

Correlation of Pavement Surface Texture to Hydraulic Roughness

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A study was performed to determine whether a correlation exists between the pavement's texture parameters, as determined by the outflow meter, texture beam, sand patch, and texture van, and the hydraulic roughness of the same pavement as measured by Manning's n -value. Because of an ever-changing texture from weathering and traffic, it is not practical to test for hydraulic roughness in the field. Therefore, the project incorporated the use of a laboratory hydraulic flume to perform flow tests on 10 different pavement types found in the field. Because wet pavements are a cause of many highway accidents as a result of hydroplaning, a correlation between surface texture and hydraulic roughness will help an engineer to determine whether a hydroplaning problem exists for a given rainfall intensity. From testing it was found that relationships exist between the texture and hydraulic roughness. It was also found that the outflow meter results were inversely related to pavement texture. With this information the engineer can use a simple texture-measuring technique to estimate the hydraulic roughness coefficient.

The purpose of the study described here was to determine whether a correlation exists between the pavement's surface texture parameters and hydraulic roughness. The surface texture was measured by the FHWA outflow meter, sand patch method, texture van, texture beam, and British pendulum methods. Pavement specimens were then tested in a flume to determine hydraulic roughness coefficients, Manning's n -values.

Hydroplaning is a phenomenon in which automobiles lose control by skimming the surface of wet roads because of the presence of a thin layer of water between the tire and the pavement. Because hydroplaning is a function of hydraulic roughness, a method is needed to determine Manning's n -value. Because of the ever-changing surface texture from weathering and traffic, it is not practical to test for hydraulic roughness in the field. Therefore, by correlating hydraulic roughness determined in the laboratory to pavement texture, which can be readily determined in the field, the engineer can quickly estimate the pavement's hydraulic roughness in the field, and thus hydraulic roughness can be periodically monitored for safety.

To achieve the goals of the study, the following objectives were accomplished:

1. A comprehensive literature review of hydroplaning, skid resistance measurement, pavement texture measurements, pavement hydraulics, and other related topics.
2. Replicating pavement textures in the hydraulic flume at Turner Fairbank Highway Research Center (TFHRC) and conduct-

ing flow tests in the laboratory to determine Manning's n -values for the pavements.

3. Obtaining field texture measurements and skid resistance measurements for similar pavement sections.

4. Data analysis to determine whether a correlation between the texture measurements and Manning's n -value exists.

SIGNIFICANCE OF SURFACE TEXTURE

Wet pavement is a major cause of highway accidents. It induces hydroplaning, reduces skid resistance, and affects vehicle control. If proper surface characteristics of the pavement are constructed and maintained on the roadway, these hazards to vehicle travel can be greatly reduced.

Roadway textures can be obtained through the design of the pavement mixtures, size and grading of the aggregates, construction procedures, or surface finishing methods or by grooving and etching existing pavements. Texture is considered to include the structure and porosity of the top layer, as well as the aggregate's individual properties of mineralogy, shape, and gradation (1).

The term *surface texture* has been used to describe qualitatively and quantitatively the appearance and feel of a pavement surface. The qualitative influence of pavement surface properties, namely, microtexture and macrotexture, on the tire-pavement skid resistance has been known for years. Recently, there has been an interest in quantifying this influence (2).

Interest in developing methods for measuring pavement texture has stemmed 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. In a study by Moore (3) a surface texture laboratory was created to investigate surface roughness. The results from laboratory tests were compared with those obtained from any of the following three sources:

1. An instrumented vehicle performing specified maneuvers,
2. A test wheel loaded against and driven by a steel drum, or
3. A simplified laboratory model to simulate the interaction between tire and pavement.

For Moore's study the texture laboratory consisted of a flow meter (to assess the relative drainage abilities of selected pavements), a profile-measuring device (to verify the predictions afforded by the outflow meter), a draping apparatus (to simulate the draping zone), a sinkage model (that duplicates the squeeze-film action in the sinkage zone), and a British portable skid resistance tester for general laboratory use.

Harwood et al. (2), along with the already mentioned test methods, used a sand patch test. The sand patch test procedure can be

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found from the guidelines of the American Concrete Paving Association (4). Additional texture measurement procedures include the grease patch, putty impressions, profilograph, texture meter, and a surf indicator. These test procedures are described in detail in works by Rose et al. (5), Hegmon and Mizoguchi (6), Rose et al. (7), Dahir and Lentz (8), Henry and Hegmon (9), and many others.

TEXTURE ANALYSIS

Efforts to understand and quantify the texture effects in tire-pavement interactions have been limited. This is a result of difficulties encountered in the experimentation or theory to determine many individual contact points between the tire and the pavement. Research has been performed to develop a method to predict the normal contact forces that are created from the surface texture (10). To demonstrate the usefulness of this method, texture-induced contact pressure and length information are computed. Contact pressure is used to analyze individual peak pressures and to construct force time histories that excite tire models for predicting vibrational response and rolling resistance. Contact length is used to approximate tire envelopment into the surface texture. This is beneficial, because information pertaining to skid resistance parameters such as void area and depth of penetration is incorporated into the analysis (11). These detailed computational algorithms can be coupled with approximations from this project to understand and predict the factors influenced by surface texture such as skid resistance, rolling resistance, and vehicle performance.

Skid Resistance

With higher-speed traffic and increasing volumes, the numbers of accidents tend to increase. Under such conditions vehicle control and maneuverability rely heavily on the friction between the tire and the pavement to avoid an accident. Water on the roadway is a major factor in highway accidents. It induces hydroplaning, reduces skid resistance, and adversely affects vehicle control.

Skid resistance is a general term used to describe the level of friction between a roadway surface and the vehicle's tire. On wet pavements speed is the most significant parameter, because the skid resistance at the tire-pavement interface decreases with increases in speed. The tire-pavement skid resistance can be measured in several testing modes: locked-wheel braking, brake slip, drive slip, and cornering slip. However, the locked-wheel method has gained the widest acceptance for skid resistance testing throughout the United States (2). The most common measurement of the locked-wheel method is the skid number (SN), which is defined as 100 times the coefficient of friction determined by a locked-wheel test. ASTM has standardized this procedure, and testing is accomplished by a two-wheel trailer towed by a truck at a constant speed of 40 mph. Water is sprayed at a standard thickness of 0.002 in. by nozzles located in front of the trailer's wheels. This requires a flow rate of 4.0 gal/min/in. of wetted width. The trailer's brakes are activated on one or both wheels. By using a standardized tire, wheel torque can be interpreted to obtain frictional force and the resulting SN.

Because periodic testing is conducted on all state highways, SNs are widely available from most states. Despite its availability, the SN is only one of many parameters needed to design safe roadways. Since the skid test is standardized to one type of tire and one depth of water, other parameters that incorporate a wider range of data

need to be developed. For example, two pavements can have similar SNs at 40 mph but can have very different SNs at higher speeds. Therefore, use of data from the skid test as well as other test procedures provides a better understanding of hydroplaning and skidding and could help to increase safety.

Hydroplaning

Total (full dynamic) hydroplaning is a phenomenon in which a tire is completely separated from the pavement by a fluid layer and the friction at the tire-pavement interface is nearly zero. Hydroplaning is caused by the buildup of fluid pressures within the tire-pavement contact zone. When the total uplift resulting from hydrodynamic pressures exceeds the downward force (vertical load), the tire moves upward to maintain the dynamic equilibrium of the forces. During hydroplaning a gust of wind, a change in road superelevation, or a slight turn can create an unpredictable and uncontrollable sliding of the vehicle (12).

EXPERIMENTAL DESIGN AND PROGRAM

Objective

The objective of the present study was to develop a correlation between pavement surface texture and hydraulic roughness as quantified by Manning's n -value. This was accomplished by

1. Using various test methods to measure surface texture,
2. Designing and building a flume to measure Manning's n -value, and
3. Collecting field data for comparisons.

The reasons for using several methods to measure surface texture were to compare each method to find the best correlation and because not all methods are available to everyone. The methods used to measure surface texture in the present study were

1. British pendulum (ASTM E303) (9),
2. Skid trailer (ASTM E274) (7),
3. Texture van (Pennsylvania State University and FHWA),
4. Texture beam (FHWA) (9),
5. Outflow meter (FHWA) (6), and
6. Sand patch (ASTM E965) (6).

Summary of Test Methods

The British pendulum tester is a dynamic pendulum impact-type tester used to measure the energy loss when a rubber slider edge scrapes over a test surface. This method measures the frictional property associated with the microtexture of the surface. It may also be used to determine the wearing or polishing properties of pavement surface materials. For this test method the pavement surface is cleaned and thoroughly wetted before testing. The pendulum slider is positioned to come barely into contact with the test surface. The pendulum is raised to a locked position and is then released, thus allowing the slider to make contact with the test surface. A drag pointer indicates the British pendulum number (BPN). The greater the friction between the slider and the test surface the more retarded the pendulum's swing, thus recording a larger BPN.

The skid trailer measures the skid resistance of paved surfaces with a specified full-scale automotive tire. This measurement represents the steady-state friction force on a locked test wheel as it is dragged over a wetted pavement surface under constant load and at a constant speed. The wheel's major plane is parallel to its direction of motion and perpendicular to the pavement. The skid resistance of the paved surface is determined from the resulting force or torque record and is reported as the SN described earlier.

However, skid resistance is primarily a function of pavement microtexture. Therefore, a correlation between skid resistance and pavement macrotexture was not successfully determined. Further details can be found in the section on test results.

The texture van is an automated device developed jointly by FHWA and Pennsylvania State University. The texture van incorporates the use of a strobe light and camera. The flashing strobe light produces shadows that the camera then photographs as an image of the pavement texture. The image is then separated into light and shadow regions, which are digitized into a computer. The area of light is then calculated and converted into a root mean square value for pavement surface height. The texture van can be operated at various speeds, allowing for a safer testing environment because the texture van can stay with the traffic flow.

The texture beam determines the texture height of test samples in the laboratory and the field. The apparatus consists of a hinged arm with a needle that drags along the surface at constant speed. A linear variable differential transducer attached to a data acquisition system records voltage differences as the needle pivots up and down along the pavement surface. The texture beam test method was developed at TFHRC.

The sand patch method is a procedure for determining the average depth of pavement surface macrotexture by applying a known volume of material (glass beads) onto the surface and measuring the total area covered. The sand patch method is not significantly affected by the surface microtexture.

The outflow meter is a device that measures the drainage characteristics of a pavement surface. A column is filled with water and placed on a clean surface. The bottom of the outflow meter has a rubber gasket that contacts the pavement surface. A stopper is removed and a timer is started, which determines how long it takes for the water to drop 2 in. The water flows through the contact zone between the rubber gasket and pavement surface. The timer is stopped when the water level falls in the outflow meter's column by 2 in. For the present study the outflow meter data are correlated to surface texture and a regression equation is developed.

Flume Design

To determine Manning's hydraulic roughness coefficient n , a flume was designed and constructed. The flume's specifications were as follows:

- Size: 20 ft long and 28 in. wide,
- Slope: 0.5 in. over 20 ft = 0.002 ft/ft,
- Water Depth: 1.0 in. (approximate), and
- Flow: varied and measured by (a) paddle wheel flow meter and (b) 90-degree V-notch weir box.

To ensure the correct slope, the flume was surveyed twice and shimmed to the correct dimensions. The water entered the flume by flowing into a head box. The head box provided an equal distribu-

tion of water over the entire width of the flume. Several fins were added to the head box to eliminate waves and turbulence that could enter the system. The paddle wheel flow meter was placed in the piping system just before the head box. The flow meter determined the amount of water entering the system. The V-notch weir box was placed at the end of the flume system to collect the exiting water, which enabled comparison with the flow meter. This ensured that the flow entering the system was equal to the flow exiting the system. This dual method of flow measurement was chosen because small amounts of water loss occurred through the seams created at the head box and the V-notch weir connections. The flume was designed so that the sides, head box, and V-notch weir box could easily be removed to change the pavement types that were to be tested. Therefore, careful monitoring was required to minimize leaks.

Pavement Types

Ten pavement types were tested in the project described here. The types of textures chosen were similar to those found in the field. The following types of pavement surfaces were investigated:

- Smooth trowel finish portland cement concrete (PCC);
- Broom finish PCC;
- Tinned finish PCC with $\frac{3}{8}$ -in. pea stone;
- Tinned finish PCC without pea stone;
- Tinned finish vertical PCC;
- Tinned finish shallow PCC without pea stone;
- Asphalt concrete (AC), Virginia Specification SM2A, rough;
- AC, Virginia Specification SM2A, smooth;
- Epoxy-treated wearing surface, sand; and
- Epoxy-treated wearing surface, crushed stone.

These surfaces were also chosen to present a wide representation of texture to better correlate to Manning's n -value. Tinned surface consists of $\frac{1}{2}$ -in. spaced grooves that are $\frac{1}{8}$ -in wide and approximately $\frac{1}{4}$ -in. deep. The tinned vertical surface means that the surface was grooved perpendicular to the flow of water. All other tinned surfaces were grooved parallel to water flow. It must be remembered that the length of the flume represents the cross section of the lane. Therefore, if the lane is cross sloped, tinning parallel to water flow is perpendicular to the vehicle travel direction.

Because of the time constraint, open-graded friction courses were not available for testing. Therefore, a standard SM2A mixture was used with a low compaction effort to find the effects of a porous surface texture on Manning's n -value. The epoxy-treated surfaces represent two common aggregate sizes used in the Virginia area for epoxy-treated bridge deck surfaces.

Test Plan

After placing the pavement in the flume, the walls, head box, and V-notch weir box were inserted. With the use of a variable-speed pump, flow was adjusted so that a depth of approximately 1 in. was maintained along the length of the flume. Flow was maintained for about one hr to allow for steady-state flow. Using three point gauges attached to a movable bridge, the water depth was recorded at 2-ft intervals. One of the point gauges was placed at the center and one on each side 5 in. in from the walls. The system with three point

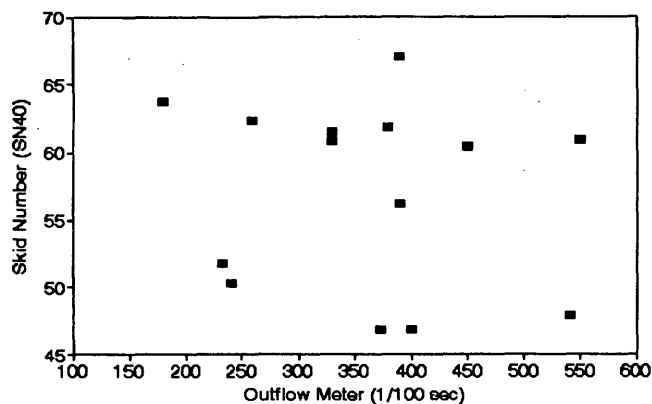


FIGURE 1 Skid resistance versus outflow meter reading in Rhode Island.

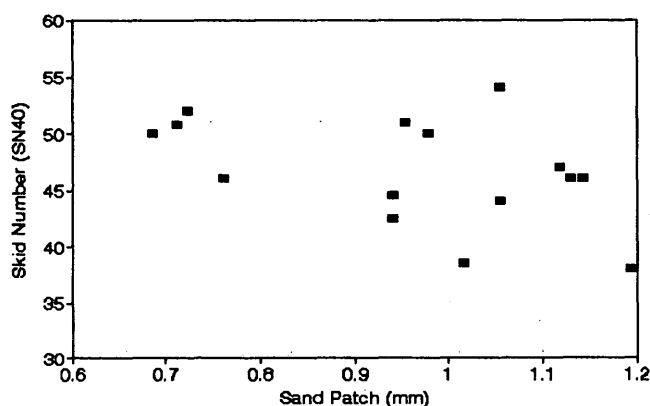


FIGURE 2 Skid number versus texture height in Washington, D.C.

gauges allowed for measurements to be made across the flume to determine whether the flow was uniform as well as laminar. Readings were taken from the flow meter and V-notch weir to determine the flow (Q) in the system. By applying Manning's equation, hydraulic roughness was determined.

Texture tests were then taken at 4-ft intervals in the center of the test flume. The head box, walls, and V-notch weir were then removed. The pavement was broken into test sections and taken for further laboratory tests. The flume was then prepared for another test pavement.

Field Study

Initially, the project concentrated on finding a relationship between skid resistance and Manning's n -value. Field tests with the skid trailer were performed along with pavement texture tests in Rhode Island, Virginia, and Washington, D.C. From investigation of these findings, no direct correlation existed between skid resistance and pavement texture. The focus of the study was then changed to determine whether a relationship existed between pavement texture and Manning's n -value. Skid testing continued in the laboratory as a secondary objective to determine whether there is any relationship between hydraulic roughness and skid resistance. Because skid resistance data are widely available, it would be helpful to find a

correlation to Manning's n -value to determine the hydroplaning characteristics of the pavements' surface.

TEST RESULTS AND ANALYSIS

Initial test results were compared to explore the relationship between skid resistance and pavement texture. Test results obtained by using the ASTM skid trailer in Rhode Island, Washington, D.C., and Virginia are shown in Figures 1 to 3, respectively. It was observed that no direct correlation can be established.

Linear regression analysis was performed on the skid data correlation to texture, and it was determined to be a poor correlation. The poor correlation may be due to the inaccuracy of positioning of the texture test with the skid patch. Also, pavement macrotexture does not significantly affect skid resistance. Therefore, it was concluded that a linear relationship between SNs and texture did not exist.

Poor correlations were also found in previous studies involving skid resistance and its relationship to texture. In a study by Dahir and Lentz (8), no fixed correlation of texture depths with SNs as measured with the skid test trailer at 40 mph was evident, as shown in Figure 4.

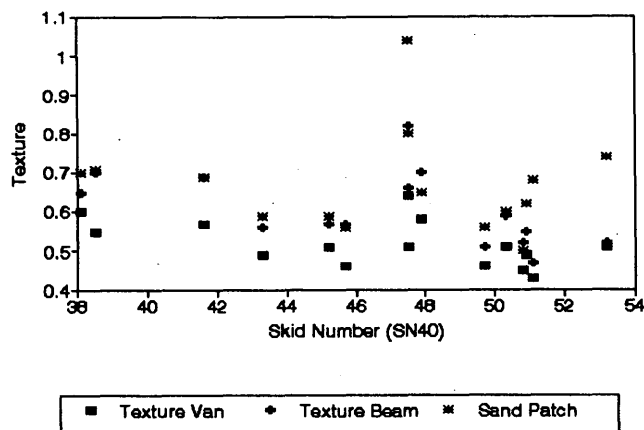


FIGURE 3 Skid number versus texture at TFHRC, McLean, Va.

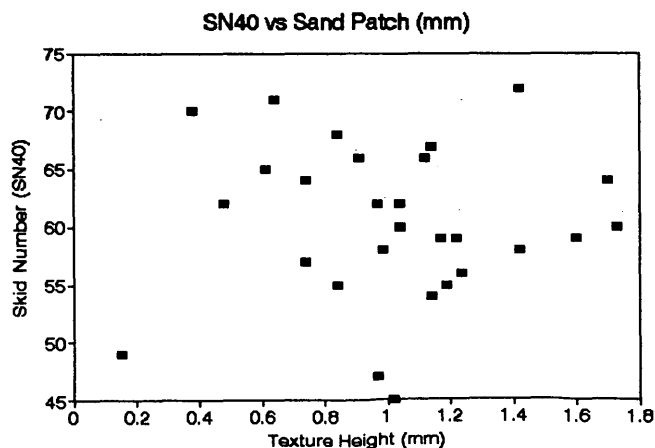


FIGURE 4 SN versus texture (8).

TABLE 1 R^2 Values for Linear Relationship Between Various Test Methods

Linear Relations R^2	Texture Van	Texture Beam	Sand Patch	Outflow Meter	British Pendulum	Manning "n"
Texture Van	100	94.0 ²	75.5 ²	89.6 ¹	22.4	80.0 ²
Texture Beam		100	74.5 ²	54.4 ¹	15.2	83.9 ²
Sand Patch			100	50.0 ¹	3.1	79.4 ²
Outflow Meter				100	4.3	22.5
British Pendulum					100	1.0
Manning "n"						100

¹. These are inverse relationships.

². These relationships were determined by excluding tinned surface outliers.

Testing then continued to compare texture measurements and Manning's n -value. In all, 15 relationships were analyzed, and the resulting R^2 values are presented in Table 1. The results show that strong correlations exist between Manning's n -value and the three methods used to determine macrotexture. Figures 5 and 6 show the relationship between texture and Manning's n -value. These scatter plots contain two datum points that are considered to be outliers and that were therefore not included in the analysis. These two points represent the two deeply tinned surfaces. The reason for the outliers is that the texture increased because of the tinning, but Manning's n -value actually decreased because the water flow was laminar through the tinned channels. Therefore, deeply tinned pavement surfaces do not follow the same linear relationship that is created by

random particle placement created by asphaltic surfaces or sand epoxy overlays.

The outflow meter was compared with texture and was found to be inversely proportional to texture height (Equation 1):

$$\text{Outflow (1/100 sec)} = \frac{1}{\text{Texture}} \text{ (mm)} \quad (1)$$

Figures 7 and 8 show that as texture increases, outflow meter times decrease and go to zero. As texture becomes smoother, outflow times will go to infinity. Figure 9 shows the representative texture heights for the different test pavements as related to hydraulic roughness.

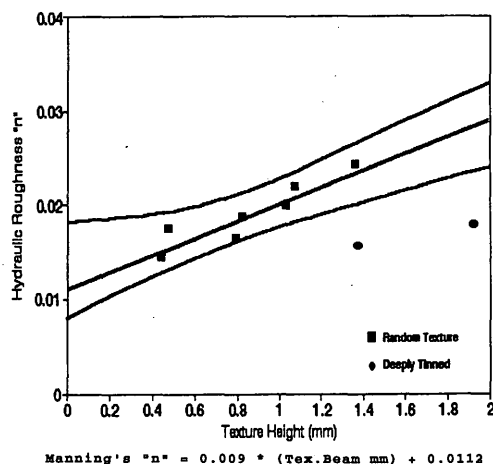


FIGURE 5 Texture beam versus hydraulic roughness.

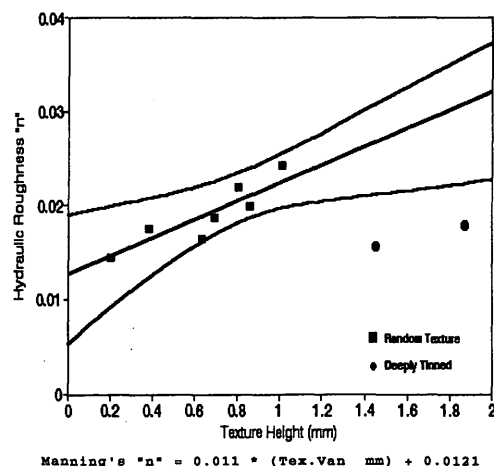


FIGURE 6 Texture van versus hydraulic roughness.

Outflow (1/100ths sec.) = (315.9 / Sand Patch mm) + 13

Outflow (1/100ths sec.) = (185.1 / Text. Beam mm) + 13

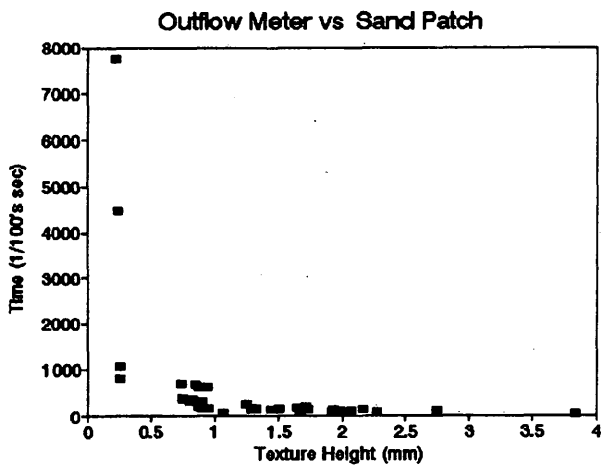


FIGURE 7 Outflow meter versus texture height.

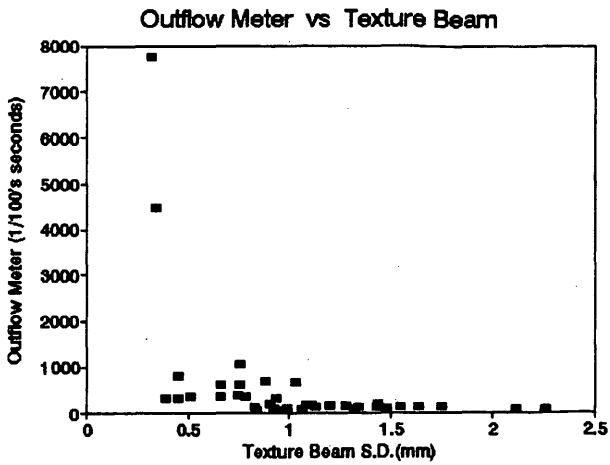


FIGURE 8 Outflow meter versus texture height.

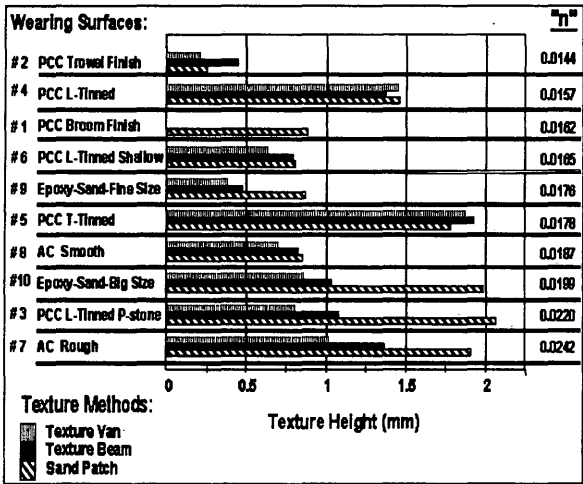


FIGURE 9 Texture height and hydraulic roughness.

Using Manning's equation, hydraulic roughness was calculated as follows:

$$Q = \frac{1.486}{n} \cdot A \cdot R^{2/3} \cdot S^{1/2} \quad (2)$$

The water depth was measured by the three point gauges. Figure 10 shows the water surface as measured by each of the gauges. Several test runs were completed for each pavement type. An average roughness value was taken for those test runs that were closest to having 1 in. of water depth flowing over the pavement surface.

The resulting Manning's *n*-values (Figure 11) were compared with textbook values. According to a work by Chow (13), a trowel-finished concrete should have a range for Manning's *n*-values from 0.011 to 0.015, with a normal reading of 0.013. The present research project's measured value was 0.0144, which is slightly above aver-

age. However, it is in the acceptable range and is a good indicator that the testing procedure was adequate.

CONCLUSION

The results reaffirmed that a fixed correlation does not exist between skid resistance, as tested by the skid trailer and British pendulum, and texture height, as measured by sand patch, texture van, and texture beam. The lack of correlation is believed to be primarily because the frictional properties of the pavement's surface are more closely related to the microtexture instead of the macrotexture of the pavement.

Among 15 correlations investigated, good linear correlations were found to exist between the three texture-measuring devices

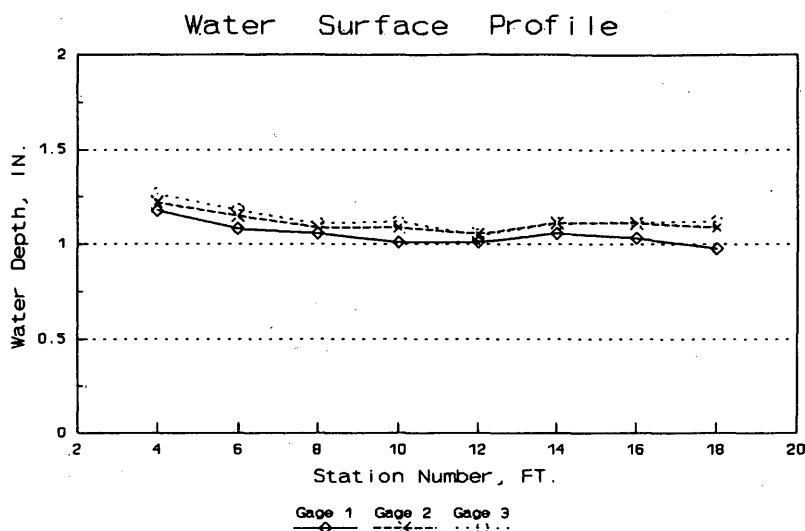


FIGURE 10 Typical water surface profile measured by three point gauges.

	Manning's "n"
Trowel Finish	0.0144
Tinned Long	0.0157
Broom Finish	0.0162
Tinned Long-Shallow	0.0165
Epoxy #1	0.0176
Tinned Perp.	0.0178
Asphalt Smooth	0.0187
Epoxy #2	0.0199
Tinned P-Stone	0.0220
Asphalt Rough	0.0242

FIGURE 11 Calculated Manning's n -value from testing in flume.

and Manning's n -value. It was concluded that a linear relationship exists between the texture van and texture beam. It was observed that linear relationships between texture and outflow meter do not exist, but inverse relationships do.

It was found that the texture van, texture beam, and sand patch methods produce similar results in comparison with the hydraulic roughness. Observations show that the texture van produced better correlations, especially with the outflow meter. These high correlations may be because of the quick sample rate analyzed by the texture van's computer.

Relationships exist between pavement surface texture and Manning's hydraulic roughness coefficient n . The equations may be helpful in future studies in incorporating hydroplaning coefficients directly from texturing devices with other parameters such as rain-fall intensity and vehicle speed. By using a simple texture measuring device to determine texture height, Manning's n -value could be calculated to determine at what water depth hydroplaning will cause an unsafe situation.

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