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THE EFFECTS OF RAINFALL INTENSITY, PAVEMENT CROSS SLOPE, SURFACE TEXTURE, AND DRAINAGE LENGTH ON PAVEMENT WATER DEPTHS

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VEHICLE-PAVEMENT INTERACTION

THE EFFECTS OF RAINFALL INTENSITY, PAVEMENT CROSS SLOPE, SURFACE TEXTURE, AND DRAINAGE LENGTH ON PAVEMENT WATER DEPTHS

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ABSTRACT

Reported herein are the results of a study concerned with determining the amount of water which can be expected to exist on various pavement types under normal ranges of pavement cross slopes, rainfall intensities, pavement textures, and drainage lengths. Equations are developed which relate these variables and their relative effects to water depth. Results are presented in both tabular and graphic form. Background information are pertinent past research pertaining to hydraulics of water flow over paved surfaces are given.

Nine different type surfaces were tested. The surfaces were placed on individual 28-foot long by 4-foot wide, double tee, prestressed concrete beams. Rainfall of uniform intensity was applied to the surface. Water depth measurements were taken at regularly spaced drainage lengths for various combinations of rainfall intensity and pavement cross slope. Multiple regression analyses were used to determine the best fit of the data.

Pavement cross slope was found to affect water depths singificantly. For a rainfall intensity of 1.5 in/hr, a surface texture of 0.03 in., and a drainage length of 24 ft., increasing the cross slope from 1/16 in/ft (1/192) to 1/4 in/ft (1/48) decreased water depths by 62 percent in the outside wheel path (approximately 21 feet from the top of the drainage area). Correspondingly, increases in surface texture decreased water depths; whereas, increases in rainfall intensity and drainage length increased water depths. The overall experimentally obtained equation is

$$d = 3.38 \times 10^{-3} (1/T)^{-.11} (L)^{.43} (I)^{.59} (1/S)^{.42} - T$$

where

d = average water depth above top of texture (in);

T = average texture depth (in);

L = drainage-path length (ft);

I = rainfall intensity (in/hr); and

S = cross slope (ft/ft).

The findings and conclusions contained herein will be useful to the highway engineer in determining proper geometric designs and paving materials commensurate with acceptable pavement friction characteristics and service demands. Suggestions for further research are also included.

OBJECTIVES AND SCOPE

The objectives of this research were:

1. To examine the relative effects of various rainfall intensities, pavement cross slopes, drainage lengths, and surface textures on resultant pavement water depths;

2. To develop an equation relating rainfall intensity, pavement cross slope, drainage length, and surface texture to pavement water depth and

3. To recommend means by which the findings and conclusions contained herein can be implemented by the highway engineer in determining proper geometric designs and paving materials commensurate with acceptable pavement water depths and service demands.

Nine different type surfaces were tested. The surfaces were placed on individual 28-foot long by 4-foot wide, double tee, prestressed, concrete beams. A uniform rainfall intensity was applied to the surface. Water depth measurements were taken at several drainage lengths for various combinations of rainfall intensity and pavement cross slope. Multiple regression analyses were used to determine the best fit of the relationships.

SUMMARY OF FINDINGS AND RESULTS

1. The experimentally determined equation relating water depth to surface texture, length of drainage path, rainfall intensity, and pavement cross slope was

$$d = \left[3.38 \times 10^{-3} (1/T)^{-.11} (L)^{.43} (I)^{.59} (1/S)^{.42}\right] - T$$

where

d = water depth above top of texture (in.);

T = average texture depth (in.);

L = drainage-path length (ft);

I = rainfall intensity (in/hr); and

S = cross slope (ft/ft).

2. Increasing surface texture resulted in a decrease in water depth for a given rainfall intensity, cross slope, and drainage length. This effect was more pronounced at the flatter cross slopes and lower rainfall intensities.

3. Greater drainage lengths increased water depths; however, the rate of increase in water depth, became smaller as drainage lengths increased.

4. Greater water depths were associated with higher rainfall intensities; notwithstanding, the adverse effect of rainfall intensity was quite pronounced, even at the lower rainfall intensitites.

5. Increases in pavement cross slope resulted in reduced water depths. This effect was very significant at the flatter cross slopes where a slight increase in cross slope resulted in a pronounced reduction in water depth. The reader is referred to Table 8 and Figure 18 for a more detailed account of findings 2 through 5.

6. Surface texture, rainfall intensity, and pavement cross slope were found to affect the average detention water* on the surfaces similar to the manner in which these variables affected water depth. Increases in surface texture and pavement cross slope resulted in decreased detention; whereas, increases in rainfall intensity increased detention. The reader is referred to Table 9 and Figure 19 for more detailed information. The experimentally determined equation was

$$Det = \left[11.80 \times 10^{-3} \, (1/T)^{-.11} \, (I)^{.57} \, (1/S)^{.31}\right] - T$$

where

Det = average water depth detention (in);

T = average texture depth (in);

I = rainfall intensity (in/hr); and

S = cross slope (ft/ft).

*The water in question is that water above a calculated median datum line which was formed by an average of the tops of the asperity peaks.

IMPLEMENTATION STATEMENT

The findings reported herein should be useful to the highway engineer in determining proper geometric designs, selecting materials and preparing guidelines for the construction of pavements with acceptable frictional characteristics for selected service demands and traffic volumes.

The findings should also be useful to highway maintenance supervisors in programing repairs and planning fiscal operations.

KEY WORDS

Rainfall Intensity, Pavement Cross Slope, Surface Texture, Drainage-Path Length, Water Depth, Water-Film Thickness, Depression Storage, Surface Detention, Surface Runoff, Equilibrium Runoff, Putty Impression Texture Test, Water Depth (Point) Gage, Rainfall/Spray Nozzles, Pavement Surface Asperities, Water Depth - Datum Plane at Top of Texture, Water Depth - Datum Plane at Bottom of Texture.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Safety on our nation's highways is a topic of utmost importance to the driving public. Concern for the prevention of traffic accidents is evidenced by every responsible agency from the Department of Transportation at the federal level to local highway authorities. The causes of traffic accidents are numerous, but the results are the same--costly destruction of property, incalculable human suffering, and an annual death toll exceeding 50,000 lives. Trends in the causes of traffic accidents have been discovered; research has been, and will continue to be, conducted in an effort to solve the problems which bring about this senseless loss of resources.

Among those topics which have recieved considerable attention over the past 30 to 40 years is the problem of providing roadway pavement surfaces which will provide adequate tire-gripping capabilities under all operating conditions, thus reducing the occurrence of accidents attributed to skidding. Skidding is the phenomenon which occurs when frictional demands on the vehicle wheels exceed that available; such loss results in an increased stopping distance, loss of directional stability, and loss of operator control. It should be reasonably obvious that this situation is of the utmost danger to the occupants of the skidding vehicle as well as to other persons or property which might be within range of the skidding vehicle.

Characteristically, a pavement becomes slippery when the prevailing conditions are such that water lubricates the tire-road surface contact area, when the inherently high skid resistance of a new surface has been worn and polished away by traffic, and/or when vehicle speeds are high enough to hydrodynamically reduce or eliminate the tire-surface contact (and thus the available friction) below the level required for vehicle maneuvers (1)*. Dearinger and Hutchinson (2) suggest that although the details of the slipperiness-skid resistance problem are quite complex, most automobile accidents involving skidding are due simply to the unfortunately common combination of a wet pavement and an attempt by the driver to perform a maneuver (braking, cornering, accelerating) at a speed too high for the conditions. The frequency of occurrence of this combination of circumstances has risen sharply in the past few years with continuing increases in traffic volumes and higher average vehicle speeds.

American highway engineers have been studying the vehicle skidding problem, particularly resistance to skidding offered by pavement surfaces, for several decades. In fact, initial technical papers (3, 4) written on the subject 30 to 40 years ago include many of our present day ideas. However, the problem was not considered to be serious since most pavement types were adequate for the low volume, low speed traffic which existed at that time. Today, as a result of increasing traffic volumes and speeds, the skidding problem is rapidly gaining in significance. Nationally, the average number of wheel passes over the same pavement section increased approximately 50 percent from 1950 to 1960 (5). Indications are that an even larger increase was experienced during the past decade. The average vehicle speed today is approximately 16 mph greater than in 1941, which is an increase of about 1 percent per year. Today's average speed for dry, modern, main rural highways is about 58 mph with 47 percent of all vehicles exceeding 60 mph and 12 percent exceeding 70 mph, with only a 1 or 2 mph reduction in speed on wet pavement (5, 6). At the dry, daylight speed, 50 percentile level, is about 61 mph in

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*Underlined numbers in parentheses refer to references in the Bibliography.

Texas. This figure is based on a Texas speed survey made in 1968 and includes data from 30 stations.

A recent survey by Highway Research Board Committee D-B4 Task Group (7), stated that "...slippery pavements were recognized as a problem of major concern in 22 states, moderate concern in 24 states, and minor concern in 2 states". The HRB survey (7), with 48 states reporting, also revealed that "...42 states were using accident data for the detection or selection of slippery pavements,...that 32 states were using skid tests data as a criterion for resurfacing or deslicking,...and that 30 states were presently conducting a research program on pavement slipperiness." By contrast, a 1958 HRB survey (8) conducted on behalf of Highway Research Board Committee D-1 on Mineral Aggregates revealed that "...only 10 of 47 state highway departments querried were actively conducting studies involving the measurement of pavement skid resistance." More than a million dollars was spent during 1970 by various research agencies in the United States on the development of knowledge on roadway vehicle interaction, particularly on skidding--causes, effects, and prevention.

Comprehensive assessments of the role of slippery pavements and skidding in highway accidents are scarce due partially to inadequate or confusing accident-reporting systems. Data extracted from a British study (9) indicated that skidding of one or more vehicles was involved in about 16 percent of all accidents reported. Of the accidents occurring on wet roads (31 percent of the total), 27 percent involved skidding. A recent British study revealed a general linear relationship between skid resistance and accident risk (10). It was concluded from a Virginia highway accident study (<u>11</u>) that "as high as 40 percent of all accidents involve skidding and in about one-third of these accidents (13 percent of the total accidents), skidding occurs before brake application."

Studies of the locations of individual skidding accidents on wet roads have shown that 'wet skids' tend to cluster on short stretches of road and the significance of these clusters may be judged by comparing the skidding rates at the individual sites with an acceptable standard (<u>12</u>, <u>13</u>). More specifically, very strong correlation between precipitation and accident involvement rate has been found (<u>14</u>). In the United States it is estimated that accidents involving cases where skidding is the primary cause result in an annual loss of life nearly 3,000 persons with an additional 100,000 persons receiving disabling injuries beyond the date of the accident (<u>15</u>).

A 1966 Arthur D. Little, Inc. report (<u>16</u>), which, in the authors' opinions, is one of the most comprehensive studies of traffic safety information ever attempted, stated that:

> Skidding has emerged as a factor of major importance to the overall traffic safety problem, and the surface characteristic of principal concern appears to be the frictional properties of the road surface, both wet and dry. While there is evidence that skidding is involved in a high proportion of accidents, current methods of reporting accidents are believed to be inadequate to determine the true extent of this factor. Since skidding occurs in many accidents, either before or after braking, it is generally overlooked as a 'cause' in most accident reports. There is a tendency to list more obvious 'causes' such as 'failure to negotiate the curve' or 'lost control of car' which are in fact not causes but results; therefore, no accurate record is maintained of the kind and the degree of skidding involvement.

Thus it may be concluded from the above quote that skidding and associated problems are actually contributing causes of more accidents than are attributed by current methods of reporting accidents. Analyses of accident records indicate that the incidence of total accidents, as well as accidents directly involving skidding, increases significantly with decreasing friction coefficients between the pavement and the tire.

The shorter the distance required to stop a vehicle in emergency situations, and the higher the available force to provide adequate cornering, the better the resultant chance to avoid or reduce the severity of accidents. And, as stopping distance and cornering capability are direct functions of a friction coefficient, a high value of friction coefficient is becoming more and more important.

Any moving object, including a wheeled vehicle, produces kinetic energy at a rate increasing with the square of its velocity. Dissipation of this energy is required in order for the moving body to come to rest. In the case of the wheeled vehicle, energy (neglecting wind resistance and change in elevation) is dissipated between the tire and the pavement and in the braking system by the creation of a friction force opposing the direction of motion of the vehicle. After wheel lockup the total friction force available to oppose the motion of the vehicle must be generated at the tire-pavement interface.

The braked wheel skid resistance coefficient, f, is related to the stopping distance of a vehicle by the expression $D = \frac{V^2}{30f}$, where D is the stopping distance in feet, and V is the vehicle speed in miles per hour. The stopping distance can therefore be decreased by increasing the skid resistance coefficient. Increasing f also results in better vehicle control (17).

A high pavement friction coefficient means a greater margin of safety in both stopping and directional control of the vehicle. The higher this margin the better because side friction or directional control and forward or stopping friction are not two separate reservoirs of safety to draw upon in an emergency. There is but one reservoir of tire-gripping capability provided by the road surface. Directional control or effective steering of the vehicle is lost at total lock up; this fact is unknown to many drivers.

Currently, technical discussion is focused upon acceptable minimum pavement skid-resistance coefficients. Recently, even the courts have been faced with decisions in this area; however, all answers in this area of concern are relative to the degree of safety intended.

The achievement of adequate pavement skid resistance is a result of the driver's responses and the interaction between the pavement and tire. This report, however, deals only with the pavement disregarding variations in friction which may be due to variations in tire design, vehicle parameters, and driver characteristics.

The main causes of pavement slipperiness are many and varied, but in very general terms are due to 1) the presence of water or other friction reducing materials in the tire-pavement contact area which, with increasing vehicle speeds, lowers the available friction and raises the frictional demand, and 2) higher traffic volumes which, through pavement wear and aggregate polish, drastically reduce built-in friction potential of most new-pavement-surface types. Many parameters affect the interactions at the tire-pavement interface. Considered to have major effects are: 1) mode of operation, i.e. rolling, slipping, or sliding, 2) pavement-surface characteristics, mainly macro- and microscopic roughness and drainage capability, 3) water-film thickness at the interface, 4) tire-tread depth and elastic and damping properties of the tire rubber, and 5) vehicle speed.

Numerous research studies have indicated that neglecting contamination, all pavement surfaces exhibit adequate skid resistance for normal stopping and cornering maneuvers when dry and clean. When wet, however, this condition is no longer in effect for certain conditions and surface types with the only different condition being the presence of water between the tire and pavement. Studying the factors affecting water-film thickness is therefore of paramount importance.

REVIEW OF LITERATURE

Nature of the Problem

Rain water forms a layer of increasing thickness as it flows to the edge of a sloped pavement surface, as shown in Figure 1. This water is a hazard to motorists due to the reduced frictional drag between the tires and wet surface and the reduced visibliity through the splash and

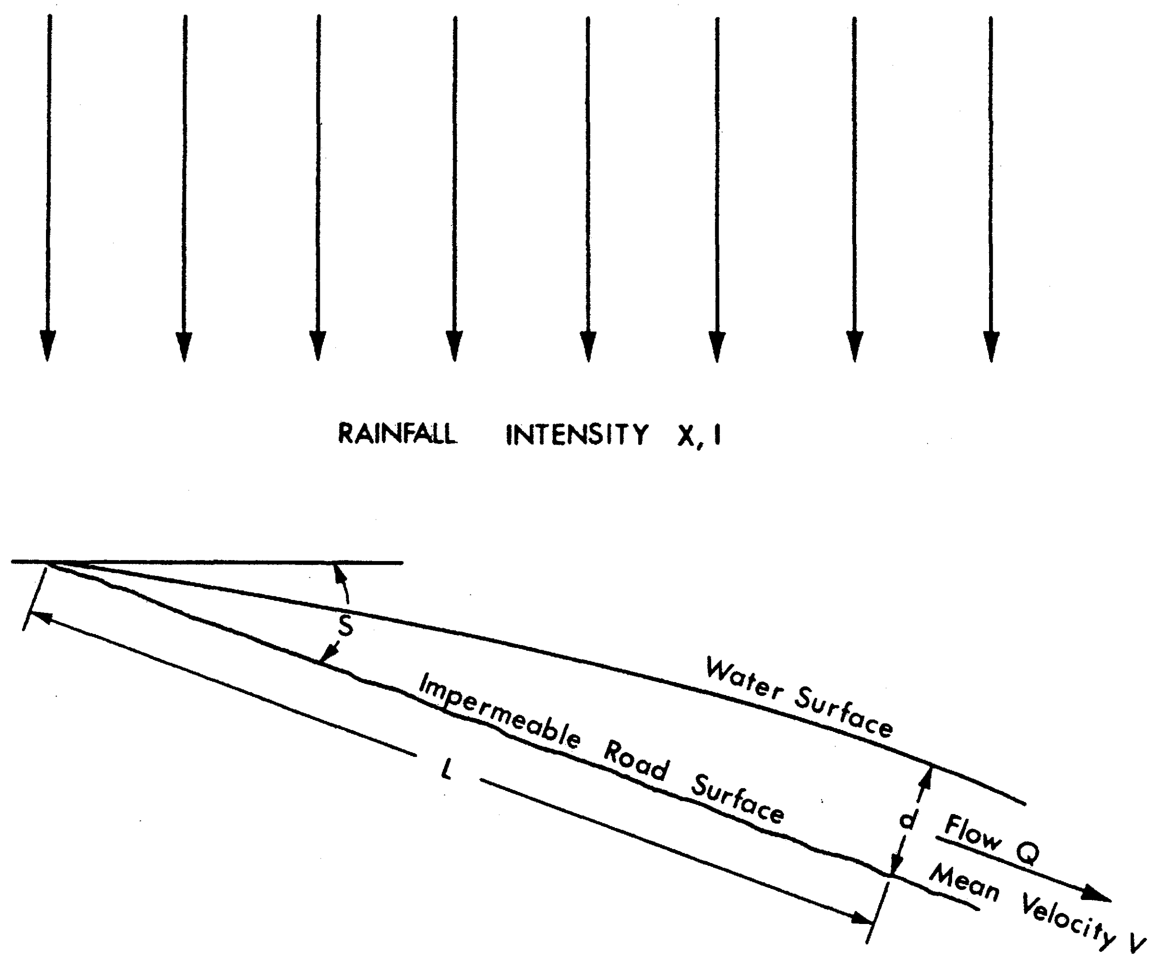

Figure 1. Diagrammatic representation of water flow over an impermeable road surface.

heavy spray. The need to remove rain water quickly from roads is even more important on multi-lane highways where greater water depths can be expected in the outside lanes. In addition, providing adequate texture in the road surface to allow escape of the remaining water under the tire is very important to achieve necessary tire-pavement adhesion, particularly on high-speed highways. A given lane of a modern highway surface is normally constructed to a slight plane cross slope. In practice, however, highways are not perfectly plane and do not always possess cross slope.

Water will flow across a surface along a line, the resultant slope of which depends on the transverse cross slope or super-elevation and longitudinal gradient (29). The slope of the flow path is

$$\frac{1}{S_3} = \sqrt{\frac{1}{S_1}^2 + \frac{1}{S_2}^2} = \sqrt{\frac{S_1^{\,2} + S_2^{\,2}}{S_1^{\,2} S_2^{\,2}}} \qquad (1)$$

where

S_3 = slope of the resultant flow path;

S_1 = cross slope; and

S_2 = longitudinal gradient.

The length of the flow path is given by

$$L_f = L\frac{S_1}{S_3} = L\sqrt{1 + \left(\frac{S_1}{S_2}\right)^2} \qquad (2)$$

where

L_f = length of flow path (ft); and

L = pavement width (ft).

An indication of the effects of various cross slope and longitudinal gradient combinations on drainage lengths as obtained from Eq. 2 are given in Table 1 for a pavement width of 24 feet. It can be seen that steep longitudinal gradients and flat cross slopes markedly increase drainage lengths.

TABLE 1

EFFECT OF CROSS SLOPE AND LONGITUDINAL GRADIENT ON DRAINAGE LENGTH

Cross Slope S_1	Longitudinal Gradient S_2	Drainage Length L_f	Increase in Drainage Length*
In/Ft	Percent	Ft	Percent
1/16	0	24	---
1/16	1	54	124
1/16	2½	122	410
1/16	5	242	910
1/16	10	480	1900
3/8	0	24	---
3/8	1	26	6
3/8	2½	32	34
3/8	5	49	106
3/8	10	90	274

*With respect to a zero longitudinal gradient.

The existence of longitudinal gradient not only increases the flow-path length but increases the water depth along the lower side of the road relative to the flat longitudinal gradient case. The problem is further complicated by horizontal and vertical curves and combinations thereof as well as at-grade intersections.

A major benefit of steep cross slope is the reduction in the volume of water which can pond in pavement deformations. This is particularly important on surfaces that exhibit wheel-track rutting in addition to localized deformations.

All road-surface types will drain surface water rapidly and reasonably completely if cross slopes are steep enough. However, the slope must not be steeper than that acceptable from general considerations of road safety, design, driveability, and appearance. Driving on steep, tangent cross slopes presents a safety hazard since the vehicle's tendency is to veer toward the low edge of the pavement. According to the American Association of State Highway Officials "Bluebook" (18), cross slopes up to ¼ inch per foot (1 in 48) are barely perceptible in relation to vehicle steering. Recommended AASHO (18) guidelines for cross slope with regard to surface type are given in Table 2. Note that cross slopes less than 1/8 inch per foot are not recommended.

TABLE 2

RECOMMENDED AASHO GUIDELINES FOR NORMAL RURAL HIGHWAY PAVEMENT CROSS SLOPES (18)

Surface	Range in Rate of Cross Slope			
Type	In/Ft	Ratio	Ft/Ft	Percent
High	1/8 - 1/4	1:96 - 1:48	0.010 - 0.020	1.0 - 2.0
Intermediate	3/16 - 3/8	1:72 - 1:36	0.015 - 0.030	1.5 - 3.0
Low	1/4 - 1/2	1:48 - 1:24	0.020 - 0.040	2.0 - 4.0

When a rainfall of constant intensity falls over a pavement surface, a series of events take place as follow (see Figure 2);

1) Initially a certain amount of water is required to fill the interstices of the surface before runoff occurs. This amount is referred to as "depression storage" and is measured in volume per unit area or average depth in inches. It depends on the initial wetness of the surface, degree of surface texture, deformations in the surface and cross slope.

2) After the amount of water required for depression storage is satisfied, runoff begins. The runoff rate increases to an equilibrium value, and for an impermeable surface, this rate is equal to the rainfall intensity. It is during this interval that the amount of water detained on the surface increases to a maximum value. The thin sheet of water on the surface at the time of constant runoff, excluding that required for depression storage, is called "surface detention." It has the same units as depression storage and can also be expressed as a value at a point or an average over an area. Surface detention depends primarily on the cross slope and rainfall intensity.

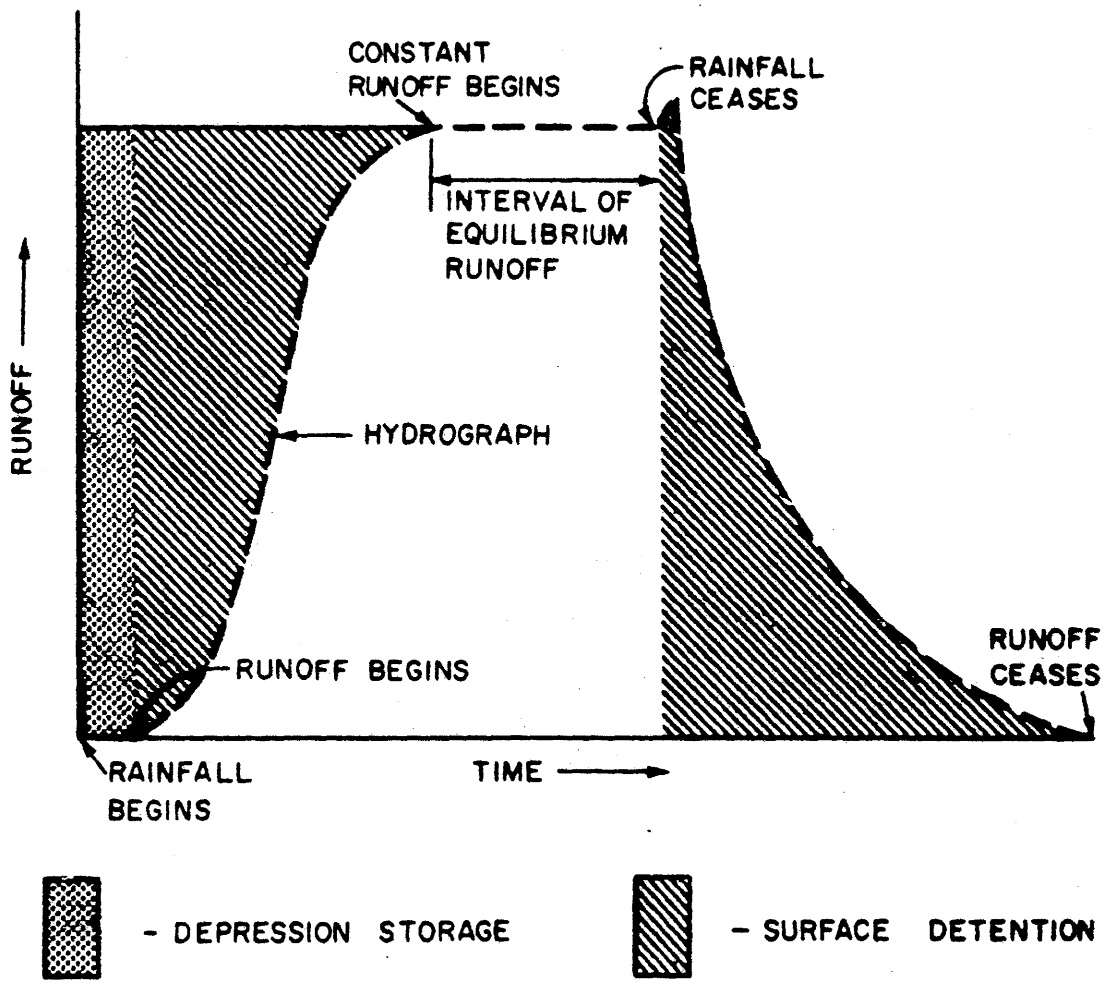

Figure 2. Rainfall runoff hydrograph.

3) When the rainfall ceases, the runoff rate decreases to zero while the depth of water held by surface detention also decreases to zero.

4) Water that is contained in depression storage decreases by surface evaporation.

Yu and McNoud (19) and Izzard (20) have reported that a momentary increase in runoff occurs immediately after the cessation of rainfall. This in effect indicates that rainfall impact increases the turbulence and hence increases the resistance to water flow over the surface during the period of rainfall.

In addition to reduced traction, surface-detention water contributes most of all to the problem of splashing during rainfall. Depression-storage water produces spray effects after runoff ceases which can persist quite long and cause marked reduction in clear visibility due to dirty water sprayed on the vehicle windshield.

Hydraulics of Water Flow

Early Investigations

Recognized research on the hydraulics of water flow evolved in 1775 with the investigations of Chezy (21). His formula for average flow velocity in canals was

$$V = C \sqrt{RS} \qquad (3)$$

where

V = average flow velocity (ft/sec);

C = Chezy discharge coefficient = $\sqrt{\frac{8g}{f}}$;

g = acceleration of gravity (ft/sec^2);

f = resistance coefficient;

R = hydraulic radius = $\frac{A}{WP}$;

A = cross sectional area of flow (ft^2);

WP = wetted perimeter (ft); and

S = slope of canal (ft/ft).

For semi-continuous (surface) flow the hydraulic radius reduces to water depth. Thus this early investigation indicated that the flow velocity--hence the time required to remove a quantity of water--varies directly with water depth and slope and indirectly with frictional resistance of the surface.

In 1981 (22) Manning proposed an equation which was extended to

$$V = \frac{1.5}{n} R^{2/3} S^{1/2} \tag{4}$$

or

$$Q = AV = A\frac{1.5}{n} R^{2/3} S^{1/2} \tag{5}$$

where n is the Manning roughness coefficient. For surface flow R reduces to the water depth d, hence, the equation becomes

$$Q = \frac{1.5}{n} A d^{2/3} S^{1/2} \tag{6}$$

Roughness coefficients were found to vary from 0.010 for very smooth glass to 0.050 for rocky stream beds.

The so-called "rational formula" (23) is also used. The expression is

$$Q = \frac{C I A}{43,200} \tag{7}$$

where

Q = flow rate (ft^3/sec);

I = rainfall intensity (in/hr);

A = area over which rainfall occurs (ft^2); and

C = coefficient which depends on the permeability and to a lesser extent the slope of the drainage area.

The equation states that the rate of runoff equals the rate of supply (rainfall excess) if the rain lasts long enough for the entire area to contribute. For an impervious area the runoff equals the rainfall supply and C = 1.

Thus

$$Q = \frac{I\ W\ L}{43,200} \tag{8}$$

where

W = width of drainage area:

L = length of drainage area; and

A = W x L

and for a unit width on an impervious surface

$$Q = \frac{I\ L}{43,200} \tag{9}$$

From the continuity principle (21) of fluid flow the following relationship is given:

$$Q = VA \tag{10}$$

where

Q = flow rate (ft^3/sec);

V - flow velocity (ft/sec); and

A = cross sectional area of flow.

Substituting Eq. 10 in Eq. 9 produces

$$A = \frac{I\ L}{43,200\ V} \tag{11}$$

and for a unit width of flow

$$A = Wd = 1d \tag{12}$$

where

W = width of flow; and

d = depth of flow

thus

$$d = \frac{I\ L}{43,200\ V} \tag{13}$$

Researchers (24) in hydraulics have suggested equations of the general form

$$V = Kd^{\alpha} S^{\beta} \tag{14}$$

where

V = velocity of flow;

d = depth of flow:

S = slope; and

K, α, β = constants

for expressing the relationship between velocity, depth, and slope. The expression for d in Eq. 13 will then take form of

$$d = K \frac{(LI)^m}{(S)^n} \tag{15}$$

where

$m = 1/(\alpha + 1)$; and

$n = \beta/(\alpha + 1)$.

Equation 15 represents the general expression relating water depth to length of drainage path, rainfall intensity and pavement cross slope. It has been experimentally determined (25) that for the particular case of laminar flow the indices in Eq. 15 would be 0.33 for both m and n.

When flow of thin films of water is laminar and steady, the resistance to flow is solely due to viscous shear. It has been experimentally determined (25), however, that free surface flow becomes unstable when the Froude number $V/\sqrt{gd}$ exceeds 2 and the Reynolds number Vd/ν exceeds 500. In these expressions V is the average flow velocity, d is water depth and ν is the kinematic viscosity. Thus on slopes greater than 1 in 42 where the water depth is greater than 0.08 inch, the water flow will tend to be non-laminar even on perfectly plane surfaces. With the combination of rough texture and the disturbing effect of raindrops on pavement surfaces, water flow is probably never laminar during rainfall.

Pertinent Research

The first significant research on the hydraulics of flow across paved surfaces was that of Horton in 1938 (26). He derived a theoretical formula describing the runoff hydrograph as

$$Q = I \tanh^{M} \left[\frac{M+1}{M} (IK)^{\frac{1}{M}} \frac{T}{60}\right] \quad (16)$$

where

Q = discharge at lower end of elemental strip of the surface (ft^3/sec/acre);

I = rainfall intensity (in/hr);

M = factor dependent on type of flow;

T = time from beginning of rainfall (min);

K = 1020S/ZnL;

S = slope of surface (percent);

n = coefficient of surface roughness;

L = length of flow path (ft); and

Z = factor of turbulence = 3/4 (3.0-M).

In 1946, Izzard (20) reported on extensive, practical experiments of overland flow. His tests were on long flumes having various slopes and surfaces. The time required for the flow to be 97 percent of the supply, i.e., the time to equilibrium, was found to be

$$t_e = \frac{2 \; V_e}{60 \; q_e} \quad (17)$$

where

t_e = equilibrium time (min); and

V_e = volume of water in surface detention at equilibrium (ft^3)

and the equilibrium flow for a strip of unit width was

$$q_e = \frac{I\ L}{43,200} \tag{18}$$

where

q_e = equilibrium discharge (ft^3/sec);

I = rainfall intensity (in/hr); and

L = distance of overload flow (ft).

Izzard found the volume of detention on the strip at equilibrium to be

$$V_e = kLq_e^{1/3} = \frac{kL^{4/3}I^{1/3}}{35.1} \tag{19}$$

where

$$k = \frac{0.007I+c}{S^{1/3}}; \tag{20}$$

S = slope (ft/ft); and

c = retardance coefficient which ranged from 0.007 for very smooth asphalt pavement to 0.017 for tar and gravel pavement.

Izzard also determined that the form of the overload flow hydrograph could be presented as a dimensionless graph; thus offering a means by which one might design street and parking-lot drainage structures.

Recently, researchers at the British Road Research Laboratory conducted extensive experiments on actual road surfaces to determine the relations between rainfall intensity, length of drainage path, slope, and water-film depths for the surface types most common on high speed roads in the United Kingdom (27, 28, 29). The surfaces, composed of brushed concrete and rolled asphalt with chippings, were extremely coarse textured having average texture depths of 0.072 in. and 0.095 in., respectively, as measured by the sand method. A large tilting platform which could be sprayed with water to simulate rainfall of various intensities was used. Cross slopes ranging from 1 in 24 (½ in/ft) to 1 in 400 (1/32 in/ft) and rainfall intensities over the range of 0.5 in/hr to 10 in/hr were used in the testing process.

Formulas for determining water depths on the surfaces were developed from experimental data. These were based on both individual depth measurements at various distances from the high end of the platform and on the amount of water retained on the surface during rainfall. The two measurement methods gave almost identical relationships for both types of surface. In addition, the distributions of water on the surfaces were very similar, which indicated that, based on the hydraulics of the rain-water flow, the surfaces could be considered to have similar roughnesses and equivalent water depths. The researchers concluded that raindrop impact was probably the significant factor affecting shallow water flow.

It is important to note, however, that the British tests were confined to extremely coarse-textured surfaces which do not generally exist on high-speed highways of the United States. Increasing the pavement slope from 1 in 60 to 1 in 30 decreased the water depth by only 11 percent, and it was concluded that the major benefit of a steep slope would be a reduction in water which could collect in the pavement deformations. This conclusion may or may not be the case with smoother-textured surfaces.

The general equation relating water depth to drainage length, rainfall intensity, and slope was determined by the British to be

$$d = \frac{0.005\ (LI)^{0.47}}{S^{0.20}} \tag{20}$$

where

d = water depth (in);

I = rainfall intensity (in/hr);

L = drainage length (ft); and

S = slope (ft/ft).

This equation includes empirically determined numerical values for the coefficient and exponents in the basic continuity equation and surface flow equations of Chezy and Manning cited earlier.

Equation 20, in which the water depth (d) is measured from a datum plane at the top of the texture, would only be valid for conditions when the water depth was above the top of the texture; the reason being that L, I and S are always positive thus precluding a negative d (water depth below top of the texture).

TEST FACILITIES AND PROCEDURES

Surface Types

Nine test surfaces were placed on individual 28½-foot long by 4-foot wide, double tee, prestressed, concrete beams. Each surface represented a section of a highway surface 2 lanes wide taken perpendicular to the direction of travel as depicted in Figure 3. A leveling course of concrete

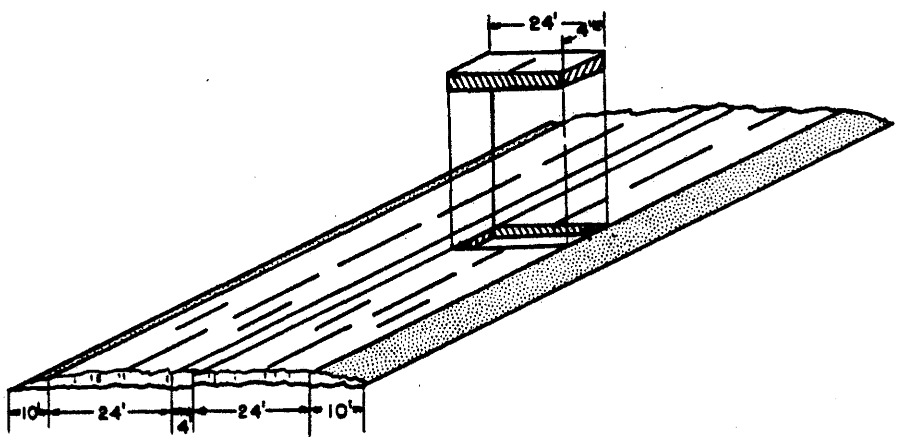

Figure 3. Representation of surface element.

was applied to each beam prior to placement of the test surface. The leveling was necessary since about 2½ inches of camber was placed in each beam during manufacturing. The desired textures for the two concrete surfaces were applied to the leveling mix since further surfacing was not required. Figures 4 and 5 contain pictures of placing a concrete and hot mix asphalt mixture, respectively. The surface treatments were applied directly to the concrete.

Descriptions of the surfaces are given in Table 3. The surfaces were chosen so as to contain the range of textures found on Texas highway pavements. Previous research had indicated that on a random sample of 41 Texas highway pavements, textures ranged from 0.00 to 0.07 inch (30). Photographs and textural profiles of the surfaces are shown in Figures 6 and 7 respectively. The range of surface texture built into the surfaces placed on the beams is 0.003 to 0.164 and the individual texture values are listed in Table 3. Depending on such features as design, construction and amount and type of service, a seal coat in the field may have a texture value greater than 0.164; however, in the survey made and reported in (30) no such surface was encountered. It was nevertheless considered advisable to include such a surface in this study.

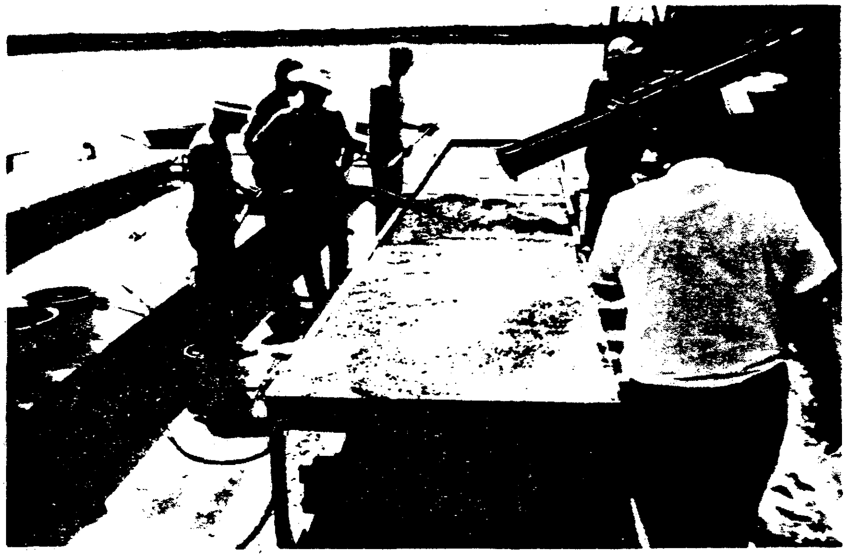

Figure 4. Placing leveling course of concrete on beam.

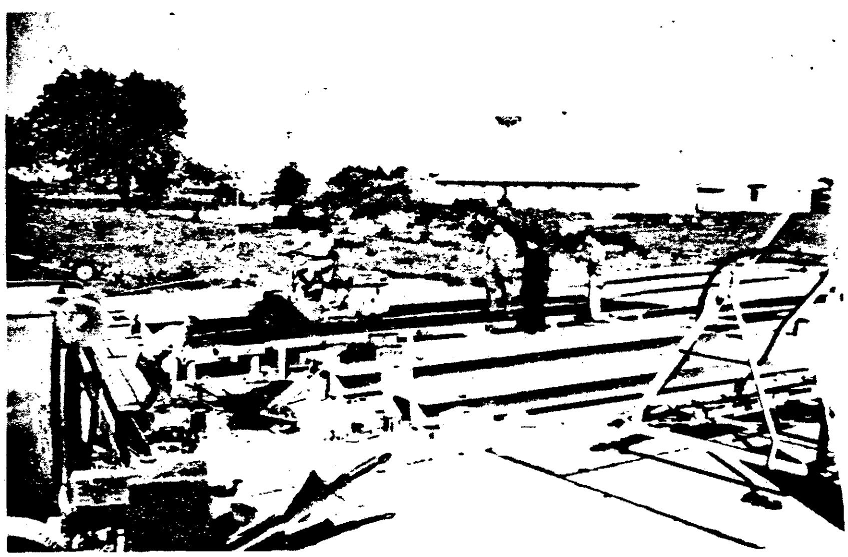

Figure 5. Placing asphalt surface on beam.

TABLE 3

DESCRIPTIONS OF THE SURFACES PLACED ON THE BEAMS

Surface Number	Surface Type	Aggregate Maximum Size, in.	Texas Highway Department Specifications	Average Texture Depth, ** in.
1	Rounded Siliceous Gravel Portland Cement Concrete (Transverse drag)*	3/4	Class A Item 364	0.035
1A	Rounded Siliceous Gravel Portland Cement Concrete (Longitudinal drag)*	3/4	Class A Item 364	0.036
2	Clay Filled Tar Emulsion (Jennite) Seal	No Aggregate	——	0.009
3	Crushed Limestone Aggregate Hot Mix Asphalt Concrete (Terrazzo Finish)	1/2	Type D Item 340	0.003
4	Crushed Siliceous Gravel Hot Mix Asphalt Concrete	1/4	Type F Item 340	0.019
5	Rounded Siliceous Gravel Hot Mix Asphalt Concrete	5/8	Type C Item 340	0.039
6	Rounded Siliceous Gravel Surface Treatment (Chip Seal)	1/2	Grade 4 Item 320	0.141
7	Synthetic Lightweight Aggregate Surface Treatment (Chip Seal)	1/2	Grade 4 Item 320	0.164
8	Synthetic Lightweight Aggregate Hot Mix Asphalt Concrete	1/2	Type L Sp. Item 2103	0.020

*With respect to direction of vehicular travel

**Obtained by Putty Impression Method (31)

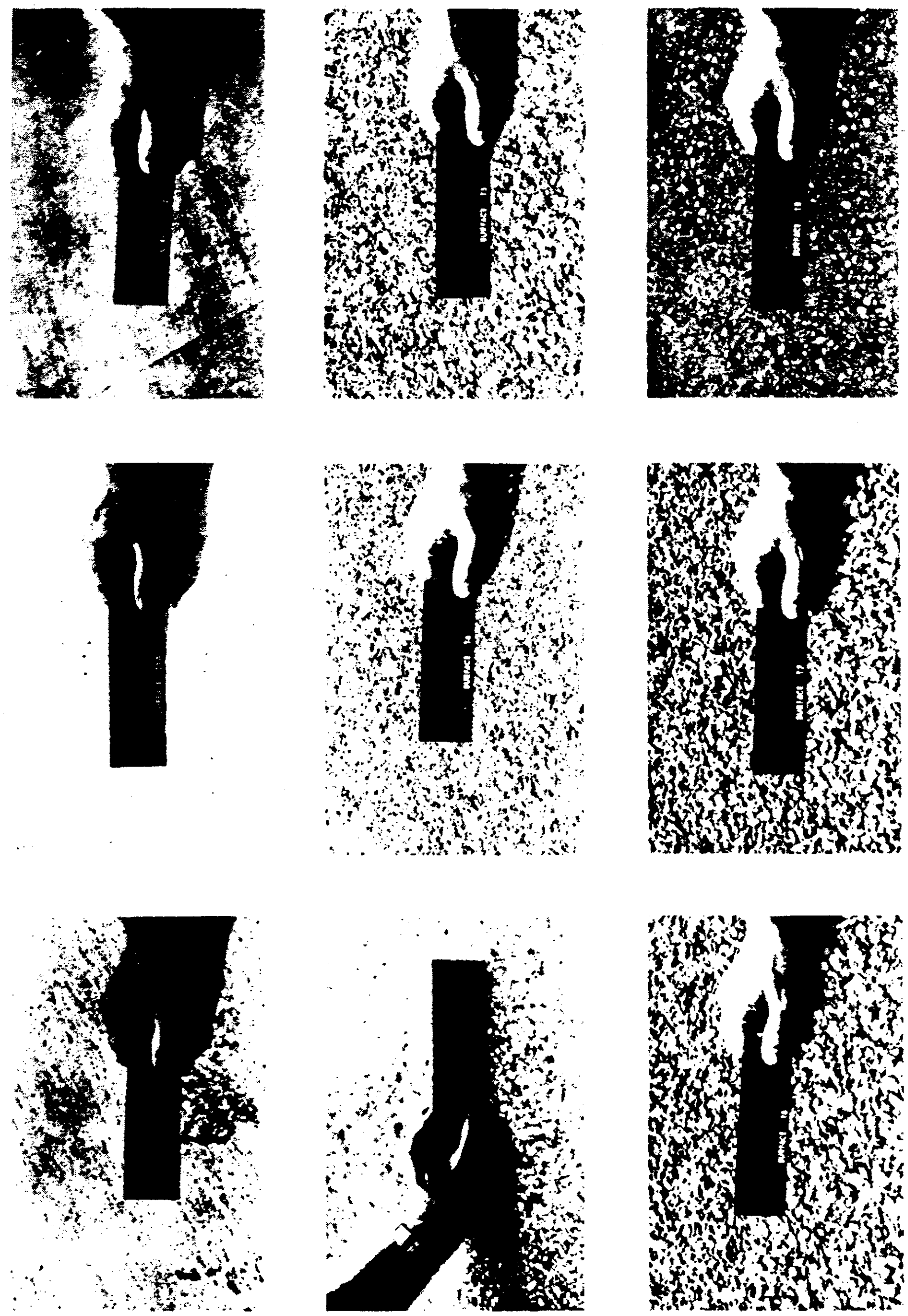

Figure 6. Photographs of the surfaces.

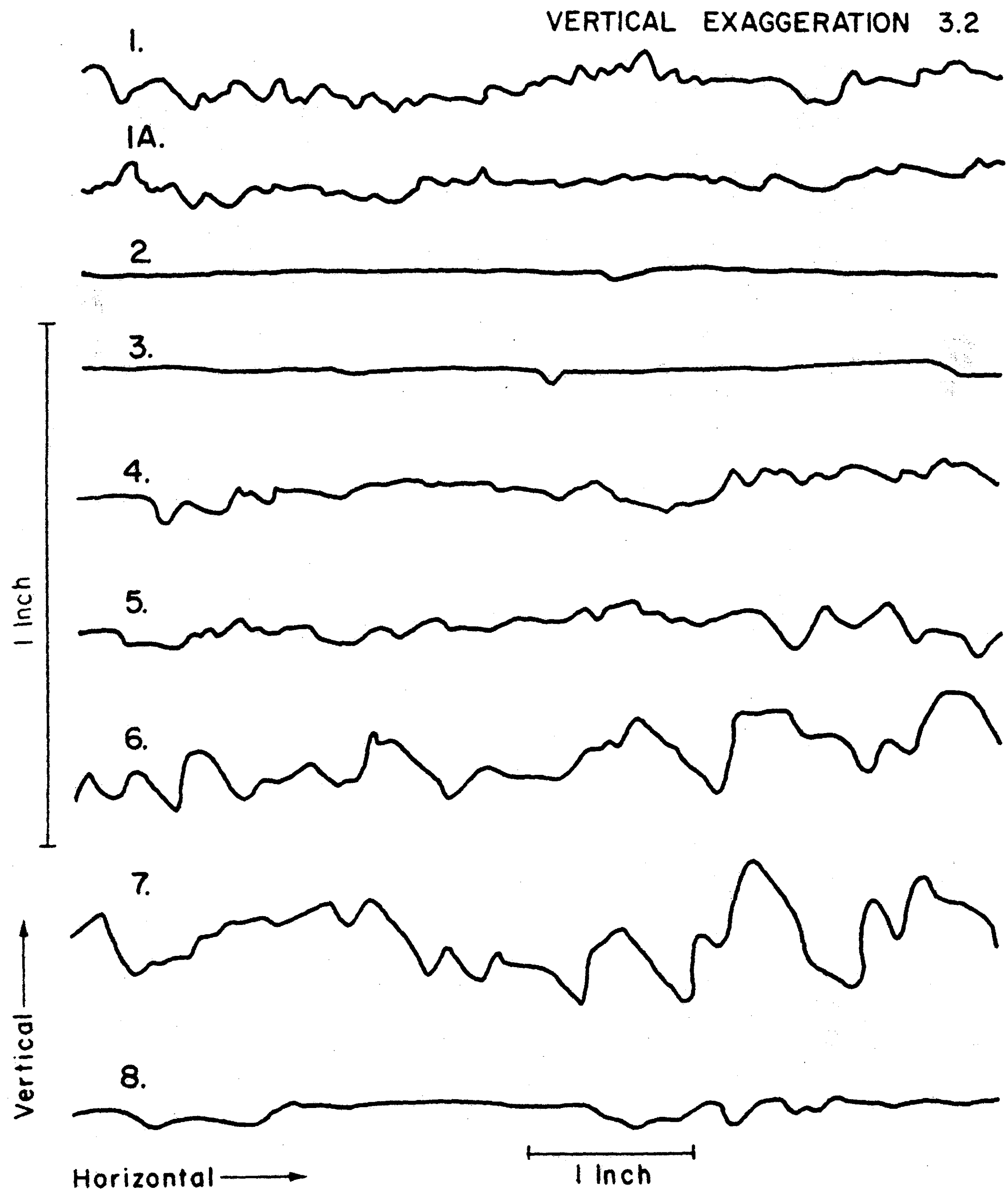

Figure 7. Textural profiles of the surfaces.

Equipment

A general view of the test equipment is shown in Figure 8 and a detailed plan view is given in Figure 9. The tests were conducted inside a former airfield hanger in order to minimize wind effects. Following are descriptions of the various components.

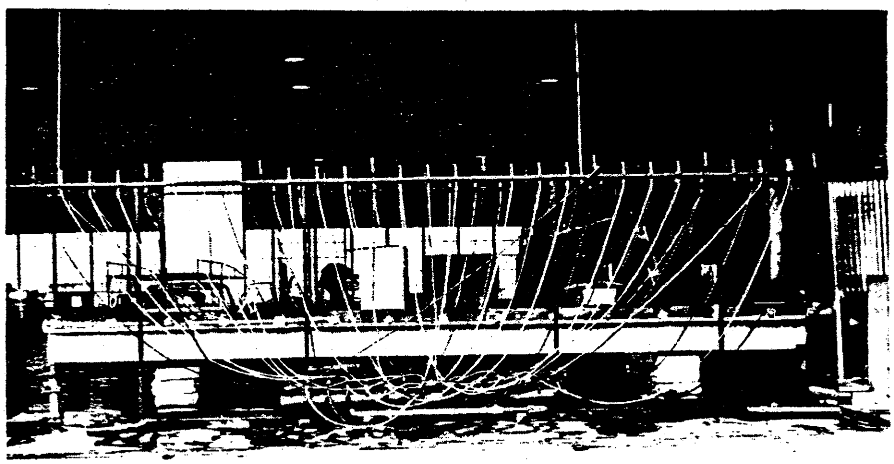

Figure 8. General view of test equipment.

The two 30-foot long by 9-foot high frames used to support the 58 U. S. Forest Service Type F nozzles were composed of 4-inch wide by 1-inch deep channel iron. The upper horizontal channels were attached to the vertical channels in such a manner that the upper channels could be pivoted thus permitting the water spray from the nozzles to be directed over the test surface. The nozzles, located approximately 1 foot to the sides and 5 feet above the test surface, were equally spaced 1 foot apart on the two frames. These nozzles differed only in the size of the orifice as given in

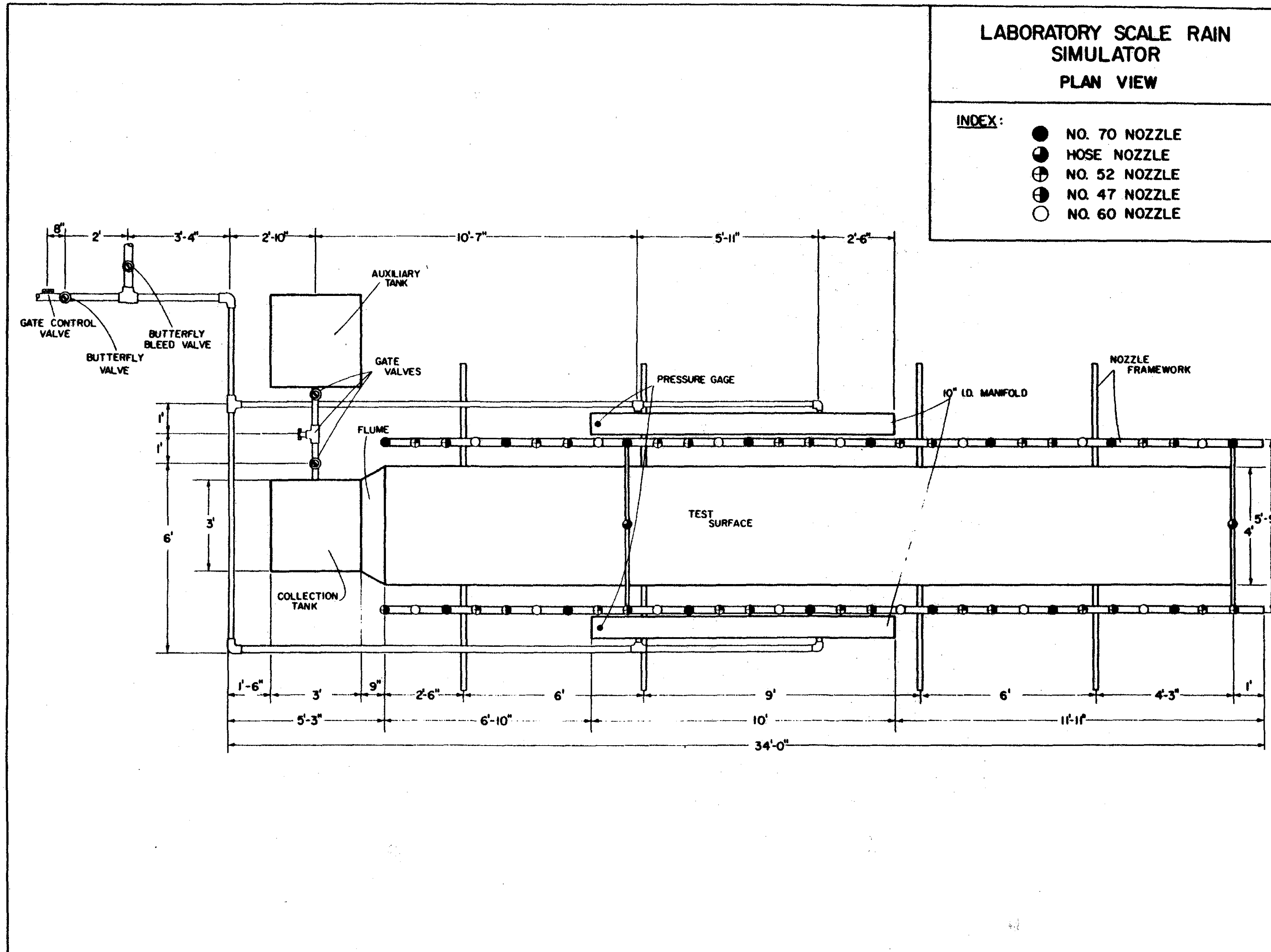

Figure 9. Detailed plan view of test equipment.

Figure 9. The orifices were placed so that every fourth nozzle had the same size orifice. This same pattern was followed on the opposite side; however, the spacing of similar orifices was offset by two nozzles so that when nozzles of a given size orifice were operating the rainfall spray would tend to be more uniform on the surface.

The two-hose type nozzles were placed directly over the test surface. One was centered at the upper end and the other centered nine feet from the lower end of the surface. This placement permitted uniform water spray over the surface. The nozzles, located 15 feet above the surface, sprayed a circular pattern; however, only the portion falling on the surface contributed to the intensity. One-half inch pipes attached to the top of the frame served as support for the nozzles. Photographs of the two nozzle types and their constituent components are given in Figure 10.

Two 10-foot long, 10-inch diameter, metal pipes sealed at both ends served as manifolds. One-half inch pipe couplings were used for connections between the ½-inch hose and manifolds. Gate valves were placed between each coupling and hose. The upper ends of the hose were attached to the upper channels.

Water was supplied to the manifolds through a 2-inch diameter pipe. Flow and pressure were controlled by both a gate valve and butterfly valve. Another butterfly valve was used for an instant bleeder valve. Water pressure gages were placed in both manifolds to monitor the water pressure.

The end of the test surface which was to simulate the outer or lower edge of the pavement was placed 4 feet above the floor on a specially designed stand. This stand was bolted to the concrete floor so as to

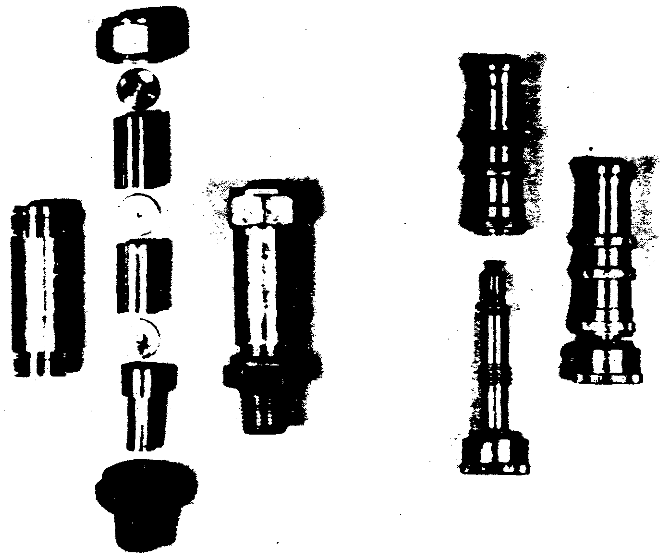

Figure 10. Nozzles used in study.

prevent the beam from moving. The outer end of the beam was placed directly on two, 2-foot high, 5-ton mechanical jacks. The jacks had a throw of 12 inches. It was therefore necessary to use a 2-inch spacer between the jack and beam in order to achieve the desired range of cross slopes.

Six-inch wide, 1-inch thick, redwood strips were attached to each side and the upper end of the beam. The strips extended 2 inches above the surface. The strips were required to prevent the water from running off the side of the beam and thus confine it to the 4-foot wide surface. The space between the strips and the surface was sealed with caulking compound. An aluminum flume was placed on the lower end of the beam for the purpose of directing the water into the collecting tank.

A 3-foot square by 2-foot deep metal tank was used to collect the water at the lower end of the beam. An auxiliary tank with similar dimensions was connected to the tank and used in combination for the higher rainfall rates. For the lower rainfall rates only one tank was needed since the capacity was sufficient to accommodate the discharge (Fig. 11).

A Stevens Type F Recorder was used for maintaining a graphic record of water-level rise in the tank plotted against time. In operation, the horizontal chart drum is turned in response to float action which is proportional to changes in water levels. The stylus is moved to the right across the width of the chart paper at a constant speed controlled by a clock. After the rate of water rise in the tank becomes constant, the

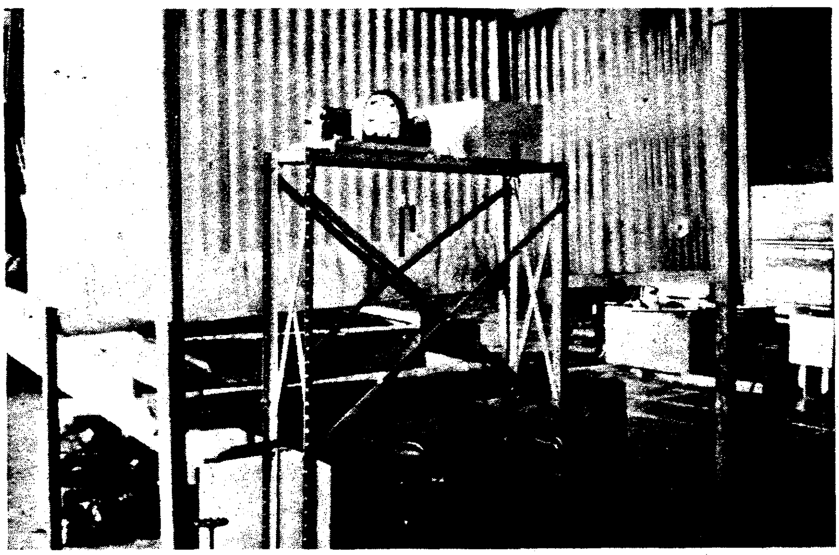

Figure 11. General view of runoff collection equipment.

rainfall intensity over the surface can be deduced from the time rate of water level rise in the tank. The recorder was positioned directly over the collecting tank and a stilling well was used to protect the float from turbulence (Fig. 12).

A Leupold and Stevens point gage was used for measuring the water depths on the surfaces. The metric scale vernier can be read directly to

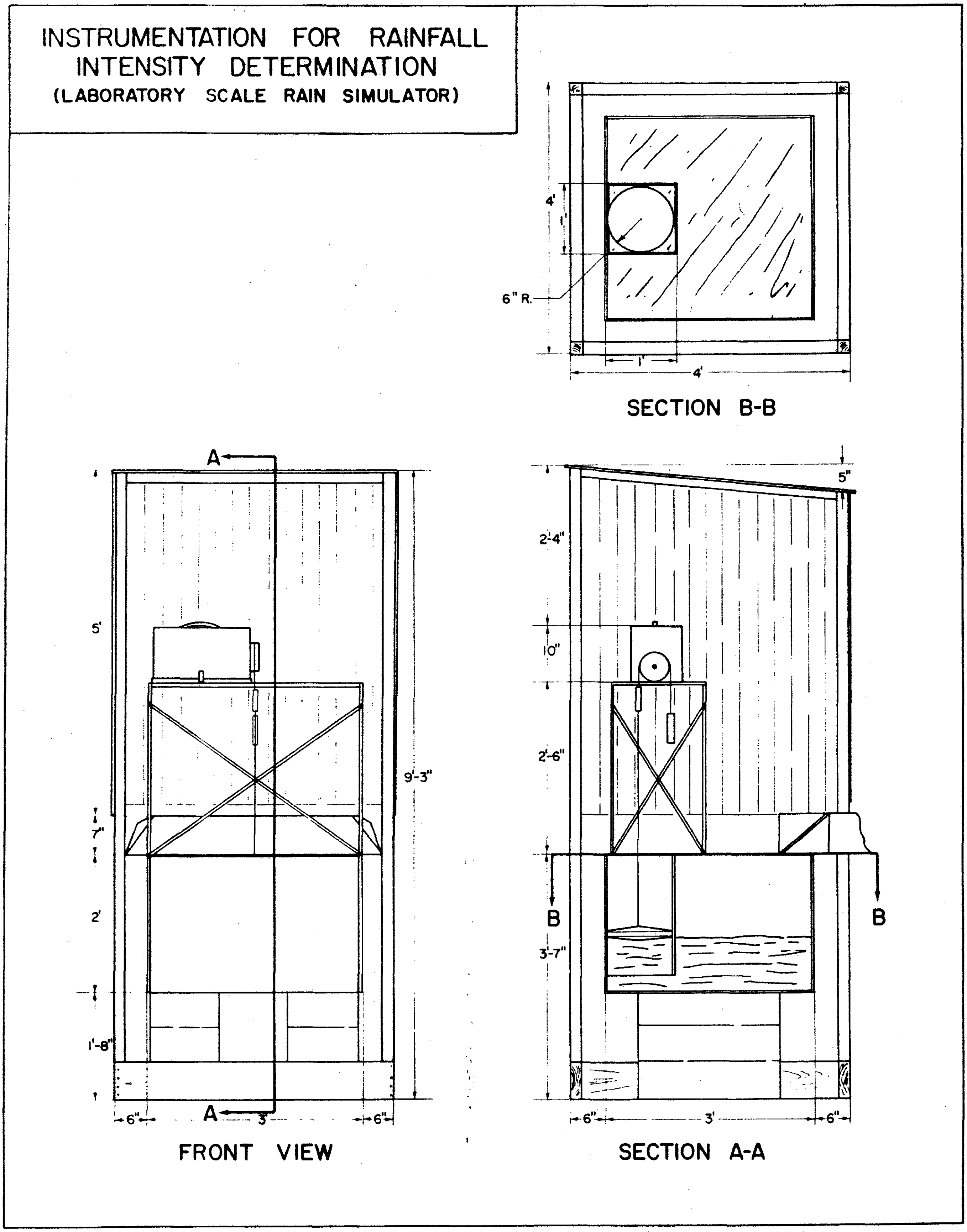

Figure 12. Detailed drawing of runoff collection equipment.

the nearest 0.2 mm. The gage was attached to a 46-inch long stand as shown in Figure 13. The gage could be moved along the full length of the stand and measurements taken accordingly.

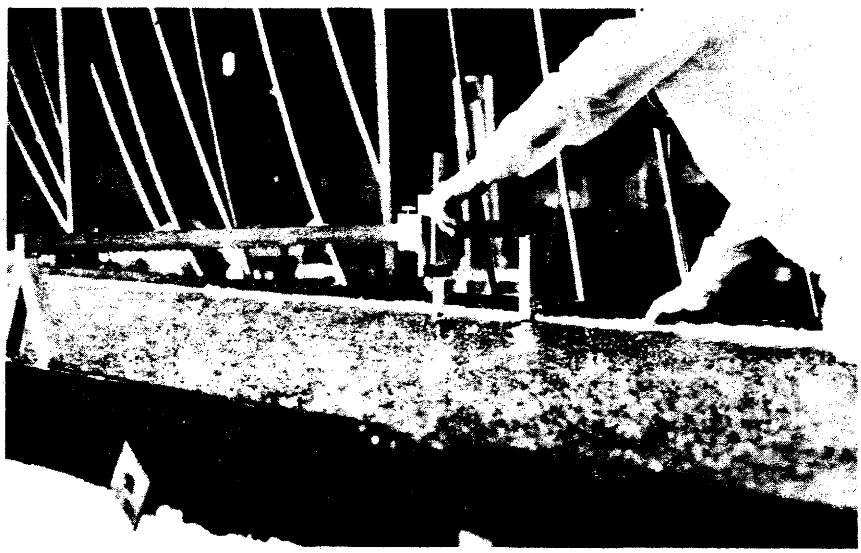

Figure 13. Point gage used for measuring water depth.

The silicone putty impression method was used for assessing the degree of surface macrotexture (Fig. 14). This method was initially developed as a means of providing surface-texture correction-factors for nuclear-density measurements and has also been used in pavement-friction research (30, 32). Equipment consists of 1) a 6-inch diameter by 1-inch thick metal plate with a 4-inch diameter, 1/16-inch deep recess machined into one side, and 2) a 15.90-gram ball of silicone putty. When placed on a smooth surface, 15.90 grams of putty will smooth out to a 4-inch diameter circle, 1/16-inch deep, thus completely filling the recess.

Figure 14. Silicone putty impression method for measuring surface macrotexture.

The silicone putty is formed into an approximate sphere and 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 road surface. The more irregular the surface texture (the higher the macrotexture) the smaller the resulting putty diameter because more material is required to fill the surface texture. Average texture depth, based on volume per unit area, is calculated from an average of four diameter measurements.

Testing Procedure

A methodical test procedure was used for each surface. Five water depth measurements, spaced equidistant across the width of the surface, were taken at four locations (approximately six feet intervals) along the drainage length of the surface. Measurements were taken at approximately 6, 12, 18, and 24 feet as measured from the upper end of the drainage area.

These 20 measurements were repeated for each cross slope-rainfall intensity combination. Twenty-five series as indicated in Table 4 were used. An additional five series at a cross slope of 1 in/ft (1:12) were taken on three surfaces. A minimum of 500 depth measurements were taken on each surface.

Zero measurements were first taken at each test spot. These were necessary in order to establish a datum plane at the top of the texture from which subsequent water-depth measurements could be referenced. Diagrammatic representations of the zero reading and water-depth readings are shown in Figure 15. A metal disk (2.125 inches in diameter) was incorporated into the zero measurements; however, its thickness was added to the gage reading as depicted in Figure 15a. Both positive (i.e., above top of texture) and negative (i.e., below top of texture) water depths were recorded.

It was desirable for the rain drop size to increase as the rainfall intensity was increased. This requirement necessitated the use of different size nozzle-orifices; the larger orifices produced higher intensities and correspondingly larger drop sizes. The intensity could also be varied by regulating the water pressure and changing the number of nozzles.

TABLE 4

TESTING SERIES

Series	Cross Slope			Approximate Rainfall Intensities
	in/ft	ft/ft	percent	in/hr
A1 - A5	1/16	1:192	0.52	0.50, 1.00, 2.00, 3.50, 5.50
B6 - B10	1/8	1:96	1.04	0.50, 1.00, 2.00, 3.50, 5.50
C11 - C15	1/4	1:48	2.08	0.50, 1.00, 2.00, 3.50, 5.50
D16 - D20	3/8	1:36	2.78	0.50, 1.00, 2.00, 3.50, 5.50
E21 - E25	1/2	1:24	4.17	0.50, 1.00, 2.00, 3.50, 5.50
F26*- F30*	1	1:12	8.33	0.50, 1.00, 2.00, 3.50, 5.50

*Only taken on three surfaces.

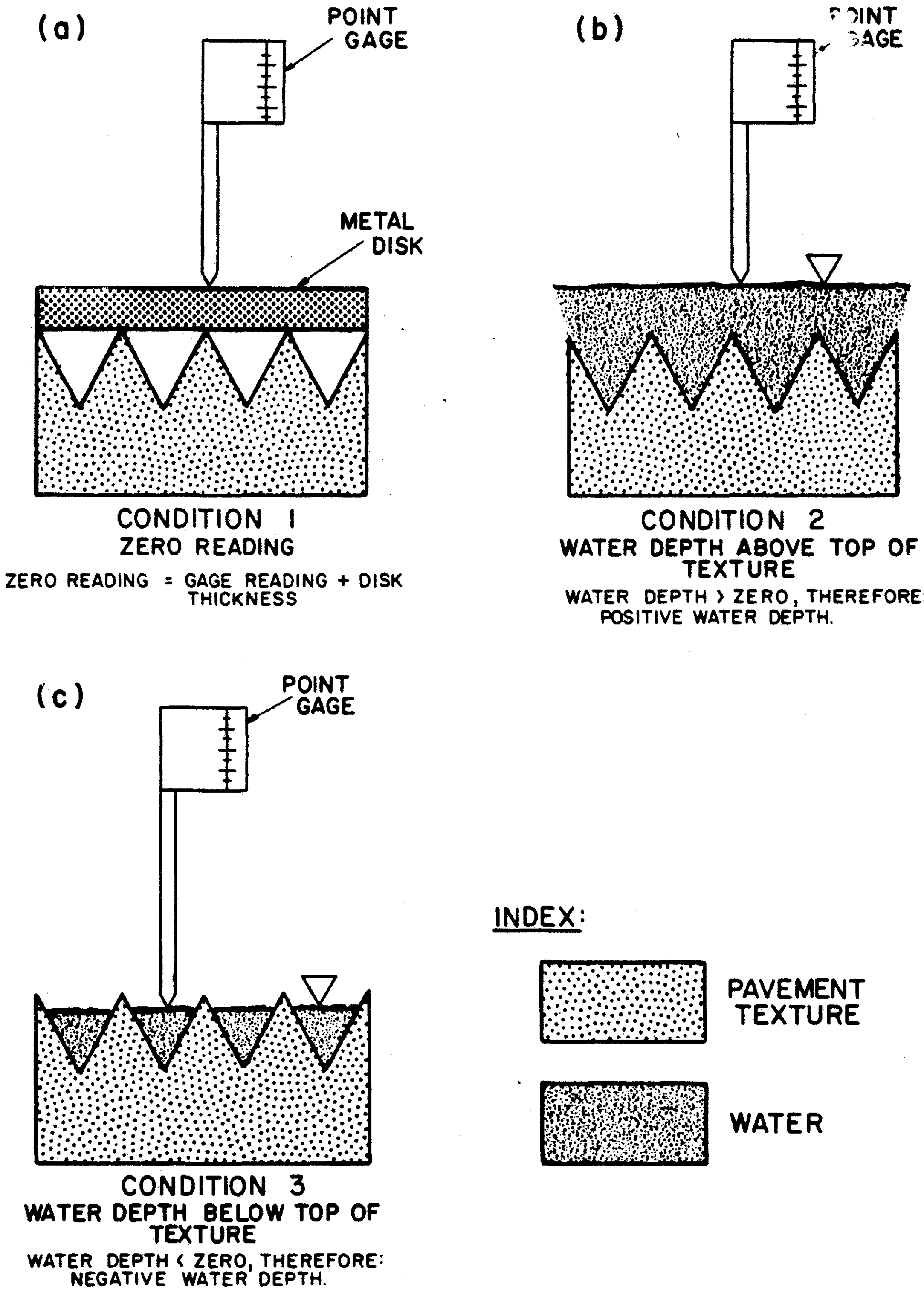

Figure 15. Diagrammatic representations of zero and water depth measurements.

A tabulation of orifice sizes, number of nozzles, and water-pressure combinations used to achieve the desired rainfall intensity and raindrop size is given in Table 5.

TABLE 5

ORIFICE SIZES, NUMBER OF NOZZLES, AND WATER PRESSURE COMBINATIONS USED

Approximate Rainfall Intensity (in/hr)	Number of Nozzles	Orifice Size (drill number)	Water Pressure (lbs/in^2)
0.50	2	hose type	25
1.00	15	70	30
2.00	15 14	70 60	15
3.50	15 14 14	70 60 52	10
5.50	15 14 14 15	70 60 52 47	12

At the conclusion of each set of measurements the rainfall was immediately stopped with the aid of the bleeder valve. At the same instant, a trough was placed under the flume and the water held in detention on the surface was diverted to a separate bucket (Fig. 16). A rubber squeegee was used to remove the depression-storage water (Fig. 17).

This volume of water held on the surface in the form of detention and depression storage was equated to an equivalent water depth in inches.

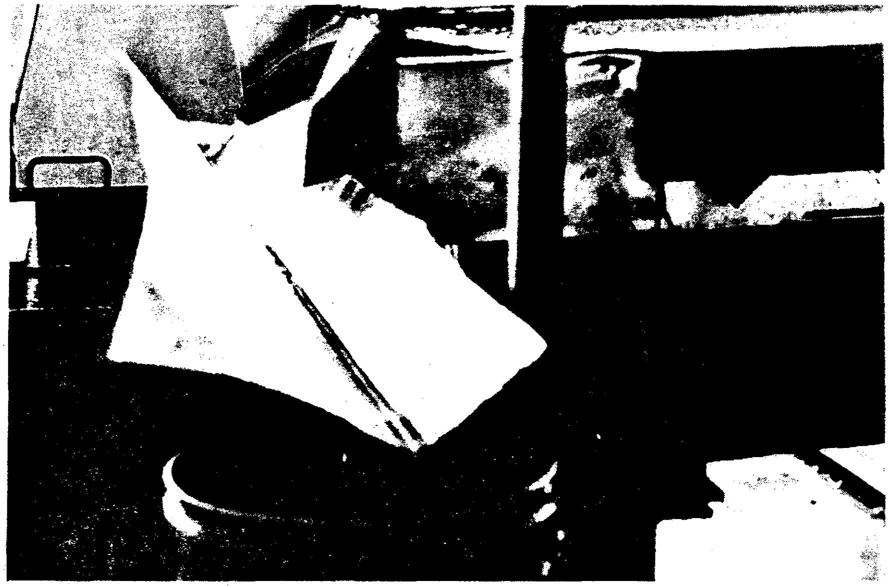

Figure 16. Method used to collect detention water.

This measure, termed 'average detention,' represents an average water depth on the surface above a datum plane at the bottom of the texture. Subtraction of the average texture depth for a particular surface from the average detention obtained under stated conditions moves the reference datum to the top of the texture. Thus the degree to which the asperity tips were or were not covered with water can be determined.

Figure 17. Rubber squeegee used for removal of depression-storage water.

ANALYSIS AND DISCUSSION OF TEST RESULTS

Data from the water-depth measurements taken at various locations on each surface are given in Table 10, Appendix A. These depths are referenced to a datum plane at the top of the road texture and provide a series of depth values corresponding to values of cross slope, rainfall intensity, and drainage-path length. Data from the average surface-detention measurements are also included in Table 10.

The water depth and detention data for each surface were analyzed using a computerized multiple-regression program to obtain the best fit of the data. These relationships for each surface are given in Tables 11, 12, and 13, Appendix B. Equations were derived for determining water depths based on both the top and bottom of the texture datum-planes. Since a logarithmic model was used, the equations based on the top of the texture datum-plane are only valid for water depths greater than zero. When the water depth above the texture approaches zero or becomes negative, equations based on a datum plane at the bottom of the texture must be used with appropriate average texture-depths subtracted from the resulting water depths. The subtraction shifts the datum plane to the top fo the texture. Logarithmic models do not accept zero or negative values.

As noted in Tables 11, 12, and 13, very high correlation coefficients were obtained for each relationship. This indicates that the three independent variables: length of drainage path, rainfall intensity, and cross slope largely influence the resulting water depths on surfaces of a given texture.

In order to determine the relative influence of macrotexture on water depth and average detention, the data from all surfaces were grouped together along with corresponding macrotexture for each surface. The combined surfaces were then analyzed both with and without texture as a variable. These overall relationship are given in Tables 6 and 7.

TABLE 6

STATISTICAL CORRELATION OF WATER-DEPTH MEASUREMENTS TAKEN DURING RAINFALL FOR ALL SURFACES

Datum Plane	Equation Number	Regression Equation	Coefficient of Determination R^2
Bottom of Texture*	21A	$d = 1.63 \times 10^{-3} (LI)^{.55} (1/S)^{.43}$	0.77
	21B	$d = 2.54 \times 10^{-3} (1/T)^{-.11} (LI)^{.55} (1/S)^{.42}$	0.80
	21C	$d = 2.12 \times 10^{-3} (L)^{.44} (I)^{.60} (1/S)^{.43}$	0.78
	21D	$d = 3.38 \times 10^{-3} (1/T)^{-.11} (L)^{.43} (I)^{.59} (1/S)^{.42}$	0.81
Top of Texture**	21E	$d = 0.55 \times 10^{-3} (LI)^{.66} (1/S)^{.43}$	0.46
	21F	$d = 0.038 \times 10^{-3} (1/T)^{.42} (LI)^{.79} (1/S)^{.56}$	0.61
	21G	$d = 0.84 \times 10^{-3} (L)^{.48} (I)^{.74} (1/S)^{.43}$	0.47
	21H	$d = 0.061 \times 10^{-3} (1/T)^{.42} (L)^{.58} (I)^{.87} (1/S)^{.56}$	0.62

*Can be changed to top of texture datum plane by subtracting average texture depth from water depth

**Only valid for water depths greater than zero. If water depth is near or less than zero, then use set of equations based on bottom of texture datum plane.

d = water depth, in.
L = length of drainage path, ft
I = rainfall intensity, in/hr
S = cross slope, ft/ft
T = average texture depth, in.
All terms significant at 5 percent level

TABLE 7

STATISTICAL CORRELATION OF AVERAGE WATER-DEPTH DETENTION MEASUREMENTS FOR ALL SURFACES

Datum Plane	Equation Number	Regression Equation	Coefficient of Determination R^2
Bottom of Texture*	22A	$Det = 7.95 \times 10^{-3} (I)^{.57} (1/S)^{.31}$	0.80
	22B	$Det = 11.80 \times 10^{-3} (1/T)^{-.11} (I)^{.57} (1/S)^{.31}$	0.85
Top of Texture**	22C	$Det = 1.44 \times 10^{-3} (I)^{.51} (1/S)^{.54}$	0.39
	22D	$Det = 0.05 \times 10^{-3} (1/T)^{.58} (I)^{.78} (1/S)^{.69}$	0.70

*Can be changed to top of texture datum plane by subtracting average texture depth from water depth.

**Only valid for water depths somewhat greater than zero. If water depth is near or less than zero, then use set based on bottom of texture datum plane.

Det = average water depth detention, in. (for L = 28 ft.)
I = rainfall intensity, in/hr
S = cross slope, ft/ft
T = average texture depth, in.

All terms significant at 5 percent level

Correlation coefficients for all surfaces combined were somewhat lower than those obtained when the surfaces were analyzed separately; however, the inclusion of texture in the expressions increased the degree of correlation, particularly in the cases where the datum plane was referenced to the top of the texture. Overall, datum planes referenced to the bottom of the texture gave the higher correlation coefficients. Similar results were obtained from the detention relationships.

Tabular representations and graphical plots of the relative effects of the variables on water depths are given in Table 8 and Figure 18, respectively. These values were determined from the highest correlation, overall experimentally obtained equation

$$d = \left[3.38 \times 10^{-3} (1/T)^{-.11} (L)^{.43} (I)^{.59} (1/S)^{.42}\right] - T \quad (23)$$

where

d = average water depth above the texture (in);

T = average texture depth (in);

L = drainage path length (ft);

I = rainfall intensity (in/hr); and

S = cross slope (ft/ft).

In its original form the equation was based on a datum plane at the bottom of the texture; however, subtraction of texture depth from the obtained depth shifts the datum plane to the top of the texture. The equation is valid for all water depths with negative values indicating water depths below the top of the texture.

As noted in Table 8, increases in cross slope result in corresponding decreases in water depths. The effect is more pronounced at the flatter cross slopes. For example, increasing cross slope rate from 1/16 (1/192) to 1/4 (1/48) in/ft will decrease the corresponding water depth by 62 percent of its 1/16 in/ft value in the outside wheel path. Note, however, that cross slopes in excess of 1/4 in/ft do not reflect as much effect on resultant water depths, particularly when the magnitude of the cross-slope increments are given consideration.

An inverse relationship between macrotexture and water depth was also found. The effect increased at the higher macrotexture levels and was more pronounced at macrotexture levels greater than 0.050 inches.

As expected, water depths increased as drainage lengths increased.

As also expected, water depths decreased as rainfall intensities decreased. A rainfall intensity of about 0.3-in/hr would be required to encapsulate the asperities on a pavement surface having 0.03-in. texture,

TABLE 8

TABULAR REPRESENTATION OF THE RELATIVE EFFECTS OF CROSS SLOPE, TEXTURE, DRAINAGE LENGTH, AND RAINFALL INTENSITY ON WATER DEPTH

Constants	Variable Cross Slope in/ft	Resultant Water Depth in.	Percent Decrease
	1/16	0.074	
Texture, 0.03 in.	1/8	0.048	35
Length, 24 ft	1/4	0.028	62
Intensity, 1.5 in/hr	3/8	0.021	72
	1/2	0.013	82
	1	0.002	97

Constants	Variable Texture, in.	Resultant Water Depth in.	Percent Decrease
	0.005	0.059	
Length, 24 ft	0.015	0.057	3
Intensity, 1.5 in/hr	0.030	0.048	19
	0.050	0.038	36
Cross Slope, 1/8 in/ft	0.075	0.011	81
	0.125	-0.034	158

Constants	Variable Drainage Length ft	Resultant Water Depth in.	Percent Increase
	6	0.013	
Intensity, 1.5 in/hr	12	0.028	115
	18	0.039	200
Cross Slope, 1/8 in/ft	24	0.048	269
Texture, 0.03 in.	36	0.062	377
	48	0.074	469

Constants	Variable Rainfall Intensity, in/hr	Resultant Water Depth in.	Percent Decrease
	5.5	0.138	
Texture, 0.03 in.	3.5	0.098	29
Length, 24 ft	2.0	0.062	55
Cross Slope, 1/8 in/ft	1.0	0.031	77
	0.5	0.011	92
	0.1	-0.014	110

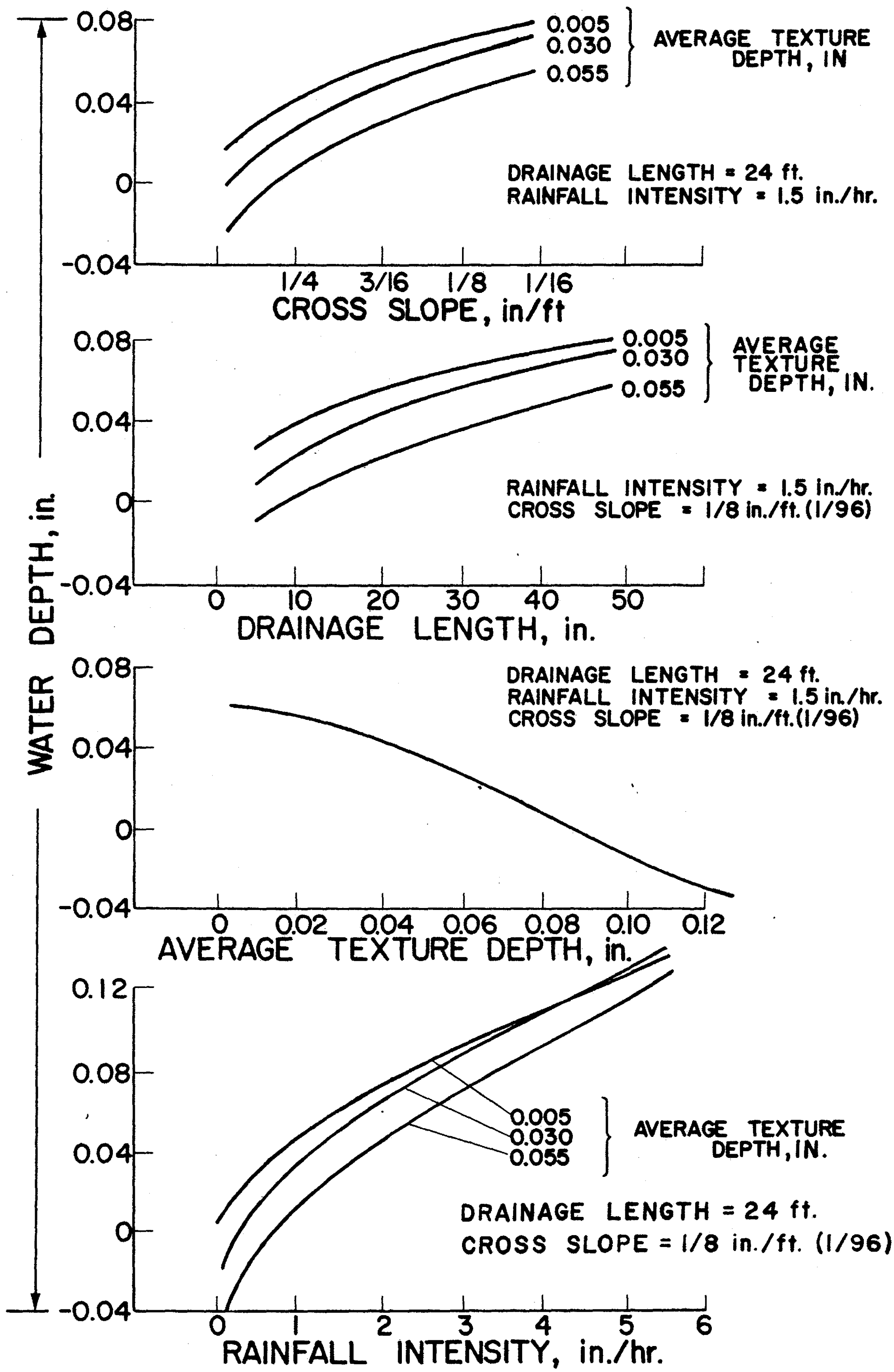

Figure 18. Plot of water depths versus variables for combined surfaces.

24-foot drainage length, and 1/8-in/ft cross slope.

Tabular representations and graphical plots of the relative effects of the variables on average surface detention are given in Table 9 and Figure 19, respectively. These values were determined from the overall experimentally obtained equation

$$\text{Det} = \left[11.80 \times 10^{-3} (1/T)^{-.11} (I)^{.57} (1/S)^{.31}\right] - T \qquad (24)$$

where

Det = average surface detention (in);

T = average texture depth (in);

I = rainfall intensity (in/hr); and

S = cross slope (ft/ft).

In its original form the equation was based on a datum plane at the bottom of the texture (neglecting depression-storage water); however, subtraction of the texture from the obtained depth shifts the datum plane to the top of the texture. The equation is valid for drainage lengths of 28 feet and less with negative values indicating average water depths below the top of the texture.

Pavement cross slope, macrotexture, and rainfall intensity were found to affect average surface detention in the same manners as the variables affected water-depth measurements, discussed previously. Increases in pavement cross slopes and macrotextures and decreases in rainfall intensities resulted in corresponding decreases in average surface detention. The average surface-detention measurements are somewhat limited in scope, however, since they are only based on 28-foot long drainage lengths.

In addition to the previous discussion of the relative effects of cross slope on water depth, another major benefit of a steeper cross slope would

TABLE 9

TABULAR REPRESENTATION OF THE RELATIVE EFFECTS OF CROSS SLOPE, TEXTURE, AND RAINFALL INTENSITY ON AVERAGE SURFACE DETENTION

Constants	Variable Cross Slope in/ft	Resultant Average Detention in.	Percent Decrease
Texture 0.03 in.	1/16	0.022	
	1/8	0.012	45
	1/4	0.004	82
	3/8	0.001	95
Intensity 1.5 in/hr	1/2	-0.003	114
	1	-0.008	136

Constants	Variable Texture in.	Resultant Average Detention in.	Percent Decrease
Cross Slope 1/8 in/ft	0.005	0.029	
	0.015	0.024	17
	0.030	0.012	59
	0.050	-0.006	121
Intensity 1.5 in/hr	0.075	-0.029	200
	0.125	-0.076	362

Constants	Variable Rainfall Intensity, in/hr	Resultant Average Detention in.	Percent Decrease
Texture 0.03 in.	5.5	0.057	
	3.5	0.038	33
	2.0	0.019	67
	1.0	0.003	95
Cross Slope 1/8 in/ft	0.5	-0.008	114
	0.1	-0.021	137

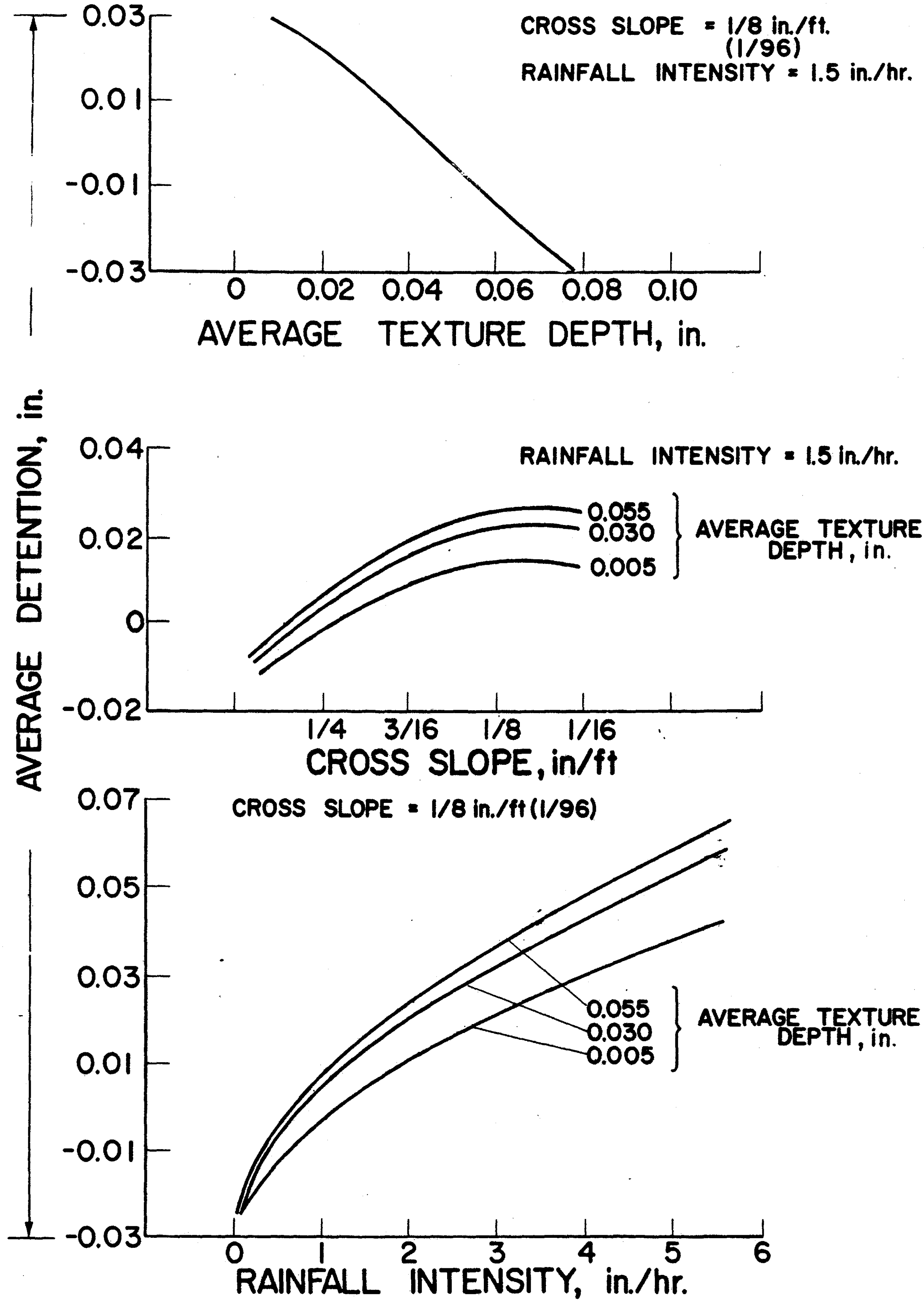

Figure 19. Plot of average surface detention versus variables for the combined surfaces.

be the reduced volume of water which could collect in pavement deformations. This is particularly so on flexible pavements where a certain amount of wheel-track depression almost always occurs because of compaction in the base and the surface. The use of paved shoulders may generally reduce the subsidence of the outside one-third of the traffic lane; such subsidence being caused previously by less construction compaction near the pavement edge and subsequently greater permanent deformation during service. Where highly compacted shoulders are used, permanent deformation can still be occurring in the traveled lanes; thus, after a period of time, a portion of the cross slope can be lost. Steeper cross slopes will reduce the effect.

It was observed during the experimental tests that after the cessation of rainfall, the steeper cross slopes drained the remaining surface water more quickly than did the flatter slopes. This is another benefit of steep cross slopes; particularly in areas of high humidity, low wind speed, and/or low temperatures. These conditions serve to increase the drying time and thus the length of the time the surface is wet. Steeper cross slopes would not only serve to remove the bulk of the water more quickly, but also would facilitate drainage of low areas and deformations.

Another possible means of reducing the wet-pavement exposure-time would be the use of a permeable surface which could absorb some of the rainfall and also permit ponded water to drain through the permeable layer to the pavement edge. Admittedly, this concept has some disadvantages.

CONCLUSIONS AND RECOMMENDATIONS

Increases in the minimum rates of pavement cross slopes appear to be warranted. It is recommended that cross slopes in the range 1/8 in/ft (1/96) to 3/8 in/ft (1/32) be used on high speed rural highways. The higher cross slope of 1/4 in/ft or more should be favored in areas with greater potential for wet weather accidents. This will not only reduce the water depth on pavements for a given rainfall intensity, but will also assist in providing for drainage of low areas and depressions that tend to lower the effectiveness of built-in cross slope. Steeper cross slopes will offer a margin of safety against ponding and subsequently long, wet-pavement exposure times. The adverse effects of excessive cross slope are recognized.

Essentially smooth-textured dense graded surfaces should not be used. Slight amounts of precipitation will result in water depths above the texture peaks and thus in poor effective drainage on these type surfaces. If such surfaces are used, a certain degree of permeability should be effected in the surface. The surface aggregate should be capable of puncturing the water film or drainage of the water into the surface should be possible.

It is suggested that research be conducted to determine the relative influences of ambient temperatures, wind velocities, and relative humidities on the drying rates of various pavement-surface types after rainfall of a given intensity has ceased. Drying rates are indicative of the time during which the pavement surface is wet. It is assumed that high relative humidity, low wind velocity, and low ambient temperature all contribute to increased exposure times and thus decreased drying rates for a given surface. Their relative effects and significance need to be determined in conjunction with the wind effects created by traffic.

An indirect method for measuring the friction contribution of microtexture would be helpful to the design engineer. Such a method should involve the use of presently used friction measuring equipment. From the research accomplished so far in this study it appears that the relationship between locked wheel skid and cornering slip at 40 mph may offer an indirect approach to the measurement of the contribution of microtexture.

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A P P E N D I X   A

TABLE 10

WATER DEPTH AND AVERAGE SURFACE-DETENTION DATA FOR EACH SURFACE TESTED

SURFACE NO. 1

ROUNDED SILICEOUS GRAVEL PORTLAND CEMENT CONCRETE, TRANVERSE DRAG*

Slope	Rainfall Intensity, in./hr.	Water Depth (in.) at drainage length (ft.) of				Average Detention, inches
		6.0	13.0	18.5	24.0	
	0.50	-0.012	-0.003	0.010	0.026	0.033
1 in 192	0.99	0.010	0.016	0.030	0.046	0.047
1/16 in/ft	2.28	0.036	0.048	0.069	0.090	0.068
1/2 %	3.47	0.049	0.081	0.097	0.105	0.086
	5.44	0.080	0.100	0.129	0.171	0.110
	0.53	-0.014	-0.018	-0.003	0.011	0.026
1 in 96	0.94	-0.004	-0.002	0.006	0.029	0.033
1/8 in/ft	2.11	0.014	0.026	0.032	0.041	0.044
1 %	3.42	0.028	0.049	0.069	0.072	0.056
	5.72	0.051	0.077	0.094	0.097	0.077
	0.60	-0.017	-0.018	-0.010	0.012	0.020
1 in 48	0.89	-0.016	-0.015	-0.002	0.018	0.027
1/4 in/ft	2.14	0.003	0.006	0.018	0.030	0.038
2 %	3.37	0.018	0.041	0.037	0.055	0.047
	6.05	0.052	0.060	0.068	0.096	0.066
	0.55	-0.018	-0.018	-0.012	0.001	0.018
1 in 36	0.90	-0.014	-0.012	-0.004	0.007	0.023
3/8 in/ft	2.16	0.009	0.009	0.014	0.033	0.034
3 %	3.82	0.017	0.023	0.038	0.052	0.046
	6.36	0.042	0.048	0.059	0.088	0.061
	0.63	-0.015	-0.020	-0.008	-0.006	0.017
1 in 24	0.98	-0.016	-0.018	-0.007	0.006	0.022
1/2 in/ft	2.33	0.001	0.014	0.011	0.031	0.032
4 %	3.76	0.014	0.029	0.029	0.051	0.042
	6.05	0.031	0.040	0.049	0.070	0.053

Average Texture Depth = 0.035 inches

*Tranverse to direction of vehicular travel

TABLE 10

(CONTINUED)

SURFACE NO. 1A

ROUNDED SILICEOUS GRAVEL PORTLAND CEMENT CONCRETE, LONGITUDINAL DRAG*

Slope	Rainfall Intensity, in./hr.	Water Depth (in.) at drainage length (ft.) of				Average Detention, inches
		6.0	12.0	18.0	24.0	
	0.56	-0.004	0.004	-0.002	0.007	0.035
1 in 192	0.84	0.001	0.015	0.023	0.030	0.041
1/16 in/ft	1.89	0.014	0.036	0.045	0.074	0.060
1/2 %	3.20	0.036	0.062	0.084	0.106	0.080
	5.32	0.060	0.091	0.124	0.150	0.107
	0.58	-0.008	-0.011	-0.018	-0.008	0.030
1 in 96	1.01	-0.004	0.004	0.010	0.012	0.036
1/8 in/ft	2.25	0.020	0.035	0.046	0.050	0.054
1 %	3.12	0.030	0.053	0.059	0.080	0.065
	5.52	0.055	0.084	0.092	0.106	0.091
	0.64	-0.016	-0.017	-0.014	-0.010	0.025
1 in 48	0.95	-0.004	-0.008	-0.003	0.001	0.028
1/4 in/ft	2.25	0.002	0.022	0.033	0.040	0.044
2 %	3.88	0.022	0.050	0.051	0.063	0.058
	5.45	0.037	0.057	0.061	0.082	0.069
	0.62	-0.025	-0.022	-0.030	-0.019	0.024
1 in 36	0.99	-0.019	-0.024	-0.018	-0.014	0.025
3/8 in/ft	2.14	-0.000	-0.003	0.008	0.017	0.037
3 %	3.29	0.008	0.020	0.010	0.033	0.047
	5.72	0.034	0.049	0.055	0.061	0.061
	0.64	-0.020	-0.018	-0.026	-0.009	0.019
1 in 24	1.00	-0.008	-0.007	-0.018	-0.002	0.024
1/2 in/ft	2.15	-0.006	0.002	-0.001	0.005	0.034
4 %	2.98	0.001	0.001	0.015	0.022	0.039
	5.55	0.021	0.034	0.035	0.050	0.055
	0.64	-0.033	-0.033	-0.033	-0.028	0.015
1 in 12	0.90	-0.031	-0.025	-0.026	-0.016	0.018
1 in/ft	1.93	-0.020	-0.009	-0.010	-0.006	0.027
8 %	3.47	-0.026	0.002	-0.006	0.015	0.033
	5.65	-0.022	0.001	0.006	0.017	0.041

Average Texture Depth = 0.036 inches

*Longitudinal to direction of vehicular travel

TABLE 10

(CONTINUED)

SURFACE NO. 2

CLAY FILLED TAR EMULSION (JENNITE) SEAL

Slope	Rainfall Intensity, in./hr.	Water Depth (in.) at drainage length (ft.) of				Average Detention, inches
		7.0	13.0	18.0	23.4	
	0.35	0.030	0.047	0.064	0.079	0.043
1 in 192	0.76	0.041	0.063	0.086	0.101	0.053
1/16 in/ft	1.85	0.069	0.092	0.110	0.124	0.072
1/2 %	2.92	0.089	0.110	0.130	0.146	0.090
	5.05	0.112	0.145	0.167	0.187	0.116
	0.22	0.005	0.011	0.014	0.014	0.020
1 in 96	0.91	0.024	0.031	0.037	0.043	0.034
1/8 in/ft	2.34	0.041	0.056	0.067	0.076	0.053
1 %	3.24	0.058	0.081	0.093	0.099	0.062
	4.66	0.081	0.101	0.115	0.130	0.075
	0.44	0.013	0.017	0.022	0.022	0.019
1 in 48	0.98	0.023	0.031	0.031	0.032	0.025
1/4 in/ft	2.10	0.042	0.048	0.057	0.054	0.036
2 %	3.22	0.061	0.069	0.072	0.076	0.042
	5.26	0.074	0.083	0.095	0.099	0.053
	0.51	0.008	0.018	0.018	0.018	0.018
1 in 36	0.96	0.014	0.023	0.024	0.025	0.022
3/8 in/ft	2.18	0.033	0.045	0.047	0.049	0.031
3 %	3.65	0.041	0.053	0.061	0.065	0.038
	5.35	0.059	0.065	0.076	0.075	0.047
	0.49	0.007	0.010	0.014	0.021	0.015
1 in 24	1.00	0.020	0.020	0.021	0.026	0.020
1/2 in/ft	1.85	0.024	0.028	0.036	0.042	0.024
4 %	3.50	0.042	0.045	0.051	0.057	0.033
	4.57	0.057	0.053	0.065	0.067	0.036

Average Texture Depth = 0.009 inches

TABLE 10

(CONTINUED)

SURFACE NO. 3

CRUSHED LIMESTONE AGGREGATE HOT MIX ASPHALT CONCRETE, TERRAZZO FINISH

Slope	Rainfall Intensity, in./hr.	Water Depth (in.) at drainage length (ft.) of				Average Detention, inches
		6.0	12.0	18.0	24.0	
	0.55	0.026	0.034	0.035	0.039	0.031
1 in 192	1.00	0.039	0.042	0.047	0.049	0.041
1/16 in/ft	2.00	0.064	0.070	0.074	0.079	0.062
1/2 %	3.34	0.079	0.087	0.095	0.099	0.078
	5.26	0.114	0.117	0.118	0.135	0.107
	0.63	0.020	0.023	0.026	0.028	0.025
1 in 96	1.06	0.031	0.031	0.040	0.047	0.037
1/8 in/ft	2.44	0.046	0.047	0.059	0.063	0.047
1 %	3.02	0.051	0.056	0.067	0.070	0.051
	5.34	0.070	0.079	0.087	0.095	0.071
	0.55	0.010	0.012	0.013	0.015	0.019
1 in 48	1.09	0.018	0.024	0.029	0.031	0.025
1/4 in/ft	2.14	0.033	0.038	0.051	0.059	0.032
2 %	3.03	0.038	0.041	0.055	0.058	0.035
	4.73	0.050	0.051	0.059	0.064	0.049
	0.58	0.010	0.012	0.019	0.021	0.017
1 in 36	1.06	0.019	0.024	0.030	0.032	0.021
3/8 in/ft	2.28	0.033	0.035	0.043	0.047	0.029
3 %	2.46	0.037	0.040	0.045	0.053	0.029
	4.82	0.041	0.045	0.058	0.063	0.041
	0.52	0.005	0.010	0.014	0.016	0.015
1 in 24	1.01	0.014	0.016	0.024	0.028	0.019
1/2 in/ft	2.15	0.030	0.031	0.039	0.043	0.024
4 %	2.90	0.033	0.035	0.043	0.051	0.028
	4.93	0.041	0.051	0.055	0.061	0.039
	0.53	0.003	0.008	0.010	0.014	0.012
1 in 12	1.04	0.010	0.018	0.018	0.022	0.015
1 in/ft	2.31	0.028	0.032	0.035	0.039	0.021
8 %	3.17	0.031	0.043	0.047	0.051	0.025
	5.05	0.035	0.045	0.049	0.055	0.032

Average Texture Depth = 0.003 inches

TABLE 10

(CONTINUED)

SURFACE NO. 4

CRUSHED SILICEOUS GRAVEL HOT MIX ASPHALT CONCRETE

Slope	Rainfall Intensity, in./hr.	Water Depth (in.) at drainage length (ft.) of				Average Detention, inches
		5.0	11.8	17.7	23.7	
	0.53	0.010	0.018	0.024	0.031	0.027
1 in 192	0.92	0.022	0.025	0.044	0.054	0.038
1/16 in/ft	2.21	0.032	0.041	0.072	0.096	0.062
1/2 %	3.11	0.045	0.061	0.105	0.135	0.073
	4.83	0.058	0.095	0.129	0.153	0.092
	0.53	0.004	0.004	0.016	0.024	0.018
1 in 96	0.97	0.018	0.019	0.031	0.036	0.027
1/8 in/ft	1.96	0.026	0.030	0.041	0.060	0.041
1 %	3.06	0.033	0.044	0.065	0.090	0.053
	5.78	0.050	0.070	0.102	0.123	0.080
	0.49	0.008	0.012	0.016	0.023	0.014
1 in 48	1.01	0.018	0.022	0.026	0.031	0.021
1/4 in/ft	2.25	0.023	0.031	0.037	0.044	0.033
2 %	3.32	0.030	0.042	0.054	0.057	0.042
	5.56	0.045	0.049	0.071	0.082	0.058
	0.52	0.001	0.004	0.008	0.010	0.013
1 in 36	0.93	0.006	0.014	0.018	0.025	0.018
3/8 in/ft	1.94	0.015	0.024	0.031	0.035	0.026
3 %	3.30	0.028	0.041	0.052	0.057	0.036
	5.35	0.039	0.061	0.066	0.081	0.051
	0.56	-0.005	-0.004	0.001	0.008	0.013
1 in 24	1.00	-0.002	0.004	0.009	0.014	0.018
1/2 in/ft	2.32	0.014	0.020	0.026	0.033	0.028
4 %	3.34	0.022	0.041	0.053	0.050	0.035
	5.48	0.031	0.055	0.065	0.071	0.046

Average Texture Depth = 0.019 inches

TABLE 10

(CONTINUED)

SURFACE NO. 5

ROUNDED SILICEOUS GRAVEL HOT MIX ASPHALT CONCRETE

Slope	Rainfall Intensity, in./hr.	Water Depth (in.) at drainage length (ft.) of				Average Detention, inches
		7.0	12.7	19.2	24.2	
	0.61	0.001	0.001	0.006	0.006	0.018
1 in 192	0.88	0.007	0.007	0.018	0.033	0.028
1/16 in/ft	1.82	0.026	0.030	0.059	0.068	0.045
1/2 %	3.56	0.061	0.073	0.107	0.118	0.083
	5.35	0.070	0.089	0.132	0.140	0.111
	0.59	0.003	-0.003	0.013	0.018	0.015
1 in 96	0.84	0.010	0.005	0.020	0.024	0.023
1/8 in/ft	2.12	0.027	0.033	0.059	0.064	0.044
1 %	2.98	0.034	0.045	0.067	0.075	0.055
	5.72	0.067	0.080	0.109	0.120	0.097
	0.63	-0.025	-0.018	-0.006	0.006	0.015
1 in 48	0.88	-0.020	-0.012	0.006	0.010	0.022
1/4 in/ft	1.93	0.019	0.029	0.041	0.045	0.035
2 %	3.02	0.040	0.050	0.072	0.084	0.045
	5.30	0.057	0.070	0.091	0.093	0.066
	0.63	-0.020	-0.015	-0.009	0.001	0.012
1 in 36	0.90	-0.010	-0.007	0.006	0.007	0.020
3/8 in/ft	1.98	0.014	0.022	0.030	0.031	0.033
3 %	3.30	0.030	0.040	0.054	0.061	0.045
	5.70	0.048	0.059	0.079	0.083	0.063
	0.62	-0.022	-0.015	-0.012	-0.003	0.014
1 in 24	0.89	-0.003	-0.003	0.006	0.003	0.018
1/2 in/ft	2.08	0.004	0.014	0.018	0.018	0.031
4 %	3.60	0.017	0.026	0.036	0.042	0.042
	5.84	0.035	0.050	0.065	0.073	0.057

Average Texture Depth = 0.039 inches

TABLE 10

(CONTINUED)

SURFACE NO. 6

ROUNDED SILICEOUS GRAVEL SURFACE TREATMENT

Slope	Rainfall Intensity, in./hr.	Water Depth (in.) at drainage length (ft.) of 6.0	12.0	18.0	24.0	Average Detention, inches
	0.32	-0.111	-0.092	-0.063	-0.041	0.008
1 in 192	0.61	-0.080	-0.051	-0.030	-0.017	0.025
1/16 in/ft	1.93	-0.042	-0.023	0.014	0.045	0.058
1/2 %	2.48	-0.019	0.008	0.043	0.079	0.075
	5.47	0.006	0.050	0.097	0.125	0.125
	0.36	-0.124	-0.112	-0.084	-0.066	0.011
1 in 96	0.64	-0.094	-0.085	-0.067	-0.048	0.022
1/8 in/ft	1.73	-0.061	-0.042	-0.034	0.010	0.047
1 %	2.70	-0.048	-0.018	0.002	0.056	0.067
	5.56	-0.018	0.020	0.054	0.111	0.110
	0.49	-0.134	-0.130	-0.116	-0.089	0.012
1 in 48	0.66	-0.118	-0.112	-0.091	-0.072	0.023
1/4 in/ft	1.88	-0.089	-0.052	-0.040	-0.006	0.040
2 %	3.05	-0.071	-0.040	-0.018	0.026	0.062
	5.44	-0.041	-0.023	0.012	0.072	0.088
	0.41	-0.159	-0.135	-0.121	-0.100	0.009
1 in 36	0.73	-0.130	-0.112	-0.097	-0.083	0.021
3/8 in/ft	1.95	-0.108	-0.080	-0.063	-0.036	0.045
3 %	2.74	-0.091	-0.065	-0.046	-0.011	0.053
	5.37	-0.053	-0.023	-0.001	0.036	0.082
	0.49	-0.165	-0.137	-0.122	-0.094	0.013
1 in 24	0.77	-0.141	-0.116	-0.097	-0.081	0.021
1/2 in/ft	1.98	-0.114	-0.072	-0.068	-0.060	0.042
4 %	3.06	-0.096	-0.057	-0.042	-0.033	0.058
	5.49	-0.065	-0.037	-0.019	-0.002	0.075

Average Texture Depth = 0.141 inches

TABLE 10

(CONTINUED)

SURFACE NO. 7

SYNTHETIC LIGHTWEIGHT AGGREGATE SURFACE TREATMENT

Slope	Rainfall Intensity, in./hr.	Water Depth (in.) at drainage length (ft.) of				Average Detention, inches
		6.0	12.0	18.0	24.0	
	0.44	-0.154	-0.145	-0.117	-0.085	0.025
1 in 192	0.76	-0.116	-0.110	-0.070	-0.038	0.040
1/16 in/ft	1.99	-0.077	-0.036	-0.020	0.030	0.082
1/2 %	3.21	-0.039	0.015	0.040	0.073	0.119
	5.30	0.001	0.061	0.093	0.127	0.156
	0.45	-0.204	-0.152	-0.151	-0.092	0.024
1 in 96	0.81	-0.124	-0.120	-0.104	-0.045	0.043
1/8 in/ft	2.04	-0.101	-0.057	-0.039	0.018	0.076
1 %	2.54	-0.101	-0.045	-0.017	0.045	0.091
	5.50	-0.059	0.001	0.034	0.095	0.138
	0.46	-0.272	-0.221	-0.179	-0.148	0.026
1 in 48	0.81	-0.215	-0.176	-0.124	-0.109	0.036
1/4 in/ft	1.85	-0.175	-0.132	-0.093	-0.046	0.063
2 %	3.06	-0.121	-0.069	-0.045	0.016	0.086
	5.45	-0.077	-0.031	0.006	0.067	0.119
	0.50	-0.286	-0.231	-0.207	-0.200	0.024
1 in 36	0.82	-0.245	-0.201	-0.166	-0.124	0.034
3/8 in/ft	1.92	-0.199	-0.134	-0.097	-0.048	0.060
3 %	2.58	-0.167	-0.112	-0.083	-0.033	0.074
	5.00	-0.128	-0.047	-0.017	0.029	0.108
	0.44	-0.242	-0.234	-0.203	-0.156	0.020
1 in 24	0.76	-0.222	-0.211	-0.172	-0.132	0.031
1/2 in/ft	1.88	-0.199	-0.137	-0.109	-0.061	0.053
4 %	2.72	-0.167	-0.103	-0.080	-0.029	0.072
	5.20	-0.135	-0.057	-0.017	0.018	0.106
	0.49	-0.283	-0.271	-0.236	-0.194	0.020
1 in 12	0.85	-0.259	-0.227	-0.205	-0.162	0.033
1 in/ft	2.01	-0.230	-0.166	-0.132	-0.081	0.053
8 %	3.05	-0.198	-0.125	-0.109	-0.053	0.069
	5.27	-0.160	-0.077	-0.057	-0.030	0.089

Average Texture Depth = 0.164 inches

TABLE 10

(CONTINUED)

SURFACE NO. 8

SYNTHETIC LIGHTWEIGHT AGGREGATE HOT MIX ASPHALT CONCRETE

Slope	Rainfall Intensity, in./hr.	Water Depth (in.) at drainage length (ft.) of				Average Detention, inches
		6.0	12.0	18.0	24.0	
	0.29	-0.011	0.008	0.016	0.022	0.021
1 in 192	0.90	0.018	0.025	0.043	0.054	0.038
1/16 in/ft	2.39	0.026	0.041	0.072	0.093	0.061
1/2 %	3.27	0.033	0.061	0.110	0.135	0.074
	5.63	0.063	0.096	0.162	0.188	0.101
	0.48	-0.002	0.004	0.013	0.016	0.017
1 in 96	0.84	0.014	0.018	0.024	0.031	0.024
1/8 in/ft	2.26	0.031	0.038	0.055	0.059	0.038
1 %	2.75	0.032	0.051	0.065	0.070	0.044
	5.61	0.041	0.067	0.102	0.119	0.072
	0.48	0.006	0.006	0.008	0.010	0.012
1 in 48	0.85	0.013	0.018	0.020	0.024	0.018
1/4 in/ft	2.16	0.015	0.028	0.040	0.037	0.027
2 %	3.16	0.027	0.041	0.049	0.058	0.035
	5.48	0.033	0.059	0.070	0.076	0.050
	0.45	-0.012	-0.007	0.003	0.010	0.009
1 in 36	0.82	0.005	0.006	0.012	0.016	0.015
3/8 in/ft	2.02	0.013	0.020	0.024	0.031	0.022
3 %	3.13	0.022	0.038	0.039	0.044	0.030
	5.09	0.033	0.058	0.062	0.071	0.039
	0.49	-0.016	-0.006	-0.004	0.002	0.010
1 in 24	0.78	-0.004	-0.002	0.006	0.016	0.012
1/2 in/ft	2.06	0.004	0.010	0.018	0.028	0.020
4 %	3.29	0.010	0.021	0.026	0.040	0.029
	5.06	0.016	0.030	0.034	0.047	0.036

Average Texture Depth = 0.020 inches

A P P E N D I X   B

TABLE 11

REGRESSION EQUATIONS FOR WATER DEPTHS TAKEN DURING RAINFALL -- BASED ON DATUM PLANE AT TOP OF TEXTURE

Surface	Regression Equation*	Correlation Coefficient R	Coefficient of Determination R^2
1	$d = 2.3 \times 10^{-5} (LI)^{1.13} (1/S)^{.72}$	0.89	0.79
	$d = 3.6 \times 10^{-5} (L)^{.88} (I)^{1.25} (1/S)^{.74}$	0.90	0.81
1A	$d = 1.96 \times 10^{-6} (LI)^{1.45} (1/S)^{.98}$	0.84	0.70
	$d = 2.89 \times 10^{-6} (L)^{1.03} (I)^{1.75} (1/S)^{1.07}$	0.87	0.75
	$d = 4.00 \times 10^{-6} (LI)^{1.06} (1/S)^{1.12}$**	0.73	0.53
	$d = 4.41 \times 10^{-6} (L)^{.60} (I)^{1.66} (1/S)^{1.24}$**	0.80	0.64
2	$d = 7.20 \times 10^{-4} (LI)^{.61} (1/S)^{.54}$	0.95	0.91
	$d = 11.00 \times 10^{-4} (L)^{.44} (I)^{.65} (1/S)^{.55}$	0.96	0.92
3	$d = 1.33 \times 10^{-3} (LI)^{.53} (1/S)^{.41}$	0.94	0.89
	$d = 2.30 \times 10^{-3} (L)^{.31} (I)^{.64} (1/S)^{.41}$	0.97	0.94
	$d = 1.50 \times 10^{-3} (LI)^{.57} (1/S)^{.36}$**	0.94	0.88
	$d = 2.55 \times 10^{-3} (L)^{.34} (I)^{.67} (1/S)^{.36}$**	0.96	0.93
4	$d = 2.15 \times 10^{-4} (LI)^{.84} (1/S)^{.54}$	0.88	0.77
	$d = 3.50 \times 10^{-4} (L)^{.62} (I)^{.95} (1/S)^{.55}$	0.89	0.79
5	$d = 7.40 \times 10^{-5} (LI)^{1.25} (1/S)^{.38}$	0.87	0.76
	$d = 2.00 \times 10^{-4} (L)^{.79} (I)^{1.41} (1/S)^{.40}$	0.90	0.81
6	$d = 1.39 \times 10^{-8} (LI)^{2.18} (1/S)^{1.15}$	0.82	0.68
	$d = 0.22 \times 10^{-8} (L)^{2.81} (I)^{1.91} (1/S)^{1.23}$	0.86	0.74
7	$d = 4.40 \times 10^{-10} (LI)^{2.78} (1/S)^{1.24}$	0.67	0.44
	$d = 2.70 \times 10^{-11} (L)^{4.15} (I)^{1.49} (1/S)^{1.39}$	0.84	0.71
	Equation was not obtained because of insufficient number of water depths above top of texture **		
8	$d = 13.30 \times 10^{-5} (LI)^{.83} (1/S)^{.63}$	0.94	0.89
	$d = 18.00 \times 10^{-5} (L)^{.70} (I)^{.87} (1/S)^{.63}$	0.95	0.89

*Only valid for water depths somewhat greater than zero.
**Equation also based on data taken at a cross slope of 1 in/ft

d = water depth, in.
L = length of drainage path, ft
I = rainfall intensity, in/hr
S = cross slope, ft/ft

All terms significant at 5 percent level

REGRESSION EQUATIONS FOR DEPTHS TAKEN DURING RAINFALL -- BASED ON DATUM PLANE AT BOTTOM OF TEXTURE

Surface	Regression Equation*	Correlation Coefficient R	Coefficient of Determination R^2
1	$d = 2.35 \times 10^{-3} (LI)^{.55} (1/S)^{.33}$	0.96	0.92
	$d = 3.30 \times 10^{-3} (L)^{.41} (I)^{.60} (1/S)^{.33}$	0.97	0.94
1A	$d = 1.40 \times 10^{-3} (LI)^{.57} (1/S)^{.42}$	0.91	0.82
	$d = 2.70 \times 10^{-3} (L)^{.27} (I)^{.70} (1/S)^{.43}$	0.95	0.90
	$d = 0.70 \times 10^{-3} (LI)^{.56} (1/S)^{.58}$**	0.88	0.77
	$d = 1.45 \times 10^{-3} (L)^{.25} (I)^{.74} (1/S)^{.57}$**	0.92	0.84
2	$d = 2.10 \times 10^{-3} (LI)^{.47} (1/S)^{.45}$	0.96	0.93
	$d = 2.90 \times 10^{-3} (L)^{.34} (I)^{.50} (1/S)^{.45}$	0.97	0.94
3	$d = 2.00 \times 10^{-3} (LI)^{.48} (1/S)^{.37}$	0.95	0.90
	$d = 3.30 \times 10^{-3} (L)^{.27} (I)^{.57} (1/S)^{.37}$	0.98	0.95
	$d = 2.40 \times 10^{-3} (LI)^{.50} (1/S)^{.32}$**	0.95	0.89
	$d = 3.90 \times 10^{-3} (L)^{.29} (I)^{.60} (1/S)^{.32}$**	0.97	0.94
4	$d = 3.70 \times 10^{-3} (LI)^{.46} (1/S)^{.30}$	0.96	0.92
	$d = 4.50 \times 10^{-3} (L)^{.36} (I)^{.50} (1/S)^{.30}$	0.97	0.94
5	$d = 4.20 \times 10^{-3} (LI)^{.53} (1/S)^{.25}$	0.95	0.91
	$d = 6.10 \times 10^{-3} (L)^{.37} (I)^{.58} (1/S)^{.25}$	0.96	0.93
6	$d = 0.98 \times 10^{-3} (LI)^{.68} (1/S)^{.55}$	0.92	0.84
	$d = 0.90 \times 10^{-3} (L)^{.71} (I)^{.67} (1/S)^{.55}$	0.92	0.84
7	$d = 0.40 \times 10^{-3} (LI)^{.89} (1/S)^{.54}$	0.92	0.85
	$d = 0.39 \times 10^{-3} (L)^{.90} (I)^{.89} (1/S)^{.54}$	0.92	0.85
	$d = 0.47 \times 10^{-3} (LI)^{.90} (1/S)^{.50}$**	0.92	0.85
	$d = 0.46 \times 10^{-3} (L)^{.91} (I)^{.89} (1/S)^{.50}$**	0.92	0.85
8	$d = 1.95 \times 10^{-3} (LI)^{.52} (1/S)^{.38}$	0.95	0.91
	$d = 2.05 \times 10^{-3} (L)^{.50} (I)^{.53} (1/S)^{.38}$	0.96	0.91

*Can be changed to top of texture datum plane by subtracting average texture depth from water depth.
**Equation also based on data taken at a cross slope of 1 in/ft.

d = water depth, in.
L = length of drainage path, ft
I = rainfall intensity, in/hr
S = cross slope, ft/ft

All terms significant at 5 percent level

TABLE 13

REGRESSION EQUATIONS FOR AVERAGE SURFACE DETENTION -- BASED ON DATUM PLANE AT BOTTOM OF TEXTURE

Surface	Regression Equation*	Correlation Coefficient R	Coefficient of Determination R^2
1	$Det = 6.60 \times 10^{-3} (I)^{.49} (I/S)^{.37}$	0.99	0.99
1A	$Det = 8.40 \times 10^{-3} (I)^{.48} (I/S)^{.32}$	1.00	0.99
	$Det = 8.40 \times 10^{-3} (I)^{.48} (I/S)^{.33}$**	1.00	0.99
2	$Det = 3.40 \times 10^{-3} (I)^{.41} (I/S)^{.54}$	1.00	0.99
3	$Det = 4.50 \times 10^{-3} (I)^{.46} (I/S)^{.43}$	0.99	0.98
	$Det = 5.40 \times 10^{-3} (I)^{.45} (I/S)^{.39}$**	0.99	0.98
4	$Det = 4.80 \times 10^{-3} (I)^{.58} (I/S)^{.39}$	1.00	0.99
5	$Det = 7.80 \times 10^{-3} (I)^{.72} (I/S)^{.26}$	0.99	0.98
6	$Det = 13.20 \times 10^{-3} (I)^{.83} (I/S)^{.16}$	0.98	0.97
7	$Det = 22.00 \times 10^{-3} (I)^{.68} (I/S)^{.16}$	1.00	0.99
	$Det = 22.50 \times 10^{-3} (I)^{.67} (I/S)^{.15}$**	0.99	0.99
8	$Det = 2.90 \times 10^{-3} (I)^{.55} (I/S)^{.49}$	0.99	0.99

*Can be changed to top of texture datum plane by subtracting average texture depth from water depth.
**Equation also based on data taken at a cross slope of 1 in/ft (for L = 28 ft.)

Det = average water depth detention, in.
I = rainfall intensity, in/hr
S = cross slope, ft/ft

All terms significant at 5 percent level