VOIDS CONCEPT FOR DESIGN OF SEAL COATS AND SURFACE TREATMENTS

Charles R. Marek and Moreland Herrin, University of Illinois

A surface treatment design procedure based on the measured voids content of an aggregate layer is presented. The procedure can be used for the design of single-application surface treatments and seal coats. Relationships are developed for the quantities of cover aggregate and asphalt binder required to produce surface treatments that should exhibit good performance characteristics in the field. Factors taken into account in the determination of these quantities include aggregate size, aggregate shape, aggregate source, aggregate quantity, aggregate fines, percentage of solvent in binder, hardness of underlying surface, embedment of aggregate into the underlying surface, temperature, and compactive effort. A design example is also presented to illustrate the use of the method and the principles it incorporates.

•SEVERAL methods for the design of surface treatments have been developed by other engineers in the past, and some of these methods have been used for a number of years (3). While the design procedure suggested here utilizes some of the basic ideas in the other methods, it contains a number of improvements that have resulted from research concerning the amount of voids existing in surface treatment aggregate layers. These improvements are as follows:

1. More precise determination of the quality of bitumen needed by taking into account (a) the nonlinear variation in the volume of voids with depth within the aggregate layer, and (b) the depth of embedment of the aggregate into the underlying surface;
2. Simplified design procedure to account for the shape of the aggregate by use of different voids curves for crushed stone and gravel; and
3. An accurate method for adjusting the amount of bitumen to account for the fines in the aggregates.

FUNDAMENTAL CONSIDERATIONS IN DESIGN PROCEDURE

The bases of the design procedure are as follows:

1. The quantity of cover aggregate required is generally that amount needed to form a layer one particle in depth over the surface being treated. In no way is the required quantity of aggregate influenced by the amount of bituminous binder material that is to be used.
2. During construction and under subsequent traffic, the aggregate particles tend to reorient until they present their least dimensions in the vertical direction.
3. Because of reorientation of the aggregate, the quantity of bitumen and, to a certain extent, the quantity of aggregate needed are related to the average least dimension of the aggregate.
4. The basic quantity of bituminous material to be used is that amount required to fill the voids existing between the aggregate particles to an optimum depth. Therefore, the amount of binder needed is a function of the volume of the voids in the cover aggregate layer that, in turn, is influenced by factors such as aggregate gradation, maximum

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size, aggregate shape and surface texture, and aggregate embedment into the underlying surface.

5. In order to determine the spray quantity of bituminous material needed, the basic quantity of bituminous material must be adjusted for (a) aggregate absorption characteristics, (b) characteristics of underlying surface (rich or dry), (c) amount of volatiles present if a cutback or an emulsion is used, and (d) increase in the volume of the bituminous material when heated for spraying.

Prior to any mathematical calculations, two important decisions must be made. The type and size of aggregate and the type of bituminous material to be used in the surface treatment must be selected. In addition, basic identifying data in regard to the aggregate and bitumen must be determined by initial tests.

SELECTION OF TYPE AND SIZE OF AGGREGATE

Two gradations of aggregates are generally used for surface treatments: graded and one-size aggregates. Graded aggregates have a reasonable amount of aggregate in each sieve fraction and a sizable amount (greater than 10 percent) passing the No. 4 sieve. A one-size aggregate usually has little material passing the No. 4 sieve and probably has more than 60 percent of the aggregate of one size.

Although a well-graded aggregate is usually considered to be the best gradation for a compacted-asphalt mixture, it is not so desirable for surface-treatment construction. Research data indicate that the one-size aggregate not only performs better in surface treatments but also provides several advantages related to the design and construction of the surface treatments. The one-size aggregates usually develop good skid-resistance qualities. In addition, one-size aggregates are usually retained better by the bituminous binder because of the reduction in the fine fraction of the aggregate. Even more important, there is a good possibility that surface treatments constructed with aggregate containing large amounts of fine material will bleed. Excess fine material acts as a filler for the bituminous material and, in essence, will increase the amount of bituminous material in the aggregate.

It is often thought that one-size aggregate is economically unfeasible because of the added cost of producing the aggregate. However, the performance of surface treatments constructed with one-size aggregate appears to be quite superior to the performance of similar constructions using graded aggregate. (The service lives of surface treatments constructed with one-size aggregates are usually considerably longer than those of surfaces constructed with graded aggregate.) It may be better to expend more money initially, in order to obtain a one-size aggregate that will perform well, than to have lower costs initially but higher maintenance costs.

It is also desirable to use a fairly large-sized aggregate (3/4 in.) instead of a small-sized aggregate. The larger size of aggregate provides good skid resistance. In addition, there is less chance of bleeding occurring with the large-sized aggregate. A small variation in the amount of bituminous material in a small aggregate may completely fill the voids, while the same variation of the bituminous material in a larger size of aggregate may have almost no effect.

Some persons dislike surface treatments constructed with large-sized aggregates because of noise and roughness. However, with the increased performance and ~~long-lived~~ better, longer life skid resistance ~~with better and~~ that can be obtained by using the large-sized aggregate, the benefits of reducing the top size to 3/8 in. should be seriously evaluated.

SELECTION OF TYPE AND GRADE OF BITUMINOUS BINDER

Consideration should be given to a number of factors when the type and grade of bituminous binder are selected. These factors include temperature, viscosity, atmospheric conditions, condition and temperature of surface to be treated, adhesion, and traffic type and speed. In order to satisfy one or more of these factors, asphalt cements, rapid-curing cutbacks, medium-curing cutbacks, and emulsions are normally used for surface treatment construction.

Based on observation and study, the authors recommend the use of a paving-grade asphalt cement for surface treatment construction, if the treatment can be placed satisfactorily. Of all of the bituminous binders that could be used for surface treatment construction, asphalt cement is perhaps the best. Primarily, asphalt cements harden quickly to provide a strong binder that holds the aggregate firmly in place. Thus, there is less chance of the aggregate being dislodged by early traffic. In addition, they provide a hard residue capable of developing a high cohesive strength. Asphalt cements also have less tendency to bleed, and their use provides a relatively impervious seal for the existing pavement surface. All of these desired qualities help ensure a surface treatment of long life.

In some instances, it may be difficult to get the aggregate suitably bonded with an asphalt cement binder. This may occur when the underlying surface is cold and causes chilling of the asphalt cement before the aggregate can be spread and compacted into the asphalt. In such cases, and in related instances, it may be desirable to use a cutback or an emulsion, but their use should be limited.

If the bituminous material to be used in the surface treatment construction is either a cutback or an emulsion, the percentage of volatiles must be determined. This should be done by distillation or, as a last resort, by estimation. In addition, the temperature to which the bituminous material must be heated in order to have adequate spraying viscosity must be determined.

AGGREGATE QUANTITY

The quantity of cover aggregate should be that amount needed to form a layer one stone in depth over the surface to be treated. This quantity is influenced by such factors as size, shape, and specific gravity of the aggregate. Usually 2 aggregate quantities are determined. One quantity is referred to as the basic quantity and is essentially the exact amount of aggregate needed to cover 1 sq yd of surface. The field-spread quantity, or normally the spread quantity, is the amount of aggregate that is to be spread on the road surface. This latter quantity is greater than the basic amount because varying allowances must be made for aggregate whip-off and construction inaccuracies. The basic aggregate quantity is usually determined first and then is modified to provide the spread quantity.

Average Least Dimension

Normally aggregate will tend to rotate under the rolling action of wheels until it is oriented with the least dimension in the vertical direction. Thus, the average of the least dimensions of the aggregate particles is an indication of the average thickness of the aggregate in the road surface. Consequently, the quantity of bituminous material needed and, to a certain extent, the quantity of aggregate needed is related to the average least dimension (ALD) of the aggregate.

The most accurate method of determining the ALD of either a one-sized or a graded aggregate is by direct measurement of the thickness of the aggregate particles after removal of all material passing the No. 4 sieve. The ALD of each aggregate particle is measured with a pair of calipers. From an average of the measured least dimension of a minimum of 100 particles, the average least dimension of the cover aggregate can be obtained.

An indirect method can be used to determine an approximate ALD of either a one-sized or a graded aggregate. Average values of the ALD of different-sizes and types of aggregates have been determined and are given in Table 1. Once the gradation of the aggregate has been determined, the weighed average of the ALD's for the various sieve fractions can be used as an estimate of the ALD of the cover aggregate.

TABLE 1

AVERAGE LEAST DIMENSION OF DIFFERENT SIEVE FRACTIONS

Sieve Fraction	ALD of Sieve Fraction	
	Crushed Stone	Gravel
>3/4 in.	0.57	0.60
1/2 to 3/4 in.	0.48	0.49
3/8 to 1/2 in.	0.36	0.37
No. 4 to 3/8 in.	0.25	0.26

The approximate least dimension is determined by multiplying the percentage of aggregate for each individual sieve fraction by the ALD for that fraction. The sum of the products is then divided by 100 minus the percentage passing the No. 4 sieve to obtain the desired estimate of the average least dimension.

Basic Quantity

The most direct method and probably the most accurate method for determining the basic quantity of cover aggregate is the test-board method. In this method, a board of known area is covered with a sufficient quantity of aggregate, with the least dimension of the aggregate particles placed upward, so that complete coverage of the board with the aggregate one thickness in depth is obtained. The weight of the aggregate on the board in pounds divided by the area of the board in square yards is the basic quantity of aggregate needed in pounds per square yard. This method is quite accurate and is especially good in that it indirectly accounts for all of the variables in the aggregate that influence the amount needed.

An estimate of the basic quantity of the aggregate can be determined by the following equation:

$$\text{Basic quantity} = 24 \times \text{ALD} \times G \qquad (1)$$

where

ALD = average least dimension of the aggregate in in.; and
G = bulk specific gravity of the aggregate.

Use of Eq. 1 provides only a rough estimate of the basic quantity and is inferior to the test-board method. It only relates the quantity needed to the ALD of the aggregate and specific gravity of the aggregate and does not take into account the shape of the aggregate.

Field-Spread Quantity

Because of loss of aggregate due to whip-off and inaccuracy in spreading of the aggregate, the quantity of aggregate to be spread on the road surface should be greater than the basic quantity. The actual amount of increase in the basic quantity should be based on the construction techniques (quality control) and equipment to be used at the particular job site. However, when the actual increase is not known, an increase in the basic quantity of 6 to 15 percent (by weight) should be satisfactory.

CONDITIONS FOR DESIGN EXAMPLE

To illustrate the procedures outlined in this paper, a design example is included. For the design example, it will be assumed that a one-sized aggregate, single-layer surface treatment is to be placed on a nonporous bituminous surface. An MC-3000 cutback asphalt is to be used for the bituminous binder. The aggregate to be used is crushed stone. The "hardness" of the underlying surface is measured to be 0.40 in. at 100 F. The anticipated surface temperature at time of construction and early treatment life is 120 F. Forty percent of the aggregate (by volume) is to be exposed to provide adequate skid resistance.

The one-sized, crushed-stone aggregate to be used has the following gradation:

Sieve Size	Percent Passing
3/4 in.	100
1/2 in.	98
3/8 in.	30
No. 4	9

The bulk specific gravity of the aggregate is 2.72. The MC-3000 was found to contain 19 percent cutterstock, and it was determined that the cutback should be heated to 220 F in order to have adequate spraying viscosity.

DETERMINATION OF AGGREGATE QUANTITY

For the design example, an approximate ALD, computed by using the data given in Table 1, is given in Table 2. Calculated estimate of ALD = 0.307/0.91 = 0.34 in.

The actual quantity of aggregate needed for the design example should be determined by using the test-board method. However, to illustrate the procedure, the basic quantity will be estimated from the ALD.

TABLE 2

ALD OF DIFFERENT SIEVE FRACTIONS USED IN DESIGN EXAMPLE

Sieve Fraction	Percent of Sieve Fraction in Aggregate	ALD of Sieve Fraction	Percent × ALD
$\frac{1}{2}$ to $\frac{3}{4}$ in.	2	0.48	0.009
$\frac{3}{8}$ to $\frac{1}{2}$ in.	68	0.36	0.245
No. 4 to $\frac{3}{8}$ in.	21	0.25	0.053
Total	91		0.307

$$\text{Basic quantity} = 24 \times \text{ALD} \times G = 24 \times 0.34 \times 2.72 = 22.2 \text{ lb/sq yd}$$

The basic quantity will be increased by 15 percent in the design example to allow for whip-off and waste.

$$\text{Spread quantity} = 22.2 \times 1.15 = 25.5 \text{ lb/sq yd}$$

DETERMINATION OF BITUMINOUS QUANTITY USING VOIDS CONCEPT

The required basic amount of bituminous material is that quantity needed to fill the voids existing between the aggregate particles to an optimum depth. Because the volume of voids between the aggregate particles is a function of (a) the size of the aggregate, (b) the shape of the aggregate, and (c) the amount of aggregate embedment into the underlying surface, the required amount of bituminous material is also related to these factors.

The first step in determining the desired basic binder quantity by the proposed procedure is to obtain a measure of the void space between aggregate particles to complete submergence when resting on a rigid (flat bottom) base. The total void space is then reduced by appropriate factors to account for (a) desired aggregate exposure to ensure a skid-resistant surface and (b) embedment of the aggregate into the underlying surface. Corrections are then applied to the resulting binder volume to account for (a) fines in the aggregate, (b) condition of the underlying surface, (c) amount of volatiles in the bituminous material used, and (d) volume change in the bituminous material due to temperature variation. The corrected volume relates the amount of binder to be applied by the distributor.

Percentage of Voids

Data obtained from an investigation (4, 8) of the void space between aggregate particles on a rigid, unyielding surface (flat bottom situation) indicated that the relationships between percentage of voids and depth (as a function of ALD) of the aggregate for both gravel and crushed stone with an ALD of 0.50 are as shown in Figure 1. The percentage of voids shown in this figure is defined as follows:

$$\text{Percentage of voids} = \frac{\text{volume of voids at depth d}}{\text{horizontal surface area} \times \text{depth d}} \times 100 \qquad (2)$$

where the volume is in cubic inches, the horizontal surface area is in square inches, and the depth is in inches. Use of Eq. 2 relates the void space as a percentage of the volume to depth d, not of the total volume to the top of the aggregate (complete aggregate submergence).

The information shown in Figure 1 is given for an ALD of 0.50 in. If an aggregate having a different ALD is to be used, the curves shown in Figure 1 must be shifted by

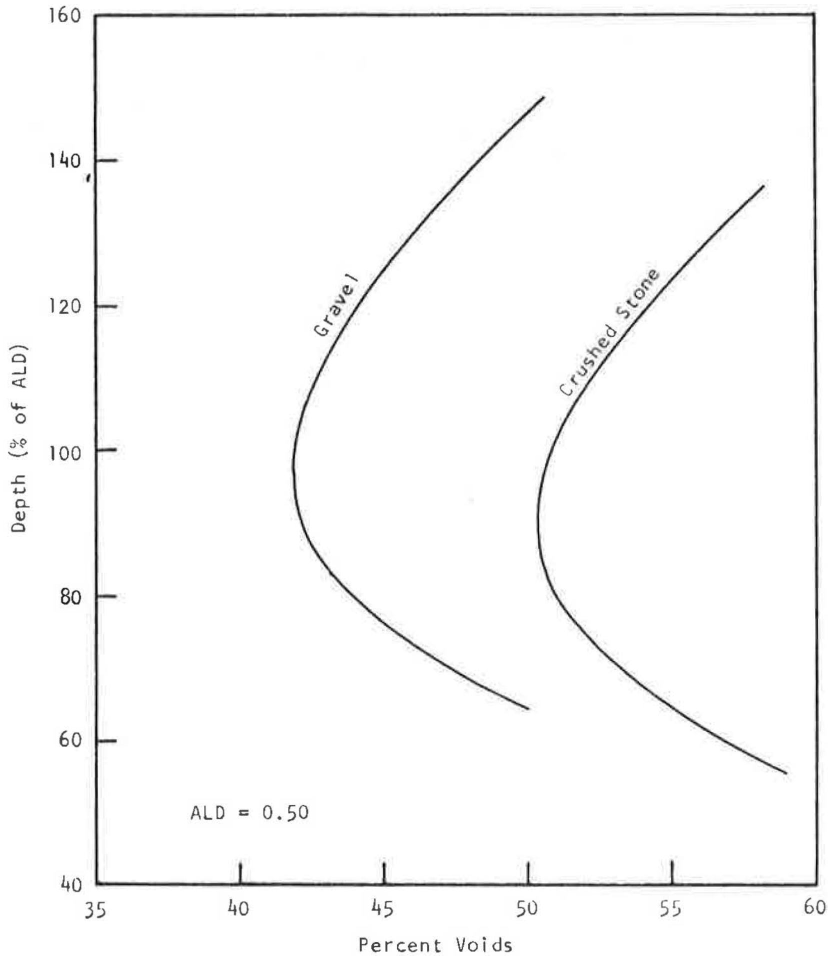

Figure 1. Variation in percentage of voids in a one-sized aggregate layer with depth as a function of the average least dimension of the aggregate (no embedment).

a factor determined by Eq. 3. This equation is applicable for both gravel and crushed stone.

$$\text{ALD factor} = 14.8 - 29.5\ (\text{ALD}) \tag{3}$$

where the ALD factor is a percent.

The data used to calculate the percentage of voids by Eq. 2 were also used to calculate the percentage of voids as a function of volume to complete aggregate submergence. The percentage of voids on this basis is defined as follows:

$$\text{Percentage of voids} = \frac{V_{v_{\text{flat bottom to depth d}}}}{\text{horizontal surface area} \times \text{depth D}} \times 100 \tag{4}$$

where $V_{v_{\text{flat bottom to depth d}}}$ is the volume of voids to any depth d measured by using a flat-bottom container with no aggregate embedment in cubic inches, and depth D is depth to a point of complete submergence of the aggregate when on a rigid base in inches. When the percentage of voids calculated by Eq. 4 is plotted against depth as a percentage of ALD, the curves for gravel and crushed stone shown in Figures 2 and 3 result. It can be observed from data shown in Figure 2 that the percentage of voids does not vary linearly with depth within the aggregate layer.

Total Percentage of Voids in Aggregate Layer

The uncorrected percentage of voids at any depth in a one-sized aggregate layer can be determined from the curves shown in Figure 1 and computed by Eq. 3 or from the curves shown in Figures 2 and 3. These were derived from data obtained in a previous investigation (4, 8).

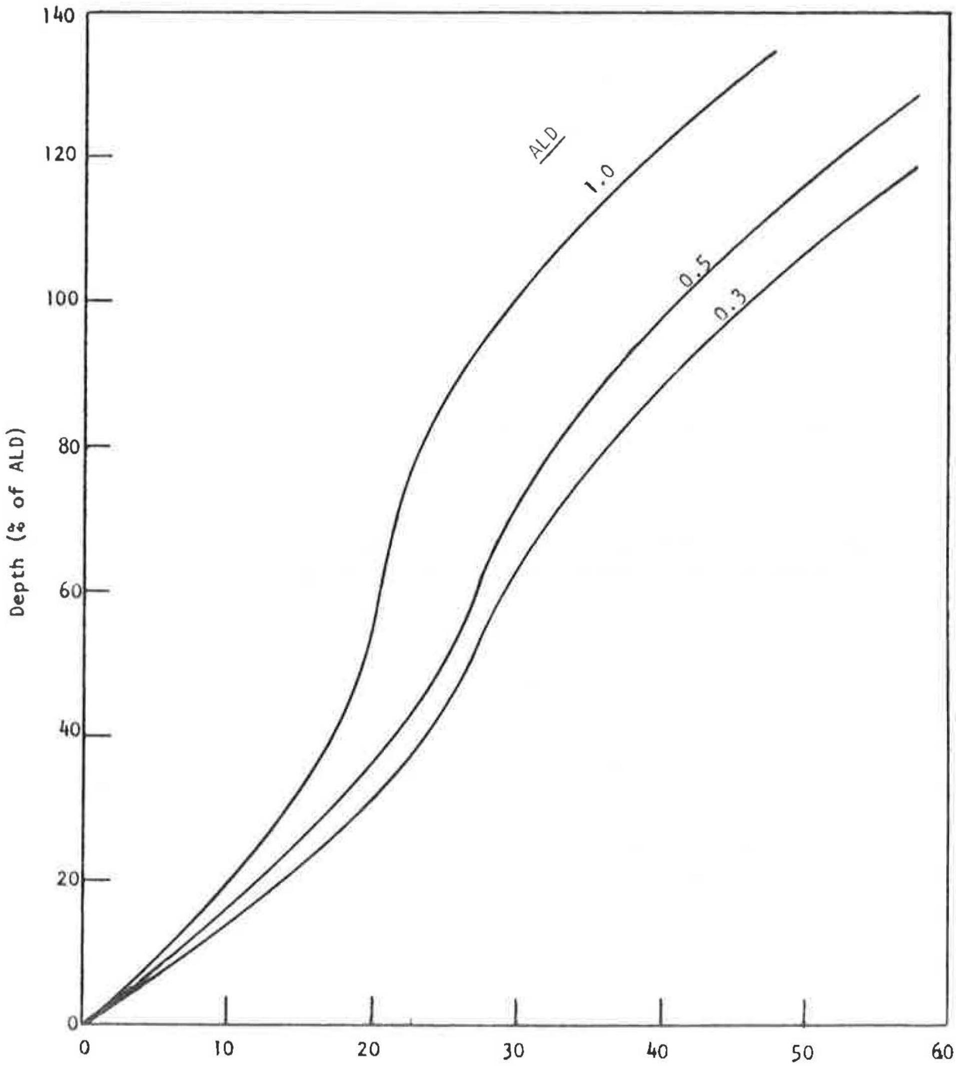

Figure 2. Relationship between percentage of voids and depth as a percentage of ALD for crushed stone.

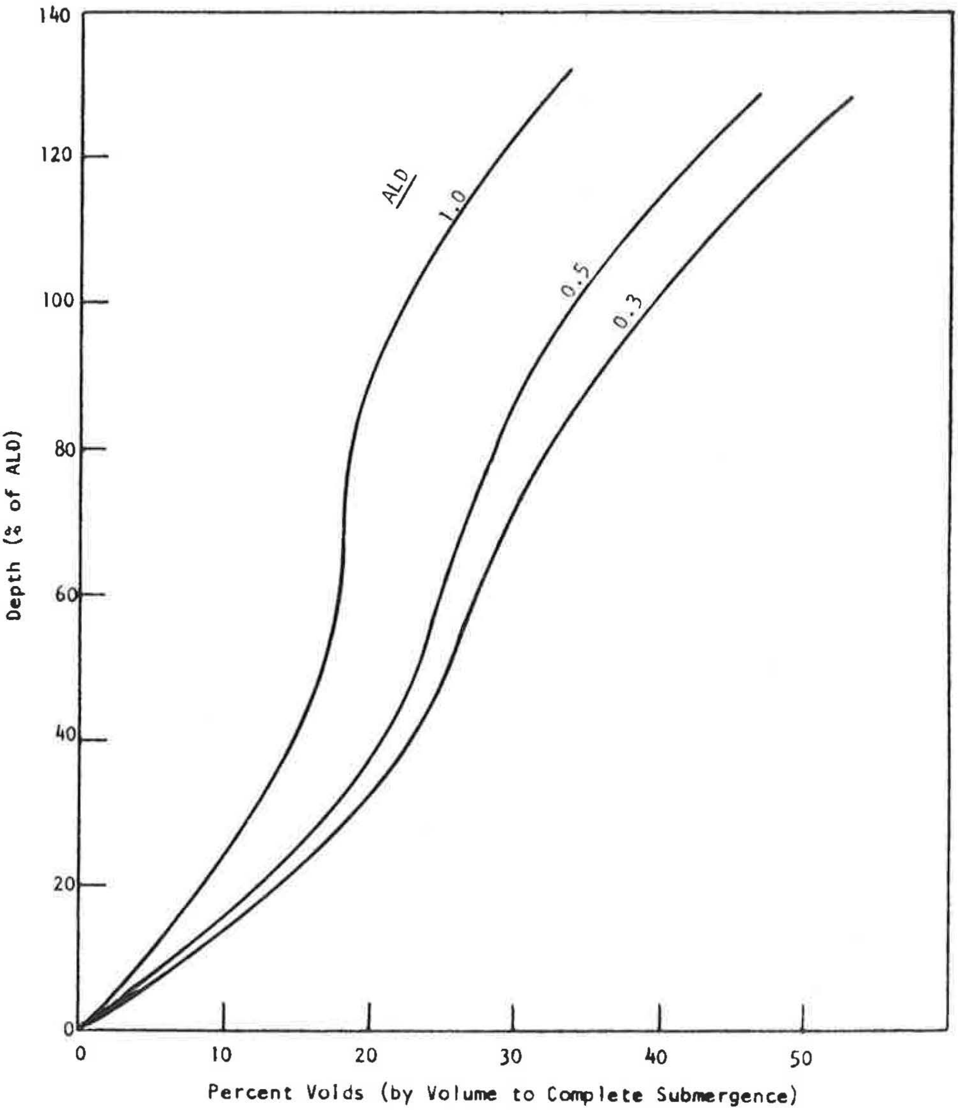

Figure 3. Relationship between percentage of voids and depth as a percentage of ALD for gravel.

The total percentage of voids at complete aggregate submergence (1.25 ALD) is determined from Figure 1 and the following equation:

$$V_{T(ALD)} = V_{T(0.5)} + 14.8 - 29.5\,(ALD) \tag{5}$$

where

$V_{T(ALD)}$ = total percentage of voids to complete submergence in an aggregate layer with a specific ALD; and

$V_{T(0.5)}$ = percentage of voids at complete submergence (125 percent of ALD) for an aggregate with an ALD = 0.50.

The total percentage of voids for the design example at complete aggregate submergence for a crushed stone with an ALD of 0.34 in. is as follows:

$$V_{T(ALD)} = 55.6 + 14.8 - 29.5\,(0.34) = 60.4 \text{ percent}$$

Reduction of Total Voids to Account for Aggregate Embedment Into Underlying Surface

The percentage reduction in void space to account for embedment of the aggregate into the underlying surface is a function of (a) the hardness of the underlying surface, (b) the temperature of this surface, and (c) the number of passes of the roller used to compact the aggregate. The relationship is shown in Figure 4. The percentage reduction shown in this figure was calculated by the following relationship:

$$\text{Percentage reduction} = \frac{V_{v_{\text{flat bottom}}} - V_{v_{\text{embedded}}}}{V_{v_{\text{flat bottom}}}} \times 100 \qquad (6)$$

where $Vv_{\text{flat bottom}}$ is the volume of voids to complete aggregate submergence measured when aggregate layer is on a rigid base (8); and Vv_{embedded} is the volume of voids to complete aggregate submergence measured after aggregate embedment (8).

Before Figure 4 can be used to determine the reduction in percentage of voids that is necessary to account for aggregate embedment, information concerning underlying surface type (series) must be obtained. This information is readily obtained by conducting a simple field test for hardness and by using data shown in Figure 5. The test for surface hardness at a given temperature is performed by using a standard Marshall compaction hammer and a 1-in. diameter hardened steel sphere. The sphere is placed in contact with the underlying surface to be tested and is subjected to 5 blows of a 10-lb weight falling through a fixed distance of 18 in. The vertical distance from the plane of the surface to the lowest point of the depression is measured with a standard penetrometer. This distance is obtained for a minimum of 5 locations on the surface being tested. The average of the 5 values is determined to give a measure of the surface hardness at the test temperature. As the hardness of the underlying surface increases, the depth of sphere penetration decreases.

For the design example, it was stated that the hardness of the underlying surface was measured to be 0.40 in. at 100 F. Thus, from Figure 5, the underlying surface is determined to be a Series 3 type.

The amount that the total percentage of voids must be reduced is obtained from data given in Figure 4. Enter the figure according to the highest temperature to which the underlying surface will be subjected; proceed upward to the type of underlying surface having the number of the roller passes to be used in compaction of the cover aggregate; and read the percentage reduction on the vertical axis.

The amount of reduction of the total voids to account for embedment into the underlying surface is computed by the following equation:

$$V_E = \frac{R}{100} \times V_{T\,(ALD)} \qquad (7)$$

where

V_E = amount (not percent) that the total percentage of voids must be reduced to account for embedment into the underlying surface; and

R = percentage reduction from Figure 4.

From Figure 4, the required percentage reduction for the design example for a Series 3 surface at 120 F and with 3 complete coverages by roller is determined to be 30

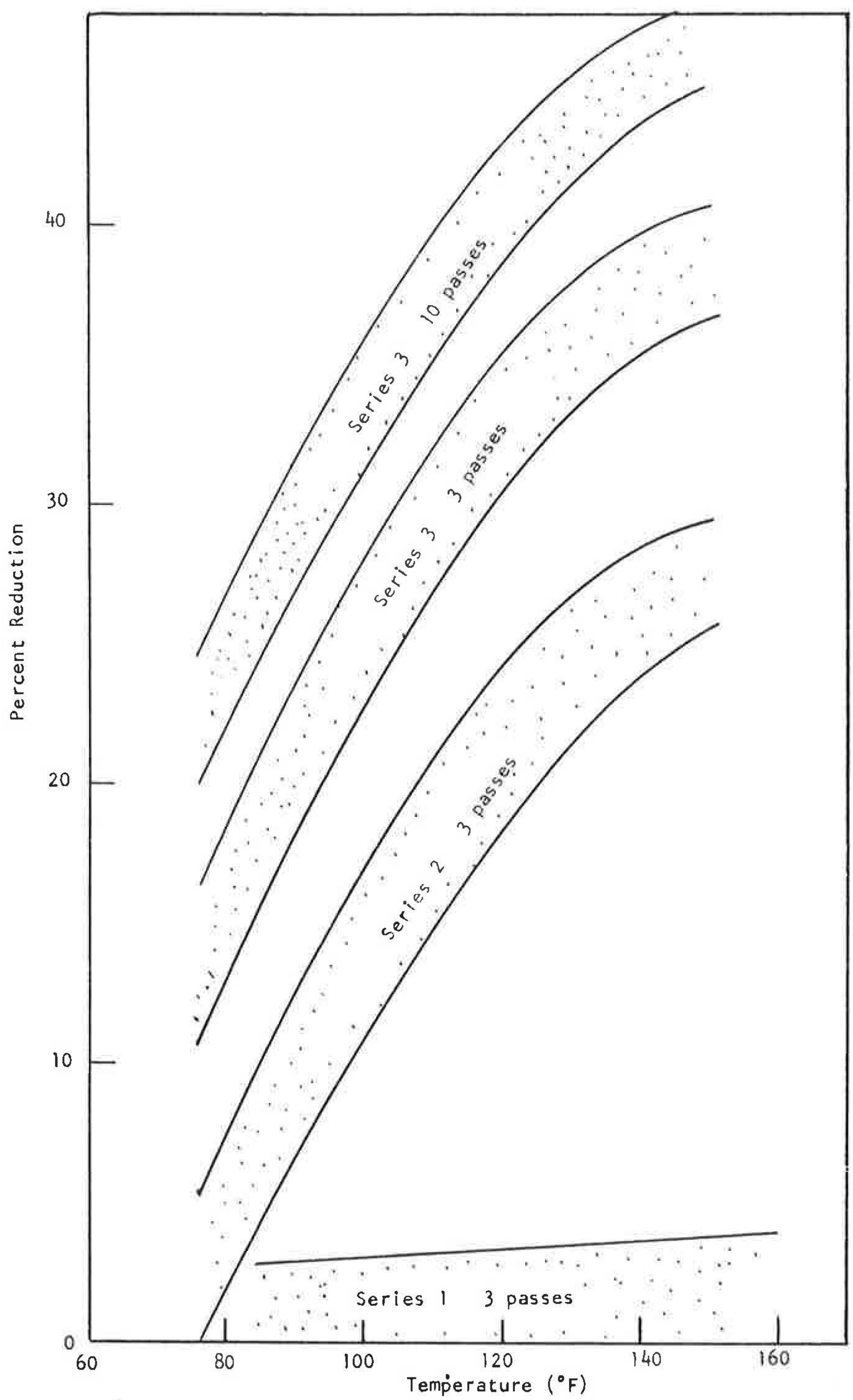

Figure 4. Percentage reduction in void space versus temperature of underlying surface.

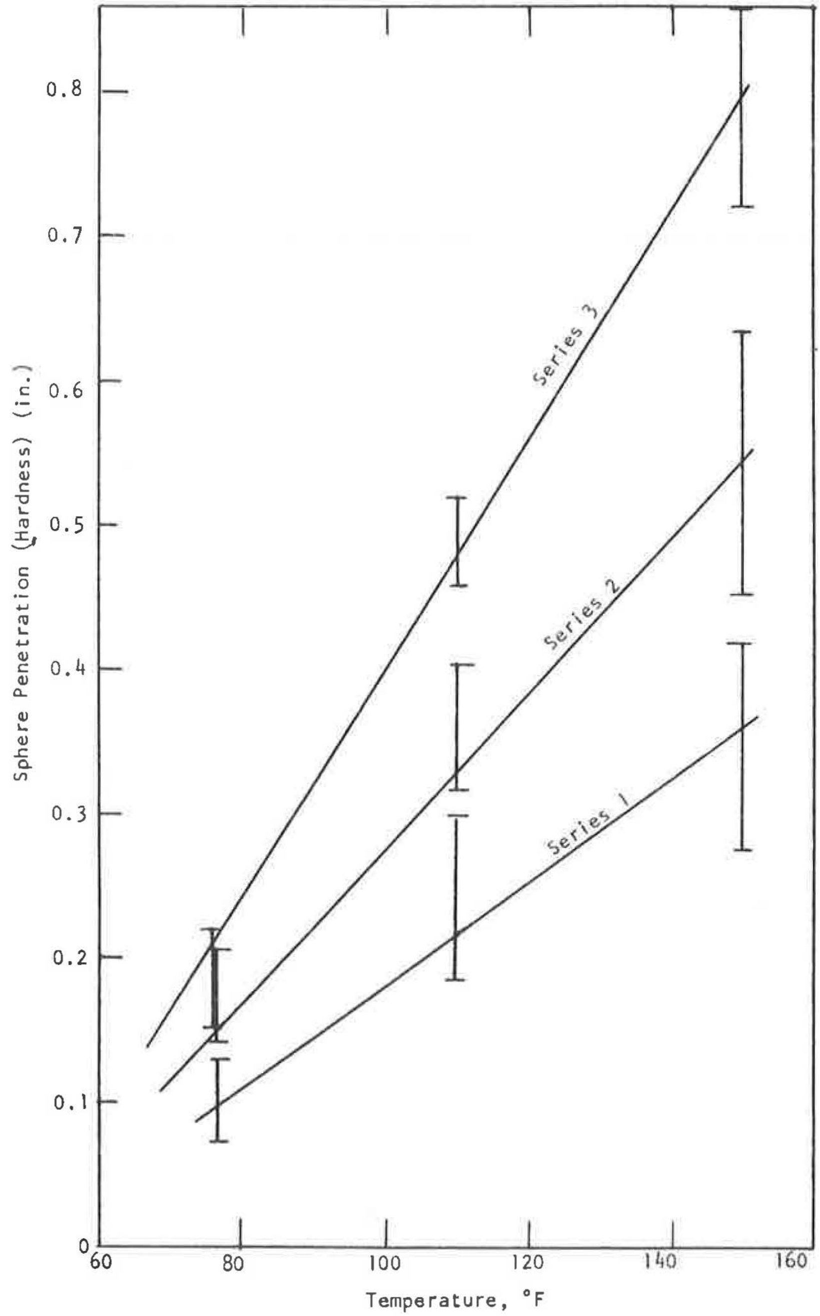

Figure 5. Relationship between hardness of underlying surfaces and temperature.

percent. That is, the void space to complete aggregate submergence for a no-embedment situation is reduced by 30 percent for the stated conditions.

The amount of reduction of the total percentage of voids is as follows:

$$V_E = \frac{R}{100} \times V_{T\,(ALD)} = \frac{30}{100} \times 60.4 = 18.1 \text{ percent}$$

Reduction of Total Voids to Provide Satisfactory Skid Resistance and Aggregate Retention

The voids within an aggregate layer should not be filled with binder to the depth of complete submergence of the aggregate. If this is done, the aggregate particles will be covered with binder. Under these conditions and especially when the temperature of the binder is increased, bleeding of the surface treatment may occur and the surface will have low skid resistance, especially when wet. Consequently, the depth of the binder in the aggregate layer should be less than the depth required for complete submergence of the aggregate.

Care should also be taken that the amount of binder is not reduced too much. If too little binder is used, the aggregate will not be held firmly in place, and there is a good probability that the aggregate will be easily dislodged by the forces produced by moving wheel loads.

At the present time, experimental data are not available to indicate critical values of these 2 parameters. Until more data are available, the following criteria are suggested:

1. In order to provide satisfactory skid resistance, about 40 percent (by volume) of the aggregate should be exposed; and
2. In all cases, the voids in the aggregate should be filled to a depth equal to or greater than 60 percent of the ALD of the aggregate. This should be done in order that sufficient bitumen is present to adequately bind the aggregate to the underlying surface.

Because the voids in the aggregate (and thus the quantity of bitumen needed) have been related to the depth in the aggregate layer, the percentage of aggregate exposed (for developing adequate skid resistance) will also be related to the depth. Such a relationship has been established and is shown in Figure 6. For design purposes, this figure may be entered with the percentage (by volume) of aggregate that must be exposed to provide adequate skid resistance to determine the depth to which the bituminous binder must be placed.

The curves shown in Figure 6 are applicable for all crushed stones or gravels of essentially one-sized gradation regardless of the ALD of the aggregate. A linear relationship does not exist between the 2 indicated variables. Further, 0 percent aggregate (by volume) is exposed when the depth of binder is 125 percent of the ALD of the aggregate.

The first step is to determine if the percentage of depth (percent ALD) is greater or less than 60 percent. If the percentage (of ALD) is greater than 60 percent, then sufficient bitumen is present to adequately bind the aggregate to the underlying surface. If it is less than 60 percent, an adjustment in the percentage of depth must be made to provide a balance between the maximum amount of bitumen needed to provide adequate skid resistance and the maximum amount of bitumen needed to provide satisfactory aggregate retention.

The amount that the total voids must be reduced to provide satisfactory depth of bitumen is computed as follows: Select either Figure 2 or 3 depending on the type of cover aggregate (gravel or crushed stone); enter the appropriate figure with the depth (percent ALD) previously determined and determine the percentage of voids to depth d based on complete submergence; and compute the amount of reduction of the total voids by the following equation:

$$V_S = V_{T\,(ALD)} - V_d \tag{8}$$

where

V_S = amount (not percent) that total percentage of voids must be reduced to provide satisfactory depth of bitumen (so as to have adequate skid resistance and aggregate retention); and

V_d = percentage of voids to depth d determined from Figure 2 or 3.

For the design example, 40 percent of the aggregate (by volume) is to be exposed to provide adequate skid resistance. From Figure 5 it is determined that a change in depth from 125 to 72 percent of ALD is required for the desired aggregate exposure. Therefore, the required depth change is 125 - 72 = 53 percent of ALD. A depth of 72 percent of ALD is greater than 60 percent. Thus, there should be sufficient bitumen present to adequately bind the aggregate to the underlying surface. Enter Figure 2

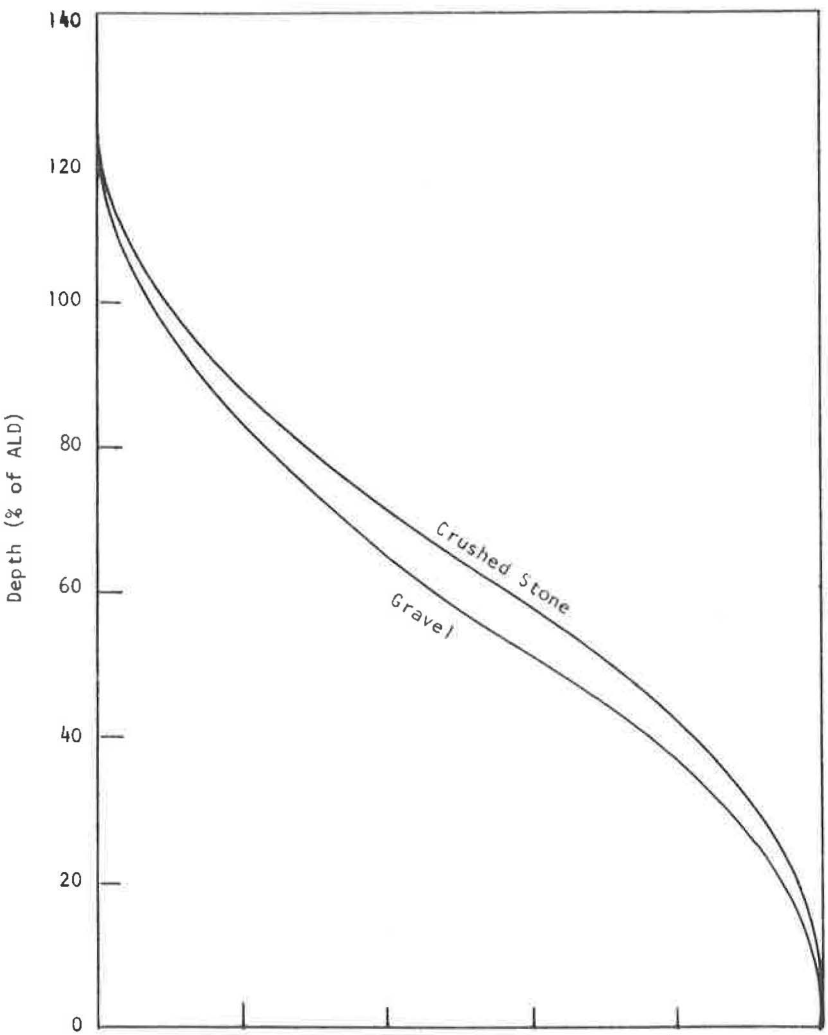

Figure 6. Relationship between percentage of aggregate exposed and percentage of depth regardless of aggregate size when the aggregate is on rigid base.

with a depth of 72 percent of ALD. For an ALD of 0.34, the value of V_d is read as 32.0 percent voids. The amount of reduction of the total percentage of voids computed by using Eq. 8 is as follows:

$$V_S = 60.4 - 32.0 = 28.4 \text{ percent}$$

Uncorrected Basic Quantity of Bitumen

In summary, the previous discussion has indicated the following:

1. The percentage of voids in an aggregate layer can be determined as a function of the specific size of the aggregate (ALD), the shape of the aggregate (gravel or crushed stone), and the depth to which the voids are determined.
2. The total percentage of voids in an aggregate layer must be reduced to account for the embedment of the aggregate into the underlying surface. The amount of this reduction is related to the hardness of the underlying surface, the temperature of this surface, and the number of passes of the roller used to compact the aggregate.
3. A further reduction in the voids in the aggregate must be made to allow adequate volume of the aggregate to be exposed above the bitumen layer so as to provide satisfactory skid resistance.
4. The percentage of voids to be filled with bitumen is determined by reducing the total percentage of voids by the amount of voids reduced by aggregate embedment into the underlying layer and by the amount of voids exposed above the top of the bitumen layer. This is expressed in equation form by

$$V_C = V_{T(ALD)} - (V_E + V_S) \qquad (9)$$

where V_C = corrected percentage of voids.

5. The uncorrected basic quantity of bitumen is computed from the following equation:

$$Q_1 = \frac{V_C}{100} \times ALD \times 7.03 \qquad (10)$$

where Q_1 = uncorrected basic quantity of bitumen in gal/sq yd. Equation 9 is used to compute the corrected percentage of voids for the design example.

$$V_C = 60.4 - (18.1 + 28.4) = 13.9 \text{ percent}$$

Thus, the uncorrected basic quantity of bitumen is

$$Q_1 = \frac{13.9}{100} \times 0.34 \times 7.03 = 0.33 \text{ gal/sq yd}$$

Bitumen Quantity Corrected to Account for Fines in the Aggregate

The fines in the aggregate that pass the No. 4 sieve materially influence the volume of binder needed. The fine material reduces the volume of voids in the aggregate and, if the bitumen quantity is not reduced, the fine material will, in effect, increase the depth of the bitumen and cause a flush surface condition to result. Thus, the quantity of the binder should be reduced to account for the fines in the aggregate.

The volume of reduction necessary to account for fines is equal to the volume of the fine material in the aggregate layer. This volume can be computed from the weight and the specific gravity of the fines. In other words, the quantity of binder needed can be determined from the following equation:

$$Q_B = Q_1 - 0.12 \times \frac{W}{G} \qquad (11)$$

where

Q_B = basic quantity of bitumen in gal/sq yd; and
W = weight of minus No. 4 material in the aggregate in lb/sq yd of surface area.

For the design example, the weight of minus No. 4 material in the aggregate = 0.09 × 22.2 = 2.0 lb/sq yd. Thus, the basic quantity of bitumen is

$$Q_B = 0.33 - 0.12 \times 2.00/2.72 = 0.24 \text{ gal/sq yd}$$

Field-Spray Quantity

The amount of bituminous material that is to be sprayed from the distributor is not the same quantity as the computed basic amount. The basic quantity must be modified to adjust for conditions that exist at the construction site. These conditions include condition of the underlying surface, amount of volatiles in the bituminous materials, and change in the volume of bituminous material as it is heated for spraying.

Correction for Condition of Underlying Surface

In the determination of the basic quantity of the bituminous material, no allowance is made for that portion of the binder that will be absorbed into the existing road surface. Few data are currently available to indicate the exact influence of the absorptive condition of the underlying surface. Until these data are available, suggested approximate adjustments that may be used are given in Table 3.

For the design example, the underlying surface is nonporous. Thus, the bitumen content should be increased by 0.00 gal/sq yd.

$$Q = 0.24 + 0.00 = 0.24 \text{ gal/sq yd}$$

Correction for Amount of Volatiles in Bituminous Material

The basic amount of the bituminous binder is the amount of residual bitumen that must be used in the surface treatment construction. If the bituminous binder to be used is an asphalt cement, no adjustment in the bitumen quantity is needed. However, if the bituminous material contains volatiles, allowance must be made for loss of the cutter-stock from cutbacks or water from emulsions. This is normally accomplished by dividing the basic amount of residual bituminous material required by the percentage of the residual bituminous material in the cutback or emulsion to be used.

Because there is 19 percent solvent in the binder being considered in the design example, the amount of MC-3000 needed is

$$Q = 0.24/(1.00 - 0.19) = 0.30 \text{ gal/sq yd}$$

Thus, 0.30 gal/sq yd of the cutback will have the required basic amount of bitumen of 0.24 gal/sq yd.

TABLE 3

BITUMEN CORRECTION TO ACCOUNT FOR TYPE OF UNDERLYING SURFACE

Type of Underlying Surface	Increase in Bitumen Quantity (gal/sq yd)
Smooth, nonporous, hard	0.00
Slightly porous, hard	0.03
Dry, old, hard	0.06
Cracked, very dry, hard	0.09

Correction for Volume Change in Bituminous Material Due to Temperature Variation

Regardless of the type of bituminous binder to be used, asphalt cement or liquid asphalt, the binder is usually heated to a temperature suitable for spraying. Thus, a final correction must be made to the bitumen quantity in order to account for the volume change produced as the bitumen is heated to the spraying temperature. This can be done by using the common temperature-volume correction tables for asphaltic materials or by assuming that the coefficient of expansion of the material is approximately 0.00035 per 1 F.

The volume correction factor for the example design (spraying temperature of 220 F) is 0.9452. Thus, the spray quantity is

$$Q_S = 0.30/0.9452 = 0.32 \text{ gal/sq yd}$$

Thus, 0.32 gal/sq yd of the MC-3000 is needed at a spraying temperature of 220 F. The corrected amount, Q_S, is the quantity of bituminous material that the distributor should spray onto the underlying surface for the example given.

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DISCUSSION

Richard L. Davis, Koppers Company, Inc., Verona, Pennsylvania

This is a very fine paper, and the authors should be commended for their effort. I am particularly pleased at their examination of the effect of depth of embedment of surface treatment aggregate into the underlying surface.

When I first read Hanson's paper (2) in the early 1950's, I noted that he estimated the percentage of voids in the aggregate as approximately 50 percent when first placed and as approximately 30 percent after rolling. It was my immediate thought that this reduction in voids was largely the result of increased embedment of the aggregate. Work that I did subsequently with a cone penetrometer indicated large differences in the rate of embedment of aggregate with temperature and type of pavement, and this appears to confirm the findings of the authors. I do not remember a previous paper that gave a method of quantitatively estimating the depth of embedment as this paper does, and for this reason I think that it deserves special recognition. However, the depth of embedment in this paper is based on 3 and 10 passes of a rubber-tired roller. This is considerably less than the depth of embedment that ultimately would be expected under traffic. Some form of correction is needed to properly estimate the ultimate depth of embedment.

My approach to estimating the binder requirements for surface treatments has been to estimate the voids in the mineral aggregate (VMA) based on the type of traffic, the condition of the underlying surface, and the type of aggregate. I have found that a good estimate of the ultimate voids in the surface treatment aggregate where the underlying bituminous pavement has heavy traffic is the VMA of the underlying pavement that presumably has reached equilibrium with the traffic. Under very heavy traffic, the VMA will usually be quite low. This means that there is not much room for binder at ultimate embedment and that the binder will not come very high on the aggregate until the aggregate is embedded. If surface treatment is attempted on a road under heavy traffic in cool weather, the embedment will be so slow that most of the aggregate will be thrown off. Those roads with heavy traffic should be surface-treated in the hottest weather so that the embedment of the aggregate can be accomplished in the shortest time possible. The authors state: "Of all the bituminous binders that could be used for surface treatment construction, asphalt cement is perhaps the best." If the authors are referring to laboratory or ideal field conditions, I would be inclined to agree. If they are referring to average field conditions, I would like to point out that in the eastern United States the first surface treatments were done with asphalt cements, and it was only because of the problems encountered that cutbacks and emulsions were developed.

The cost of surface treatment construction is greatly influenced by the percentage of the time that a surface treatment crew can work. Restricting the surface treatment crew to that portion of the time when conditions are ideal is not practical in the eastern United States. An indication as to why ideal conditions are important to the application of asphalt cement to surface treatment construction might be the following. I calculated the time for a $^3/_8$ in. piece of stone to penetrate through a $^1/_2$ gal layer of cutback, asphalt cement, and asphalt emulsion at 77 F with the following result:

Grade	Time in Seconds
RC-250	$^1/_4$
RS-2	$^1/_4$
150 to 200 penetration asphalt cement	1,250