Skid tests on contaminated and cleaned sections of pavement also verified these results.

Particles smaller than 7 µm appear to have no significant effect on the SN_0 values for the surfaces used in this study. A collection system that separates particles out in stages from 10 µm to 500 µm would be more useful in determining relationships between SN_0 and dust loadings.

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Recent Developments in Pavement Texture Research

G. G. BALMER AND R. R. HEGMON

This paper summarizes the state of the art of research on pavement texture, which has intensified during the last few years. The importance of texture for increased safety on wet roads has been established. The distinct contributions of microtexture and macrotexture to friction between tire and pavement are shown, and methods being developed for providing and maintaining adequate texture are discussed. Research now in progress both on improving methods of texture measurement and on developing models for predicting skid resistance and gradients of skid resistance and speed from texture measurements is described.

Effective pavement texture is essential for safer wet-weather highway travel. The fine features (microtexture) furnish a gritty surface to penetrate the thin water films and produce skid resistance through good adhesion between the tire and pavement surfaces. The coarse features (macrotexture) provide drainage channels for water expulsion between the tire and the roadway. This allows better tire contact with the pavement to improve skid resistance and mitigate hydroplaning (1,2). It yields a flatter gradient of wet-pavement skid resistance and speed that helps sustain good friction for high-speed traffic, because the water can escape faster through a coarser texture. A knobby or coarse-textured surface also causes larger rubber deformations, which result in hysteresis losses in the tire. These increase the tire friction characteristics.

Furthermore, it has been shown that the wet-pavement accident rate decreases as skid resistance increases (3). Thus, effective pavement texture is an important factor in traffic safety.

TEXTURE CLASSES AND FUNCTIONS

The fine features of a pavement surface are distinguished from the coarse features because of the different influences of these parameters on interactions between tire and pavement.

The microtexture contributes to skid resistance at all speeds, and it is the prevailing influence at speeds less than 50 km/h (31 miles/h). In contrast, the macrotexture is less important at low speeds, but a coarse macrotexture is essential for safer high-speed travel on wet pavements. Average texture depths of 0.5 mm (0.02 in) and less can be classified as microtexture and those larger as macrotexture.

TEXTURE CHARACTERISTICS

The pavement microtexture develops skid resistance through adhesion between the tire and the roadway. The sharp, fine particles (asperities) in the surface penetrate the thin water films and thus permit an intimate contact between the tire and the roadway. Microtexture depends largely on the mineral composition and the rugosity of the aggregates. The fine, hard grains in the coarse aggregates or fine aggregates bonded in the surface of the pavement provide the microtexture.

Ideally, aggregates for bituminous concrete should be composed of hard, coarse, angular minerals well bonded into a softer matrix so that gradual differential wear will occur (4).

Pavement macrotexture can be obtained by controlling the gradation (5,6) of the surface aggregates in a bituminous mixture such as the open-graded asphalt friction course. The surface aggregates must not polish readily if enduring skid resistance is to be maintained. Figure 1 (from the Texas Transportation Institute) is a photograph of a newly placed open-graded asphalt friction course. The coarse texture is visible in the foreground. Chip-seal surface treatments also produce a coarse macrotexture; however, these surfaces have a limited life because of the rapid erosion of the surface aggregates by traffic and weathering.

The macrotexture for portland cement concrete (PCC) pavement is produced by the finishing techniques (1). Excellent texture can be obtained by using steel tines (Figure 2). (Figures 2-4 are from experimentation by the Georgia State Department of Transportation.) In this photograph alternate tines have been bent upward to increase the spacing between tines. Steel tines (rakes or combs, as they are sometimes called) can be incorporated into the paving train to produce striations in the plastic

Figure 1. Open-graded asphalt friction course.

Figure 2. Steel tines.

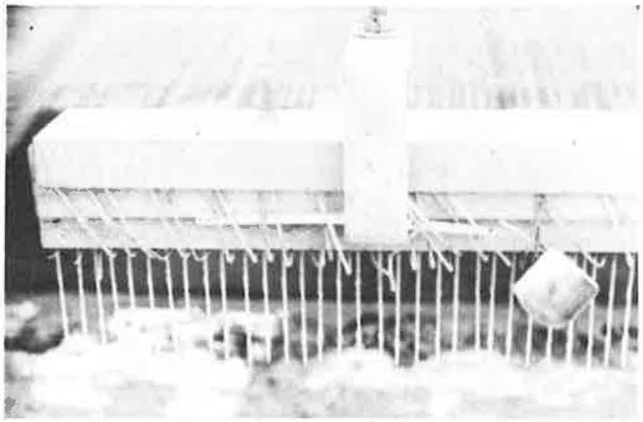


Figure 3. Typical tine-finished surface.

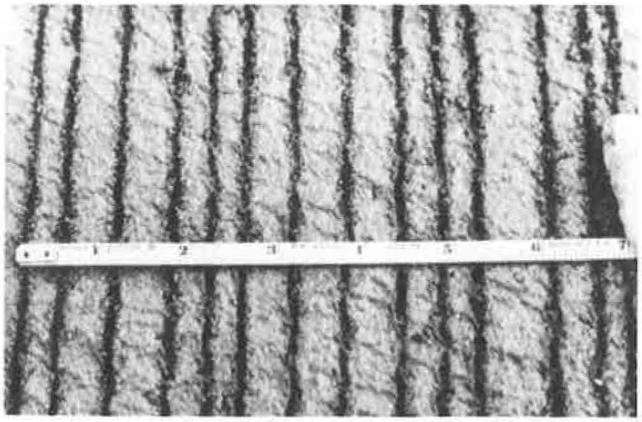
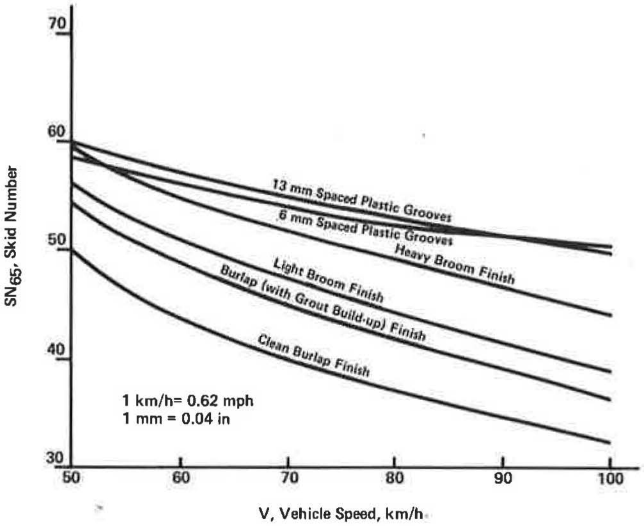


Figure 4. Gradient curves.



concrete. Figure 3 shows a typical tine-finished surface. The vibrating float developed in England (7) will also provide deep channels for surface water drainage. In the past, coarse brooms have been used for finishing PCC pavements, but such textures are usually not so good as the tine-finished textures.

In the photointerpretation method, developed by Schonfeld (6), texture is described by six parameters that are visually determined from sets of stereophotographs; for macrotexture of projections, the parameters are (a) height, (b) width, (c) angularity, and (d) density; for microtexture, they are (e) harshness, and (f) background harshness. A guide for the application of this method has recently been published (8).

GRADIENT

It is well known that the wet-pavement skid resistance decreases as vehicle speed increases (Figure 4). This is because the water has less time to escape from the contact areas between the tire and the road as the speed increases. Note that the skid numbers (SNs) are larger and the slopes flatter for the deep-finished surfaces (which have more space for water expulsion) than for the shallow-finished pavements. The former are the tine-finished surfaces labeled "spaced plastic grooves" in Figure 4.

Because of the wet-pavement surface, the friction-speed curve has a negative slope or a positive gradient as defined in the following equation:

$$G = -[d(SN)/dV] \qquad (1)$$

where G is the gradient of skid resistance and speed and [d(SN)/dV] is the derivative of the SN with respect to vehicle speed (V) or the slope of the friction-speed curve at speed V. The gradient is greatly dependent on the macrotexture. A coarse macrotexture yields a flatter or better gradient.

Skid-resistance tests at one speed can be used to approximate the skid number (SN_V) for another speed (V), provided the gradient is known or can be determined. If one of the test speeds is 65 km/h (40 miles/h), SN_V can be computed from

Table 1. Values of SN_{65} computed from texture parameters.

	D (mm)							
BPN	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
30	7	8	8	8	9	9	9	9
40	16	18	19	20	20	20	21	21
50	25	28	30	31	32	32	33	33
60	34	39	41	42	43	44	44	45
70	44	49	52	53	55	55	56	57
80	53	59	63	65	66	67	68	69
90	62	70	74	76	78	79	80	81

$$SN_V = SN_{65} - (V - 65)G \tag{2}$$

Equation 2 can be generalized to determine the skid resistance from other test speeds. The accuracy of prediction decreases as the speed difference increases, because gradients are dependent on speed.

GRADIENT OF PERCENT-NORMALIZED SKID RESISTANCE AND SPEED

Research (4,9,10) has shown that the gradient not only is a function of macrotexture, but it also depends on the level of skid resistance. This led to the concept of the gradient of percent-normalized skid resistance and speed (PNG_V), defined for a particular speed (V) as

$$PNG_V = -(100/SN_V)[d(SN)/dV]_V \tag{3}$$

Equation 3 is the exact expression for the PNG, but it can be used only if an analytical relation between the SN and the speed has been established.

If the skid resistance is measured at two speeds (V_1 and V_2), PNG can be computed approximately from the following:

$$PNG_V = -\left\{100(SN_2 - SN_1)/[(V_2 - V_1)(SN_2 + SN_1)/2\right\} \tag{4}$$

MODELS FOR FRICTION-SPEED CURVE AND PNG

Several models have been suggested to empirically represent the friction-speed curve. Leu and Henry (11) fitted the following exponential equation to skid-resistance speed data:

$$SN = p \exp(qV) \tag{5}$$

where p and q are constants, and exp is the base of natural logarithms. The constants in Equation 5 can be determined by as few as two points from the relationship between skid resistance and speed. If Equation 3 is applied to this model, it is found that

$$PNG = 100q \tag{6}$$

where q is a constant and thus independent of speed.

Other models have been proposed; however, none has been sufficiently validated.

MODEL FOR SKID RESISTANCE

The microtexture and macrotexture can be separated and combined in the model for skid resistance:

$$SN_V = SN_0 \exp[-(PNG/100)V] \tag{7}$$

where

SN_0 = intercept between SN and zero speed (a function of the microtexture),

PNG = percent-normalized gradient (a function of the macrotexture), and

V = speed selected for predicting SN_V.

A more-general form of the equation is

$$SN_V = SN_R \exp\left\{-[(PNG/100)(V - R)]\right\} \tag{8}$$

where R is any particular speed.

Skid tests (ASTM E274) and texture measurements (9,10) were conducted on 20 bituminous test pavements in West Virginia. Several techniques were used to measure pavement texture, and the data were analyzed from different approaches.

When British pendulum tests (ASTM E303) were conducted and a least-squares analysis was computed on the test data, the following equation was obtained:

$$SN_0 = 1.38BPN - 31 \tag{9}$$

where BPN is the British pendulum number.

One operator, from the West Virginia Department of Highways, conducted all the sandpatch (12) macrotexture measurements in order to obtain reliable results. The procedures were meticulous; therefore, consistency was achieved in the measurements.

An empirical model was introduced to express the relationship between PNG and the mean texture depth (D):

$$PNG = aD^c \tag{10}$$

The quantities a and c are constants.

An analysis of the data yielded

$$PNG = 0.73(D)^{-0.47} \tag{11}$$

where D is the sandpatch texture depth (mm).

When the test results of Equations 9 and 11 are substituted in Equation 7, and the velocity is converted to metric units, Equation 7 becomes

$$SN_V = (1.38BPN - 31) \exp[-0.0045V(D)^{-0.47}] \tag{12}$$

Numerical values may differ for data obtained from other sources, and they certainly will vary for different measurement techniques. Additional experimental measurements will help to stabilize the numerical values for Equation 7.

Equation 12 can be approximated by the following:

$$SN_{65} = (1.38BPN - 31) \exp[-(0.29/\sqrt{D})] \tag{13}$$

when V is 65 km/h (40 miles/h). The numerical values of Table 1 are computed from Equation 13.

RELATION OF TEXTURE PARAMETERS TO SKID RESISTANCE

The numerical values of Table 1 illustrate the effect of the texture parameters on the skid resistance. In the table, BPN represents the microtexture values; D represents the macrotexture. Table 1 shows that adequate microtexture is essential for good SNs, and the skid resistance increases as the microtexture increases.

SN also becomes larger as the macrotexture becomes larger, especially for large microtexture values. The dashed line separates values below and above an SN value of 40 for SN_{65}.

As examples, the table indicates that an SN value of 28 should be expected from a microtexture value of 50 and a macrotexture depth of 1 mm (0.04 in). A better value of 52 is to be expected from a microtexture value of 70 and a macrotexture depth of 1.5 mm (0.06 in).

Figure 5. Effect of macrotexture on skid resistance.

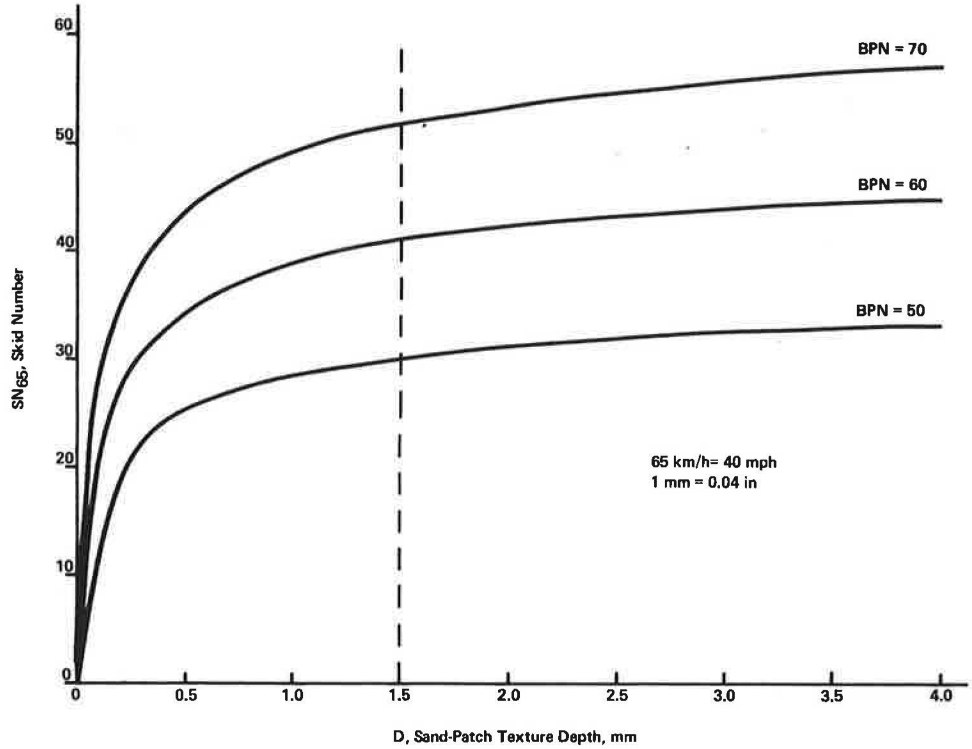
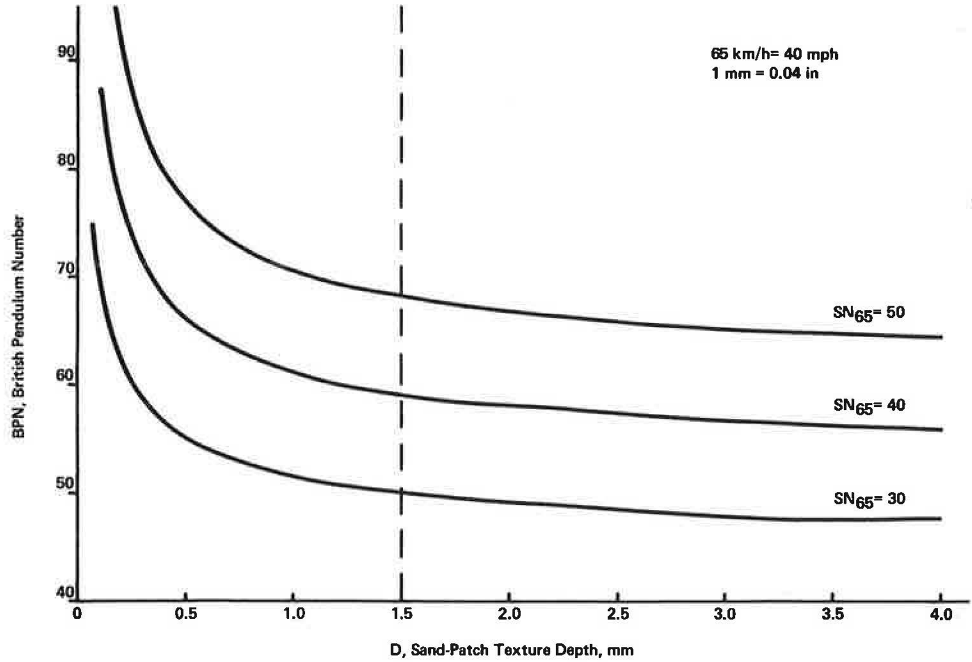


Figure 6. Texture requirements for specific skid resistance.



Similar tables can be calculated from Equation 12 for other speeds.

The influence of texture parameters on skid resistance is further illustrated in Figures 5 and 6. These curves are drawn from values computed from Equation 13. Relationships between two quantities can be shown graphically while a third quantity is held constant. Clearly, the SN in Figure 5 increases rapidly as the sandpatch texture depth increases to 1.5 mm for constant BPN values. Although the skid resistance increases above this value, the rate of change is smaller. A large value of microtexture is essential for adequate skid resistance when the macrotexture is small. This is illustrated in Figure 6.

Graphs can also be drawn to show the relationship between the microtexture and the SN for a constant macrotexture.

OTHER METHODS OF TEXTURE MEASUREMENT

The pavement microtexture can also be evaluated by locked-wheel skid tests at low speeds or by a microtexture profile tracer. The silicone putty impression test, the outflow meter, or a macrotexture tracer can be used to measure macrotexture. The profile tracer methods are limited mostly to laboratory use. If one or more of these methods are used, adjustments may be required in the texture numerical parameter values for the models.

ADDITIONAL RESEARCH

Research is being conducted to develop better texture-measurement techniques. Methods for both microtexture and macrotexture are under investigation.

Automated equipment in the laboratory (13) is being used to measure the aggregate shape factor (ratio of the average asperity height to the average width) for microtexture. The results from such measurements are correlating well with the polished stone value (PV) from the British wheel (ASTM D3319). The larger shape factors have larger polish values.

Research is also being conducted on macrotexture measurement at highway traffic speeds. It is directed toward a texture profile, a root-mean-square descriptor, or other similar descriptors, and it should relate to skid resistance, the gradient of skid resistance and speed, and the gradient of percentage of speed.

There is an implementation study in progress in which several states are evaluating the surface drainage measurement technique by means of the outflow meter.

FUTURE RESEARCH

There is a need for more research on pavement texture to determine its influence on noise generation, tire wear, pavement wear, and energy consumption. Other factors (4) to be considered are splash and spray, surface drainage during heavy precipitation, freeze-and-thaw behavior, night visibility, and snow-and-ice removal.

CONCLUSIONS

Skid resistance is determined and can be predicted for a selected vehicle speed from pavement-texture parameters. Empirical models provide a systematic basis for these predictions; however, the models cannot account for seasonal variations without supplemental information.

Adequate microtexture is essential for good skid resistance at all speeds and is the predominant factor for speeds less than 50 km/h (31 miles/h). Beneficial microtexture can be obtained from coarse aggregates that contain hard, angular, fine particles or harsh fine aggregates bonded in bituminous surfaces. Excellent microtexture is achieved for PCC pavements constructed by using hard, angular surface sands.

Coarse macrotexture is necessary for safe high-speed travel on wet pavements. It provides roadway surface voids to relieve the water pressure beneath the traveling tire. This reduces hydroplaning tendencies and increases the skid resistance because of better contact between tire and pavement.

Open-graded asphalt friction courses produce coarse macrotexture surfaces through mix design and selection of the proper aggregate sizes. Coarse macrotexture for PCC pavements can be obtained by deep tine finishes of the plastic concrete or by grooved hardened pavements.

Coarse-textured pavements finished by using steel tines develop larger SNs and smaller gradients than inferior-textured surfaces. The smaller gradients are especially important for better skid resistance at higher speeds.

Research and experience have shown that metal tines preceded by a burlap drag or other type of drag finish are practical and dependable means of providing excellent texture on PCC pavements.

The sample computations by using the texture and skid-resistance models show the interaction of both texture parameters for providing an adequate level of skid resistance. In particular, Table 1 and Figures 4-6 show that SNs increase significantly as the microtexture increases. It can be seen in Figure 5 that the skid resistance improves very rapidly as the macrotexture varies from 0 to 1.5 mm. Figure 6 shows that excellent microtexture is required to provide sufficient skid resistance when the macrotexture is small. The water-film thickness must also be thin enough for the microtexture to be effective; otherwise, there is a tendency for hydroplaning.

It appears that microtexture can be represented by measurements with the British pendulum tester. The macrotexture can be evaluated by the sandpatch or similar methods. There are also other techniques for measuring pavement texture, and research is continuing to appraise pavement surface characteristics at traffic speeds.

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