—	52.38	50.88	51.94	39.44	435.104	128.26	0.0235	0.0224	.6250	.2635
T-2	—	63.63	56.90	59.63	46.56	428.020	141.98	0.0195	0.0235	.2500	.1907
T-3	—	72.31	69.25	74.44	49.88	355.00	118.85	0.0149	0.0093	.5000	.2714
T-4	—	29.38	20.19	28.25	14.69	215.42	—	0.0136	0.0019	.7700	.7700
T-5	—	56.19	46.19	48.44	35.44	450.10	—	0.0203	0.0203	.6250	.2315

Aggregate Size Factors

Since pavement surface textures are partly affected by the variation in sizes of aggregates, factors relating to aggregates were considered in the correlation analyses subsequently described. Two aggregate size factors were considered for the aggregates used either in the pavement mixes for asphalt concrete surface courses or in the asphalt surface treatments; these are the top size factor and the weighted particle-size factor. The first factor is merely the maximum size of the aggregate as determined by a sieve analysis. The second factor is the sum of the product of the top sizes in the different aggregate fractions such as coarse, medium, and fine and the corresponding percentages by weight of the fractions in the aggregate.

Information to determine these factors for the various pavement surfaces was obtained from previous reports (9, 27). The top sizes of 0.250 inch, 0.0787 inch, and 0.0165 inch were used for the medium, fine, and the field sand fractions respectively. For the bituminous surface number T-4 with no aggregates exposed on the surface, a value of 0.77 inches was used in place of both the top size factor and the weighted particle-size factor. This value corresponds to the width of the ribs on the standard E-17 test tire. For the portland cement concrete surface number T-5, a value of 0.625 inches was used as a maximum finish factor in place of the top size factor, and a weighted finish factor of 0.200 inches was used in place of the weighted particle-size factor. These changes were made because no coarse aggregate particles were exposed on T-5 surface. However, some textures resulting from the finishing operation were observed. The fine aggregate fraction was assumed to be 40 percent with a top size of 0.078 inches, providing 0.032 inches to the weighted finish factor.

All values of the aggregate size factors for the six highway pavement surfaces and for the five Research Annex surfaces are shown in Table 1 together with the other data obtained from the experimental program.

Regression Analyses

The average skid numbers, surface textures, and aggregate size factors shown in Table 1 were analyzed by using a multiple regression analysis programmed for computation on an IBM 360/65 computer. In the analyses, the skid numbers were considered as the dependent variables and the Surfindicator textures, macrotextures, and the aggregate size factors as the independent variables. The following regression analyses with the relationships in the arithmetic, semilogarithmic and in the logarithmic forms were conducted:

Analysis 1. The regression of the four sets of skid numbers shown in Table 1 on the Surfindicator texture measured on the surfaces (t_s) or on the aggregates (t_a),

Analysis 2. The regression of the set of skid numbers providing the highest correlation coefficients in Analysis 1 on the Surfindicator texture, t_s or t_a, and on the macrotexture measured either by the Profilograph (T_{pro}) or by the putty impression method (T_p);

Analysis 3. The regression of the same set of skid numbers used in Analysis 2 on the Surfindicator texture, t_s or t_a, top size factor (TS), and on the weighted particle-size factor (WPS); and

Analysis 4. The regression of the same set of skid numbers used in Analysis 2 on the Surfindicator texture, t_s and t_a, macrotexture, T_{pro} or T_p, top size factor (TS), and on the weighted particle-size factor (WPS).

Results of Analyses

Tables 2 through 5 show the correlation coefficients determined in Analyses 1 through 4 respectively. As shown in Table 1, the OWP, BWP, and the centerline of highway surface number 3 had macrotextures of zero measured by the Profilograph, and these three locations were not considered

TABLE 2

CORRELATION COEFFICIENTS FOR SKID NUMBER-SURFINDICATOR TEXTURE RELATIONSHIPS

(ANALYSIS 1)

Surfindicator Texture	Skid Number				Log Skid Number			
	E-17 Tire		Smooth Tire		E-17 Tire		Smooth Tire	
	20 mph	40 mph	20 mph	40 mph	20 mph	40 mph	20 mph	40 mph
t_s*	0.693	0.395	0.463	0.314	0.743	0.489	0.506	0.346
Log t_s	0.677	0.407	0.458	0.322	0.736	0.509	0.507	0.364
t_a*	0.636	0.462	0.531	0.563	0.631	0.505	0.551	0.564
Log t_a	0.610	0.460	0.503	0.550	0.609	0.503	0.525	0.554

*t_s = Surfindicator texture measured on the surfaces.
t_a = Surfindicator texture measured on the aggregates.

TABLE 3

CORRELATION COEFFICIENTS FOR SKID NUMBER - SURFINDICATOR TEXTURE AND MACROTEXTURE RELATIONSHIPS (ANALYSIS 2)

Skid Number	t_s T_{pro}	Log T_s Log T_{pro}	t_a T_{pro}*	Log t_a Log T_{pro}
SN_{E20}*	0.737	0.746	0.741	0.791
Log SN_{E20}	0.770	0.779	0.736	0.789
Skid Number	t_s T_p*	Log t_s Log T_p	t_a T_p	Log t_a Log T_p
SN_{E20}	0.693	0.693	0.734	0.787
Log SN_{E20}	0.744	0.742	0.734	0.787

*T_{pro} = average peak height obtained from Profilograph measurement.

T_p = average texture depth obtained from putty impression method.

SN_{E20} = skid number measured with E-17 tire skidding at 20 mph.

TABLE 4

CORRELATION COEFFICIENTS FOR SKID NUMBER - SURFINDICATOR TEXTURE AND AGGREGATE SIZE FACTOR RELATIONSHIPS (ANALYSIS 3)

Skid Number	t_s (TS)* (WPS)*	Log t_s Log (TS) Log (WPS)	t_a (TS) (WPS)	Log t_a Log (TS) Log (WPS)
SN_{E20}	0.699	0.694	0.803	0.811
Log SN_{E20}	0.750	0.746	0.799	0.810

*TS = top size factor.
WPS = weighted particle size factor.

TABLE 5

CORRELATION COEFFICIENTS FOR SKID NUMBER - SURFINDICATOR TEXTURE, MACROTEXTURE, AND AGGREGATE SIZE FACTOR RELATIONSHIPS (ANALYSIS 4)

Skid Number	t_s; T_{pro}; (TS); (WPS)	Log t_s; Log T_{pro}; Log (TS); Log (WPS)	t_a; T_{pro}; (TS); (WPS)	Log t_a; Log T_{pro}; Log (TS); Log (WPS)
SN_{E20}	0.759	0.768	0.847	0.869
Log SN_{E20}	0.790	0.798	0.843	0.868
Skid Number	t_s; T_p; (TS); (WPS)	Log t_s; Log T_p; Log (TS); Log (WPS)	t_a; T_p; (TS); (WPS)	Log t_a; Log T_p; Log (TS); Log (WPS)
SN_{E20}	0.699	0.703	0.806	0.818
Log SN_{E20}	0.750	0.749	0.801	0.818

in any of the analyses involving the Profilograph texture.

Discussion of Analyzed Results

Skid Number - Surfindicator Texture Relationships

As shown in Table 2, the correlation coefficients, R, or the linear associations between the skid numbers and the Surfindicator textures are not very high. The highest R value of 0.743 was obtained from the regression of the logarithm of the skid number measured with the E-17 tire at the speed of 20 mph, with the Surfindicator texture measured on the surfaces, t_s. The highest R value involving the Surfindicator texture measured on the aggregates, t_a, is 0.636. This value results when SN_{E20} is arithmetically related to t_a and is lower by 0.017 than the 0.743 for the semilogarithmic relationship involving t_s. The fact that the highest R values are obtained with SN_{E20} seems logical. Since the E-17 tire has grooves that provide passages for the escape of water applied by the self-watering system, there is a lower hydrodynamic lift pressure at the speed of 20 mph than at the speed of 40 mph. Thus, it is indicated that the E-17 tire has a better contact with the pavement and a better "feel" of the surface textures at 20 mph.

A value of R = 0.685 was reported for the regression of SN_{E40} on t_s (8). This value was based on some preliminary measurements. The corresponding value of R in Table 2 is 0.395 which is much lower than 0.685. There appears to be reasonable explanation for the difference in the values, except that nine of the 11 surfaces in the preliminary investigation were constructed with hot-mix asphalt concrete. Four of the 11 hot-mixes had the same type of coarse aggregate. The surfaces in the experimental program of this research included hot-mix surfaces as well as surface treatments using rounded gravels and crushed aggregate. Possibly, there are textures of some surfaces that the Surfindicator cannot adequately measure. Thus, a considerable scatter of the data may be present for a variety of surface types.

Approximate values of $100R^2$ corresponding to the highest R values from Table 2 are 55 and 40. These values indicate the percentages of the variation in SN_{E20} accounted by the differences in t_s and t_a, respectively. The low R^2 values indicate that the entire effect of the surface texture cannot be obtained or be measured by the Surfindicator, and that other factors in addition to t_s or t_a may be associated with SN_{E20}. Since pavement surfaces have nonumiform textures, and the Surfindicator is sensitive to variations in the speed of stylus movement, even though partial compensation for the sensitivity is provided for in the instrument, some measurement errors are unavoidable. The effects of these factors can be observed by the fluctuating needle on the dial gauge. For some surfaces tested, the range of fluctuation was over 100 microinches, and it was difficult to obtain average values estimated from the readings indicated by the fluctuating needle. Readings permanently recorded on a chart would be a definite improvement in the Surfindicator.

The possibilities of other factors in addition to t_s or t_a being associated with SN_{E20} are discussed in the subsequent sections. These factors, the macrotextures, and the aggregate size factors, are included separately and together as independent variables along with t_s and t_a.

Surfindicator Textures and Macrotextures

In Analysis 2, the correlation of SN_{E20} on the Surfindicator textures, t_s or t_a, and on macrotextures, T_{pro} or T_p, were determined by multiple regression analyses. The resulting R values are shown in Table 3. A comparison of the R values in Table 3 and those in Table 2 shows, in general, that the R values are increased when the macrotextures are included as independent variables with the Surfindicator textures. Greater increases result by including T_{pro} than by including T_p as one of the independent variables. Greater increases are also associated with t_a rather than t_s as one of the independent variables. Thus it logically follows that the highest R values are obtained with t_a and T_{pro} as the independent variables, and the lowest R values are obtained with t_s and T_p as the independent variables.

Surfindicator Textures and Aggregate Size Factors

In Analysis 3, SN_{E20} was correlated with the Surfindicator textures and the aggregate size factors as the independent variables. As previously discussed, the aggregate size factors include the top size factor (TS) and the weighted particle-size factor (WPS). The resulting R values are shown in Table 4. A comparison of the R values in Table 4 with those in Table 2 shows, in general, that the R values increase when the aggregate size factors are included as independent variables with the Surfindicator textures. Higher R values ard obtained with the aggregate size factors and t_a as the independent variables than with the aggregate size factors and t_s as the independent variables.

Surfindicator Textures, Macrotextures, and Aggregate Size Factors

The R values shown in Table 5 are the results of Analysis 4 which is a combination of Analysis 2 and Analysis 3. As shown in Table 5, the regression of SN_{E20} with the highest R values involves t_a and T_{pro} as two of the four independent variables, followed by the regressions with t_a and T_p, t_s and T_{pro}, and with t_s and T_p. This ranking seems to follow the findings from Analyses 2 and 3 discussed previously. In general, the results shown in Table 5 are higher when compared to those in Table 4 or in Table 3.

Only the relationship with t_s, T_p, (TS), and (WPS) as independent variables show no increase in R values over the relationships with t_s, (TS), and (WPS) as independent variables in Analysis 3.

Selection of Independent Variables

Step Down Method

As shown by the results of Analyses 2, 3, and 4, the consideration of the macrotextures and aggregate size factor as independent variables along with the Surfindicator textures in multiple regression analyses has resulted in increasing R values over those obtained by the simple regressions of SN_{E20} on the Surfindicator textures. However, multiple regressions on every combination of the four independent variables were not conducted to determine the contribution of each independent variable. Perhaps one or two of these independent variables may contribute little or nothing to the basic relationships and may be eliminated without much sacrifice in the R value. The problem of determining the variables of importance may be approached by the step down method (29). In this method, the regression of SN_{E20} on all of the independent variable is determined (Analysis 4). The variable contributing the least to the relationship is eliminated if its contribution is below a preselected level, and the regression on the remaining independent variables is determined. The process is continued until no variable qualifies for elimination.

The step down method was applied to the relationships in Analysis 4 with the elimination of the independent variables based on the ten percent significance level of the Student-t values. This significance level was merely based on the decision that an independent variable should not be in the relationship by chance more than one out of ten times. Use of the t test is justified, since the difference between the sample coefficient and population coefficient for an independent variable devided by standard error of the sample coefficient is distributed as the Student t (29). Thus, the null hypothesis that the population coefficient is zero can be tested by the t test. The t test and the test of significance for the R values used previously are identical (29).

<u>Results of Step Down Method</u>

Tables 6 and 7 show the significant independent variables, the significance levels of the t values associated with the coefficients, and the R values resulting from the regressions on the significant independent variables. Only two forms of each relationship shown in Table 5 were considered in the step down method. As discussed previously, the independent variables with significance levels of 10 percent or more were eliminated by the step down method.

<u>Discussion of Results</u>

As shown in Table 6, the Surfindicator texture measured on the surface, t_s, and the macrotexture measured with the Profilograph, T_{pro}, are the significant independent variables in the relationships shown. The macrotexture measured with the putty impression method, T_p, and the aggregate size factors, TS and WPS, are not significant at the 10 percent significance level. As shown in Table 6, the significance level of T_{pro} is approximately 8.5 percent for the log-log form of the relationship, but evidently higher than 10 percent for the semilogarithmic form. However, the significance level of t_s are very good.

A comparison of the R values in Table 6 with those in Table 5 for the relationships involving t_s as an independent variable shows only small differences in the R values. The largest difference is 0.037. Thus, it appears that the independent variables, T_p, TS, and WPS add very little to the linear association established by t_s or by t_s and T_{pro} and need not be

TABLE 6

SIGNIFICANT INDEPENDENT VARIABLES SELECTED BY STEP DOWN METHOD
(SURFINDICATOR TEXTURE MEASURED ON SURFACES)

Relationship	Significant Independent Variables	Significance Levels of t Values (Percent)	R Values
Log SN_{E20} with: t_s, T_{pro}, (TS), (WPS)	t_s	0.0014	0.753
Log SN_{E20} with: t_s, Log T_{pro}, Log (TS), Log (WPS)	Log t_s Log T_{pro}	0.0016 8.5399	0.779
Log SN_{E20} with: t_s, T_p, (TS), (WPS)	t_s	0.0006	0.743
Log SN_{E20} with: Log t_s, Log T_p, Log (TS), Log (WPS)	Log t_s	0.0008	0.736

TABLE 7

SIGNIFICANT INDEPENDENT VARIABLES SELECTED BY STEP DOWN METHOD
(SURFINDICATOR TEXTURE MEASURED ON AGGREGATES)

Relationship	Significant Independent Variables	Significance Levels of t Values (Percent)	R Values
SN_{E20} with: Log t_a, Log T_{pro}, Log (TS), Log (WPS)	Log t_a Log T_{pro} Log (WPS)	0.0209 1.3425 0.6718	0.868
Log SN_{E20} with: Log t_a, Log T_{pro}, Log (TS), Log (WPS)	Log t_a Log T_{pro} Log (WPS)	0.0222 1.4488 0.6697	0.867
SN_{E20} with: Log t_a, Log T_p, Log (TS), Log (WPS)	Log t_a Log (WPS)	0.0555 0.0968	0.807
Log SN_{E20} with: Log t_a, Log T_p, Log (TS), Log (WPS)	Log t_a Log (WPS)	0.0568 0.0962	0.807

considered in the final relationships. The two relationships shown in Table 6 with t_s as the independent variable but with different R values resulted from the difference in the number of observations.

For the relationships shown in Table 7, the Surfindicator texture measured on the aggregates, t_a and WPS are the significant independent variables. T_{pro} is also significant, but T_p is not significant. The significance levels are better than two percent for T_{pro}, better than one percent for WPS and are better than 0.1 percent for t_a. These values indicate that the variables contribute significantly to the measure of the linear association with SN_{E20}.

A comparison of the R values in Table 7 with those in Table 5 for the relationships involving t_s as an independent variable shows only slight difference in the R values. The largest difference is 0.011. Thus the nonsignificant independent variables, TS and T_p, add very little to the linear association established by the significant independent variables and should not be considered in the final relationships. Since the R values shown in Table 7 are nearly identical for the two forms of each relationship, either form may be used.

Tentative Relationships

Based on the variable selection by the step down method, some tentative relationships for estimating SN_{E20} are given together with the values of R, R^2, and MSD in the subsequent paragraphs. The relationships are considered as tentative relationships, since additional research may uncover other variables related to SN_{E20} or improvements in the method of measuring textures may improve the relationships.

The average result of the Surfindicator texture measured on the surface, t_s, of a pavement can be used to estimate SN_{E20} by

$$SN_{E20} = 14.159(1.003)^{t_s} \tag{2}$$

$$R = 0.753$$

$$R^2 = 0.567$$

$$MSD = 0.072$$

If the Profilograph texture, T_{pro}, is obtained in addition to t_s, the SN_{E20} can be estimated by

$$SN_{E20} = 0.053 t_s^{1.109} T_{pro}^{-0.093} \tag{3}$$

$$R = 0.779$$

$$R^2 = 0.607$$

$$MSD = 0.070$$

It should be noted that the introduction of T_{pro} does not increase the R value much over the R value obtained by Equation 2.

When the Surfindicator textures of exposed coarse aggregate particles, t_a, are measured, the average result together with the value of the weighted particle-size factor (WPS) can be used to estimate SN_{E20} by

$$SN_{E20} = 2.128 t_a^{0.542} (WPS)^{-0.393} \tag{4}$$

$$R = 0.807$$

$$R^2 = 0.651$$

$$MSD = 0.063$$

The average result of the Profilograph textures, T_{pro}, can be considered together with t_a and WPS to estimate SN_{E20} by

$$SN_{E20} = 1.725 t_a^{0.523} T_{pro}^{-0.144} (WPS)^{-0.291} \tag{5}$$

$$R = 0.867$$

$$R^2 = 0.752$$

$$MSD = 0.055$$

Equations 2 through 5 show that estimates of SN_{E20} can be made incorporating one, two, or three independent variables. For pavement surfaces without coarse aggregate particles, only t_s can be measured with the Surfindicator, and Equation 2 or Equation 3, if T_{pro} is measured, may be used in the estimation of SN_{E20}. The R^2 values for these equations indicate that 57 percent of the variation in SN_{E20} is accounted by the changes in t_s and 61 percent for t_s and T_{pro}. It is possible that another factor not considered in this experimental investigation may be a significant independent variable in the relationships.

For pavement surfaces with exposed coarse-aggregate particles, t_a should be measured and WPS should be determined to estimate SN_{E20} from Equation 4. In addition, T_{pro} should also be measured to estimate SN_{E20} from Equation 5. The R^2 value for Equation 5 appears to be higher than that for Equation 4. Thus, Equation 5 should be used in preference to Equation 4.

CONCLUSIONS

The results of regression analyses of skid numbers versus small-scale pavement surface textures indicate that the 20 mph skid numbers measured with a standard ASTM E 274-65T skid trailer equipped with a standard E-17 tire provide the highest correlation coefficients. Skid numbers measured with the E-17 tire at 40 mph, and skid numbers measured with a smooth tread tire at 20 mph or 40 mph provide lower correlation coefficient. The small-scale textures on the surfaces or on exposed aggregate particles in terms of centerline average heights can be measured with the Clevite BL-185 Surfindicator. The correlation coefficients for the SN_{E20} - Surfindicator texture relationships are statistically significant at the one percent level. However, the coefficients are not very high.

The correlation coefficients for the SN_{E20}- Surfindicator texture relationships increase when macrotextures and aggregate size factors are considered with the Surfindicator textures as independent variables in multiple regression analyses. The macrotextures include the average peak height obtained from the Texas Highway Department Profilograph and the average texture depth obtained from the putty impression method. The aggregate size factors include the top size factor (the maximum size of the aggregate) and the weighted particle-size factor defined as the sum of the products of the top size in each aggregate fraction and the percentage of each aggregate fraction by weight in the total aggregate. Of the four additional independent variables, the Profilograph texture is the only significant variable in the relationship involving the Surfindicator texture measured on the surface. However, the Profilograph texture and the weighted particle-size factor are significant factors in the relationship involving the Surfindicator texture measured on the aggregate particles.

Estimates of SN_{E20} as measured with a standard locked-wheel skid trailer, may be made from tentative empirical equations by using the average results of: (1) the Surfindicator textures taken on the surface and the Profilograph textures, or (2) the Surfindicator textures taken on exposed aggregates, Profilograph textures, and the weighted particle-size factor. The tentative equations are:

1. $SN_{E20} = 0.053t_s^{1.109} \; T_{pro}^{-0.093}$

2. $SN_{E20} = 1/.725t_a^{0.523} \; T_{pro}^{-.0144} \; (WPS)^{-0.291}$

where

SN_{E20} = skid number measured with the E-17 tire and at the speed of 20 mph,

t_s = Surfindicator texture measured on the surfaces,

t_a = Surfindicator texture measured on exposed aggregate particles,

T_{pro} = Profilograph texture, and

WPS = weighted particle-size factor.

The percent decrease in skid number caused by an increase in the skidding speed from 20 to 60 mph, G, may be estimated by any one of the following empirical equations:

1. $G = 223.748 \; (0.002369)^{A_V}$
2. $G = 146.304 \; (0.002569)^{A_V}$
3. $G = 79.106 \; (0.046095)^{A_V}$
4. $G = 118.518 \; (0.011774)^{A_V}$

where

G = percent decrease in skid number, and

A_V = total void area that includes the void area of the tire grooves and the pavement surface void area.

The surface void area is determined from the Profilograph texture, Texturemeter texture, modified sand-patch texture or the putty impression texture for the first, second, third, and the fourth equation, respectively.

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