A General Method of Design for Seal Coats and Surface Treatments

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N. W. MCLEOD[1]

SYNOPSIS

It is the principal objective of this paper to demonstrate that one equation for the quantity of cover aggregate required and another equation for the quantity of asphalt binder to be applied, can be used for the design of either single application or multiple application surface treatments and seal coats.

The required characteristics of both cover aggregates and asphalt binders are reviewed. The superiority of one-size over graded cover aggregates is demonstrated.

Equations are developed for the quantities of cover aggregate and asphalt binder required for single application surface treatments and seal coats. A sample calculation illustrates their use for this purpose.

It is shown that these same equations can be employed for the design of multiple seal coats and surface treatments. Sample calculations are included to illustrate their use in this respect.

The principles of construction for single and multiple application surface treatments and seal coats are reviewed.

KEY WORDS single surface treatment, multiple surface treatment, asphalt emulsion, liquid asphalt, asphalt cement, design, construction.

I. INTRODUCTION

It is one of the principal objectives of this paper to demonstrate that two design equations, one for determining the quantities of asphalt binder to be applied per square yard, and the other for establishing the quantities of cover stone to be applied per square yard, can be successfully employed for the design of either single application or multiple application surface treatments and seal coats.

The most important asphalt surface in North America is hot-mix asphalt concrete. When one leaves the North American continent however, it very quickly beccmes apparent that traffic volumes on most of the world's highways would not justify the cost of hot-mix asphalt pavements. Consequently, on a world wide basis, the most important type of asphalt surface is a surface treatment on a consolidated granular base. From the point of view of economy, if they were properly designed and constructed, asphalt surface treatments on consolidated granular bases should be much more widely used here in North America for surfacing secondary highways, residential streets, and roads carrying lower traffic volumes.

For an excellent review of currently available information on surface treatments and seal coats, the reader is referred to the Highway

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Research Board Special Report 96, "State of the Art: Surface Treatments, Summary of Existing Literature," by Herrin, Marek, and Majidzadeh, published in 1968.

In a paper presented before the AAPT Meeting in 1960 (1), the method of design that is employed by the Country Roads Board of Victoria, Australia, and by the National Roads Board of New Zealand, to build the most consistently successful surface treatments to be seen in the world was described. New Zealand specializes in double surface treatments, the second layer being placed about two years after the first, while single application surface treatments are generally used in Australia. Figures 1 to 6 are pictures of surface treatments taken by the author during a trip to New Zealand and Australia in 1967. Figures 1 and 2 are an overall view and a close-up of a double surface treatment

Fig. 1. New Zealand. Double Surface Treatment on Consolidated Granular Base, 15 Years Old, Carrying 3000 Vehicles per Day. Excellent Condition.

in New Zealand that is 15 years old and that is carrying 3000 vehicles per day. It appeared to be capable of serving the same traffic volume for an additional 15 years without further attention. Figure 3 illustrates a 4-lane divided highway in New Zealand, in which the asphalt surface is only a double surface treatment on a consolidated granular base. In New Zealand this type of construction is expected to carry up to 20,000 vehicles per day. Figures 4 and 5 are a panorama and a close-up of another first-rate double surface treatment on a well compacted granular base in New Zealand. Figure 6 provides a view of a

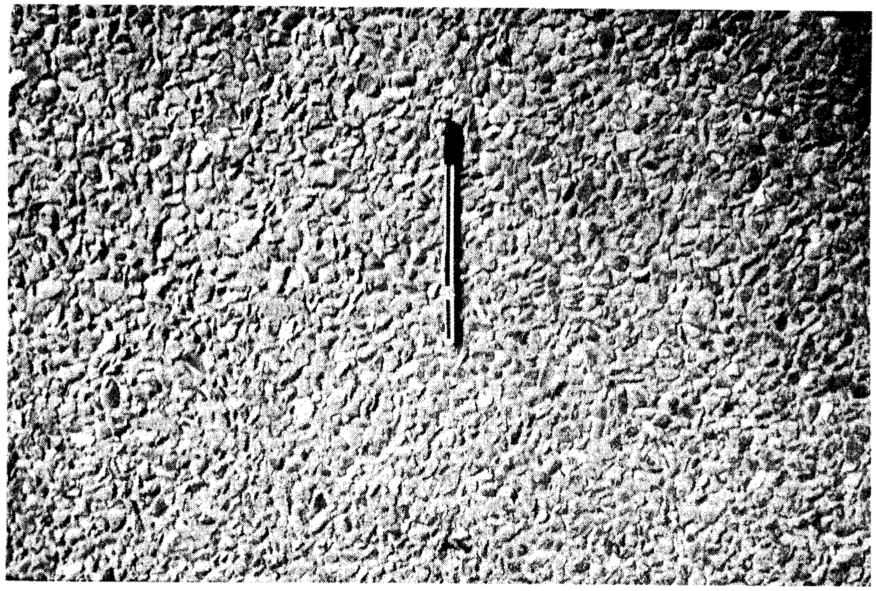

Fig. 2. Close-Up of Surface Treatment Shown in Figure 1.

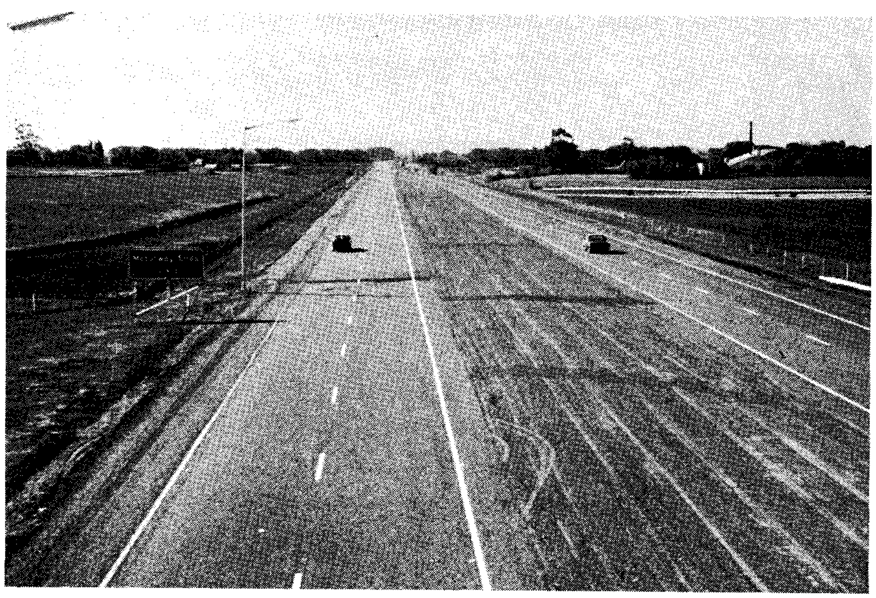

Fig. 3. New Zealand. Double Surface Treatment on Consolidated Granular Base on 4-Lane Divided Highway. This Construction Not Uncommonly Carries More Than 20,000 Vehicles per Day.

Fig. 4. New Zealand. Main Highway Taupo to Wellington. Double Surface Treatment on Consolidated Granular Base.

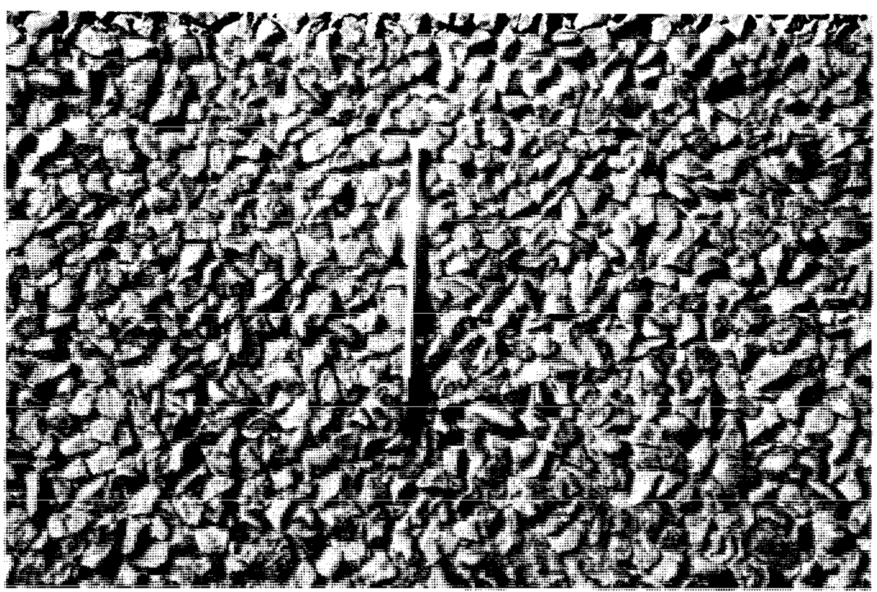

Fig. 5. Close-Up of Surface Treatment Shown in Figure 4.

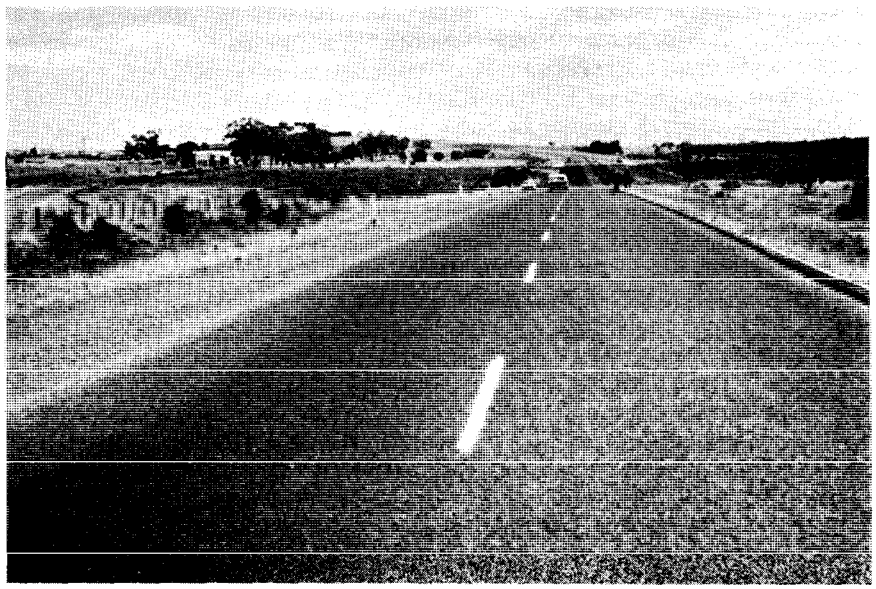

Fig. 6. Victoria, Australia. Single Surface Treatment on Consolidated Granular Base on 4-Lane Divided Highway between Melbourne and Sydney--the Hume Highway Near Melbourne, 6 Years Old, Carrying 4000 Vehicles per Day.

4-lane divided highway section of the Hume Highway between Melbourne and Sydney, near Melbourne, Australia. It is a single surface treatment on a consolidated granular base. It is 6 years old, and is carrying 4,000 vehicles per day, many of them being heavily loaded trucks.

A modification of the methods of design employed so successfully in Victoria, Australia, and in New Zealand, forms the basis for the method of design to be recommended in this paper.

II. DEFINITIONS FOR SURFACE TREATMENTS AND SEAL COATS

Unfortunately, there are still no universally accepted definitions for the terms "seal coats" and "surface treatments." Consequently, for this paper, definitions for these expressions will be employed that have been proposed by several other writers (2), (3), (4), and that have been recommended by Subcommittee MC-A3(3) of the Highway Research Board Committee MC-A3 on Bituminous Surface Treatments, in its "Report on Designation for Surface Treatments," October, 1965.

Therefore, a "surface treatment" is defined as a bituminous surface that results from one or more successive alternate applications of bituminous binder and cover aggregate to a prepared consolidated gravel, crushed stone, waterbound macadam, earth, stabilized soil, or similar base. A "seal coat" is defined as a bituminous surface that results from one or more successive alternate applications of bituminous binder and cover aggregate to an existing paved surface.

III. TYPES OF SURFACE TREATMENTS AND SEAL COATS

There are several different types of surface treatments and seal coats as follows:

A. Single application
- (1) one-size cover aggregate
- (2) graded cover aggregate

B. Multiple application
- (1) double application
- (2) triple application
- (3) quadruple application

Single application surface treatments and seal coats are by far the most common type. They consist of a single application of asphalt binder to a prepared surface, followed by a single application of cover aggregate. They are assumed to be one-stone particle thick.

Double, triple, and quadruple application surface treatments consist of two, three, and four successive alternate applications of asphalt binder and cover stone, respectively. The cover stone employed for each successive layer is approximately one-half the size of that used for the immediately preceding layer.

IV. A STRONG FOUNDATION IS NEEDED

Like any other asphalt surface, a surface treatment or seal coat will fail quickly and disastrously unless it is placed on an adequate foundation.

Experience of the Department of Highways of New Brunswick, where typical Canadian road building conditions of frost and snow in winter, and rain, sun, and hot weather in summer, occur, illustrates the need for an adequate foundation for surface treatments. Following the serious failure of many miles of surface treatments laid initially without proper attention to the foundation, New Brunswick now has 4,000 miles of its secondary road system surfaced with very successful surface treatments. Success followed when the Department of Highways embarked on a 2-year program, in which an adequate foundation was constructed the first year, and the surface treatment itself was not laid until the second year.

V. PRINCIPAL FAULTS

The principal faults in surface treatments and seal coats were discussed in detail in the earlier paper (1), and will be reviewed only briefly here. They are (a) streaking, (b) flushing or bleeding, (c) loss of cover aggregate, and (d) failure to establish a satisfactory bond between the existing surface and the new surface treatment or seal coat.

Streaking is due to the failure to apply asphalt uniformly inch by inch across the road surface. The unevenness of the asphalt binder application shows up as gray or dark streaks due to a deficiency or excess of asphalt binder in the finished surface treatment or seal coat. Streaking may be caused by one or more of several factors. Partially plugged spray nozzles, spray nozzles of poor design, spray nozzles of different size in the spray bar, spray nozzles at various wrong angles in the spray bar, incorrect height of the spray bar above the road surface, varying the rate of discharge from the spray nozzles in gallons per minute per nozzle to obtain specified rates of application per square yard, and trying to spray the asphalt binder at too low a temperature, are some of the more common causes.

Flushed or bleeding surface treatments or seal coats are usually caused by the application of too much bituminous binder, the excess binder oozing out of the cover aggregate onto the surface. Flushing or bleeding may also result from a loss of a portion of the cover aggregate for any reason, such as rain falling shortly after construction, use of too hard an asphalt binder with which the cover aggregate fails to develop adequate adhesion, and use of cover stone that is too dirty or too wet to establish good adhesion to the asphalt binder.

Serious loss of cover aggregate occurs when for any reason there is inadequate embedment of the stone particles in the asphalt binder. Not enough asphalt binder may have been applied, too much of the asphalt binder may have been absorbed by the existing surface, or the asphalt binder applied may be too hard for the prevailing weather or climate. Late season construction can result in grave loss of cover stone when there is not enough warm weather traffic following construction to achieve sufficient embedment of the aggregate particles in the asphalt binder. Wet weather and freezing conditions tend to accelerate the loss of cover stone whenever it is poorly embedded.

A new seal coat or surface treatment may fail to establish a good bond with an existing surface due to a layer of dust or dirt, because the existing surface is wet or too cold, or because the asphalt binder is too hard. Normally, only a small area of a few square inches, or a few square feet, or occasionally a few square yards, but sometimes an entire surface treatment or seal coat fails for this reason.

VI. MATERIALS

Before considering the method of design to be presented, some essential characteristics of the materials employed for surface treatments and seal coats will be outlined. This will provide necessary background information. This topic was covered in considerable detail in the earlier paper (1) and only the items pertinent to the present paper will be reviewed here. The materials of construction for seal coats and surface treatments are cover aggregates and asphalt binders, which may consist of asphalt cements, asphalt emulsions, or liquid asphalts. These will be considered separately.

A. COVER AGGREGATES

1. General

In general, cover aggregates should consist of hard, tough, clean, dry fragments of stone, that have been produced either from quarried rock, or from clean, hard gravel. For high traffic volumes the Los Angeles abrasion rating should preferably be less than 20, while for light traffic it should not exceed a maximum value of 35, but frequently does.

2. Particle Shape

The preferred particle shape for cover aggregate is cubical or tetrahedral, and flat particles should be avoided. The tendency of an aggregate toward particle flatness is measured by the Flakiness Index test (Appendix A). The Flakiness Index represents the percentage by weight of flat particles having a least dimension smaller than 60 per cent of the mean size of each of one or more of the coarser sieve fractions. As an example, for aggregate passing a 3/4 inch square sieve and retained on a 1/2 inch square sieve, the mean sieve size is five-eighths of an inch, and the Flakiness Index of this particular size fraction would be the percentage by weight of particles having a least dimension smaller than three-eights of an inch (3/8 being 60 per cent of 5/8). The lower the Flakiness Index for any sample of cover aggregate, the more nearly the aggregate particles approximate cubical shape. As indicated by Table I, The National Association of Australian State Road Authorities (5) specifies 35 per cent as the maximum permissible Flakiness Index rating.

New Zealand controls particle shape by stipulating a maximum of 2.25 for the ratio of the average greatest dimension to the average least dimension of a cover aggregate. To meet this specification, New Zealand contractors have to employ a hammer mill or impact breaker, which tends to provide more cubically shaped particles than other types of rock crushers.

3. Gradation

Typical grading requirements specified by the National Association of Australian State Road Authorities (5) for one-size aggregates are recorded in Table I.

In North America, the nearest approach to one-size cover aggregates are the aggregate gradations specified in AASHO M-43, listed in Table II. In comparison with the one-size aggregates specified in Table I, the materials covered by Table II are graded aggregates.

When designing single application surface treatments and seal coats, it is assumed that the finished surface is just one-stone particle thick, Figure 7. In an earlier paper (1), grading curves were worked out to determine the range of gradation of coarse and fine aggregates that would make it theoretically possible to have a surface treatment or

Table I. Typical Gradation Requirements for One-Size Cover Aggregate (National Association of Australian State Road Authorities)

SIZE NUMBER	NOMINAL SIZE SQUARE OPENINGS	PER CENT PASSING BY DRY WEIGHT U.S. STANDARD SIEVES SQUARE OPENINGS									PARTICLE SHAPE
		1	3/4	5/8	1/2	3/8	1/4	NO. 4	NO. 8	NO. 16	FLAKINESS INDEX MAX.
E	3/4"	100	95 - 100	-	0 - 20	0 - 5	-	-	-	0 - 0.5	35
F	5/8"		100	95 - 100	-	0 - 15	0 - 5	-	-	0 - 0.5	35
G	1/2"		100	-	95 - 100	0 - 30	0 - 5	-	-	0 - 0.5	35
H	3/8"				100	95 - 100	0 - 40	0 - 5	-	0 - 0.5	35
I	NO. 4						100	95 - 100	0 - 40	0 - 0.5	35

seal coat exactly two stone particles thick. Four of the grading curves for aggregates with maximum particle sizes of 3/8, 1/2, 5/8, and 3/4 inch, obtained on this basis, are illustrated in Figure 8.

In Figure 9, a comparison is made between one of these theoretical grading curves with grading curves for Aggregates No's 7 and 78 from Table II. It is clear that Aggregate No. 78 contains more than enough fine aggregate to theoretically provide a surface treatment or seal coat 2-stone particles thick, while Aggregate No. 7 is at least borderline in this respect.

The correct asphalt binder application should embed every cover aggregate particle in asphalt to 70 per cent of its depth, and particles that are embedded less than 50 per cent in asphalt binder are likely to be torn out by traffic.

Figure 10, which pertains to Aggregate No. 68 from Table II, illustrates the difficulty in providing the proper asphalt content for a graded cover aggregate. If it is assumed that the correct quantity of asphalt binder to be applied will embed the median particle size (the size corresponding to 50 per cent passing) to 70 per cent of its depth, Figure 10 demonstrates that this quantity of asphalt binder will completely

Table II. Standard Sizes of Coarse Aggregate for Highway Construction (AASHO M 43, ASTM D 448)

Size Number	Nominal Size Square Openings	Amounts finer than each laboratory sieve (square openings), percentage by weight.									
		1-1/2	1	3/4	1/2	3/8	No. 4	No. 8	No. 16	No. 50	No. 100
5	1 to 1½	100	90 to 100	20 to 55	0 to 5	0 to 5					
56	1 to 3/8	100	90 to 100	40 to 75	15 to 35	0 to 15	0 to 5				
57	1 to No.4	100	95 to 100	-	25 to 60	-	0 to 10	0 to 5			
6	3/4 to 3/8		100	90 to 100	20 to 55	0 to 15	0 to 5	-			
67	3/4 to No.4		100	90 to 100	-	20 to 55	0 to 10	0 to 5			
68	3/4 to No.8		100	90 to 100	-	20 to 65	5 to 25	0 to 10	0 to 5		
7	1/2 to No.4			100	90 to 100	40 to 70	0 to 15	0 to 5	-		
78	1/2 to No.8			100	90 to 100	40 to 75	5 to 25	0 to 10	0 to 5		
8	3/8 to No.8				100	85 to 100	10 to 30	0 to 10	0 to 5		
89	3/8 to No.16				100	90 to 100	20 to 55	5 to 30	0 to 10	0 to 5	
9	No.4 to No.16					100	85 to 100	10 to 40	0 to 10	0 to 5	
10	No.4 to 0*					100	85 to 100	-	-	-	10 to 30

* Screenings   NOTE: All Sieve Sizes Expressed in Terms of US Standard Sieve Series.

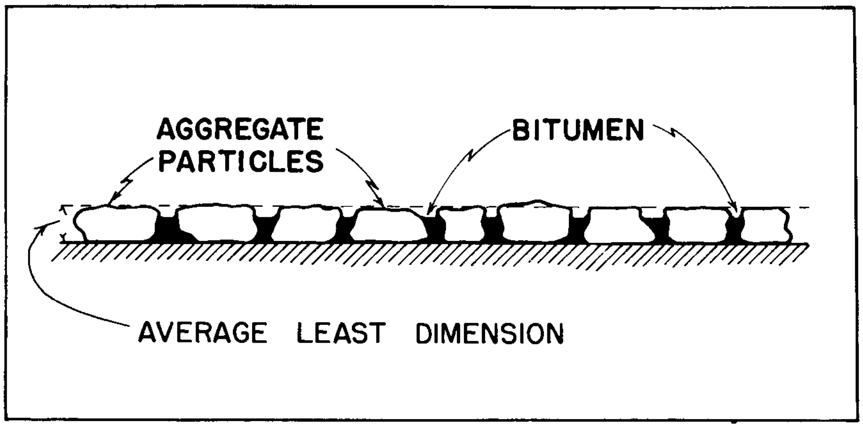

Fig. 7. Illustrating the Average Least Dimension of Cover Aggregate Particles, and the Ultimate Positions of These Particles in a Surface Treatment or Seal Coat After Considerable Traffic. (The Least Dimension of Each Particle Is Vertical.)

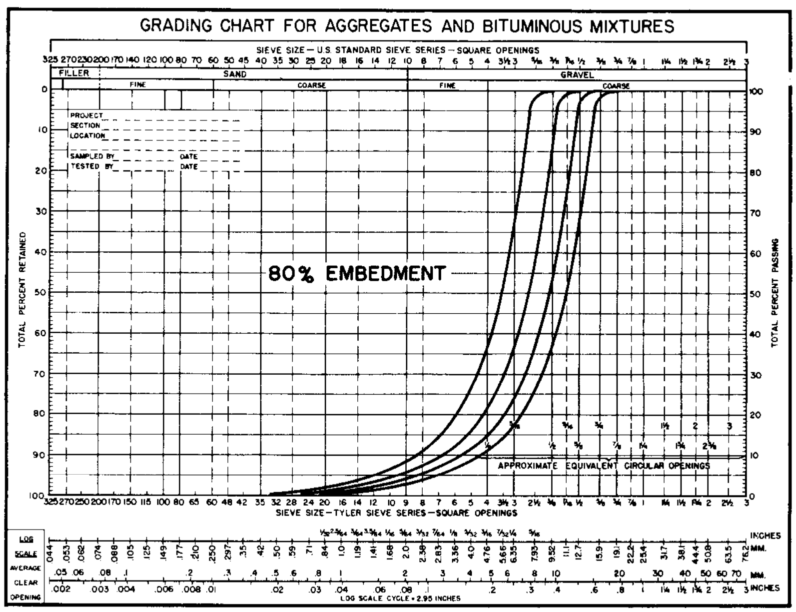

Fig. 8. Grading Curves for Cover Aggregates Capable of Providing Seal Coats or Surface Treatments Exactly 2-Stone Particles Thick Under Ideal Conditions.

submerge 29 per cent of this aggregate, while 32 per cent of the aggregate particles (the largest particles) will be immersed less than 50 per cent of their depth, and will therefore tend to be dislodged by traffic. Figure 10 emphasizes that the proper asphalt binder application for one of the size fractions of a graded cover aggregate, can be far from correct for even a majority of size fractions.

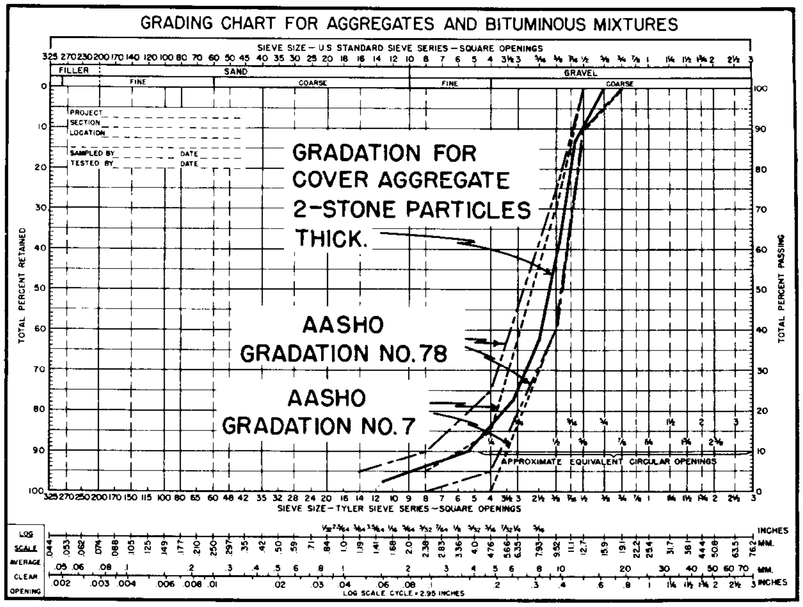

Fig. 9. Illustrating That AASHO Coarse Aggregate Gradations No. 7 and No. 78 Could Provide Seal Coats or Surface Treatments at Least 2-Stone Particles Thick.

Figures 11 and 12 examine one-size cover aggregates on this same basis. The solid curve in Figures 11 and 12 represents the widest possible range of gradation of particle sizes that will just satisfy the grading limits specified for Aggregate G from Table I. The broken line curve in Figure 11 illustrates the corresponding gradation of aggregate particles that could theoretically provide a single application seal coat or surface treatment exactly 2-stone particles thick. It can be seen that one-size Aggregate G does not contain sufficient fine aggregate to provide a single application surface treatment or seal coat 2-stone particles thick.

Figure 12, which applies to one-size Aggregate G demonstrates that when enough asphalt binder is applied to embed the median particle size to 70 per cent of its thickness, only 15 per cent of the cover aggregate (the smallest sizes) would be completely submerged in asphalt binder, while just three per cent of the particles (the largest sizes) would be embedded to less than 50 per cent of their depth.

A comparison of Figure 12 with Figure 10 makes it quite clear that when the optimum quantity of asphalt binder is applied, it satisfies the asphalt binder requirements for a much higher percentage of the particle sizes in a one-size cover aggregate, Table I, than in a graded aggregate, Table II. In addition, when graded cover aggregate is used, the finer particles tend to form a covering on the asphalt binder during construction that delays the wetting and the development of good adhesion between the binder and the larger stone particles. Many of these larger particles are therefore dislodged by traffic before adequate embedment in the asphalt binder can occur. All of these factors indicate that single surface treatments or seal coats that are constructed with graded cover aggregates, Table II, are likely to be less uniform, to be inferior in appearance, and to have a shorter service life than those made with one-size cover stone, Table I. Nevertheless, in spite of these disadvantages, large mileages of seal coats and surface treatments are likely to continue to be constructed with graded cover aggregates, chiefly because they can be produced at lower cost than one-size cover stone. However, it should be noted that the Country Roads Board, Victoria, Australia, employs only one-size cover aggregates although their cost delivered into roadside stockpiles averages approximately $6.00 (US) per cubic yard.

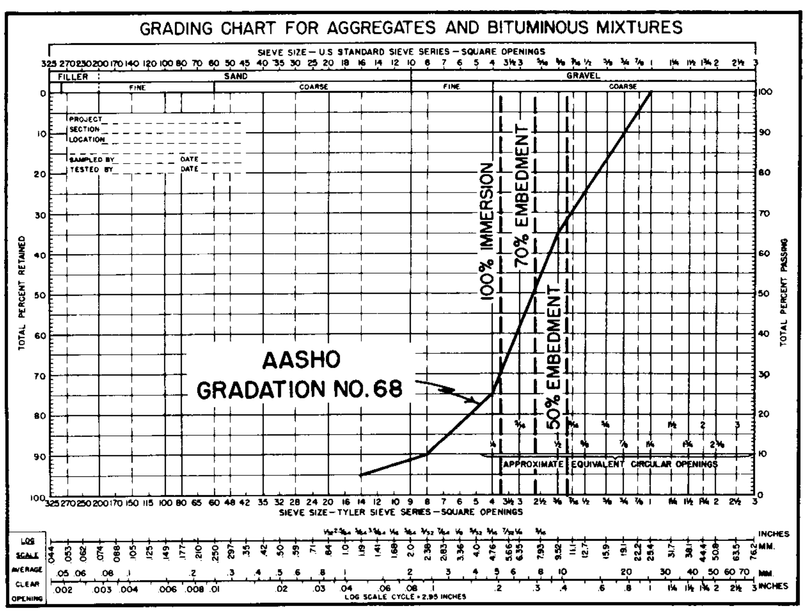

Fig. 10. Illustrating Poor Embedment of AASHO Coarse Aggregate Gradation No. 68 in Asphalt Binder.

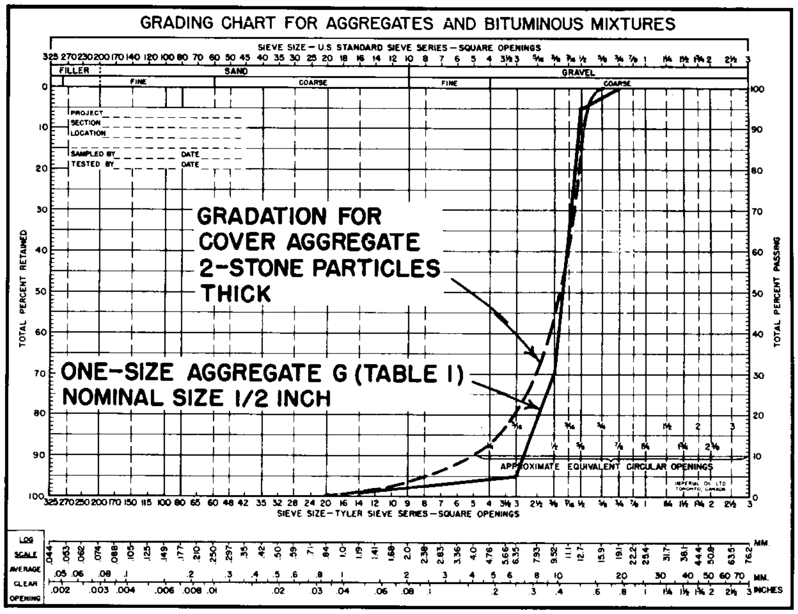

Fig. 11. Illustrating that Grading Curve for One-Size Cover Aggregate G Will Provide a Seal Coat or Surface Treatment Only 1-Stone Particle Thick.

4. Average Least Dimension versus Spread Modulus of Cover Aggregates

Hanson (6) made a most important contribution to the design of surface treatments and seal coats when he observed that after considerable traffic, particles of cover aggregate tend to lie on their flattest sides, Figure 7, with their shortest dimension vertical. Hanson recognized that this means that the average thickness of a seal coat or surface treatment is equal to the average of the smallest dimension of the cover aggregate particles, which he termed the Average Least Dimension or ALD. A method of test for measuring the Average Least Dimension of a cover aggregate is described in Appendix A.

The importance of the Average Least Dimension of the cover stone in both the design and service performance of an asphalt surface treatment or seal coat is illustrated in Figure 13. Both aggregates shown in the two diagrams of Figure 13 would be purchased as 1/2 inch cover stone, because each aggregate will just pass a 1/2 inch square opening. Nevertheless, because it is comprised of cubically shaped particles, the Average Least Dimension of the aggregate in the top diagram is 0.5 inch, while because it consists of elongated flat particles, the ALD of the aggregate in the bottom diagram is only 0.2 inch. If, in accordance with the practice of the Country Roads Board, Victoria, Australia, it is assumed that after substantial warm weather traffic the ultimate void space between the cover aggregate particles in a seal coat or surface treatment is 20 per cent, and that at the optimum asphalt binder application this void space is 70 per cent filled with residual asphalt, the quantity of the aggregate in the top diagram of Figure 13 to be applied for a surface treatment or seal coat is 49 pounds per square yard, and of the cover stone in the lower diagram is only 20 pounds per square yard. Also, the optimum quantity of asphalt binder required for the cover stone in the upper diagram is 0.394 US gallon per square yard (0.328 Imperial gal/sq. yd.) (1.78 litres per square metre), and for the cover aggregate in the bottom diagram is only 0.157 US gallon per

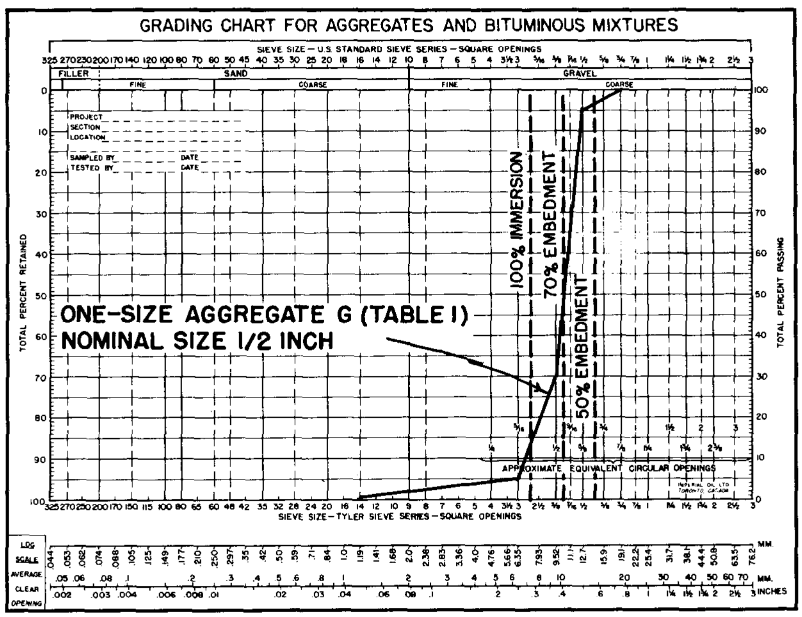

Fig. 12. Illustrating Excellent Embedment of One-Size Aggregate G in Asphalt Binder.

square yard (0.131 Imperial gal/sq. yd.) (0.71 litres per square metre). Consequently, Figure 13 emphasizes that both the asphalt binder and cover aggregate requirements per square yard for a seal coat or surface treatment depend on the cover aggregate's Average Least Dimension.

Figure 13 also provides an explanation for the wide differences in surface treatment and seal coat behaviour in service, and for the poor performance that so often results from the common current practice of recommending a quarter of a gallon of asphalt binder and 25 pounds of cover stone per square yard, or some similar combination of quantities, regardless of the shape of the cover aggregate particles.

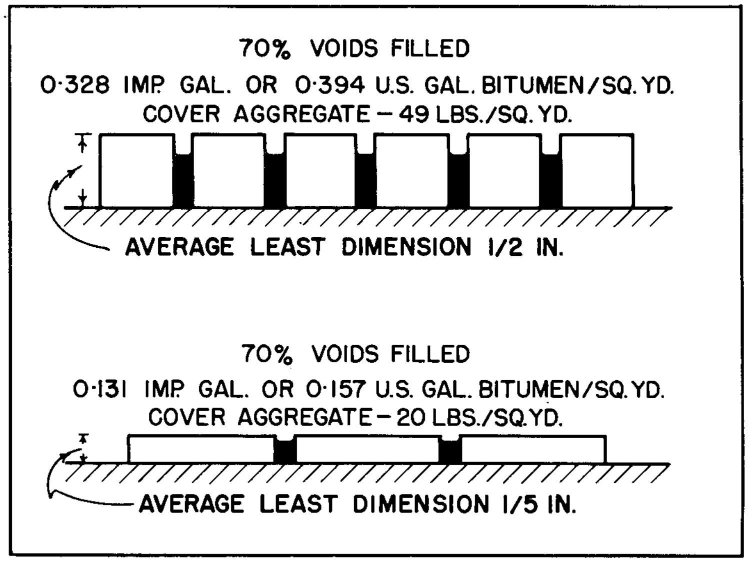

Fig. 13. Comparing Bitumen and Cover Aggregate Requirements per Square Yard for Seal Coats Made with 1/2 Inch Cover Aggregates of Different Particle Shapes --One Cubical, the Other Flat and Elongated.

In some sections of North America the design of surface treatments and seal coats to be constructed with graded cover aggregates, is based upon a measurement termed the Spread Modulus. It is assumed that the Spread Modulus provides a measure of the average thickness of a surface treatment or seal coat. As determined by some organizations, the Spread Modulus is calculated as the weighted average of the mean particle size of the largest 20 per cent, the middle 60 per cent, and the smallest 20 per cent of a graded cover aggregate. Therefore,

$$\begin{aligned} M &= 0.2\left(\frac{a+b}{2}\right) + 0.6\left(\frac{b+c}{2}\right) + 0.2\left(\frac{c+d}{2}\right) \\ &= 0.1\,(a+b) + 0.3\,(b+c) + 0.1\,(c+d) \end{aligned} \qquad [1]$$

where

M = the Spread Modulus, which is a measure of the average thickness in inches of a layer of graded cover aggregate
a = sieve opening in inches for 100 per cent passing
b = sieve opening in inches for 80 per cent passing
c = sieve opening in inches for 20 per cent passing
d = sieve opening in inches for 0 per cent passing

The following example illustrates the calculation of the Spread Modulus M by means of Equation [1] for the grading curve shown in Figure 14 for AASHO Aggregate No. 7.

$$M = 0.1\,(0.625 + 0.44) + 0.3\,(0.44 + 0.225) + 0.1\,(0.225 + 0.033)$$

$$= 0.332 \text{ inch.}$$

Like one-size cover stone, graded cover aggregates in seal coats and surface treatments are gradually reoriented by traffic until the aggregate particles are lying on their flattest sides, with their smallest dimensions vertical to the surface, Figure 7. Therefore, after

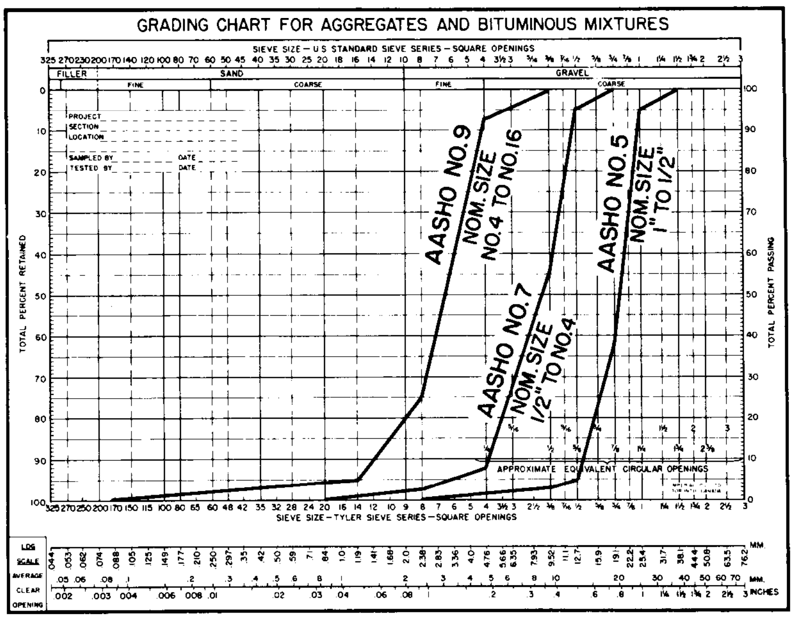

Fig. 14. Average Grading Curves for Three Standard Graded Cover Aggregates.

thorough compaction by warm weather traffic the average thickness of a surface treatment or seal coat made with graded cover stone is governed by the aggregate's Average Least Dimension.

It follows that unless there is some constant ratio between the Spread Modulus M, and the Average Least Dimension H of cover aggregates, the Spread Modulus M cannot be used to provide a simple rational method of design for seal coats and surface treatments constructed with all cover aggregates.

The relationship between the Spread Modulus M and the Average Least Dimension H is shown in Table III for each of twenty-five

Table III. Test Data on One-Size Cover Aggregates

Average Least Dimension Inches (1)	Spread Modulus M Inches (2)	Median Size (50% Passing) Inches (3)	ASTM Bulk Specific Gravity (4)	Loose Bulk Weight Pounds per cu.ft. (5)	Voids Fraction Loose Weight Condition (6)	Flakiness Index Per cent (7)	$\frac{M}{ALD}$ (8)
0.42	0.61	0.61	2.798	91.0	0.479	23.3	1.45
0.42	0.55	0.56	2.680	90.7	0.457	15.1	1.31
0.39	0.58	0.60	2.695	83.1	0.506	32.7	1.49
0.37	0.50	0.54	2.660	90.6	0.454	26.9	1.35
0.37	0.49	0.47	2.690	94.4	0.438	9.5	1.32
0.36	0.46	0.46	2.660	100.2	0.396	10.5	1.28
0.35	0.42	0.44	2.576	-	-	6.0	1.20
0.35	0.47	0.49	-	-	-	22.0	1.34
0.34	0.44	0.43	2.720	97.5	0.425	9.0	1.29
0.32	0.36	0.40	2.690	89.0	0.47	9.9	1.13
0.32	0.48	0.49	2.680	78.1	0.533	31.8	1.50
0.31	0.44	0.44	2.801	91.7	0.475	21.7	1.42
0.31	0.43	0.44	2.760	-	-	21.8	1.39
0.31	0.35	0.37	2.720	108.0	0.364	4.0	1.14
0.30	0.46	0.43	2.803	90.1	0.485	25.0	1.53
0.30	0.41	0.41	-	-	-	20.3	1.37
0.30	0.40	0.42	-	-	-	24.9	1.33
0.27	0.38	0.40	2.685	83.7	0.5	31.1	1.41
0.24	0.32	0.32	2.748	87.4	0.49	16.2	1.33
0.23	0.32	0.31	2.797	90.5	0.48	20.6	1.39
0.22	0.28	0.28	2.660	87.9	0.47	14.7	1.27
0.22	0.27	0.28	2.641	92.8	0.438	9.8	1.23
0.21	0.27	0.28	2.631	90.4	0.45	18.6	1.29
0.20	0.25	0.25	2.670	102.7	0.383	15.1	1.25
0.18	0.26	0.27	2.650	88.3	0.466	34.7	1.44
					Overall Average		1.34

one-size cover aggregates, and in Table IV for twenty-five graded aggregates. In addition, Figure 15 provides a graph of the ratio of the Spread Modulus over the Average Least Dimension, M/H, versus Flakiness Index for the cover aggregates of Tables III and IV. Flakiness Index values provide a measure of the tendency of aggregate particles toward flatness in one dimension, and of the degree by which they fail to be perfect cubes.

The data in the right hand columns of Tables III and IV demonstrate that the ratio of Spread Modulus M to Average Least Dimension H, M/H, is far from being a constant. Values for this ratio range from 1.13 to 1.53 for the one-size cover aggregates of Table III, and from 1.11 to 1.50 for the graded cover aggregates of Table IV.

While there is considerable scatter of data, Figure 15 indicates that in general, the ratio of M/H increases with an increase in the Flakiness Index of cover aggregates. This is to be expected, since for an aggregate consisting of 1/2 inch cubes for example, M/H would have a value of 1.0. The value of M/H would be expected to increase gradually as the particles of cover aggregates become flatter in one dimension, that is, as their Flakiness Index values increase.

Tables III and IV indicate overall average values for M/H of 1.34 and 1.32, respectively. Therefore, for cover aggregates with M/H values in the vicinity of 1.33, long experience would gradually indicate the approximately correct asphalt binder applications to employ. However, only poor results could be expected for seal coats and surface

Table IV. Test Data on Graded Cover Aggregates

Average Least Dimension Inches (1)	Spread Modulus M Inches (2)	Median Size Inches (3)	ASTM Bulk Specific Gravity (4)	Loose Bulk Weight pounds per cu.ft. (5)	Voids Fraction Loose Weight Condition (6)	Flakiness Index Per cent (7)	$\frac{M}{ALD}$ (8)
0.46	0.58	0.56	2.720	108.0	0.364	5.2	1.26
0.38	0.56	0.55	2.690	87.8	0.477	25.5	1.47
0.37	0.50	0.49	2.658	92.1	0.445	13.8	1.35
0.36	0.50	0.52	2.692	-	-	27.2	1.39
0.36	0.44	0.46	2.630	98.3	0.401	12.5	1.22
0.31	0.40	0.40	2.663	86.9	0.447	12.9	1.29
0.29	0.35	0.36	2.684	90.7	0.460	10.0	1.21
0.28	0.38	0.40	-	-	-	23.0	1.36
0.28	0.36	0.37	2.673	-	-	17.6	1.29
0.27	0.36	0.35	2.690	99.5	0.407	9.0	1.33
0.27	0.35	0.37	-	-	-	19.7	1.30
0.26	0.36	0.36	2.728	-	-	24.3	1.38
0.26	0.34	0.34	2.680	86.2	0.487	17.5	1.31
0.26	0.29	0.32	2.680	102.2	0.387	9.3	1.11
0.25	0.33	0.33	2.686	89.8	0.463	13.4	1.32
0.24	0.32	0.32	2.748	87.4	0.490	16.2	1.33
0.23	0.30	0.31	2.660	94.1	0.433	21.0	1.30
0.22	0.30	0.30	2.690	91.4	0.455	22.8	1.36
0.22	0.27	0.28	2.655	89.2	0.462	10.9	1.23
0.22	0.33	0.32	-	-	-	26.6	1.50
0.21	0.30	0.30	2.664	82.6	0.504	25.4	1.43
0.21	0.28	0.28	-	-	-	18.0	1.33
0.21	0.26	0.26	2.682	-	-	10.5	1.24
0.20	0.26	0.26	2.730	-	-	12.5	1.30
0.18	0.27	0.27	2.660	91.3	0.449	31.8	1.50
					Overall Average		1.32

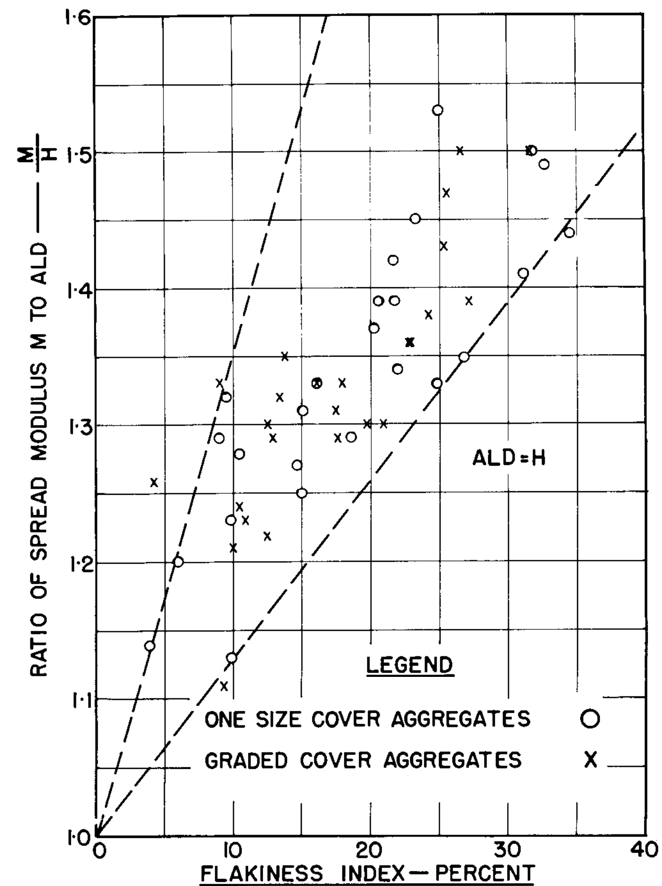

Fig. 15. Illustrating the Influence of Flakiness Index on the Ratio of Spread Modulus M to Average Least Dimension H for Cover Aggregates.

treatments designed on the basis of the Spread Modulus M, when the M/H values for the cover aggregates are quite different from 1.33.

Since a constant ratio between the Spread Modulus M and the Average Least Dimension of cover aggregates does not exist, the use of the Spread Modulus M as a basis for the design of surface treatments and seal coats can be expected to require the use of too much asphalt binder in some cases, and not enough asphalt binder in others. Consequently, in this paper, no further reference to the cover aggregate's Spread Modulus will be made, since it does not appear to be a reliable guide to the design of surface treatments and seal coats with either graded or one-size cover stone. Instead, the method of design to be advocated here will be based on the cover aggregate's Average Least

Dimension H, which provides a much more trustworthy indication of the average thickness of a surface treatment or seal coat made with either a one-size or graded cover aggregate after it has been thoroughly compacted by traffic.

It is to be strongly emphasized that if during the expected service life of a surface treatment or seal coat, there is some possibility that the cover aggregate particles may be forced by traffic part way into the surface on which the seal coat or surface treatment is to be constructed, this degree of penetration of the cover stone must be allowed for when determining the quantity of asphalt binder to be applied. Otherwise, a flushed or bleeding surface may result. In this case, the quantity of asphalt binder required should be based on the "effective" Average Least Dimension of the cover aggregate, which is its measured Average Least Dimension minus its estimated depth of penetration into the surface to which the surface treatment or seal coat is to be applied.

Incidentally, data in Columns 2 and 3 in Tables III and IV demonstrate that in spite of the somewhat involved methods employed to calculate the Spread Modulus M of a cover aggregate, for example Equation [1], the value derived for the Spread Modulus M for any given sample of cover aggregate is almost always very nearly equal to the aggregate's median particle size, which is obtained by merely reading from the grading chart the sieve opening corresponding to the particle size for 50 per cent passing.

5. Voids Fraction and Specific Gravity of Cover Aggregate

In this paper the design requirements for quantities of cover aggregates to be applied per square yard for a seal coat or surface treatment are based on the ASTM bulk specific gravity of the cover stone, and on the fraction of voids in its loose weight condition.

The ASTM bulk specific gravity G of a cover aggregate can be determined by ASTM C 127 for the corase aggregate fraction, and by ASTM C 128 for the fine aggregate portion. If a cover aggregate must be used for which the ASTM bulk specific gravity is not known, a list of aggregates of different mineralogical compositions and their corresponding ASTM bulk specific gravities is provided in Table V.

The fraction of voids V in a cover aggregate on a loose weight basis requires that the loose weight of a sample of the aggregate be measured by means of ASTM C 29, and it is then calculated on the basis of the following equation:

$$V = 1 - \frac{W}{62.4G} \qquad [2]$$

where

V = fraction of voids in the cover stone in its loose weight condition

W = weight of cover stone in its loose weight condition as measured by ASTM C 29
G = ASTM bulk specific gravity of the cover aggregate

For example, if the loose weight W of a sample of cover aggregate is 96 pounds per cubic foot, and if its ASTM bulk specific gravity is 2.66, the fraction of voids V in the cover aggregate in its loose weight condition is

$$V = 1 - \frac{96}{(2.66)(62.4)} = 1 - 0.578 = 0.422$$

Table V. Typical Values for ASTM Bulk Specific Gravities of Various Types of Aggregates

Aggregate Type	ASTM Bulk Specific Gravity
Gravel	2.65
Limestone	2.70
Dolomite	2.70
Traprock	2.90
Granite	2.65
Gneis	2.70
Quartzite	2.70
Rhyolite	2.60

6. Influence of Cover Aggregate Size on Service Performance

From observations of the field performance of numerous surface treatments and seal coats, it appears that successful service behaviour more often results when large size cover aggregate rather than small size is employed. As illustrated by Figures 16 and 17, this would seem to be due to the larger safety factor in terms of gallons per square yard or litres per square metre with regard to the application of either too much or too little asphalt binder that the use of larger cover stone provides. Added advantages associated with larger size cover aggregate of acceptable quality are longer service life for a surface treatment or seal coat, and the ability to carry higher traffic volumes.

The amount of asphalt binder to be applied should on the average embed the cover stone particles to 70 per cent of their depth. Dangerous flushing or bleeding will occur if the quantity of asphalt binder embeds the cover stone to 100 per cent of its average thickness. Consequently, the difference in asphalt quantity per square yard between 70 per cent and 100 per cent average embedment of the cover aggregate provides a measure of the factor of safety against applying too much asphalt. On the other hand, serious loss of cover stone can be expected

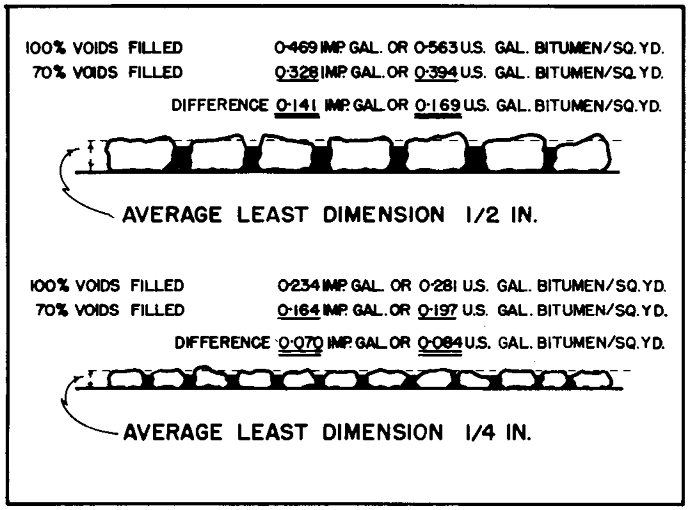

Fig. 16. Illustrating that Surface Treatments or Seal Coats Made with Larger Cover Aggregates Are Less Sensitive to Small Variations in Bitumen Application Than When Smaller Cover Aggregates Are Used.

if the quantity of asphalt binder applied embeds the cover stone to less than 50 per cent of its average depth. Therefore, the difference in asphalt quantity per square yard between 70 per cent and 50 per cent embedment of the cover aggregate provides a measure of the factor of safety against applying too little asphalt binder.

For the larger cover stone illustrated in the top diagram of Figure 16, which has an Average Least Dimension of 0.5 inch, 70 per cent average embedment of the cover stone requires a 0.394 US gallon per square yard (0.328 Imperial gal/sq. yd.) (1.78 litres per square metre) of asphalt binder, while 0.563 US gallon per square yard (0.469 Imperial gal/sq. yd.) (2.55 litres per square metre) would provide an average embedment of 100 per cent. A measure of the margin of safety against serious flushing or bleeding of the seal coat or surface treatment in this case is given by the difference between 100 per cent and 70 per cent embedment, 0.563 - 0.394 = 0.169 US gallon per square yard (0.141 Imperial gal/sq. yd.) (0.77 litre per square metre). Similarly, the bottom diagram in Figure 16 shows that for a smaller aggregate with an ALD of 0.25 inch, a measure of the margin of safety against flushing or bleeding is given by 0.281 - 0.197 = 0.084 US gallon per square yard (0.07 Imperial gal/sq. yd.) (0.38 litre per square metre).

Figure 16 demonstrates therefore, that the margin of safety against flushing or bleeding of a surface treatment or seal coat is very much greater, 0.169 versus 0.084 US gallon per square yard, or about 1/6 versus 1/12 US gallon per square yard (about 1/7 versus 1/14 Imperial gal/sq. yd.) (about 3/4 versus 3/8 litre per square metre), when the larger size cover aggregate is employed.

For the small size cover aggregate illustrated by the diagram at the top of Figure 17, with an ALD of 0.2 inch, 70 per cent embedment of the cover stone requires 0.157 US gallon per square yard (0.131 Imperial gal/sq. yd.) (0.71 litre per square metre) of asphalt binder, while 50 per cent embedment needs 0.113 US gallon per square yard (0.094 Imperial gal/sq. yd.) (0.51 litre per square metre). A measure of the margin of safety against loss of this particular cover stone is given by the difference in the asphalt requirement for 70 per cent and for 50 per cent embedment, 0.157 - 0.113 = 0.044 US gallon per square yard (0.037 Imperial gal/sq. yd.) (0.20 litre per square metre). Similarly, the sketch at the bottom of Figure 17 shows that for the much larger cover stone with an ALD of 0.6 inch, the margin of safety against serious loss of cover aggregate is 0.472 - 0.337 = 0.135 US gallon per square yard (0.112 Imperial gal/sq. yd.) (0.61 litre per square metre).

For the particular comparison illustrated in Figure 17 therefore, the margin of safety against loss of cover stone because not enough asphalt binder has been applied is very much greater, 0.135 versus 0.044 US gallon per square yard, or about 1/7.5 versus 1/23 US gallon per

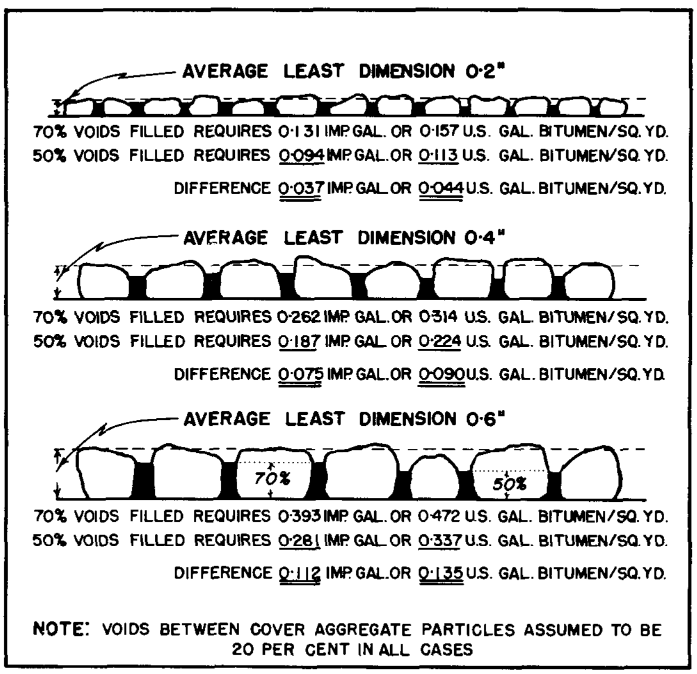

Fig. 17. Influence of Cover Aggregate Size on the Critical Range of Bitumen Quantity Required for a Seal Coat or Surface Treatment.

square yard (about 1/9 versus 1/27 Imperial gal/sq. yd.) (about 3/5 versus 1/5 litre per square metre), in favour of the larger size cover stone.

Consequently, Figures 16 and 17 demonstrate that the margin of safety against flushing or bleeding caused by the application of too much asphalt binder, or against loss of cover stone resulting from not applying enough binder, is very much greater for large size than for small size cover stone. On a percentage basis, the margins of safety illustrated in Figures 16 and 17 against applying either too much or too little asphalt binder are the same both for large size and for small size cover aggregate. However, the amount of play, backlash, or irregularity of operation in the various parts of an asphalt distributor that is in poor mechanical condition, and that may be badly worn, improperly adjusted, carelessly operated, etc., may introduce variations into the quantity of bitumen being applied that do not occur on a percentage basis.

Incidentally, Figures 16 and 17 also demonstrate the need for calibrating and frequently checking asphalt distributors so that the quantity of asphalt binder being applied per square yard is known precisely. For example, the top diagram of Figure 17, which pertains to 3/8 inch cover stone, demonstrates that unless the quantity of asphalt binder being sprayed is known within 1/23 US gallon per square yard (1/27 Imperial gal/sq. yd.) (1/5 litre per square metre), serious loss of cover aggregate could occur due to not enough asphalt binder being applied. This could easily happen if the distributor was thought to be applying 0.157 US gallon per square yard (0.131 Imperial gal/sq. yd.) (0.71 litre per square metre), but was actually applying less than 0.113 US gallon per square yard (0.094 Imperial gal/sq. yd.) (0.51 litre per square metre) needed for a minimum average cover aggregate embedment of at least 50 per cent. How many asphalt distributors can actually apply asphalt binder uniformly and consistently within 1/23 US gallon per square yard (1/27 Imperial gal/sq. yd.) (1/5 litre per square metre) of the quantity that good design has specified? Consequently, Figures 16 and 17 emphasize the fact that in addition to the care taken when designing the quantity of asphalt binder to be applied, it is equally important for the asphalt distributor to be in good mechanical condition, and that it be operated to apply accurately and uniformly the quantity of asphalt binder per unit of area called for by the design procedure being employed.

7. Adhesion between Cover Aggregate and Asphalt Binder

The development of rapid adhesion between cover aggregate and asphalt binder depends very largely on the degree of fluidity of the binder when the cover aggregate is applied. Good adhesion will develop very slowly if the asphalt binder is too hard or too viscous. Nevertheless, assuming that the asphalt binder is of the proper viscosity, to be rapidly wetted by the binder, and to develop fast adhesion, the cover stone should be free from dust or dirt, it should be dry (except when the binder is an asphalt emulsion), and it should not be markedly hydrophilic.

Every effort should be made therefore, to have the aggregate as clean as possible, by washing it, if necessary.

The development of rapid adhesion between the cover aggregate and the asphalt binder can be accelerated by precoating the aggregate. The National Roads Board of New Zealand requires all cover aggregate used for surface treatments and seal coats on state roads to be precoated. Before precoating, the cover stone must be washed to remove dust and dirt. Since coal tar is plentiful, precoating of the cover stone is achieved by mixing it with from one to one and one-half gallons of light coal tar per cubic yard. The cover stone may be passed through a drier and then into a pugmill where the coal tar is added. Alternatively, the cover stone is sprayed with coal tar as it passes through a loading chute into the truck. Elsewhere, precoating may consist of coating the cover aggregate with about one per cent by weight of MC 30 (MC 0) or MC 70 (MC 1).

Figures 18 and 19 illustrate precoating cover aggregate with diesel fuel oil in Australia. The workman in the foreground in Figure 18 is operating a hand pump to transfer diesel fuel oil from the drum to the spray nozzle being directed by the second workman onto the aggregate being lifted from the stockpile by a bucket elevator, Figure 19. This operation could be mechanized. In going through the trommel screen on the way to the truck, fine material is removed, and the diesel fuel oil is distributed more evenly over the surface of the cover aggregate.

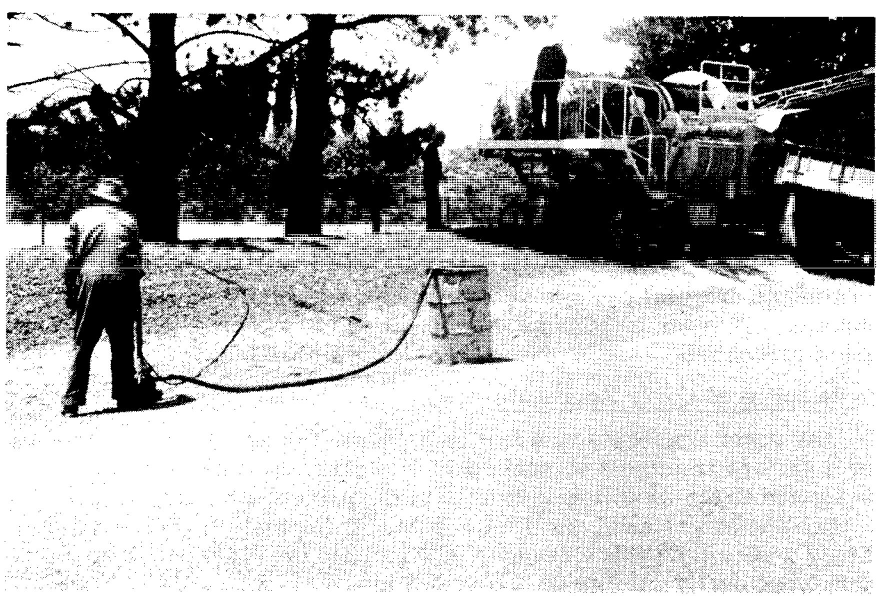

Fig. 18. Victoria, Australia. Precoating Cover Aggregate with Diesel Fuel Oil as It Is Being Lifted from Stockpile to Haulage Truck.

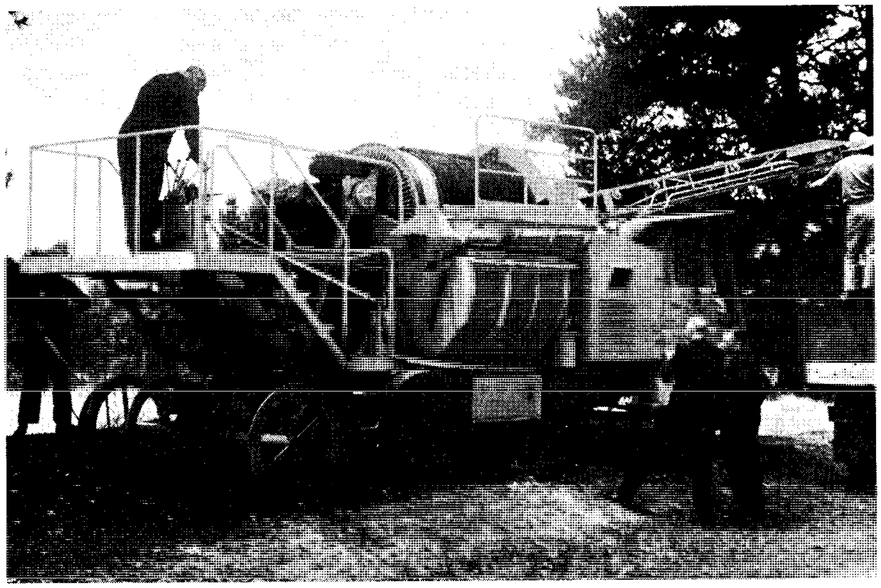

Fig. 19. Victoria, Australia. Stockpiled Cover Aggregate Is Sprayed with Diesel Fuel Oil as It Is Lifted by Bucket Elevator to Trommel Screen on Way to Haulage Truck. Trommel Screen Assists in Coating the Aggregate Particles with Fuel Oil, and Screens Out Any Fine Material.

From 0.5 to 2.5 gallons of diesel fuel oil are applied per cubic yard of aggregate. The quantity of diesel fuel oil coating on each stone particle should dampen it, but there should be no tendency for fluid to drip from any particle. The cover aggregate should preferably be applied the same day that it is precoated.

Because it promotes the development of rapid wetting and good adhesion, precoating of the cover aggregate enables successful surface treatments and seal coats to be constructed with more viscous asphalt binders, and under less favourable conditions than when the cover stone is not precoated.

8. Selection of Cover Aggregate

Any cover aggregate size that is listed in Tables I or II may be used for a surface treatment or seal coat. However, the size selected should be related to the conditions expected at the project site, such as:

(a) The nature and type of asphalt binder to be used. For example, if only a very fluid asphalt binder is available, the cover stone size should ordinarily not exceed 3/8 or 1/2 inch.

(b) Nature and volume of traffic anticipated. Larger size cover stone may be specified for higher traffic volumes.

(c) Nature and condition of the existing surface. If the base or existing surface is soft or weak, large size cover stone may be partly forced into it by a roller or traffic, and should therefore normally be avoided.

(d) Type of treatment, single or multiple application. While only one aggregate size is selected for a single application seal coat or surface treatment, at least two aggregate sizes are ordinarily required for multiple application construction.

B. ASPHALT BINDER

1. Residual Asphalt

The asphalt binder may consist of an asphalt cement, an asphalt emulsion, or a liquid asphalt. Like many others, the author has observed that regardless of which of these three types of asphalt binder is used, in successful surface treatments and seal coats the average degree of embedment of the cover aggregate particles in the residual asphalt is about 70 per cent. The gradual rise of asphalt binder around cover aggregate particles is illustrated in Figure 20, which demonstrates that after a substantial amount of warm weather traffic, the

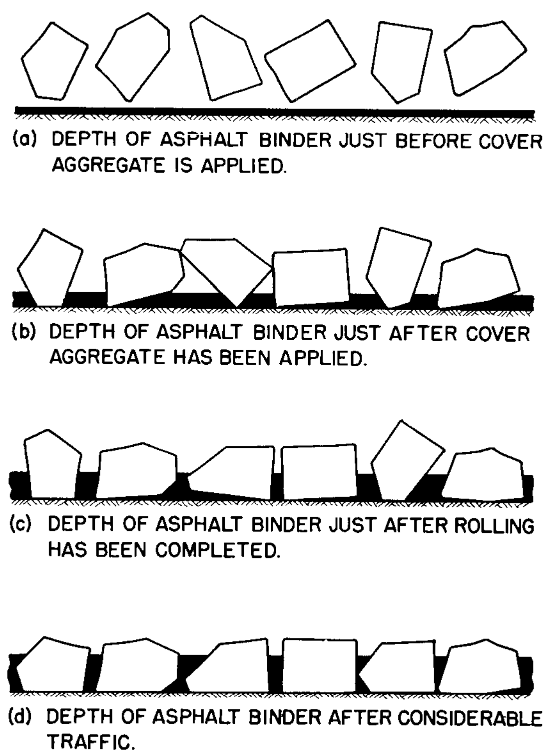

Fig. 20. Illustrating Gradually Increasing Depth of Asphalt Binder between Initial and Final Stages of a Seal Coat or Surface Treatment.

depth of the asphalt binder is from four to six times its thickness immediately before the cover stone is applied. Consequently, in agreement with the Country Roads Board (7), British Road Research Laboratory (8), Idaho Department of Highways (9), Kerr (10), Hanson (6), Tagle (11), Nevitt (12), Kearby (13), Winnitoy (14), and Benson (4), the author recommends that the design of a surface treatment or seal coat should be based on the residual asphalt content of the asphalt binder. This means that when determining the quantity of an asphalt binder to be applied, allowance must be made for the solvent content of liquid asphalts, and for the water content of asphalt emulsions and also their solvent content, if any. The fraction of residual asphalt "R" in any liquid asphalt binder is the fraction of the residue from distillation to 680 F, and in any asphalt emulsion is the fraction of the residue from distillation to 500 F. For asphalt cements, "R" = 1.0. When this information is not available for any particular asphalt binder being used, representative values for "R" for a wide range of asphalt binders are given in Table VI.

Table VI. Average Values for Fraction "R" of Residual Asphalt (by Volume) Contained in Asphalt Binders Used for Surface Treatments and Seal Coats

Asphalt Binder	Fraction of Residual Asphalt "R" by Volume
Asphalt Cements	1.00
Liquid Asphalts	
RC 3000	0.87
RC 800	0.84
RC 250	0.79
RC 70	0.71
RC 5	0.87
RC 4	0.85
RC 3	0.82
RC 2	0.78
RC 1	0.73
RC 0	0.62
Asphalt Emulsions	
RS 3K	0.69
RS 2K	0.63
RS 2	0.65
RS 1	0.58

2. Asphalt Application Temperatures

For successful seal coat and surface treatment construction, it is important that the asphalt binder in the distributor be at a sufficiently high temperature to fan out properly from the spray nozzles. Spraying asphalt binder that is too cold is a common cause of streaking in a finished surface treatment or seal coat, because the spray nozzles are unable to apply the asphalt binder uniformly inch by inch across the road surface.

Recommended spraying temperatures for asphalt emulsion grades used for seal coats and surface treatments are as follows:

Asphalt Emulsion Grade	Recommended Temperature for Spraying
RS-1	75 to 130 F
RS-2	110 to 160 F
CRS-1	75 to 130 F
CRS-2	110 to 160 F

Spraying temperatures that are recommended for liquid asphalts and asphalt cements can be read from the viscosity-temperature chart of Figure 21 for these materials. Figure 21 provides viscosity versus temperature curves for the recently adopted grades RC 70, 250, 800

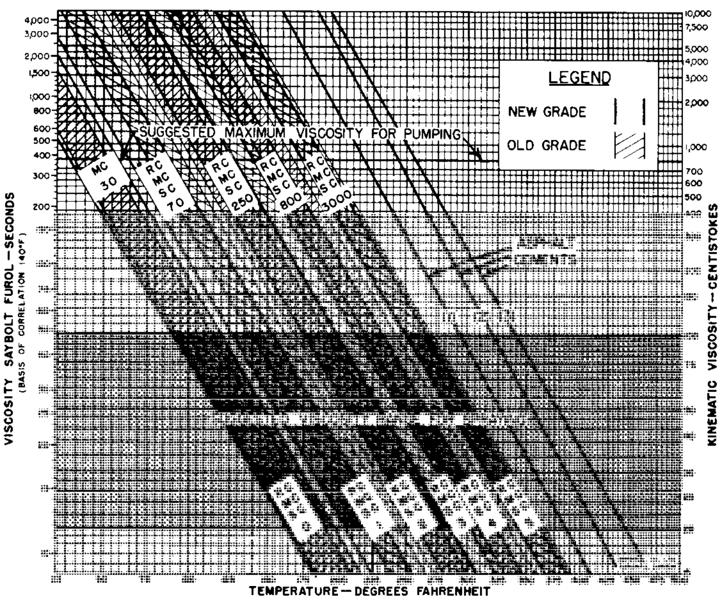

Fig. 21. Illustrating the Viscosity Limits for Liquid Asphalt Grades, with Recommended Viscosity Range for Spraying for Seal Coat and Surface Treatment Construction.

and 3000, and similar information for the older designations RC 0, 1, 2, 3, 4, and 5, which are still in use in many countries. The spraying temperatures recommended in Figure 21 correspond to a range of viscosity from 20 to 100 centistokes (10 to 50 seconds Saybolt Furol). If 50 centistokes is selected as the optimum viscosity for spraying, Figure 21 indicates that the spraying temperature for RC 800 for example, is 255 F, while for RC 2, it shows that the spraying temperature should be 210 F.

In hot climates, asphalt cements ranging in penetration at 77 F from 85/100 to 200/300, are used successfully as binders. The asphalt supplier can provide the temperature viscosity curves for these asphalt cements. For asphalt cement No. 2 for example, if 50 centistokes is selected as the spraying viscosity, Figure 21 indicates that the corresponding spraying temperature should be 355 F.

3. Volume of Asphalt Binder at Its Spraying Temperature

The quantity of asphalt binder that is calculated for use when designing a seal coat or surface treatment, is based upon its volume measured at 60 F. However, as already indicated, spraying temperatures may range from 75 F to more than 350 F. Like most materials, asphalt binders expand when heated, and to control the quantities being applied during construction, measurements of asphalt binder must be made in the distributor at the spraying temperature. Depending upon their specific gravities, and the temperature, the coefficients of expansion of asphalt materials range from 0.00035 to 0.00045 per F over the range of construction and service temperatures to which they are normally subjected. For asphalt emulsions, the coefficient of expansion is about 0.00025 per F.

ASTM Designation D 1250 provides comprehensive tables of volume corrections to be made due to coefficients of expansion, when the temperature of petroleum products is other than 60 F. Figure 22 has been prepared from the data in these tables. Figure 22 indicates by how much a given volume of asphalt binder at 60 F changes in volume when it is heated or cooled to some other temperature within the range of 0 to 500 F. The three curves in Figure 22 illustrate these volume changes for three different groups of asphalt binders. Line (1) pertains to asphalt binders with specific gravities within the range of 0.850 to 0.966 (Group 1), which would usually be the lower viscosity liquid asphalt grades such as RC 70 or RC 250 (RC 1 or RC 2). Line (2) is employed for asphalt binders, usually asphalt cements and the more viscous grades of liquid asphalts having specific gravities higher than 0.966 (Group 0). Line (3) provides temperature volume corrections for asphalt emulsions.

Suppose for example, that the specified rate of application of an asphalt binder at 60 F is 0.28 gallon per square yard, and that Figure 21 indicates that the application temperature should be 250 F. If the specific gravity of the asphalt binder at 60 F is higher than 0.966, Line (2) in Figure 22 shows that one gallon of asphalt at 60 F expands to 1.07 gallon at 250 F, which is a volume increase of seven per cent. Therefore, the required rate of application at 250 F is (0.28) (1.07) = 0.30 gallon per square yard.

4. Selecting the Asphalt Binder

For the particular conditions associated with each surface treatment or seal coat project, the asphalt binder should be selected to satisfy the following two basic requirements:

(a) It must be fluid enough *at the road surface temperature* to rapidly wet the particles of cover stone as soon as they are spread

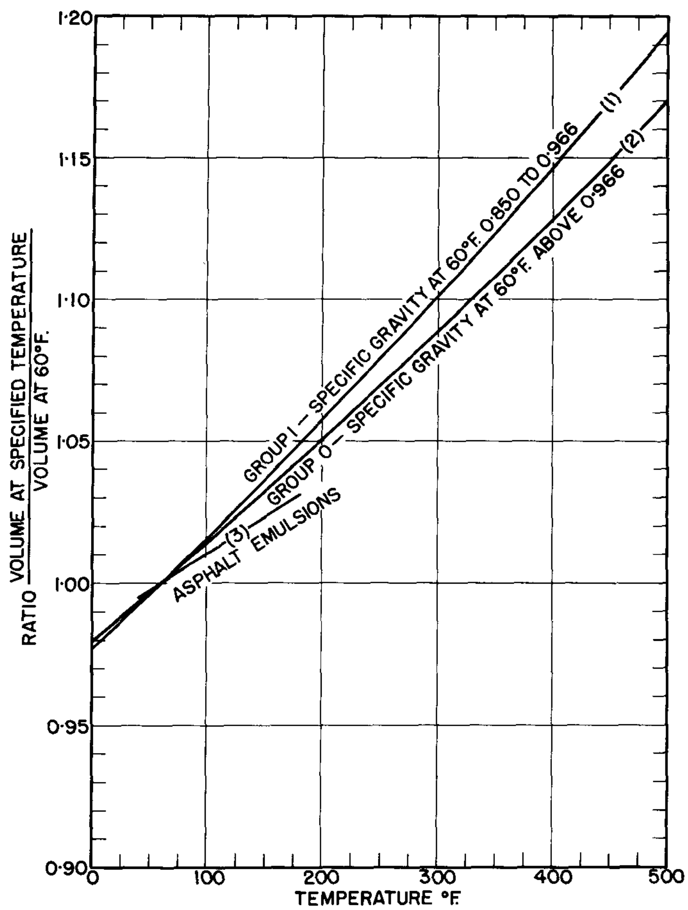

Fig. 22. Influence of Temperature on Volume Change in Asphalt Binders.

over it, and thereby promote fast initial adhesion between the cover aggregate and the binder. When the binder is selected with this degree of fluidity in mind, it will also ordinarily establish a firm bond to any clean dry surface to which it is applied.

(b) Immediately after construction, the asphalt binder should be viscous enough to cement the cover stone so tenaciously to the road surface, that the stone particles are not dislodged by passing vehicles when the new seal coat or surface treatment is opened to traffic.

It is obvious that these two basic requirements are completely opposite to each other, the first requiring a fluid, the second a viscous material. Consequently, a compromise must be made, and with actual job conditions always in mind, the asphalt binder selected should be fluid enough to provide for satisfactory wetting, and the development of rapid initial adhesion between the cover aggregate and the binder, but viscous enough for good aggregate retention when traffic begins to use the finished surface treatment or seal coat.

The selection of the asphalt binder should also be influenced by the road surface temperature, by the size of the cover aggregate, and by the climate of the region. Regardless of its spraying temperature, the asphalt binder chills to the road surface temperature within two minutes after application (15, 16). In cool weather therefore, a more fluid asphalt binder should be selected, for example RC 250 (RC 2) instead of the RC 800 (RC 4) that may have been employed in warm weather, if rapid adhesion is to be developed between the binder and the cover stone. Consequently, it is usually wrong to insist that a single asphalt binder, for example, 150/200 penetration, or RS-2, or RC 800, must always be employed for a seal coat or surface treatment regardless of job circumstances. Nevertheless, this is sometimes done. When all other conditions are the same, experience has demonstrated that large size cover stone requires the application of a more viscous asphalt binder to hold it in place against the dislodging tendency of traffic immediately after construction, than small size cover aggregate. Probably because of the higher daily temperatures and longer period of hot weather, for the same size of cover aggregate, a more viscous asphalt binder can be specified in a hot climate for the same road surface temperature than in a temperate or colder climate.

With all these factors in mind, the selection of liquid asphalt and asphalt cement binders for a wide range of conditions is summarized in Figures 23, 24, 25, and 26 both for cooler and for hot climates. The basis for Figures 23 to 26 has been discussed elsewhere (1). In each of these four figures, the ordinate represents viscosity of the binder, and the abscissa, road surface temperature. A rough correlation between ambient air temperature on sunny days and road surface temperature is also indicated, but the basic relationship illustrated in these four figures is in terms of road surface temperature which can be easily measured with suitable thermometers. The diagonal lines from upper left to lower right on each figure are viscosity versus road surface temperature curves for the grades of asphalt binder indicated. The horizontal lines on each figure represent different nominal sizes of cover stone. Figures 23 and 24 are based on rapid curing liquid asphalt grades RC 0 to RC 5, while Figures 25 and 26 are based on the corresponding new designations RC 70 to RC 3000. Figures 23 and 25 are for use in cooler climates like those of the Northern United States, Canada and Western Europe north of the Alps Mountains. Figures 24 and 26 are intended to be employed in tropical or sub-tropical climates like the Southern United States, and Australia. Similar charts could be prepared for intermediate climates, or for the special climatic conditions of certain regions.

It is very easy to use Figures 23, 24, 25, and 26 for the selection of the correct grade of asphalt binder. Suppose for example, that in one of the Northern States or Canada, the size of cover stone to be used

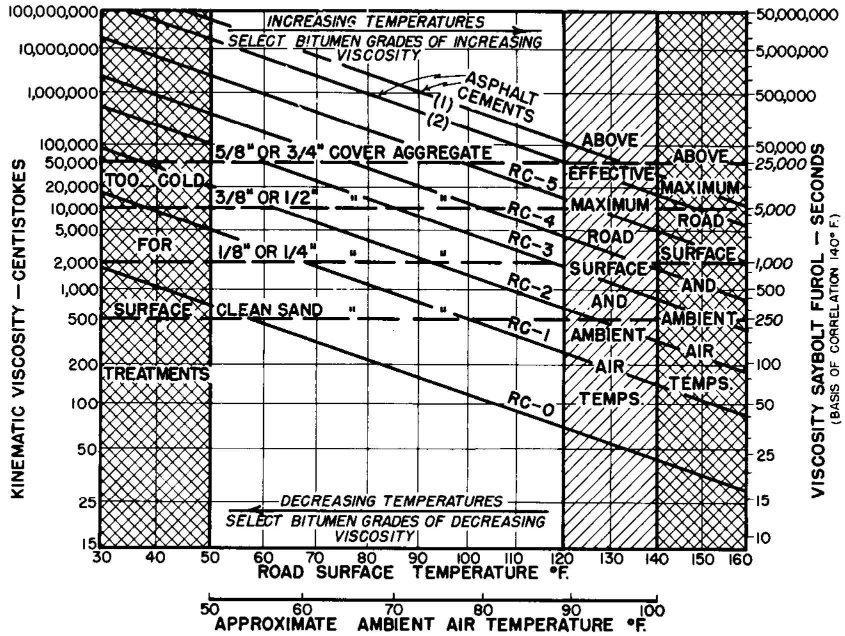

Fig. 23. Influence of Road Surface Temperatures and Size of Cover Aggregate on Selection of Bituminous Binder for Surface Treatments or Seal Coats in Cooler Climates. Old Liquid Asphalt Designations.

is 1/2 inch (Aggregate G from Table I), and that the road surface temperature is 110 F. What grade of asphalt binder should be selected? Enter the bottom of Figure 25 at a road surface temperature of 110 F, and proceed vertically upward to intersect with the horizontal line labelled "3/8 or 1/2 inch cover aggregate". The nearest diagonal line to this point of intersection is the viscosity temperature curve for RC 800. Consequently, the grade of asphalt binder to be selected is RC 800. Employing a similar procedure with Figure 23 indicates that RC 4 would be selected.

Figures 24 and 26 show that for the same conditions in a tropical or sub-tropical climate, a grade of asphalt cement having the viscosity temperature characteristics of Line (3) should be selected.

Figures 23 to 26 indicate that when other conditions are equal, the grade of asphalt binder to be selected should vary with the road surface temperature. In North America, and in other parts of the world where the asphalt binders used are all made at refineries, it would of course be impossible as a practical construction operation to vary the grade of asphalt binder being applied with the change in road surface temperature hour by hour during the day. However, at the very least, Figures 23 to 26 emphasize that harder grades of asphalt binder should be used in warm or hot weather, and softer grades in cold weather.

The need for an asphalt binder with sufficient fluidity to develop rapid adhesion to the cover stone as soon as it is applied, but with much higher viscosity to retain the cover stone when the finished job is opened to traffic, is quite effectively satisfied by the use of rapid setting, RS, asphalt emulsions, and by the use of rapid curing, RC, liquid asphalts. An RC liquid asphalt grade that is just fluid enough to provide fast and adequate adhesion to the cover stone, normally loses much of its gasoline solvent by evaporation during the construction period. This results in the substantial increase in viscosity required to retain the cover stone when controlled traffic begins to travel over the newly completed surface treatment or seal coat. RS asphalt emulsions perform in a somewhat similar manner. They are normally

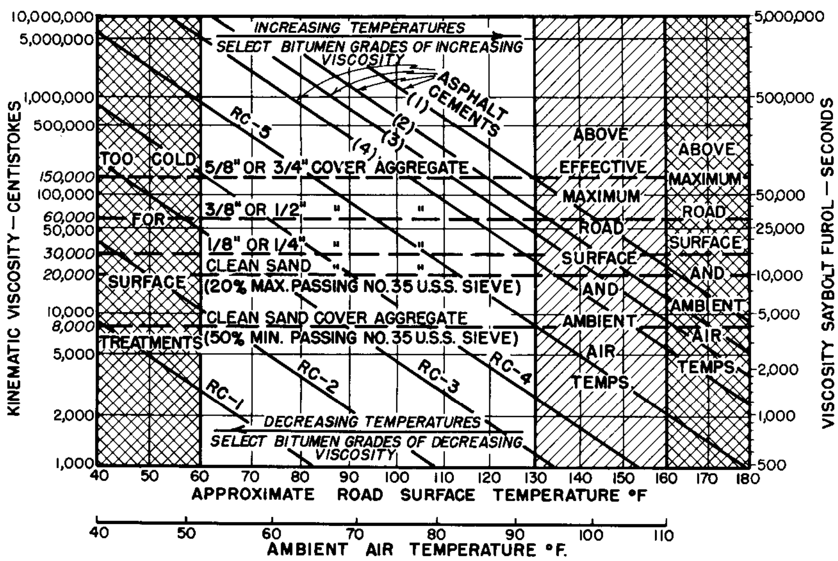

Fig. 24. Influence of Road Surface Temperatures and Size of Cover Aggregate on Selection of Bituminous Binder for Surface Treatments or Seal Coats in Hotter Climates. Old Liquid Asphalt Designations.

sufficiently fluid when applied to develop fast initial adhesion to the cover stone. By partially breaking during construction operations, they become much more viscous, and they have usually developed satisfactory aggregate retention when construction is complete and controlled traffic is permitted.

The necessary compromise between the two opposite requirements for an asphalt binder must be considered with particular care when the binder selected is an asphalt cement, since its viscosity at any given road surface temperature can be expected to change very little between the beginning and the end of the construction period. An asphalt cement contains neither solvent nor water that it can lose. Consequently, a soft asphalt cement may be selected that is fluid enough to develop rapid initial adhesion to the cover aggregate, but is not sufficiently viscous to retain the cover aggregate when the finished surface treatment or seal coat is opened to traffic, or vice versa. The former set of conditions is more likely to occur in the hottest weather, and the latter in cool or cold weather. When an attempt is made to employ asphalt cement binders in cooler climates, Figures 23 and 25, or under cool weather conditions in hot climates, there is usually a tendency to select asphalt cements that are viscous enough for good aggregate retention, but that are not sufficiently fluid to wet a large area of each aggregate particle quickly, and thereby develop fast and adequate adhesion to the cover stone immediately after it has been spread. Whenever this poor wetting or adhesion occurs, much of the cover aggregate may be removed by vehicles as soon as traffic is permitted when construction is complete.

When using asphalt emulsion binders, the lower viscosity RS-1 and CRS-1 are usually selected for the smaller sizes of cover aggregate. RS-2 and CRS-2 grades are normally chosen when the cover aggregate is 3/8 inch and larger.

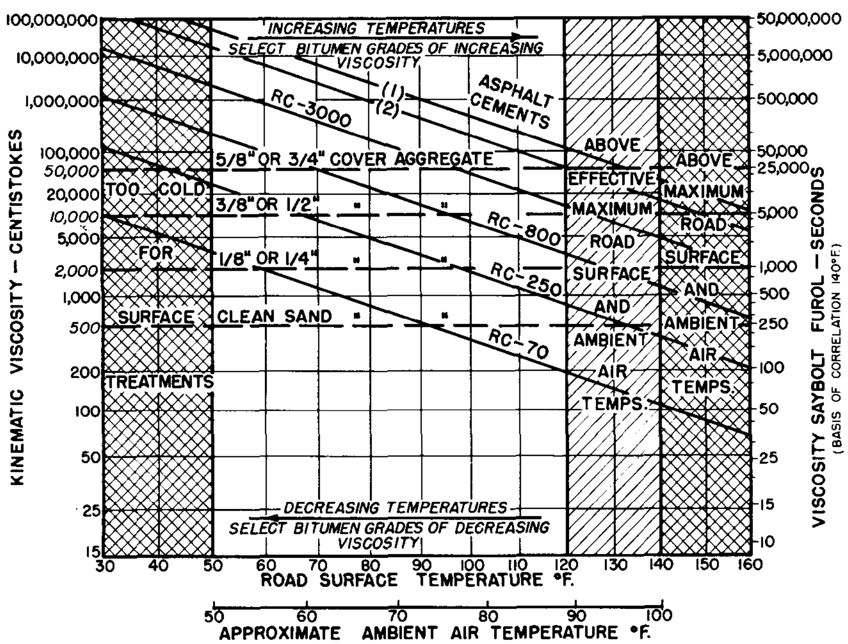

Fig. 25. Influence of Road Surface Temperatures and Size of Cover Aggregate on Selection of Bituminous Binder for Surface Treatments and Seal Coats in Cooler Climates. New Liquid Asphalt Designations.

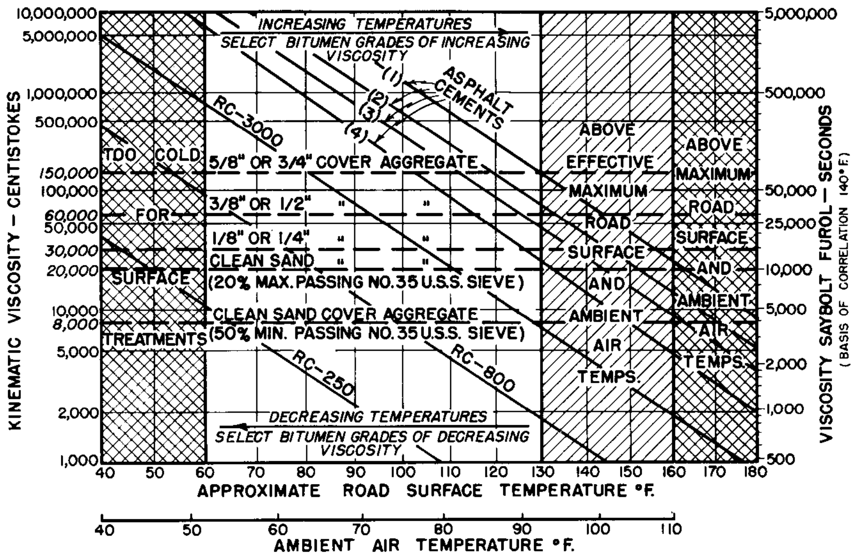

Fig. 26. Influence of Road Surface Temperatures and Size of Cover Aggregate on Selection of Bituminous Binder for Surface Treatments or Seal Coats in Hotter Climates. New Liquid Asphalt Designations.

RS-1 and RS-2 asphalt emulsions are anionic, while CRS-1 and CRS-2 are cationic. Cationic emulsions are considered to be more effective for use under difficult conditions such as cool, damp weather.

5. Influence of Traffic Volume on the Quantity of Asphalt Binder to be Applied

The quantity of asphalt binder to be applied for a seal coat or surface treatment is affected very substantially by the traffic volume it is expected to carry. Much less asphalt binder should be applied when the traffic volume is high than when it is low. This is because the void space between the cover aggregate particles becomes less under high than under low traffic volumes.

From his investigations, Hanson (6) concluded that the optimum asphalt application for a seal coat or surface treatment should fill 70 per cent of the ultimate void space between the cover aggregate particles. The ultimate void space is the minimum void space between the cover aggregate particles in a surface treatment or seal coat that eventually results from exposure to the volume of traffic being carried. On the average therefore, at the optimum asphalt content, the cover aggregate particles should ultimately be embedded for 0.7 of their depth.

Experience of both the National Roads Board of New Zealand (17), and of the Australian State Road Authorities (5), has been that the ultimate per cent of voids between the particles of cover stone varies with the traffic volume. Therefore, the asphalt application required to provide the optimum embedment of the cover aggregate in residual asphalt at all times, could be obtained by multiplying the ultimate void space associated with each traffic volume by 0.7.

However, the Country Roads Board prefers to assume that the theoretical void space between the cover aggregate particles remains constant at 20 per cent. Based on many years of experience, to determine the optimum residual asphalt contents for seal coats or surface treatments for different traffic volumes, they multiply this assumed constant ultimate void space of 20 per cent by the appropriate Traffic Factor "T" in Table VII, to provide 0.7 embedment of the cover aggregate in all cases.

Table VII. Values of Traffic Factor "T" for Surface Treatments and Seal Coats

Cover Aggregate	Values of Traffic Factor "T"				
	Traffic Volume - Vehicles per day				
	Under 100	100 to 500	500 to 1000	1000 to 2000	Above 2000
Recognized good types of angular cover aggregates	0.85	0.75	0.7	0.65	0.60

NOTE: For rounded cover aggregates, the values of the Traffic Factor "T" given above should in each case be increased by 0.05. For example, for a traffic volume of 100 to 500 vehicles per day, the Traffic Factor "T" given above for angular cover aggregate is 0.75, but it would become 0.75 + 0.05 = 0.80 if rounded cover aggregate were to be used.

6. Other Factors That Influence the Asphalt Binder Requirement

Two other factors that influence the quantity of asphalt binder to be applied for a surface treatment or seal coat are:

(a) The quantity of asphalt binder that is lost by absorption into the cover aggregate

(b) the quantity of asphalt binder that is lost in the texture of the surface to which it is applied.

The amount of asphalt binder absorbed by most normal cover aggregates is so small, that the correction, A, to allow for it, is normally neglected when determining the total quantity of asphalt binder to be applied for a surface treatment or seal coat. In the case of cover stone that is known to be quite absorptive, the Country Roads Board increases the asphalt binder application by 0.03 US gallon per square yard, (0.025 Imperial gal/sq. yd.) (0.136 litre/sq. metre). This amounts to an asphalt absorption of about one per cent and two per cent by weight for 3/4 inch and 3/8 inch cover stone particles, respectively.

When cover stone that is likely to be unusually absorptive must be used, such as certain limestones, volcanic pumice, and some expanded shale light weight aggregates, their asphalt absorption values should be checked by Rice's vacuum saturation method, ASTM D 2041. To reduce or eliminate their absorption after application as cover stone, these highly absorptive aggregates may be first dried by heating, cooled to from 150 to 200 F, and then thoroughly and uniformly coated in a pug-mill with from one to two per cent of MC 70 (MC 1) or MC 250 (MC 2) liquid asphalt. The quantity of MC 70 (MC 1) or MC 250 (MC 2) employed should not prevent the precoated aggregate from flowing freely when applied by mechanical cover aggregate spreaders. This precoating of the cover stone will also contribute greatly to the development of fast initial adhesion between the cover aggregate and the asphalt binder.

A correction S in gallons per square yard, Table VIII, must be added to the quantity of asphalt binder applied for a surface treatment or seal coat because of the texture of the existing surface. Depending upon the texture and nature of the existing surface, as indicated by Table VIII, it may be rated black, smooth, or hungry, and the corresponding asphalt binder correction may be negative, nil, or positive,

Table VIII. Correction "S" to the Asphalt Binder Requirement Due to the Textural Rating of an Existing Surface

Textural Rating of Existing Surface	Required Correction "S" to Asphalt Binder Requirement Residual Asphalt			
	Operation	U.S. gal/ sq.yd.	Imp. gal/ sq.yd.	Litre/sq.m.
Black	Subtract	up to 0.06	up to 0.05	up to 0.272
Smooth	Nil	Nil	Nil	Nil
Hungry 1h	Add	0.03	0.025	0.136
Hungry 2h	Add	0.06	0.05	0.272
Hungry 3h	Add	0.09	0.075	0.408

respectively. An existing surface that is rated "smooth" is one that is firm and smooth into which no asphalt binder will be lost, and which contains no excess of binder. Therefore, the correction S is nil. If an existing surface is flushed or bleeding, a correction S of up to 0.06 US gallon per square yard (0.05 Imperial gal/sq. yd.) (0.272 litre/sq. metre), is subtracted from the asphalt requirement for a "smooth" surface. If the existing surface is rated "hungry," it may receive a rating of 1h, 2h, or 3h, depending upon the estimate of the loss of asphalt binder into the surface texture. As indicated by Table VIII, if the existing surface is rated 1h, 2h, or 3h, the correction S of 0.03, 0.06, or 0.09 US gallon per square yard (0.025, 0.05, or 0.075 Imperial gal/sq. yd.) (0.136, 0.272, or 0.408 litre/sq. metre), respectively, is added to the normal asphalt binder requirement.

An existing bituminous surface that is to be seal coated should be carefully examined *in the wheel paths* when its degree of textural roughness is being estimated. Furthermore, the hunger rating 1h, 2h, or 3h, assessed to an existing surface should be influenced by the size of the cover aggregate to be employed for the seal coat. Because large 3/4 inch cover stone particles would tend to remain on the top of any existing surface texture, an existing surface might require a textural rating of 3h. On the other hand, if 3/8 inch cover stone were to be used, many of the particles might nestle into the voids in the textural roughness of the surface, and with this smaller size cover aggregate the hunger rating would be only 2h and even 1h.

Attempts have been made to develop quantitative methods for measuring the textural roughness of a surface by means of oil, water, or fine sand (11), (15). The reported degree of success with any of these methods is so variable, that their value for general practice appears to be questionable.

Any existing surface that is rated 2h or 3h is likely to have such a variable surface texture, that the finished seal coat or surface treatment may not be too successful. For surfaces with these textural ratings, it is strongly recommended that they be swept and thoroughly cleaned, and then given a pretreatment consisting of about 0.1 gallon per square yard (about 0.5 litre/sq. metre) of RC 70 (RC 1) liquid asphalt, or RS-1 or CRS-1 asphalt emulsion, covered with from six to ten pounds per square yard of clean fine sand, and opened to traffic. The sand should be periodically broomed back over the surface. This pretreatment should preferably be left under traffic for from several weeks to one year. The rating of this surface will then ordinarily be "smooth," and experience has shown that a very successful seal coat or surface treatment can then be applied.

When rating an existing surface for smoothness or roughness of texture, and for degree of "hunger," a very clear distinction must be made between surface texture, and the porosity if any, of the surface or pavement. Porosity refers to the internal void space in a pavement, into which a substantial portion or even the whole of the asphalt binder could be absorbed, leading to serious loss of the cover stone because not enough binder is left on the surface to hold it in place. Relatively new dense graded hot-mix or cold-mix asphalt surfaces constructed either as complete pavements or as maintenance patches, are usually quite porous even when they appear to be smooth and tight. The application of a few drops of lubricating oil (taken if necessary from the dipstick on the engine of an automobile), can be useful for identifying a porous surface. If the oil remains on the surface, little or no harmful porosity exists, and the normal allowance for the textural rating of the surface, for example, 1h, 2h, etc., is the only correction (Table VIII) to the asphalt binder requirement that is needed. On the other hand, if the oil is more or less completely absorbed into the surface within a few minutes, it is evidence of sufficient porosity that a considerable portion of an asphalt binder, particularly of the liquid asphalt type, applied for a surface treatment or seal coat, could be lost by absorption. In this case, the surface should be given a pretreatment of about 0.1 gallon per square yard (about 0.5 litre/sq. metre) of RC 0 or RC 70 (RC 1) liquid asphalt, or of RS-1 or CRS-1 asphalt emulsion, covered with from six to ten pounds per square yard of clean fine sand, and left to traffic for from several weeks to one year, with occasional brooming of the sand back over the surface. This pretreatment will plug the pores in the existing surface, its textural rating will then ordinarily be smooth, and a seal coat or surface treatment can then be successfully applied.

VII. DESIGN OF SINGLE APPLICATION SURFACE TREATMENTS AND SEAL COATS

It is the principal objective of any adequate method of design for surface treatments or seal coats to obtain answers to each of the following six basic questions:

1. What type and size of cover aggregate is to be used?
2. How many pounds of cover aggregate should be applied per square yard?
3. What type and grade of asphalt binder is to be selected?
4. What spraying temperature should be specified for the asphalt binder?
5. How much asphalt binder in gallons per square yard measured at 60 F should be applied?
6. How much asphalt binder should be applied, measured in gallons per square yard at the spraying temperature?

The first thorough investigation of the design of single application surface treatments and seal coats was undertaken by Hanson (6), whose studies were conducted in both the field and the laboratory. Hanson's principal findings were as follows:

1. Single application surface treatments and seal coats are essentially one-stone particle thick.
2. When cover aggregate is first applied during seal coat or surface treatment construction, the cover stone particles occupy random positions, and the voids between the aggregate particles are approximately 50 per cent, Figure 27.
3. During the rolling operation, the cover aggregate particles are partly reoriented, and the void space between the stone particles at the end of average rolling is approximately 30 per cent.
4. After considerable warm weather traffic, the particles of cover stone become reoriented into their final positions, and the void space between the particles is approximately 20 per cent, Figure 7.
5. Following substantial warm weather traffic, the cover stone particles are lying on their flattest sides with their thinnest dimension vertical, Figure 7. This means that the final average thickness of a single application seal coat or surface treatment is given by the Average Least Dimension of the cover stone particles, Figure 7. A laboratory procedure for determining the Average Least Dimension of any cover aggregate is provided in Appendix A.
6. The optimum asphalt application for a surface treatment or seal coat should be just sufficient to fill the ultimate 20 per cent of void space between the cover aggregate particles about two-thirds (70 per

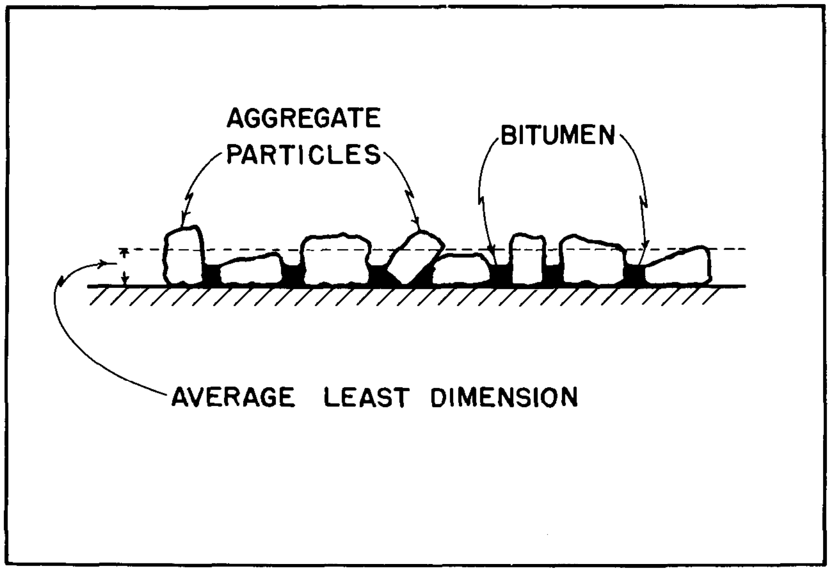

Fig. 27. Illustrating the Haphazard Positions of Cover Aggregate Particles Immediately After Application from a Stone Chip Spreader.

cent) with residual asphalt. That is, on the average each cover stone particle is embedded in residual asphalt to about 70 per cent of its thinnest dimension.

On the basis of many years of experience with Hanson's method of design, the Country Roads Board of Victoria, Australia has found that the fraction "T" of the 20 per cent of ultimate void space assumed for the cover aggregate, to be filled with residual asphalt, should vary with the traffic volume anticipated, Table VII.

A. SINGLE APPLICATION DESIGN WITH ONE-SIZE AGGREGATE

1. Quantity of One-Size Cover Aggregate to be Applied per Square Yard

The design of single application seal coats and surface treatments with one-size cover aggregate in New Zealand and Australia is based on Hanson's (6) findings (a) that the average thickness of a seal coat or surface treatment is given by the Average Least Dimension of the cover stone, and (b) that after substantial traffic, the voids between the cover aggregate particles are 20 per cent. This means that after ultimate compaction by traffic, the cover stone particles occupy 80 per cent of the volume of a seal coat or surface treatment. Therefore, as has been indicated elsewhere (18), the quantity of cover aggregate to be applied as pounds per square yard can be derived as follows, (basis of calculation is one square yard):

$$C = \left(\frac{36 \times 36 \times 0.8H}{1728}\right) 62.4GE \qquad [3]$$

which simplifies to

$$C = 37.4HGE$$

where

C = number of pounds of cover aggregate to be applied per square yard
H = Average Least Dimension of cover aggregate in inches
G = ASTM bulk specific gravity of the cover aggregate
E = wastage factor due to per cent of cover stone lost due to whip-off by traffic and to unevenness of spread, Table IX.

As an example of the use of Equation [3], if the Average Least Dimension H of the cover stone is 0.27 inch, if its ASTM bulk specific gravity G is 2.68, and if the anticipated loss of cover aggregate due to whip-off by traffic is five per cent, the quantity of cover stone to be applied is

Table IX. Cover Aggregate Wastage Factors

Per Cent Wastage Allowed for	Wastage Factor E
1	1.01
2	1.02
3	1.03
4	1.04
5	1.05
6	1.06
7	1.07
8	1.08
9	1.09
10	1.10
11	1.11
12	1.12
13	1.13
14	1.14
15	1.15
16	1.16
17	1.17
18	1.18
19	1.19
20	1.20

* Due to whip-off by traffic and to uneven application.

$$C = (37.4)(0.27)(2.68)(1.05)$$

$$= 28.4 \text{ pounds per square yard.}$$

2. Quantity of Asphalt Binder to be Applied per Square Yard

The quantity of asphalt binder measured at 60 F to be applied *per square yard* can be derived as follows, (basis of calculation is one square yard):

$$B = \left(\frac{36 \times 36 \times 0.2H}{231}\right)\left(\frac{T}{R}\right) + \frac{S + A}{R}$$

which simplifies to

$$B = \frac{1.122HT + S + A}{R}$$

where

- B = total asphalt binder to be applied in US gallons per square yard
- H = Average Least Dimension of cover stone measured in inches
- T = traffic factor, which depends upon the anticipated traffic volume, Table VII
- R = fraction of residual asphalt in the asphalt binder selected, Table VI
- S = surface texture correction in US gallons per square yard measured at 60 F, resulting from expected gain or loss of asphalt binder due to the textural characteristics of the existing surface, Table VIII
- A = absorption correction in gallons per square yard measured at 60 F due to loss of asphalt binder by absorption into the particles of cover stone. With all but unusually absorptive aggregates, this correction can be neglected. When necessary, the Country Roads Board makes an aggregate absorption correction of 0.03 US gallon per square yard, (0.025 Imperial gal/sq. yd.) (0.136 litre/sq. metre).

For example, suppose the Average Least Dimension of the cover aggregate is 0.27 inch, the anticipated traffic volume is 700 vehicles per day, the fraction of residual asphalt in the asphalt binder is 80 per cent, the textural rating of the existing surface is 1h and the cover stone is relatively non-absorptive. Substituting in Equation [4] gives

$$B = \frac{(1.22)(0.27)(0.7) + 0.03 + 0}{0.8}$$

$$= \frac{0.21 + 0.03}{0.8} = 0.30 \text{ US gallons per square yard.}$$

B. SINGLE APPLICATION DESIGN WITH GRADED COVER AGGREGATE

When utilizing Equation [4] for determining the quantity of asphalt binder to be applied for a seal coat or surface treatment, the author has sometimes experienced difficulty because too much asphalt binder has been applied and some flushing or bleeding has occurred. This has been particularly true when using a graded cover aggregate, which is ordinarily the only cover material available. This experience has led to questioning the assumption that the ultimate void space between the cover aggregate particles in a surface treatment or seal coat is always approximately 20 per cent.

There does not appear to be any laboratory test that is capable of duplicating the action of substantial warm weather traffic in orienting cover aggregate particles into their positions of maximum density. Consequently, if a correction to the assumed ultimate voids value of 20 per cent is to be made, it must be determined on the loose weight basis.

The Country Roads Board establishes the amount of cover aggregate to be applied as square yards per cubic yard (but equivalent to Equation [3]), by assuming that in its loose condition as applied, the voids between the aggregate particles are 50 per cent. During the past few years, the author has measured the voids in a large number of both one-size and graded cover aggregates in the loose weight condition by means of ASTM C 29. As indicated by Tables III and IV, very seldom are the voids in the loose weight condition exactly 50 per cent. Occasionally they may be less than 40 per cent.

The assumption is made that if a cover aggregate with 50 per cent voids in the loose weight condition, closes up under traffic to 20 per cent voids as assumed by the Country Roads Board, then if for example, the voids in a cover aggregate in the loose weight condition are only 40 per cent, the voids in the cover stone in a seal coat or surface treatment after substantial warm weather traffic will be only $40/50 \times 20 = 16$ per cent.

It can be seen that when the ultimate voids in a cover aggregate are only 16 per cent, if the asphalt binder to be applied is based on an assumed 20 per cent of voids, Equation [4], twenty-five per cent ($20/16 \times 100 = 125$) too much asphalt binder will have been applied, and serious flushing or bleeding could be expected. This is in agreement with the author's experience when calculating the quantity of asphalt binder to be applied by means of Equation [4].

The fraction of voids V in a cover aggregate can be determined by means of Equation [2] described in a previous section.

1. Quantity of Graded Cover Aggregate to be Applied per Square Yard

Introducing this correction due to the fraction of voids V in the cover aggregate, leads to the following modification of Equation [3] for determining the quantity of a graded cover aggregate to be applied per square yard, (basis of calculation is one square yard):

$$C = \frac{36 \times 36 \times \left(1 - \frac{V}{0.5}\, 0.2\right) H}{1728}\, 62.4GE$$

$$= \frac{36 \times 36 \times (1 - 0.4V)H}{1728}\, 62.4GE$$

which simplifies to

$$C = 46.8(1 - 0.4V)HGE \qquad [5]$$

where each symbol has the significance already defined for it.

For example, suppose the Average Least Dimension H of the graded cover aggregate = 0.27 inch, the fraction of voids V = 0.4, the ASTM bulk specific gravity G = 2.68, and E = 1.05, then

$$C = (46.8)(1 - 0.4 \times 0.4)(0.27)(2.68)(1.05)$$

$$= 29.9 \text{ pounds per square yard.}$$

Compared with the previous calculation, the voids correction has increased the quantity of cover aggregate to be applied per square yard by 29.9 - 28.4 = 1.5 pounds.

2. Quantity of Asphalt Binder to be Applied per Square Yard

The voids correction V results in the following modification of Equation [4] for determining the quantity of asphalt binder to be applied per square yard, (basis of calculation is one square yard):

$$B = \left(\frac{36 \times 36 \times \frac{V}{0.5}\, 0.2H}{231}\right)\left(\frac{T}{R}\right) + \frac{S + A}{R}$$

$$= \left(\frac{36 \times 36 \times 0.4VH}{231}\right)\left(\frac{T}{R}\right) + \frac{S + A}{R}$$

which simplifies to

$$B = \frac{2.244HTV + S + A}{R} \qquad [6]$$

where each symbol has already been defined.

For example, if the Average Least Dimension of the cover aggregate, H, is 0.27 inch, if the expected traffic volume is 700 vehicles per day, if the voids fraction V is 0.4, if the fraction of residual asphalt in the asphalt binder is 80 per cent, if the textural rating of the existing surface is 1h, and if the cover stone is relatively non-absorptive, substituting the appropriate values in Equation [6] gives

$$B = \frac{(2.244)(0.27)(0.7)(0.4) + 0.03 + 0}{0.8}$$

$$= \frac{0.17 + 0.3}{0.8}$$

$$= 0.25 \text{ US gallon per square yard.}$$

In comparison with the previous sample calculation, the voids correction has reduced the quantity of asphalt binder to be applied by 0.30 - 0.25 = 0.05 US gallon per square yard, a difference of 20 per cent.

C. COMPARISON OF DESIGN EQUATIONS BASED ON ONE-SIZE AND GRADED COVER AGGREGATES FOR SINGLE APPLICATION SEAL COATS AND SURFACE TREATMENTS

It should be recognized that one-size cover aggregates, in which the voids in the loose weight condition are 50 per cent, and to which Equations [3] and [4] therefore apply, *are only a special category of graded cover aggregates*, which represent the general case. Since this is so, it can be shown that when the fraction of voids V in a cover aggregate is 0.5, Equation [3] giving the required quantity of one-size cover aggregate per square yard, and Equation [4] providing the quantity of asphalt binder to be applied per square yard, can be easily derived from Equations [5] and [6] respectively, which pertain to graded cover aggregates.

When V = 0.5 is substituted in Equation [5] we have

$$C = 46.8(1 - 0.4V)HGE \qquad [5]$$

$$= 46.8(1 - 0.4 \times 0.5)HGE$$

$$= 46.8(1 - 0.2)HGE$$

$$= 46.8(0.8)HGE$$

$$= 37.4 \text{ HGE} \qquad [3]$$

Also, when V = 0.5 is substituted in Equation [6] it follows that

$$B = \frac{2.244 \text{ HVT} + S + A}{R} \qquad [6]$$

$$= \frac{2.244 \text{ HT}(0.5) + S + A}{R}$$

$$= \frac{1.122 \text{ HT} + S + A}{R} \qquad [4]$$

Consequently, if the fraction of voids $V = 0.5$ is assumed or determined for one-size cover aggregate in the loose condition, use of Equations [5] and [6] will result in exactly the same rates of application of cover aggregate and asphalt binder respectively, as Equations [3] and [4]. Whenever the rates of application of any given cover stone and asphalt binder provided by Equations [5] and [6] are different than those given by Equations [3] and [4] respectively, it is because the fraction of voids V in the cover aggregate does not have a value of exactly 0.5 for the loose weight condition. Table III shows that the value of the voids fraction V even in a one-size aggregate usually differs from 0.5.

It is clear therefore that Equations [5] and [6] are general equations of design for single application surface treatments and seal coats. Consequently, regardless of whether one-size or graded cover aggregates are to be employed, the quantities of cover stone and of asphalt binder to be applied per square yard, should be determined by means of Equation [5] and [6] respectively.

D. OTHER UNITS OF MEASUREMENT FOR RATES OF APPLICATION OF ASPHALT BINDER AND COVER STONE

For surface treatment and seal coat design, the unit of measurement employed in this paper for quantity of cover stone to be spread is pounds per square yard, and for the rate of application of asphalt binder is US gallons per square yard. However, when applying cover aggregate, other units of measurement than pounds per square yard are used to express the quantity to be spread, for example, square yards per cubic yard. In much of the world, liquid measure is expressed in terms of Imperial gallons. Furthermore, over a large part of the world, weights and volumes are measured in units of the metric system.

Therefore, in Table X, equivalent equations are listed in terms of several units of measurement that may be employed for the quantity of cover stone to be applied on either a weight or volume basis per unit of area, in both the English and Metric systems of measurement. In Table XI, equivalent equations in both English and Metric units of measurement are given for the volume of asphalt binder to be applied per unit of area.

For the same design criteria, each of the equations in Table X requires the same rate of application of cover stone, and identical rates of application of asphalt binder are indicated by all equations in Table XI.

Table X. Equivalent Equations in Both English and Metric Systems of Measurement for Total Quantity of Cover Aggregate to Be Applied per Unit of Area for a Surface Treatment or Seal Coat

UNIT OF MEASUREMENT	EQUATION
ENGLISH SYSTEM (H measured in inches).	
BY WEIGHT	
pounds per square yard	$C = 46.8\,(1-0.4V)\,HGE$ OR $C = \frac{0.75\,(1-0.4V)\,HWE}{1-V}$
square yards per short ton (2000 pounds)	$C = \frac{42.74}{(1-0.4V)\,HGE}$ OR $C = \frac{2667\,(1-V)}{(1-0.4V)\,HWE}$
square yards per long ton (2240 pounds)	$C = \frac{47.86}{(1-0.4V)\,HGE}$ OR $C = \frac{2987\,(1-V)}{(1-0.4V)\,HWE}$
BY VOLUME	
cubic feet per square yard (loose weight)	$C = \frac{0.75\,(1-0.4V)\,HE}{1-V}$
square yards per cubic yard (loose weight)	$C = \frac{36\,(1-V)}{(1-0.4V)\,HE}$
METRIC SYSTEM (H measured in Millimetres)	
BY WEIGHT	
kilograms per square metre	$C = (1-0.4V)\,HGE$ OR $C = \frac{(1-0.4V)\,HWE}{1-V}$
BY VOLUME	
litres per square metre (loose weight)	$C = \frac{(1-0.4V)\,HE}{1-V}$
square metres per cubic metre (loose weight)	$C = \frac{1000\,(1-V)}{(1-0.4V)\,HE}$

Table XI. Equivalent Equations in Both English and Metric Systems of Measurement for the Optimum Quantity of Asphalt Binder to Be Applied per Unit of Area for a Seal Coat or Surface Treatment

UNIT OF MEASUREMENT	EQUATION
ENGLISH SYSTEM (H measured in inches)	
U.S. gallons per square yard	$B = \frac{2.244\,HTV + S + A}{R}$
Imperial gallons per square yard	$B = \frac{1.868\,HTV + S + A}{R}$
METRIC SYSTEM (H measured in Millimetres)	
Litres per square metre	$B = \frac{0.4\,HTV + S + A}{R}$

E. SAMPLE CALCULATION FOR DETERMINING RATES OF APPLICATION OF COVER AGGREGATE AND ASPHALT BINDER FOR A SINGLE APPLICATION SURFACE TREATMENT OR SEAL COAT

I. THE FOLLOWING CONDITIONS ARE ASSUMED

(a) Climate—cool
(b) Traffic volume—800 vehicles per day
(c) Road surface temperature--70 F
(d) Textural rating of existing road surface—1h
(e) Properties of cover aggregate selected
  (1) Nominal size—1/2 inch
  (2) Size Number (Table II)—AASHO No. 7 (Figure 14)
  (3) Median size—0.35
  (4) Flakiness Index—9.5
  (5) Average Least Dimension H—0.28
  (6) ASTM bulk specific gravity G—2.67
  (7) Dry loose weight W—91 pounds per cubic foot
  (8) Fraction of voids $V = 1 - \frac{91}{(62.4)(2.67)} = 0.454$
  (9) Asphalt absorption A—negligible
  (10) Loss by whip-off, etc.—5 per cent
  (11) Wastage factor E (Table IX)—1.05

II. THE FOLLOWING ITEMS OF INFORMATION ARE REQUIRED

(a) What grade of asphalt binder should be selected?
(b) What spraying temperature is recommended?
(c) How much asphalt binder measured at 60 F should be applied per square yard?
(d) How much asphalt binder measured at the spraying temperature should be applied per square yard?
(e) What quantity of cover aggregate should be spread per square yard?

III. SOLUTION

(a) Figure 25, which is applicable to cooler climates like that of the Northern USA and Canada, indicates that for 1/2 inch cover aggregate and a road surface temperature of 70 F, if a liquid asphalt binder is selected, the grade should be RC 250.
(b) From Figure 21, for an optimum spraying viscosity of 50 centistokes, the recommended spraying temperature for RC 250 is 215 F.
(c) The volume correction factor for RC 250 at 215 F, Figure 22, Line (1), is 1.06.
(d) Fraction of residual asphalt R in RC 250, Table VI, is 0.79.
(e) Traffic Factor T for a volume of 800 vehicles per day, Table VII, is 0.7.
(f) Asphalt binder correction for a textural rating of 1h—add 0.03 US gallon per square yard.
(g) Asphalt binder correction A for loss of asphalt by absorption into the cover stone—Nil.

(h) Total rate of application of RC 250 measured at 60 F; Equation [6]:

$$B = \frac{(2.244)(0.28)(0.7)(0.454) + 0.03 + 0}{0.79}$$

$$= \frac{0.20 + 0.03}{0.79} = 0.29 \text{ US gallon per square yard}$$

(i) Total rate of application of RC 250 measured at the spraying temperature of 215 F:

$$= (0.29)(1.06) = 0.31 \text{ US gallon per square yard}$$

(j) Rate of application of dry cover aggregate, Equation [5]:

$$C = (46.8)(1 - 0.4 \times 0.454)(0.28)(2.67)(1.05)$$

$$= (46.8)(1 - 0.18)(0.28)(2.67)(1.05)$$

$$= 30.1 \text{ pounds per square yard.}$$

IV. THE SOLUTION CAN THEREFORE BE SUMMARIZED AS FOLLOWS:

(a) Grade of asphalt binder to be used—RC 250
(b) Spraying temperature for RC 250—215 F
(c) Rate of application of RC 250 at 60 F—0.29 US gallon per square yard
(d) Rate of application of RC 250 at spraying temperature of 215 F —0.31 US gallon per square yard
(e) Rate of application of dry cover aggregate--30.1 pounds per square yard.

Note: Table XII is a suggested data sheet that may be used for the design of single application surface treatments and seal coats, and it provides a more concise illustration of these design calculations.

V. USE OF ASPHALT EMULSION BINDER

If CRS-2 asphalt emulsion had been selected for this design example, instead of RC 250, the design calculations would be very similar to those just illustrated. For CRS-2 asphalt emulsion, Table VI indicates that an average value for the fraction of residual asphalt R is 0.69. For a spraying temperature of 160 F, the volume correction factor, Figure 22, Line (3), is 1.025. The following design summary would have been obtained:

(a) Grade of asphalt binder to be used--CRS-2
(b) Spraying temperature for CRS-2—160 F (max)
(c) Rate of application of CRS-2 asphalt emulsion measured at 60 F—0.33 US gallon per square yard

Table XII. Design Data Sheet. For Determining Quantities of Asphalt Binders and Cover Aggregates for a Single Surface Treatment or Seal Coat

Date
Project
Location

Report By
Checked By

A. Given Conditions

1. Traffic volume - 800 vehicles per day
2. Road surface temperature - 70°F
3. Textural rating of existing surface - 1h
4. Properties of cover aggregate selected:
   (a) Nominal size - 1/2 inch
   (b) Size number - No. 7
   (c) Median size - 0.35 inch
   (d) Flakiness Index - 9.5
   (e) Average Least Dimension H - 0.28
   (f) Weight lb/cu.ft.(loose)W - 91
   (g) ASTM bulk specific gravity G - 2.67
   (h) Voids fraction V - 0.454
   (i) Asphalt absorption A - negligible
   (j) Expected loss by whip-off percent - 5
   (k) Wastage factor E (Table 9 - 1.05)

B. Solution

5. Quantity of cover aggregate to be applied (Equation 5)
   C = 46.8(1 - 0.4V)HGE = (46.8)(0.82)(0.28)(2.67)(1.05) = 30.1 pounds per sq.yd.
6. Grade of asphalt binder selected (Figure 23) - RC 250
7. Recommended spraying temperature (Figure 19) - 215°F
8. Residual asphalt factor R - 0.79
9. Traffic Factor T (Table 7) - 0.7
10. Surface textural correction S - add 0.03 US gallons/square yard
11. Quantity of RC 250 asphalt binder required at 60°F (Equation 6)

$$B = \frac{2.244\ HTV}{R} + S + A = \frac{(2.244)(0.28)(0.7)(0.454)}{0.79} + 0.03 + 0$$

   = 0.29 US gallons per square yard
12. Correction factor for RC 800 for spraying temperature of 235 F (Figure 20) - 1.06
13. Quantity of RC 250 asphalt binder to be applied at 215°F = (0.29)(1.06) 0.31 US gallon/square yard.

C. Summary

(a) Cover aggregate selected - Size Number - No. 7 (1/2 inch).
(b) Quantity of cover aggregate to be applied - 30.1 lbs/sq.yd.
(c) Asphalt binder selected - RC 250
(d) Spraying temperature for RC 250 - 215°F
(e) Quantity of RC 250 at 60°F required - 0.29 US gallon/sq.yd.
(f) Quantity of RC 250 to be applied at 215°F - 0.31 gallon/sq.yd.

(d) Rate of application of CRS-2 asphalt emulsion measured at a spraying temperature of 160 F—0.34 US gallon per square yard
(e) Rate of application of dry cover aggregate—30.1 pounds per square yard.

VI. USE OF ASPHALT CEMENT BINDER

For the same design conditions, but in a hot climate, an asphalt cement of 150/200 penetration might be employed as the binder. The spraying temperature is assumed to be 340 F for the particular 150/200 penetration asphalt cement selected, and the volume correction factor from Figure 22, Line (2) is 1.10. The required calculations are similar to those already illustrated, and they provide the following design summary:

(a) Grade of asphalt binder to be used—150/200 penetration asphalt cement
(b) Spraying temperature for 150/200 penetration asphalt cement --340 F.
(c) Rate of application of 150/200 penetration asphalt cement measured at 60 F—0.23 US gallon per square yard
(d) Rate of application of 150/200 penetration asphalt cement measured at a spraying temperature of 340 F--0.25 US gallon per square yard.

(e) Rate of application of dry cover aggregate—30.1 pounds per square yard.

VII. COMPARISON OF MATERIAL REQUIREMENTS PER SQUARE YARD

Materials	150/200 Penetration Asphalt Cement	RC 250 Liquid Asphalt	CRS-2 Asphalt Emulsion
Asphalt Binder, U.S. gallons per square yard at 60 F	0.23	0.29	0.33
Cover Aggregate, pounds per square yard	30.1	30.1	30.1

F. MODIFICATION OF SINGLE APPLICATION SURFACE TREATMENT AND SEAL COAT CONSTRUCTION TO ELIMINATE WINDSHIELD AND VEHICLE DAMAGE DUE TO FLYING PARTICLES OF COVER AGGREGATE

There are two serious criticisms of single application surface treatments and seal coats as they are presently constructed. These are:

1. The damage to windshields, headlights, and bodies of motor vehicles that occurs due to the loose particles of cover stone that fast traffic throws into the air for several days immediately after construction.

2. The shortness of the construction season. At least one month of warm weather traffic is required to reorient the cover aggregate particles and firmly embed them in the asphalt binder before winter arrives. In Canada, this means that no single application surface treatment or seal coat should be constructed after the end of August.

Several years ago, one of our provincial departments of highways is reported to have received claims for $300,000 for motor vehicle damage, when several miles of single application seal coat were constructed on a main highway immediately before a July 1 and July 4 long week-end, the dates of national holidays for Canada and the United States, respectively. The criticism based on damage to motor vehicles from flying particles of cover aggregate immediately after construction is so serious, that seal coats are usually not even considered (in North America) for resurfacing heavily travelled asphalt pavements.

The reason why cover aggregate particles are so susceptible to dislodgment by fast traffic immediately after construction, is that assuming the 30 per cent of voids in the cover stone immediately after rolling as reported by Hanson (6), the aggregate particles are embedded less than 50 per cent on the average, and the embedment of the largest particles of a graded cover aggregate may be only 25 per cent or less.

This is quite obvious to anyone who examines the particles of cover stone that end up on the road shoulder following single application seal coat or surface treatment construction. Consequently, for some days just after construction, the larger cover aggregate particles are easily dislodged and thrown into the air by fast traffic, because of their low degree of embedment in the asphalt binder.

There is a rather simple solution to this problem of damage to motor vehicles due to flying cover stone particles. It involves applying the asphalt binder for a single application seal coat or surface treatment in two applications, with the cover stone being applied after the first application. Since the second application is sprayed over the cover aggregate, the cover stone particles are firmly cemented to the road surface. Following the second application of asphalt binder would be an application of clean sand or stone screenings just sufficient to prevent the asphalt binder from sticking to the tires. By employing this method of construction, the only flying particles at any time would come from the sand, and these do not ordinarily cause any motor vehicle damage.

By employing two applications of asphalt binder for single surface treatments or seal coats, the construction season is also lengthened because the second application of asphalt binder cements the cover stone particles to the road surface. It is not necessary to have one month of warm weather traffic to enable the cover stone particles to become reoriented and embedded 70 (hopefully) per cent of their depth in asphalt binder on the average, before winter arrives.

For construction in warm weather, 60 per cent of the total asphalt binder would be sprayed as the first application followed by the cover aggregate, and 40 per cent of the asphalt binder would be applied for the second application. After the end of August, or an equivalent period, the first application would consist of 40 per cent of the total asphalt required, followed by the cover aggregate, and 60 per cent of the asphalt would be sprayed for the second application. Because of the limited amount of warm weather traffic after the end of August (in Canada), a higher percentage of asphalt binder should be applied for the second application to cement the cover stone to the road surface.

Since this in effect is a double surface treatment, designing for the quantity of asphalt binder and cover stone to be applied will be described in the next section under multiple surface treatments.

VIII. DESIGN OF MULTIPLE SURFACE TREATMENTS AND SEAL COATS

Multiple surface treatments and seal coats consist of two, sometimes three, and occasionally four successive alternate applications of asphalt binder and cover aggregate. For each successive layer, the size of the cover stone should be one-half the size of the cover aggregate employed for the immediately preceding layer. When larger sizes of cover aggregate are employed, the thickness of the surface treatment or seal coat may approach or exceed one inch.

The principal criticisms of single application surface treatments or seal coats are (a) shortness of the construction season because of the need for at least one month of warm weather traffic to provide adequate embedment of the cover stone particles before winter arrives, (b) the damage to motor vehicles from flying stone particles that occurs for several days following construction, (c) the tire noise when large size cover stone is used, and (d) loss of larger particles from the surface when a graded cover aggregate is employed.

Each of these criticisms can be avoided by changing to a double or other multiple surface treatment or seal coat. Because the largest cover stone is used for the first layer, and because these large particles are firmly cemented to the road surface by the second application of asphalt binder, only some of the smaller aggregate particles applied for the second layer can be dislodged by fast traffic, and damage to motor vehicles is minor or nil. Because the first layer of large size cover stone is fastened securely to the road surface by the second application of asphalt binder, there is no need for warm weather traffic to obtain adequate embedment of the cover aggregate in the asphalt binder. Therefore, the construction season can be lengthened substantially. Since the smaller aggregate particles employed for the second layer fill the large void spaces in the much larger cover aggregate in the first layer, tire noise is effectively suppressed. Furthermore, the normal loss of the largest particles of graded cover aggregate from a single surface treatment or seal coat because of insufficient embedment in the binder, is averted, because the second application of asphalt cements them firmly into place. Consequently, multiple seal coats or surface treatments should be considered:

(a) for heavier traffic volumes

(b) to provide a longer construction season

(c) to minimize broken windshields and other motor vehicle damage from flying stone particles for several days following construction

(d) when graded cover aggregates must be used

(e) to eliminate tire noise

(f) for effective surface treatments over stabilized soil bases

(g) to facilitate street cleaning in urban areas

(h) when coarse aggregates are of inferior quality

(i) to provide better traction for vehicles on paved surfaces from which snow and ice are not completely removed. The tips of the cover stone particles projecting above a layer of compacted snow or ice promote improved traction.

The method of design for multiple surface treatments and seal coats that is recommended in this paper, is based on the assumption that the quantity of asphalt binder and cover aggregate required for *each layer* of a multiple surface treatment or seal coat is identical, with minor adjustments, to the quantity of asphalt binder and cover aggregate that would be applied if each layer were to serve as an isolated single application surface treatment or seal coat. On this basis, Equations [5] and [6] that were developed for single application surface treatments and seal coats can also be employed with slight modification for the design of multiple surface treatments and seal coats.

This means, as indicated in the opening paragraph in the introduction to this paper, that *the same equations* can be employed for the design of *either single application or multiple application seal coats and surface treatments.*

Methods for determining the quantities of asphalt binder and cover aggregate to be applied for each layer of a multiple surface treatment or seal coat have been published by ASTM (19), AASHO (20), Bureau of Public Roads (21), Federal Aviation Agency (22), Country Roads Board (7), (1), National Association of Australian State Road Authorities (5), Tagle (11), Benson (4), and The Asphalt Institute (23). These methods range from the purely empirical, which consist of tabulations of recommended quantities for each layer arrived at from experience, through semi-empirical, to theoretical procedures.

A careful investigation and comparison of these several methods has shown that they do not agree among themselves, and that for some of them the amount of cover stone required is too little, while the quantity of asphalt binder stipulated is excessive. This investigation has also shown that the quantities of cover aggregate and asphalt binder indicated by Equations [5] and [6] respectively, for multiple surface treatments and seal coats, approximate the averages of the quantities of these two materials required by the above methods. However, the design of multiple surface treatments and seal coats by means of Equations [5] and [6] is somewhat unique, in that consideration is given to each of the following important factors: gradation of cover aggregate in each layer; reorientation of the cover aggregate in a surface treatment or seal coat under traffic, and therefore recognition of the need for determining each cover aggregate's Average Least Dimension; traffic volume to be carried; fraction of residual asphalt in the asphalt binder; asphalt binder correction for the textural characteristics of the surface to which the multiple surface treatment or seal coat is to be applied; and correction for the loss, if any, of a portion of the asphalt binder into the cover aggregate.

A. DESIGN ASSUMPTIONS FOR MULTIPLE SURFACE TREATMENTS AND SEAL COATS

1. It is assumed that each successive layer of a multiple surface treatment or seal coat will be built immediately after the preceding layer has been constructed, with no traffic being permitted between layers.

When a year or more of service is scheduled for the first layer of a double surface treatment before the second layer is applied, the double surface treatment becomes in effect two single surface treatments insofar as both design and construction is concerned.

2. Each layer of a multiple surface treatment is assumed to be one-stone particle thick.

3. For the first layer of a multiple surface treatment or seal coat, the cover aggregate should preferably be one-size cover stone, Table I, but graded cover aggregate with a limited amount of finer sizes, Table II, may be employed for all layers.

4. The size of the cover aggregate selected for each layer of a multiple surface treatment or seal coat should be approximately one-half the size of the cover stone employed for the immediately preceding layer. For example, if Aggregate E (3/4 inch one-size aggregate) from Table I, or Aggregate No. 6 (3/4 inch to 3/8 inch graded aggregate) from Table II, is selected for the first layer of a double surface treatment, the cover aggregate for the second layer should be either Aggregate H (3/8 to 1/4 inch one-size aggregate) from Table I, or Aggregate No. 8 (3/8 inch to No. 8 graded aggregate) from Table II.

5. The total quantities of asphalt binder and cover aggregate required for a multiple surface treatment or seal coat are obtained by assuming (with some minor qualifications), that each layer is to be designed as though it were an independent single application surface treatment or seal coat.

6. The quantity of cover aggregate to be applied for the first layer of a multiple surface treatment is to be calculated by Equation [5].

7. The quantity of cover aggregate required for the second layer of a double surface treatment or seal coat, or for each of the second and third layers of a triple surface treatment or seal coat, is calculated by the following modification of Equation [5]:

$$C = M\, 46.8(1 - 0.4V)HGE \qquad [7]$$

where M is a multiplying factor that must be evaluated by experience with local conditions of climate, traffic, aggregate, etc., and may be less than or greater than 1.0, depending on local conditions. While the author has always used a value for $M = 1.0$, experience elsewhere may indicate the need for employing a value of $M = 0.9$, 0.8, 1.1, etc.

The other symbols have been already defined.

8. It is to be emphasized that for the cover aggregate for every layer of a multiple surface treatment or seal coat, the normal value for the wastage factor $E = 1.0$. That is, when cover aggregate is applied by a competently operated self-propelled aggregate spreader, or similar well controlled spreading equipment, when calculating the quantity of cover aggregate to be applied for every layer of a multiple surface treatment or seal coat, no allowance is ordinarily made for loss of aggregate due to whip-off, or for any slight unevenness of spread.

9. The Average Least Dimension H of the cover aggregate for each layer should be measured by the procedure outlined in Appendix A.

10. The loose weight W of the cover aggregate for each layer should be determined by ASTM C 29.

11. The fraction of voids V in each cover aggregate in its loose weight condition is calculated by means of Equation [2].

12. The grade of asphalt binder selected for a multiple surface treatment or seal coat depends upon whether a liquid asphalt, an asphalt emulsion, or an asphalt cement is to be used. In a multiple surfact treatment or seal coat, a smaller size of cover aggregate is normally employed for each successive layer, and this would normally call for a different grade of asphalt binder for each layer. However, to simplify construction operations, a single grade of asphalt binder should be specified for all layers of a multiple surface treatment or seal coat.

In the case of liquid asphalt or asphalt cement binders, it is recommended that the single grade of asphalt binder selected should be one grade softer than would ordinarily be selected from Figures 23 to 26 for the climate, road surface temperature, and size of cover aggregate to be applied for the first layer of a multiple seal coat or surface treatment. For example, if Figure 25 indicated that RC 3000 would normally be selected for the road surface temperature and for the cover aggregate size for the first layer, then RC 800 should be chosen for both applications for a double surface treatment, and for all three applications for a triple surface treatment.

When the asphalt binder is to be an asphalt emulsion, either RS-2 or CRS-2 would usually be applied for all layers of a multiple surface treatment or seal coat, unless the cover aggregate for each layer is quite small, when either RS-1 or CRS-1 might be selected.

13. The quantity of asphalt binder calculated for each layer of a multiple seal coat or surface treatment is determined by the following modification of Equation [6]:

$$B = K\left(\frac{2.244\ HVT + S + A}{R}\right) \qquad [8]$$

where

K - is a multiplying factor that must be determined by experience with local conditions of climate, traffic, aggregate, etc., and may have a value either less than or greater than 1.0. Within the author's experience K = 1.0. However, for heavy traffic in tropical climates, K may have a value of 0.9 or some other value less than 1.0, while elsewhere, experience may indicate the need for employing a value for K higher than 1.0. The other symbols have the significance already defined for them.

14. The correction S, Table VIII, should be made to the quantity of asphalt binder required for the *first* layer on the basis of the textural characteristics of the surface on which the multiple surface treatment or seal coat is to be placed.

15. *No correction* S, for the textural characteristics of the surface to which it is applied (the surface of the first layer in the case of a

double surface treatment or seal coat, or the surfaces of the first and second layers in the case of a triple surface treatment), is to be made when calculating the quantity of asphalt binder required for the second layer of a double surface treatment or seal coat, or for the second and third applications of asphalt binder to be applied for a triple surface treatment or seal coat.

16. For most cover aggregates, the correction A for loss of a portion of the asphalt binder by absorption into the aggregate is nil. However, a correction A should be added when the cover aggregate employed is decidedly absorptive (asphalt absorption more than two (2) per cent by Rice's vacuum saturation method ASTM D 2041). The Country Roads Board adds a correction A of 0.03 US gallon per square yard (0.025 Imperial gallon/sq. yd.) (0.136 litre/sq. metre), when an allowance for absorption by any cover aggregate must be made.

17. For a multiple seal coat or surface treatment constructed during the early warm weather portion of the construction season, the large aggregate particles in the first layer are rapidly oriented by warm weather traffic to provide adequate embedment in the asphalt binder. Therefore, for construction in early season warm weather, a larger percentage of the total asphalt binder requirement should be sprayed for the first application.

On the other hand, for late season construction of multiple surface treatments or seal coats, sufficient warm weather traffic may not occur before winter arrives to embed the first layer of cover aggregate particles adequately, and the multiple surface treatment may be damaged by loss of cover stone during the ensuing winter or spring, or even earlier. Therefore, during late season construction, to achieve better retention of the cover aggregate in the first layer, a smaller percentage of the total asphalt requirement should be sprayed for the first application, and a larger percentage should be applied for the second application for a double surface treatment or seal coat, or for the total of the second and third applications for a triple seal coat or surface treatment.

Consequently, after the total quantity of asphalt binder required for a double surface treatment or seal coat has been determined, it should be applied as follows:

(a) During the warm weather portion of the construction season:
1st application, 60 per cent of the total asphalt binder
2nd application, 40 per cent of the total asphalt binder

(b) For late season construction:
1st application, 40 per cent of the total asphalt binder
2nd application, 60 per cent of the total asphalt binder

For a triple surface treatment or seal coat, the total asphalt binder requirement should be applied as follows:

(a) During the warm weather portion of the construction season:
1st application, 40 per cent of the total asphalt binder
2nd application, 40 per cent of the total asphalt binder
3rd application, 20 per cent of the total asphalt binder

(b) For late season construction:
1st application, 30 per cent of the total asphalt binder
2nd application, 40 per cent of the total asphalt binder
3rd application, 30 per cent of the total asphalt binder

The application of these assumptions to the actual design of a multiple surface treatment or seal coat will be illustrated by sample calculations for the design of first a double, and then a triple surface treatment or seal coat.

B. SAMPLE CALCULATION FOR THE DESIGN OF A DOUBLE SURFACE TREATMENT OR SEAL COAT

I. THE FOLLOWING CONDITIONS ARE ASSUMED

(a) Climate--cool
(b) Traffic volume--1700 vehicles per day
(c) Road surface temperature—100 F
(d) Textural rating of the existing road surface—1h
(e) Properties of the graded cover aggregates selected:
(1) For first layer, AASHO No. 5, Table II, Figure 14
(2) For second layer AASHO No. 7, Table II, Figure 14
(3) Average Least Dimension H, AASHO No. 5—0.53 inch
(4) Average Least Dimension H, AASHO No. 7—0.25 inch
(5) ASTM bulk specific gravity G, AASHO No. 5—2.68
(6) ASTM bulk specific gravity G, AASHO No. 7—2.65
(7) Loose weight W, AASHO No. 5—98 pounds/cu. ft.
(8) Loose weight W, AASHO No. 7—94 pounds/cu. ft.
(9) Fraction of voids V, AASHO No. 5—0.414
(10) Fraction of voids V, AASHO No. 7—0.432
(11) Asphalt absorption, both aggregates—Nil
(12) Wastage factor E, Table IX, first layer—1.0
second layer—1.0

II. THE FOLLOWING ITEMS OF INFORMATION ARE REQUIRED

(a) What quantity of cover stone in pounds per square yard is required for each layer?
(b) What grade of asphalt binder should be selected?
(c) What spraying temperature is recommended?
(d) What quantity of asphalt binder per square yard measured at 60 F should be sprayed for each application?
(e) What quantity of asphalt binder per square yard measured at the spraying temperature should be sprayed for each application?

III. SOLUTION

1. Cover Aggregate Requirements

The quantity per square yard of cover aggregate No. 5 to be applied for the first layer, and of cover aggregate No. 7 required for the second layer can each be calculated by means of Equation [7]:

$$C = M\ 46.8(1 - 0.4V)HGE \quad [7]$$

While the author has so far always used a value for M = 1.0, experience elsewhere may indicate the need to employ a value for M that is less than or greater than 1.0 to obtain satisfactory results.

(a) Required quantity of aggregate No. 5 for the first application of cover stone

$$C = (1.0)(46.8)(1 - 0.4 \times 0.414)(0.53)(2.68)(1.0)$$

$$= (1.0)(46.8)(0.834)(0.53)(2.68)(1.0)$$

$$= 55.4 \text{ pounds per square yard.}$$

(b) Required quantity of aggregate No. 7 for the second application of cover stone

$$C = (1.0)(46.8)(1 - 0.4 \times 0.432)(0.25)(2.65)(1.0)$$

$$= (1.0)(46.8)(0.827)(0.25)(2.65)(1.0)$$

$$= 25.6 \text{ pounds per square yard.}$$

(c) Therefore, the total quantity of cover aggregate required for this double surface treatment or seal coat is 55.4 + 25.6 = 81.0 pounds per square yard.

2. Asphalt Binder Requirements

(a) For cooler climates like that of Canada and the Northern U.S.A., for 1 inch to 1/2 inch graded cover aggregate (Aggregate No. 5, Table II, Figure 14), and for a road surface temperature of 100 F, if an RC liquid asphalt binder is to be used, Figure 25 indicates that RC 3000 should be selected. However, to simplify construction operations, only one asphalt binder is to be employed for both applications, and because a somewhat softer asphalt binder is required to achieve fast wetting and firm adhesion to the smaller aggregate of the second layer, the asphalt binder should be one grade softer than RC 3000. Therefore, the asphalt binder selected for both applications is RC 800.

(b) Figure 21 indicates that for average conditions a spraying viscosity of 50 centistokes is required, and for RC 800 it is seen that this corresponds to a spraying temperature of 255 F.

(c) The quantity of RC 800 asphalt binder in U.S. gallons per square yard measured at 60 F, required for each layer is provided by Equation [8]

$$B = K\left(\frac{2.244\ HTV + S + A}{R}\right) \quad [8]$$

In keeping with the author's experience, a value of K = 1.0 is assumed here. However, experience elsewhere may indicate that a value for K that is less than or greater than 1.0 provides more satisfactory results.

Therefore:

(1) Quantity of RC 800 asphalt binder measured at 60 F required for this first layer is

$$B = \frac{(1.00)(2.244)(0.53)(0.65)(0.414) + 0.03 + 0}{0.84}$$

$$= \frac{0.32 + 0.03}{0.84} = 0.42 \text{ U.S. gallon per square yard.}$$

(2) Quantity of RC 800 asphalt binder measured at 60 F required for the second layer is

$$B = \frac{(1.00)(2.244)(0.25)(0.65)(0.432) + 0 + 0}{0.84}$$

$$= 0.19 \text{ U.S. gallon per square yard.}$$

(3) Total quantity of RC 800 liquid asphalt binder measured at 60 F to be applied for this double surface treatment or seal coat

$$= 0.42 + 0.19 = 0.61 \text{ US gallon per square yard.}$$

(d) For a spraying temperature of 255 F, Line (2), Figure 22 indicates that the correction factor for volumetric expansion of the asphalt binder is 1.07. Therefore, the total quantity of RC 800 to be applied at a spraying temperature of 255 F is (0.61)(1.07) = 0.65 U.S. gallon per square yard.

(e) For the *warm weather portion* of the construction season, 60 per cent of the total asphalt binder requirement should be sprayed for the first application and 40 per cent for the second. Therefore, the following quantities of RC 800 asphalt binder should be sprayed for each application:

For warm weather construction

Application	U.S. gal/sq. yd. Measured at 60 F	U.S. gal/sq. yd. Measured at Spraying Temperature, 255 F
First	0.37	0.39
Second	0.24	0.26
	0.61	0.65

(f) For *late season construction,* to more securely cement the coarser cover aggregate in the first layer to the road surface, 40 per cent of the total asphalt binder requirement should be sprayed for the first application, and 60 per cent for the second. The following quantities of RC 800 asphalt binder should therefore be sprayed for each application:

For late season construction

Application	U.S. gal/sq. yd. Measured at 60 F	U.S. gal/sq. yd. Measured at Spraying Temperature, 255 F
First	0.24	0.26
Second	0.37	0.39
	0.61	0.65

IV. SUMMARY

1. For the warm weather portion of the construction season:

Application	Asphalt Binder				Cover Aggregate	
	Grade	Spraying Temp. F	US gal/sq.yd. at 60 F	US gal/sq.yd. at Spray Temp.	Size Designation	lb/sq.yd.
First	RC 800	255	0.37	0.39	No. 5	55.4
Second	RC 800	255	0.24	0.26	No. 7	25.6
	Total Quantities		0.61	0.65		81.0

2. For late season construction:*

Application	Asphalt Binder				Cover Aggregate	
	Grade	Spraying Temp. F	US gal/sq. yd. at 60 F	US gal/sq.yd. at Spray Temp.	Size Designation	lb/sq.yd.
First	RC 800	255	0.24	0.26	No. 5	55.4
Second	RC 800	255	0.37	0.39	No. 7	25.6
	Total Quantities		0.61	0.65		81.0

*Note: Because lower road surface temperatures tend to prevail during construction in cool weather late in the season, RC 250 would probably be substituted quite frequently for RC 800, and the quantities of asphalt binder for each application would be increased somewhat due to the smaller fraction of residual asphalt in RC 250, Table VI.

V. USE OF ASPHALT EMULSION BINDER

If RS-2 asphalt emulsion had been selected for this double surface treatment or seal coat instead of RC 800, the design calculations are similar to those just illustrated. Table VI indicates that an average value for the fraction R of residual asphalt in RS-2 asphalt emulsion is 0.65, and Line (3) in Figure 22 shows that for a maximum spraying temperature of 160 F, the correction factor for volumetric expansion is 1.025. When using RS-2 asphalt emulsion, the following summary is obtained for the same design conditions:

1. For the warm weather portion of the construction season:

	Asphalt Binder				Cover Aggregate	
Application	Grade	Spraying Temp. F	US gal/sq.yd. at 60 F	US gal/sq.yd. at Spray Temp.	Size Designation	lb/sq.yd.
First	RS-2	160	0.47	0.48	No. 5	55.4
Second	RS-2	160	0.31	0.32	No. 7	25.6
	Total Quantities		0.70	0.80		81.0

2. For late season construction:

	Asphalt Binder				Cover Aggregate	
Application	Grade	Spraying Temp. F	US gal/sq.yd. at 60 F	US gal/sq.yd. at Spray Temp.	Size Designation	lb/sq.yd.
First	RS-2	160	0.31	0.32	No. 5	55.4
Second	RS-2	160	0.47	0.48	No. 7	25.6
	Total Quantities		0.78	0.80		81.0

VI. USE OF AN ASPHALT CEMENT BINDER

If the same design conditions existed in a hot climate, 200/300 penetration asphalt cement, Figures 24 and 26, might be selected as the binder for a double surface treatment or seal coat, instead of RC 800, or RS-2, but the design calculations are similar to those already illustrated. As shown by Table VI, the fraction R or residual asphalt in 200/300 penetration asphalt cement is 1.0. Depending upon its viscosity temperature characteristics, the spraying temperature for 200/300 penetration asphalt could be 320 F, Figure 21, and as indicated by Line (2), Figure 22, the volume correction factor for this spraying temperature is 1.10. Consequently, when using 200/300 penetration for the same conditions of design, the following summary is obtained:

1. For the warm weather portion of the construction season:

Application	Asphalt Binder				Cover Aggregate	
	Grade	Spraying Temp. F	US gal/sq. yd. at 60 F.	US gal/sq.yd. at Spray Temp.	Size Designation	lb/sq.yd.
First	200/300 pen.	320	0.31	0.34	No. 5	55.4
Second	200/300 pen.	320	0.20	0.22	No. 7	25.6
	Total Quantities		0.51	0.56		81.0

2. For late season construction:*

Application	Asphalt Binder				Cover Aggregate	
	Grade	Spraying Temp. F	US gal/sq. yd. at 60 F.	US gal/sq.yd. at Spray Temp.	Size Designation	lb/sq.yd.
First	200/300 pen.	320	0.20	0.22	No. 5	55.4
Second	200/300 pen.	320	0.31	0.34	No. 7	25.6
	Total quantities		0.51	0.56		81.0

*Note: For late season construction in even a hot climate, if the weather is cool, 200/300 penetration asphalt cement could be too hard a grade of asphalt binder to use, and better results might be obtained by using one of the liquid asphalt or asphalt emulsion binders.

VII. COMPARISON OF TOTAL MATERIAL REQUIREMENTS PER SQUARE YARD

The following table summarizes the total material requirements per square yard for this particular double surface treatment or seal coat:

Materials	200/300 Penetration Asphalt Cement	RC 800 Liquid Asphalt	RS-2 Asphalt Emulsion
Asphalt binder US gallons per square yard at 60 F	0.51	0.61	0.78
Cover aggregate pounds per square yard	81.0	81.0	81.0

C. SAMPLE CALCULATION FOR THE DESIGN OF A TRIPLE SURFACE TREATMENT OR SEAL COAT

I. THE FOLLOWING CONDITIONS ARE ASSUMED:

The triple surface treatment or seal coat is to consist of a third layer to be added to the double surface treatment or seal coat of the previous sample calculation (B above). Consequently, all of the conditions assumed for the previous sample calculation apply with the following additions:

(a) Properties of cover aggregate for the third layer:

(1) Gradation—AASHO No. 9, Table II, Figure 14.

(2) Average Least Dimension H—from Table IV assume

$$\frac{\text{50 per cent passing size}}{1.32} = \frac{0.14}{1.32} = 0.106 \text{ inch}$$

(3) ASTM bulk specific gravity $G = 2.66$

(4) Loose weight $W = 88$ pounds per cubic foot

(5) Fraction of voids $V = 0.47$

(6) Asphalt absorption = nil

(7) Wastage factor $E = 1.0$

II. THE FOLLOWING ADDITIONAL ITEMS OF INFORMATION ARE REQUIRED

(a) What quantity of cover stone is required for the third layer?

(b) What quantity of asphalt binder measured at 60 F is required for the third layer?

(c) What quantity of asphalt binder measured at the spraying temperature is required for the third layer?

III. SOLUTION

(a) The quantity of cover aggregate required for the third layer is given by Equation [7]:

$$\begin{aligned} C &= (1.0)(46.8)(1 - 0.4 \times 0.47)(0.106)(2.66)(1.0) \\ &= (1.0)(46.8)(0.812)(0.106)(2.66)(1.0) \\ &= 10.7 \text{ pounds per square yard.} \end{aligned}$$

(b) The quantity of RC 800 asphalt binder measured at 60 F required for the third layer is given by Equation [8]

$$B = \frac{(1.0)(2.244)(0.106)(0.65)(0.47) + 0 + 0}{0.84}$$

$$= 0.09 \text{ US gallon per square yard.}$$

(c) The quantity of RC 800 asphalt measured at the spraying temperature of 255 F required for the third layer = (0.09)(1.07) = 0.10 US gallon per square yard.

(d) The total quantity of RC 800 asphalt binder required for all three layers

(1) Measured at 60 F = 0.42 + 0.19 + 0.09 = 0.70 US gallon per square yard

(2) Measured at a spraying temperature of 255 F = (0.70)(1.07) = 0.75 US gallon per square yard.

(e) The quantity of RS-2 asphalt emulsion binder measured at 60 F required for the third layer is given by Equation [8]

$$B = \frac{(1.0)(2.244)(0.106)(0.65)(0.47) + 0 + 0}{0.65}$$

$$= 0.11 \text{ US gallon per square yard.}$$

(f) The quantity of RS-2 asphalt emulsion binder measured at a spraying temperature of 160 F required for the third layer = (0.11)(1.025) = 0.11 US gallon per square yard.

(g) The total quantity of RS-2 asphalt emulsion required for all three layers:

(1) Measured at 60 F = 0.54 + 0.24 + 0.11 = 0.89 US gallon per square yard.

(2) Measured at a spraying temperature of 160 F = (0.89)(1.025) = 0.91 US gallon per square yard.

(h) The quantity of 200/300 penetration asphalt cement measured at 60 F required for the third layer is given by Equation [7]

$$B = \frac{(1.0)(2.244)(0.106)(0.65)(0.47) + 0 + 0}{1.0}$$

$$= 0.07 \text{ US gallon per square yard}$$

(i) The quantity of 200/300 penetration asphalt cement measured at a spraying temperature of 320 F required for the third layer = (0.07)(1.10) = 0.08 US gallon per square yard.

(j) The total quantity of 200/300 penetration asphalt required for all three layers:

(1) Measured at 60 F = 0.35 + 0.16 + 0.07 = 0.58 US gallon per square yard.

(2) Measured at a spraying temperature of 320 F = (0.58)(1.10) = 0.64 US gallon per square yard.

IV. SUMMARY OF MATERIAL QUANTITIES REQUIRED FOR EACH APPLICATION DURING THE CONSTRUCTION OF A TRIPLE SURFACE TREATMENT OR SEAL COAT

For the construction of a triple surface treatment or seal coat during warm weather, 40 per cent of the total asphalt binder requirement should be applied for the first application, 40 per cent for the second application, and 20 per cent for the third. For late season construction, 30 per cent of the total asphalt binder requirement should be applied for the first application, 40 per cent for the second, and 30 per cent for the third application. In summary therefore:

1. For warm weather construction:

	Asphalt Binder				Cover Aggregate	
Application	Grade	Spraying Temp. F	US gal/sq.yd. at 60 F	US gal/sq.yd. at Spray Temp.	Size Designation	lb/sq.yd.
Asphalt Binder--Liquid Asphalt RC 800						
First	RC 800	255	0.28	0.30	No. 5	55.4
Second	RC 800	255	0.28	0.30	No. 7	25.6
Third	RC 800	255	0.14	0.15	No. 9	10.7
	Total Quantities		0.70	0.75		91.7
Asphalt Binder—Asphalt Emulsion RS-2						
First	RS-2	160	0.35	0.36	No. 5	55.4
Second	RS-2	160	0.36	0.37	No. 7	25.6
Third	RS-2	160	0.18	0.18	No. 9	10.7
	Total Quantities		0.89	0.91		91.7
Asphalt Binder—200/300 penetration asphalt cement						
First	200/300 pen.	320	0.23	0.25	No. 5	55.4
Second	200/300 pen.	320	0.23	0.26	No. 7	25.6
Third	200/300 pen.	320	0.12	0.13	No. 9	10.7
	Total quantities		0.58	0.64		91.7

2. For late season construction:

Application	Grade	Spraying Temp. F	US gal/sq.yd. at 60 F	US gal/sq.yd. at Spray Temp.	Size Designation	lb/sq.yd.
		Asphalt Binder			Cover Aggregate	
Asphalt Binder--Liquid Asphalt RC 800						
First	RC 800	255	0.21	0.22	No. 5	55.4
Second	RC 800	255	0.28	0.30	No. 7	25.6
Third	RC 800	255	0.21	0.23	No. 9	10.7
	Total quantities		0.70	0.75		91.7
Asphalt Binder—Asphalt Emulsion RS-2						
First	RS-2	160	0.26	0.27	No. 5	55.4
Second	RS-2	160	0.36	0.36	No. 7	25.6
Third	RS-2	160	0.27	0.28	No. 9	10.7
	Total quantities		0.89	0.91		91.7
Asphalt Binder--200/300 penetration Asphalt Cement						
First	200/300 pen.	320	0.17	0.19	No. 5	55.4
Second	200/300 pen.	320	0.23	0.26	No. 7	25.6
Third	200/300 pen.	320	0.18	0.19	No. 9	10.7
	Total quantities		0.58	0.64		91.7

V. COMPARISON OF TOTAL MATERIAL REQUIREMENTS PER SQUARE YARD

The following table summarizes the total material requirements per square yard for this particular triple surface treatment or seal coat:

Materials	Material Requirements per Square Yard		
	200/300 Penetration Asphalt Cement	RC 800 Liquid Asphalt	RS-2 Asphalt Emulsion
Asphalt binder, gal/sq. yd. at 60 F	0.58	0.70	0.89
Cover aggregate, pounds per square yard	91.7	91.7	91.7

IX. CONSTRUCTION OF SURFACE TREATMENTS AND SEAL COATS

It has been shown that design procedures are available to determine the optimum quantities of asphalt binder and cover aggregate to be applied for either single application or multiple application surface treatments and seal coats.

It is the objective of the construction equipment and procedures employed, to apply these quantities accurately and uniformly to the road surface under suitable weather and other conditions, and to protect the surface treatment or seal coat from damage by vehicles both during construction and during the critical initial period after it is opened to traffic following construction. Consequently, the service performance of seal coats and surface treatments is influenced by each of the following factors:

(a) climate and weather
(b) preparation of the existing surface
(c) construction equipment
(d) construction operations
(e) traffic control during construction and during the critical initial period following construction.

1. Climate and Weather

Seal coats and surface treatments are more likely to be successful if they are constructed in warm dry weather in the early summer. Traffic during the ensuing hot weather provides adequate embedment of the cover aggregate in the asphalt binder, improves the adhesion between the binder and aggregate, and increases the strength or stability of the surface treatment or seal coat by developing firmer cover aggregate interlock.

During construction, asphalt binder and cover aggregate should be applied only during daylight hours, and when the ambient air temperature is not less than 50 F and rising. The road surface should be dry when liquid asphalt and asphalt cement binders are used, but may be damp when the binder is an asphalt emulsion. High atmospheric humidity which may delay the development of good adhesion between the cover aggregate and asphalt binder, the imminence of rain which can damage a newly finished surface, or any other temporary conditions likely to have a detrimental effect on the success of the finished surface treatment or seal coat, should be carefully considered when deciding whether construction operations should proceed or be stopped at any time.

In the Northern United States and Canada, single surface treatments should not be constructed after August 31 so as to allow for about one month of warm weather traffic that is necessary to obtain adequate embedment of the cover stone particles before winter arrives. Multiple surface treatments on the other hand, while preferably constructed in warm weather, can be built much later in the construction season.

2. Preparation of the Existing Surface

The preparation of a consolidated crushed stone or gravel surface for a surface treatment requires blading to the specified cross-section, watering if necessary, and compaction by rolling and by traffic to provide a firm, smooth, uniform surface. The surface is then primed with from 0.1 to 0.25 gallon of MC 70 (MC 1) per square yard (0.5 to 1.25 litre per square metre) if it is tightly bonded or of medium porosity, and with from 0.2 to 0.5 gallon per square yard (1.0 to 2.5 litre per square metre) if it is a relatively porous, poorly bonded surface. The primer should be left to cure for several days before the seal coat is applied. If traffic is likely to damage the primed surface, the primer may be followed by an application of from six to ten pounds per square yard of clean, fine sand. All loose and foreign material is swept or otherwise removed from the surface immediately before the surface treatment is applied.

Before a seal coat is constructed, all defects and breaks in an old paved surface should be adequately repaired. When large areas of an old bituminous surface are seriously cracked and badly worn, an emulsified asphalt sand slurry seal may be applied to fill the cracks and give a uniform texture to the entire surface. Immediately before a seal coat is applied the old paved surface should be thoroughly swept with a power broom to remove all loose and foreign material. The removal of any hardened mud or similar extraneous material may require the use of a pick and shovel, followed by washing with water, if necessary.

3. Construction Equipment

The basic equipment for the construction of a surface treatment or seal coat should include:

(a) asphalt distributor
(b) aggregate spreader
(c) rollers
(d) rotary broom and other cleaning equipment
(e) broom drag
(f) trucks for hauling cover aggregate.

The asphalt distributor must be able to apply asphalt binder uniformly across and along the road surface at the specified rate per square yard. The asphalt distributor should preferably be one in which the asphalt pump is synchronized with the forward speed of the truck in such a way that the same quantity of asphalt binder is applied per square yard regardless of small variations in the forward speed of the distributor due to changes in grade, direction of travel, etc. To establish its general mechanical condition, the distributor should be calibrated at a central testing station (24), (25), (26). Cotton pads should be employed (15) to check the transverse and longitudinal distribution of asphalt binder across the road surface on the job. The asphalt distributor should be operated to apply asphalt binder within $\pm$ 7.5 per cent of the average application in the longitudinal direction, and within ± 10 per cent of the average application for any 4-inch width in the transverse direction.

When a double surface treatment or seal coat is being constructed, for the second application of asphalt binder, *the asphalt distributor should be operated in the opposite direction* to that employed for the first application. This will avoid two applications of either too much or too little binder over the same widths of road surface due to either a deficiency or excess of asphalt binder being applied by one or more spray nozzles. Furthermore, for half-width construction, the centre joint for asphalt application on successive layers should be offset by from six to twelve inches.

It is the function of the aggregate spreader to apply cover aggregate uniformly at the specified rate per square yard. If it is of the self-propelled type, its system for discharging aggregate onto the road surface should be synchronized with the forward speed of the spreader. This tends to ensure uniform application of cover stone in spite of small differences in the forward speed of the spreader due to changes in grade, direction of travel, etc.

The aggregate spreader should be tested to establish its ability to spread the specified quantity of cover aggregate per square yard. Figure 28 illustrates the use of a steel pan of exactly one square yard for this purpose. An even better arrangement would be three steel pans, 18 inches to each side (0.25 square yard) uniformly distributed across the width of road surface covered by the aggregate spreader.

After the cover stone has been applied, it is the purpose of the rolling operation to press the cover stone particles firmly into the asphalt binder to improve embedment, to promote adhesion, and to obtain better cover aggregate interlock. For single surface treatments or seal coats, the rollers should be of the pneumatic-tire type. No existing surface is entirely smooth, and pneumatic tires are able to reach down into small depressions and firmly press the cover aggregate into the asphalt binder. However, *for multiple surface treatments or seal coats* pneumatic-tire rollers should be employed for initial rolling, but *two passes by a steel-wheel roller should be made for the final rolling of each layer.* Steel wheel rollers appear to orient cover aggregate particles into a flatter surface, which is important when constructing multiple surface treatments.

A rotary broom should be used to clean the existing surface immediately before a seal coat or surface treatment is applied. To remove the layer of dust that is often heaviest near the edges of an existing surface, a blower may be required. In extreme cases, the surface may have to be cleaned by flushing with water. Lumps of clay or other hard foreign material may have to be removed with picks and shovels.

If the cover aggregate spreading equipment is unable to apply cover aggregate at a uniform rate per square yard, it should be followed by a broom drag for this purpose. When operating a broom drag, care must be taken to avoid turning over any cover aggregate particles that are already embedded in the asphalt binder.

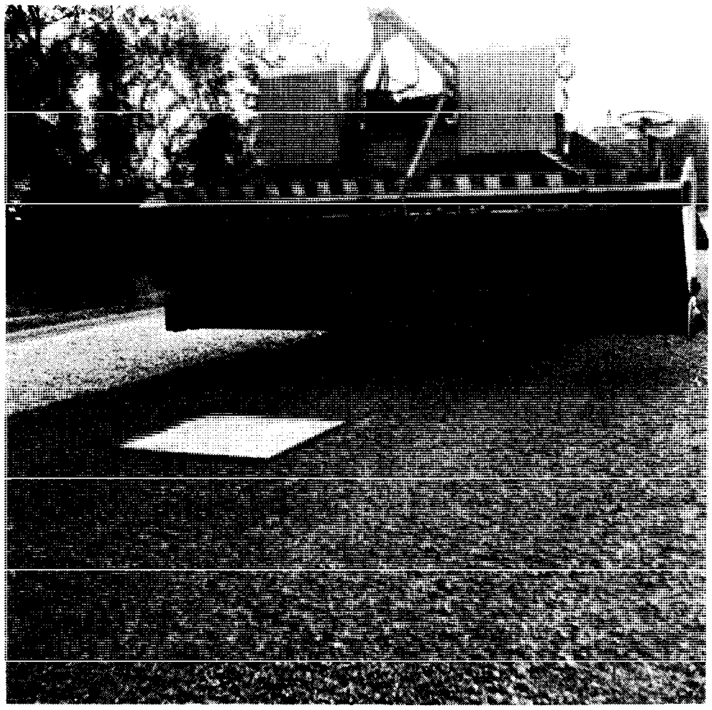

Fig. 28. Use of a One Square Yard Steel Pan to Adjust Cover Aggregate Spreader to the Setting Required for Application of Cover Aggregate at the Specified Rate per Square Yard.

An adequate number of trucks should be provided to avoid any delay in construction operations due to lack of cover aggregate. The bodies of the trucks should be designed to avoid any impingement of the truck body on the aggregate spreader at any time.

4. Construction Operations

Construction operations for a seal coat or surface treatment proceed in the following order:

(a) Spraying the asphalt binder
(b) Spreading the cover aggregate
(c) Broom dragging if necessary to obtain more uniform aggregate distribution
(d) Rolling
(e) The repetition of this sequence one or more times for a multiple surface treatment or seal coat.

Figure 29 illustrates this sequence of construction operations, and also demonstrates excellent seal coat and surface treatment construction practice. The asphalt distributor is only a short distance ahead of the self-propelled cover aggregate spreader. This promotes faster wetting and the development of better initial adhesion between the cover aggregate and the asphalt binder. The forward self-propelled pneumatic-tire roller is working immediately behind the aggregate spreader, and makes its first pass over the cover aggregate within a few minutes after the asphalt binder has been sprayed. This provides more effective embedment of the cover aggregate in the asphalt binder, and also promotes better adhesion between the cover aggregate and the asphalt binder.

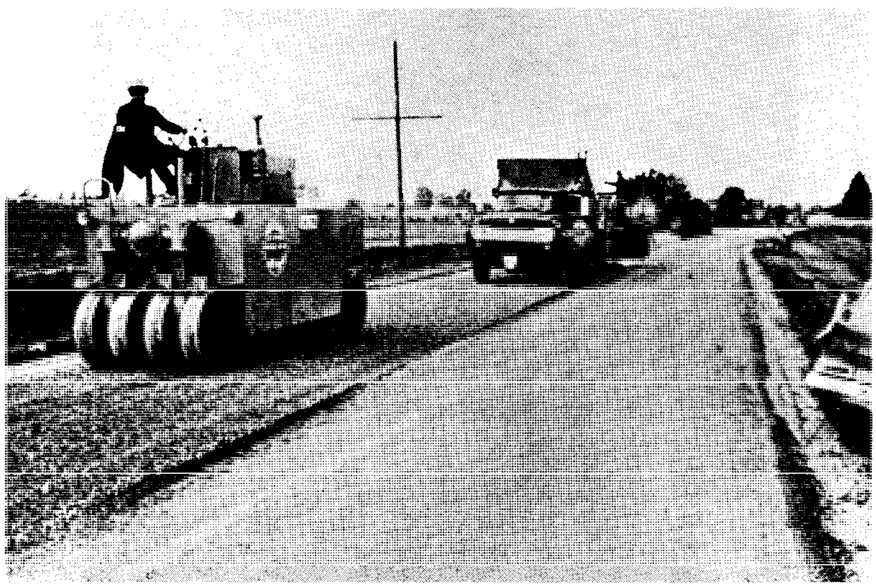

Fig. 29. Illustrating Excellent Technique for Seal Coat or Surface Treatment Construction. The Bituminous Distributor, Self-Propelled Flaherty Chip Spreader, Truck Loads of Stone Chips, and Roller, Work Together in Such Close Coordination that the First Pass of the Roller Over the Cover Aggregate Is Completed within a Very Few Minutes After the Bituminous Binder Has Been Applied to the Road Surface. (North America).
U.S.

Figure 30 was taken during the construction of a double surface treatment, and illustrates the junction at the centre of the road between the No. 5 cover aggregate of the first application on the right, and the No. 7 cover aggregate on the left, with the black strip of asphalt binder from the second application left for overlap during half-width construction, between them. The striking difference in surface texture between the coarser No. 5 cover stone for the first layer on the right, and the finer No. 7 cover aggregate on the left, can be easily observed.

As pointed out earlier, *when constructing a multiple surface treatment or seal coat,* while initial rolling of every layer should be done

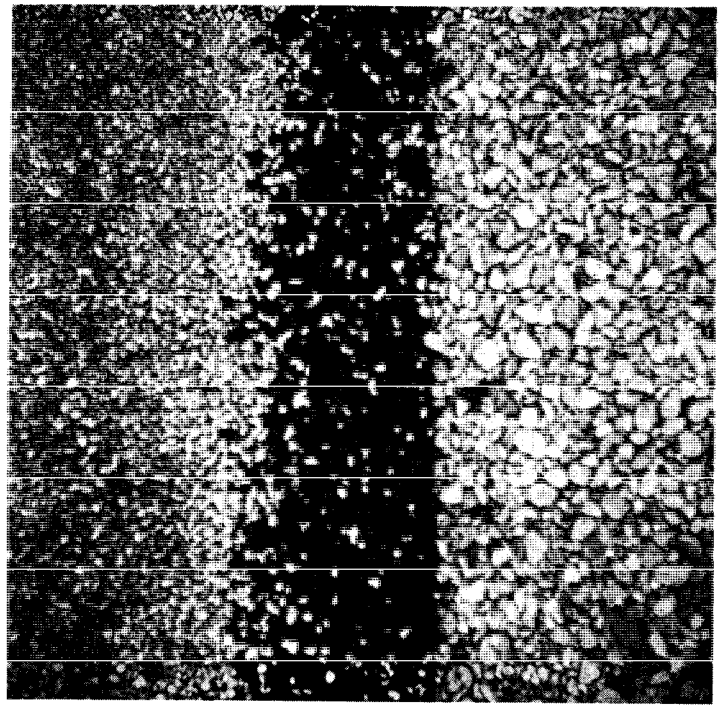

Fig. 30. Illustrating Coarse Aggregate Used for the Bottom Layer on the Right and Finer Aggregate on the Left for the Top Layer of a Double Surface Treatment, Together with a Portion of the Second Application of Asphalt Binder.

with a pneumatic-tire roller, *each layer should receive two passes with a steel-wheel roller before the next layer is placed.*

Figure 31, illustrates a finished double surface treatment 3-years old, that was designed and constructed in accordance with the principles that have been described in this paper.

5. Traffic Control

The objectives of traffic control are to protect workmen, construction equipment, and motor vehicles, and to avoid damage to the surface treatment or seal coat as construction proceeds and during the critical period when the finished job is first opened to traffic.

Whenever possible, traffic should be detoured until construction is complete. When detouring is not possible, half width construction is essential, with traffic being confined to the lane not under construction.

Traffic control through the section under construction should be maintained by means of a pilot truck for convoying groups of vehicles, warning signs, traffic lane markers, and flagmen.

All traffic should be kept off seal coats and surface treatments during their construction. This includes construction equipment which should be routed to the work site in the direction opposite to that in which construction is progressing.

When rolling is complete, and the new surface treatment or seal coat is opened to traffic, it requires protection from high speed vehicles. Flagmen should be provided, and traffic should be convoyed over the new surface at speeds that are low enough to avoid damage to it.

The length of time during which a newly constructed surface treatment or seal coat must be protected against high speed traffic, depends upon existing conditions. It can vary from a few hours in hot dry weather, to one or more days in humid, cool, or wet weather.

Fig. 31. Canada. Illustrating the Excellent Appearance of a Double Surface Treatment on a Consolidated Granular Base, in Its Third Year of Service, that Was Designed and Constructed in Accordance with the Principles Described in the Paper.

X. OPENING A NEWLY CONSTRUCTED SURFACE TREATMENT OR SEAL COAT TO TRAFFIC

There are several reasons why a newly constructed seal coat or surface treatment is particularly susceptible to damage by fast traffic. These factors should be kept clearly in mind when considering the time of day for opening a newly constructed surface treatment or seal coat to traffic, and the need for rigidly controlling traffic speeds for several hours and sometimes for the first one or two days.

1. Immediately after rolling, the voids in the cover aggregate are still about 30 per cent (6), and therefore the cover aggregate interlock is only partially developed. Also the cover aggregate is only partly embedded in the asphalt binder and is not yet firmly cemented into place. If an RS asphalt emulsion has been employed as binder, it will be only partially broken, and not yet firm. If the asphalt binder is an RC liquid asphalt, it will contain considerable solvent or cutter stock and will still be relatively fluid. Consequently, for reasons associated partly with the cover aggregate and in part with the asphalt binder, a newly constructed seal coat or surface treatment does not yet have high stability, and it can be quickly and badly damaged by the disruptive forces of high speed traffic.

2. Because of this lower initial stability, for the first day, and particularly for the first several hours, traffic speeds should be kept low by means of flagmen, convoy vehicles, etc.

3. During hot sunny weather, the most critical time of day to open a new seal coat or surface treatment to traffic is between mid-day and late afternoon. The high road surface temperatures during these hours make the asphalt binder much more fluid, and it is least able to hold the cover stone. By waiting until late evening, or after dark to open the surface treatment or seal coat to traffic, the asphalt binder becomes much firmer at the lower evening temperatures, and its greater cementing power provides increased resistance to loss of cover stone under traffic.

For example, suppose that because the cover aggregate size is 1/2 inch, and because the morning road surface temperature is 70 F, that RC 250 has been selected as the asphalt binder, Figure 25, and that the construction of the seal coat or surface treatment has been completed by two o'clock. When should it be opened to traffic? Figure 25 indicates that at a road surface temperature of 70 F, the viscosity of RC 250 is 9000 centistokes. However, by two o'clock on a hot sunny day, the road surface temperature may be 120 F, and Figure 2 shows that the viscosity of RC 250 at this temperature is only about 900 centistokes, which is only one-tenth of its morning viscosity. By waiting until after dark to open a surface treatment or seal coat completed in the early afternoon to traffic, the road surface temperature may have dropped to 70 F. At the same time, due to evaporation of solvent or cutter stock, the RC 250 will probably have become RC 800. At 70 F, Figure 25 shows that the viscosity of RC 800 is 50,000 centistokes.

Consequently, under the conditions assumed for this illustration, the afternoon viscosity of this binder is only about one tenth of its morning viscosity, while its viscosity is about 55 times as great in the evening as in midafternoon. Therefore, a hot afternoon is the poorest time to open a new surface treatment or seal coat to traffic. Just after dark is the best time, partly because of the very much higher viscosity of the asphalt binder, and partly because controlled evening and night traffic will develop increased stability in the seal coat or surface treatment before it enters the high temperature period of the next day. Since this principle applies to all asphalt binders, it is good engineering practice to recognize it and to use it whenever possible as a guide when opening a new surface treatment or seal coat to traffic.

4. If rain begins to fall within a few hours after its construction, a new seal coat or surface treatment should be barricaded, and no traffic should be permitted until it has become thoroughly dry.

SUMMARY

1. One equation for asphalt binder, and one equation for cover aggregate requirements are proposed for both single application and multiple application surface treatments and seal coats.

2. Four major faults of surface treatments and seal coats and their causes are briefly described.

3. The advantages of one-size over graded cover aggregates are illustrated and discussed.

4. Cover aggregate and asphalt binder characteristics and requirements are reviewed.

5. The design of a single application seal coat or surface treatment is described and is illustrated with a sample calculation.

6. The advantages of multiple application surface treatments and seal coats are outlined.

7. Designs of a double and of a triple seal coat or surface treatment are described and are illustrated by sample calculations.

8. Principles of construction for single and multiple surface treatments and seal coats are briefly outlined.

9. Factors to be considered when opening a newly constructed seal coat or surface treatment to traffic are reviewed.

ACKNOWLEDGMENT

Grateful acknowledgment is made to my associate, Mr. C. L. Perkins, for his competent drafting of the diagrams, and for his able assistance with some of the calculations required for this paper.

LITERATURE CITED

1. N. W. McLeod, "Basic Principles for the Design and Construction of Seal Coats and Surface Treatments with Cutback Asphalts and Asphalt Cements," *Proceedings of the Association of Asphalt Paving Technologists*, Supplement to Vol. 29 (1960).
2. L. I. Hewes, *American Highway Practice*, Vol. 2, Chapter I. New York: John Wiley and Sons, Inc., 1942.
3. L. I. Hewes and C. H. Oglesby, *Highway Engineering*, Chapter 17. New York: John Wiley and Sons, Inc., 1954.
4. F. J. Benson, "Seal Coats and Surface Treatments," *Proceedings, 44th Purdue Road School*, Purdue University (1950).
5. National Association of Australian State Road Authorities, "Principles and Practice of Bituminous Surfacing, Volume 1—Sprayed Work," 1965.
6. F. M. Hanson, "Bituminous Surface Treatments of Rural Highways," *Proceedings, New Zealand Society of Civil Engineers*, Vol. 21 (1934-35).
7. Country Roads Board, Victoria, Australia, "Bituminous Surfacing of Roads," Handbook Part B, 1954.
8. British Road Research Laboratory, "Bituminous Materials in Road Construction," Her Majesty's Stationery Office, London, England, 1962.
9. Idaho Department of Highway, Boise, Idaho, "Standard Method of Design of Seal Coats and Single Surface Treatments."
10. J. W. G. Kerr, "Experience with Surface Treatments in British Columbia," *Proceedings, Canadian Good Roads Association* (1957).
11. E. F. Tagle, "El Ensayo de Cubicidad, La Regla 9.5.3," Administracion General de Vialidad Nacional, Buenos Aires, Argentina, Publicaciones Tecnicas Vol. No. 43, 1946.
12. H. G. Nevitt, "Aggregate for Seal Coating," *Proceedings of the Association of Asphalt Paving Technologists*, Vol. 20 (1951).
13. J. P. Kearby, "Tests and Theories on Penetration Surfaces," *Proceedings, Highway Research Board*, Vol. 32 (1953).
14. W. E. Winnitoy, "Theory and Design of Seal Coats," *Proceedings, Canadian Technical Asphalt Association*, Vol. 2 (1957).
15. E. Zube, "Seal Coats, Laboratory Contributions Toward Better Performance," *Highway Research Board, Bulletin 215* (1959).
16. E. J. Dickinson, "The Wetting of Air-Dry Stone by Bituminous Binders in the Road Surface Dressing Operation," *Journal of the Institute of Petroleum*, Vol. 47, No. 445 (January, 1961).
17. National Roads Board, Wellington, New Zealand, "Manual of Sealing and Paving Practice," 1968.
18. N. W. McLeod, "Do's and Don'ts of Seal Coating," Presented, American Road Builders Association, 11th Annual National Highway Conference for County Highway Engineers and Officials, Gatlinburg, Tennessee, September 15-18, 1963.
19. American Society for Testing and Materials, American Society for Testing and Materials Designation D 1369, "Recommended Practice for Quantities of Materials for Bituminous Surface Treatments."
20. American Association of State Highway Officials, "Specifications for Bituminous Surface Treatment of Highways."
21. U.S. Bureau of Public Roads, "Standard Specification for Construction of Roads and Bridges on Federal Highway Projects."
22. Federal Aviation Agency, "Standard Specifications for Construction of Airports," June, 1959.
23. The Asphalt Institute, "Asphalt Surface Treatments and Asphalt Penetration Macadam," Manual Series No. 13, 1964.

24. Country Roads Board, Victoria Australia, "Annual Report 1937."
25. National Institute for Road Research, Pretoria, South Africa, "Binder Distributors," Bulletin No. 1, 1956.
26. Allan Leslie, "Surface Treatment: The Performance of Asphalt Distributors," *Proceedings, Canadian Good Roads Association* (1964).

APPENDIX A

METHOD FOR DETERMINING THE AVERAGE LEAST DIMENSION OF COVER AGGREGATES FOR BITUMINOUS SURFACE TREATMENTS AND SEAL COATS[2]

This method describes a simplified procedure which is to be followed to determine the Average Least Dimension of a cover aggregate intended for use in a bituminous surface treatment or seal coat.

METHOD:

(a) The Sieve Analysis shall be carried out by the method described in Part 1.
(b) The Flakiness Index shall be determined by the method described in Part 2.
(c) The Average Least Dimension shall be determined from Figure C.

PART 1

SIEVE ANALYSIS

SAMPLE:

Weight of Sample for Sieve Analysis (U.S. Standard Sieves square openings).

Table A-1.

Nominal Size	Minimum Weight of Sample for Sieving
Inches	Grams
2	20,000
1-1/2	15,000
1	10,000
3/4	5,000
5/8	4,000
1/2	2,500
3/8	1,000
1/4	750

METHOD:

The surface-dry sample shall be weighed and the following distribution of particle sizes obtained by means of sieves with square openings, employing the procedure laid down in A.S.T.M. C 136.

[2] With credit to The Country Roads Board, Victoria, Australia.

Passing	Retained
1-1/2 inch	1 inch
1 inch	3/4 inch
3/4 inch	5/8 inch
5/8 inch	1/2 inch
1/2 inch	3/8 inch
3/8 inch	1/4 inch
1/4 inch	No. 4
No. 4	No. 8
No. 8	No. 16
No. 16	

WEIGHING:

On completion of sieving, the material retained on each sieve shall be weighed on a balance sensitive to 0.1% of weight of the test sample. This is recorded on the work sheet and the weight passing each sieve is expressed as a percentage of the total weight of the sample.

REPORT:

Results are reported to the nearest one per cent, and the grading curve is plotted as illustrated in Figure A.

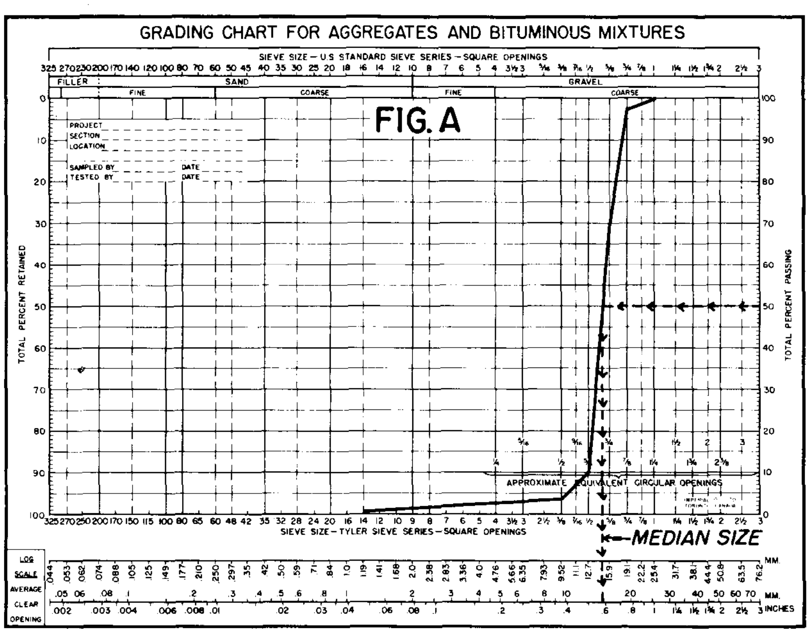

Fig. A. Grading Chart for Aggregates and Bituminous Mixtures.

MEDIAN SIZE:

The Median Size is that theoretical sieve size in inches through which 50% of the material will pass.

The Median Size may be read off from the scale at the bottom of Figure A.

PART 2

FLAKINESS INDEX

SAMPLE:

The material employed in this test shall consist of all aggregate used in the sieve analysis that falls within the size ranges specified below.

ONE-SIZE AGGREGATES

Table A-2. One-Size Aggregates

Size Number*	Nominal Range of Sizes U.S. Standard Sieves Square Openings		All Material Larger Than
	Passing	Retained	
E	3/4 inch	1/2 inch	1/2 inch
F	5/8 "	3/8 "	3/8 "
G	1/2 "	3/8 "	3/8 "
H	3/8 "	1/4 "	1/4 "

*Country Roads Board Size Designation

GRADED AGGREGATES

Table A-3. Graded Aggregates

Size Number*	Nominal Range of Sizes U.S. Standard Sieves Square Openings		Material			Material			Material	
	Passing	Retained	Pass.	Ret.		Pass.	Ret.		Pass.	Ret.
5	1 inch	1/2 inch	1"	3/4"	and	3/4"	1/2"		-	-
6	3/4 "	3/8 "	3/4"	1/2"	"	1/2"	3/8"		-	-
7	1/2 "	No. 4	1/2"	3/8"	"	3/8"	1/4"		-	-
8	3/8 "	No. 8	3/8"	1/4"	"	1/4"	No.4		-	-
56	1 "	3/8 inch	1"	3/4"	"	3/4"	1/2"		-	-
67	3/4 "	No. 4	3/4"	1/2"	"	1/2"	3/8"	and	3/8"	1/4"
68	3/4 "	No. 8	3/4"	1/2"	"	1/2"	3/8"	"	3/8"	1/4"
78	1/2 "	No. 8	1/2"	3/8"	"	3/8"	1/4"	"	1/4"	No.4

*A.S.T.M. Designation: D448
AASHO Designation: M 43

METHOD:

Each fraction of material, as shown in the previous paragraph, shall be tested particle by particle for its ability to pass through an appropriate slotted sieve[3]

[3] See British Standards Institution 812.

Table A-4.

Size of Material Passing	Retained	Slot Width Inch	Approximate Width of Slotted Sieves Issued Inch
1-1/2"	1"	0.750	0.757
1"	3/4"	0.525	0.532
3/4"	1/2"	0.375	0.384
1/2"	3/8"	0.263	0.258
3/8"	1/4"	0.184	0.184
1/4"	No. 4	0.131	0.123

(or a gauge made by filing an elongated slot of the required width in a sheet of metal 1/16" thick). The size of slots required for each fraction is given in Table A-4 and illustrated in Figure B.

WEIGHING:

The total amount passing the appropriate slotted sieve openings shall be weighed to an accuracy of at least 0.1 per cent of the weight of the test sample.

FLAKINESS INDEX:

The Flakiness Index is the total weight of the material passing the appropriate slotted sieve openings expressed as a percentage of the combined weight of the fractions tested on the slotted sieve.

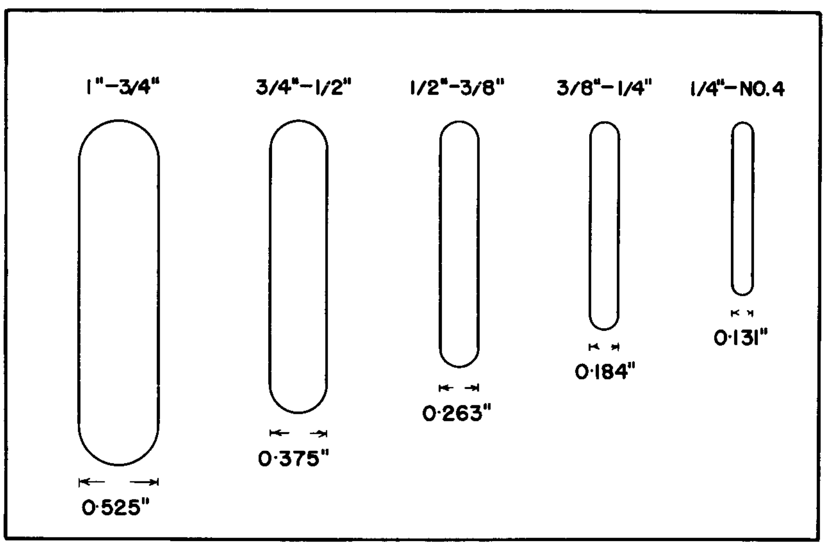

Fig. B. Slotted Sieve Openings for Testing Aggregates for Elongated Flat Particles.

EXAMPLE

(a) SIEVE ANALYSIS

The Material is One-Size Aggregate "E".
From the Grading Curve, Figure A, the *Median Size* is *0.58* inch.

Table A-5. Full Grading
(Total Weight of Dry Sample = 6,600 grams)

Sieve No. U.S. Standard Square Opening	Weight Retained Grams	Weight Passing Grams	Total Passing Per Cent
1"	-	6600	100
3/4"	60	6540	99.1
1/2"	4984	1556	23.6
3/8"	1418	138	2.1
1/4"	96	42	0.6
No. 4	4	38	0.5

The Material is One-Size Aggregate "E".

From the Grading Curve, Figure A, the Median Size is 0.58 inch.

(b) FLAKINESS INDEX

Table A-6. Flakiness Index

Sieve Size U.S. Standard Square Opening Inch	Width of Slotted Sieve Inch	Weight Retained Slotted Sieve Grams	Weight Passing Slotted Sieve Grams	Total Weight Grams	Flakiness Index Per Cent
1 - 3/4	0.525	50	10	60	
3/4 - 1/2	0.375	3666	1318	4984	
Total		3716	1328	5044	26.3

Note: Where there is an insignificant amount of material (not more than 5%) of any one size, it may be neglected in determination of Flakiness Index. Material 1" - 3/4" could be neglected in above Flakiness Index test and the result would not be appreciably changed.

(c) AVERAGE LEAST DIMENSION

On Figure C, proceed horizontally from the median size on the vertical axis to the diagonal line representing the flakiness index for the sample. From this point of intersection, proceed vertically to the horizontal axis and read off the Average Least Dimension.

For this particular aggregate sample, the median size is 0.58 inch, and the flakiness index is 26 per cent. The broken line on Figure C indicates that the Average Least Dimension (A.L.D.) of this sample is 0.40 inch (reading to the nearest 0.01 inch).

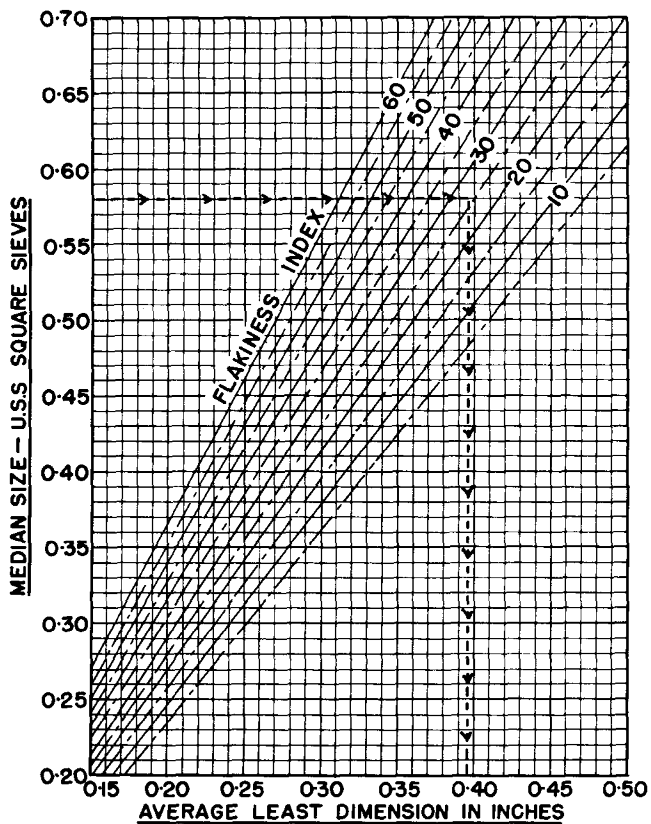

Fig. C. Determination of Average Least Dimension of Cover Aggregate.

Discussion

MR. C. W. CHAFFIN (Prepared Discussion): I congratulate Dr. McLeod on this very excellent paper of such a practical and immediately useful nature. Most of us are aware of the extensive study on this subject started by the author over a decade ago and summarized in the 1960 Proceedings supplement. This presentation today is a very fitting culmination to this work. It gives a design and construction procedure for seal coats and surface treatments which embodies the best ideas from the several previously published methods, as well as significant contributions from the author.

This type construction is certainly important in Texas. In fact, over 90% of our approximately 37,000 miles of secondary roads (Farm to Market and Ranch to Market) system is of the surface treatment type. In addition, several thousand miles of our primary system is also surface treatment. Then each year several hundred miles of seal coat is placed not only on original surface treatments, but on many miles of asphaltic concrete, even on the Interstate system.

The method of design presented here today is worthy of serious study by all who do this type of work, and it is recommended that it be adapted to your local conditions without delay.

Now an observation or two based on our Texas experience. The author calls our attention to the advantages of precoated aggregate. We certainly agree to this for crushed limestone cover material. It is used almost entirely for seal coats on our primary highways. We use a little heavier material (higher asphalt content) than the MC-30 or MC-70 mentioned in the paper. Texas has a special precoat material, but it is very close to MC-250, the main difference is that it has a little less volatile diluent in it. This material makes a precoated limestone aggregate that will stockpile satisfactorily for several months.

The prevention of windshield damage due to flying aggregate depends entirely on bonding almost every particle in the case of conventional large aggregate. We have found that lightweight or synthetic aggregate completely eliminates this problem. This aggregate also adheres excellently to the binder and has maintained superior skid resistance. It is now being used extensively for seal coats on our primary system.

The paper suggests that a seal coat may have better chance of success in cooler weather if a portion of the asphalt binder is placed in two applications but the last application necessarily being followed by application of sand or stone screenings. The author cautions that this is a special case of a double seal. It is agreed that a double has somewhat a better chance of success under adverse conditions, but a caution is offered in that one be sure to note that the author states that this type design is covered under the multiple course procedure. If you merely apply the asphalt for a single surface design in two applications, followed by an application of sand or fine stone screenings, this finer material will fill the voids and flush out the asphalt.

Dr. McLeod's design takes in consideration the condition of the old surface to be sealed. The problem often is one of non-uniformity of the old surface and here is an additional suggestion for your consideration. Generally the old surface in case of a surface treatment will be smoother in the wheel paths while it will be dry next to the center line and along the edges, unless it is a very narrow highway. Since this pattern usually is uniform in the longitudinal direction, it can be taken into account by using smaller nozzles over the smoother wheel paths and larger nozzles along the center and edge. You may even wish to try such an adjustment on the original construction of a surface treatment.

Again, this paper presented today is extremely useful and it is predicted that its principles will become a manual of seal coat and surface treatment design for many.

MR. A. E. HOLBERG (Prepared Discussion): I wish to compliment you, Dr. McLeod on your detailed and well prepared presentation. I had an opportunity to review your paper briefly prior to your presentation and also like to extend my compliments to Mr. Perkins for the drafting of the excellent diagrams.

May I very briefly review the situation in Canada. Most Provinces use predominantly Emulsified Asphalt for Seal Coats and Surface Treatments and there is a pronounced trend toward the use of Cationic Emulsified Asphalt, designated CRS in the United States and RSK in Canada. In some parts of Canada we have consistently successful seal coats and in other parts occasionally Surface Treatments and Seal Coats produced have performed poorly. When one examines success and failures, one recognizes the importance of good workmanship, equipment and proper selection of aggregates and binder versus lack of control and poor supervision.

Most engineers involved with Surface Treatments and Seal Coats are familiar with the basic design principles that are employed by the Country Roads Board of Victoria and the National Roads Board of New Zealand and some of these principles have been included in local design methods. Projects concerned are considerable in some Provinces. The Highways Department in Alberta maintains a special work crew and every new highway in the Province is Seal Coated and up to 12 miles of 24' pavement are Seal Coated within a 10 hour day and the distributor is being re-loaded while in continuous spraying. The Department of Highways in British Columbia kept records on Seal Coat and Surface Treatment work back to the year 1954 and detailed data since 1958. The same Department published a report September 1967 which draws the conclusion that Seal Coats with Emulsified Asphalt over a period of up to 8 years are performing well with a minimum of maintenance and that on some Seal Coated sections on the Trans-Canada Highway close to 5 million vehicles have travelled during the period concerned. The conclusion in the report reads:

> "Some excellent sealcoats have been constructed in this Province using Emulsified Asphalts and it would appear from the results of its use in recent years that the emulsion has a definite place in our sealcoat work. Preference is shown towards the Cationic Emulsion as it is not so slow in breaking or setting up as the Anionic which with our undependable weather becomes a great asset. Stripping tests carried our in our Laboratories indicated that it has superior coating qualities on many of our aggregates."

It seems to me, that engineers from Australia or New Zealand would find it most interesting to study Canadian experience with Emulsified Asphalts. As you well know, Cationic Emulsified Asphalts have not been available in Australia and New Zealand for any length of time, while we in Canada use them extensively for Seal Coat and Surface Treatment work since 1959. I am in full agreement with you, that the method of design that is employed by the Country Roads Board of Victoria and the National Roads Board of New Zealand is most valuable but it is based on many years of field experience using liquid asphalts (cutbacks). To my knowledge Cationic Emulsified Asphalts as we use them have not been involved in these studies. It seems to me therefore, that the audience and the reader of your paper should be aware, that the application of the Australian/New Zealand design method to Emulsified Asphalts is your very own recommendation. Some of these recommendations may be applicable but at this time we have in my opinion not sufficient field data to confirm or deny the general method of design as proposed by you and applicable to Emulsified Asphalt.

MR. C. F. PARKER: I would also like to congratulate Dr. McLeod on this fine paper. I have heard him present many papers over the past 20 years and they have all been excellent.

I do have one question. He has given us very little information on the quality of the aggregate used in these seal coats, specific gravity, absorption, wear tests, and so on. What is the quality of these aggregates?

DR. MCLEOD: With respect to cover aggregates, New Zealand has probably the finest cover stone available throughout the country of any nation in the world. New Zealand specifies a maximum Los Angeles abrasion rating of 20 for cover stone. In Australia, the maximum Los Angeles abrasion ratings specified are 18 for a traffic volume of at least 1500 vehicles per day, 27 for traffic volumes between 300 and 1500 vehicles per day, and 35 for traffic volumes below 300 vehicles per day.

Concerning particle shape, New Zealand has the most restrictive specification of any country. New Zealand specifies a maximum of 2.25 for the ratio of the average greatest dimension to the average least dimension of a cover aggregate. This ensures particles that are more nearly cubical or tetrahedral in shape. While the specification says nothing about the crushing method to be used, New Zealand contractors have found by experience that this requirement for particle shape normally means that cover aggregates for seal coats and surface treatments must be crushed in a hammer mill or impact breaker. This type of crushing equipment seems to result in particles that are more nearly cubical in shape.

In Australia, particle shape for cover aggregate is controlled by a flakiness index test, which is a British Standards Institution test, B.S. 812. Very roughly, the flakiness index test measures the degree by which particles fail to be perfect cubes, because of flattening of the particles. Australia specifies a maximum flakiness index requirement of 35.

With regard to grading, Australia obtains essentially one-size cover stone by specifying that at least two-thirds by weight of the aggregate passing a sieve of specified size must be retained on a sieve opening that is seven-tenths of the specified size. New Zealand obtains basically one-size aggregate by specifying that a minimum high percentage (ranging from 65 to 80 per cent as the specified size of cover stone becomes smaller) of the aggregate must lie within 0.1 inch from the aggregate's Average Least Dimension.

New Zealand restricts the amount of fine particles by specifying that not more than one (1) per cent of a seal coat or surface treatment aggregate can pass a No. 8 sieve. Australia achieves the same objective by permitting not more than 0.5 per cent to pass the No. 16 sieve.

MR. V. OBRCIAN: I noticed on the occasion of my trip to Nigeria that they use two cover aggregates. Is this something that we would have to take into account for obtaining the average dimension that you mentioned?

DR. MCLEOD: I have seen the surface treatments in Nigeria to which you refer. When designing a surface treatment or seal coat, three items of information on the cover aggregate should be obtained. First, its Average Least Dimension should be determined. This requires use of the Flakiness Index Test. Second, the loose weight of the cover aggregate in pounds per cubic foot or in kilograms per litre should be measured by means of ASTM C 29. Third, the ASTM bulk specific gravity of the cover stone should be determined. From these three items of data, the average thickness of a surface treatment or seal coat, and the void space between the cover aggregate particles are determined. This information is needed in order to calculate the quantities of asphalt binder and of cover stone that are required per unit of area.

In many countries, it is difficult to obtain one-size cover stone. While surface treatments and seal coats can be constructed with graded cover aggregates, the degree of success achieved is normally going to be limited, particularly if these aggregates contain excessive fines.

MR. OBRCIAN: I am sorry if I confused you. They do not use the graded aggregate. They use a one size type aggregate.

MR. J. M. EDWARDS: I would like to support Dr. McLeod's reference to the fact that a very large percentage of the world's roads are maintained by surface treatments. I certainly also have to support his approach to the design of such treatments. There is, however, one factor which I think is important but which was not covered in his presentation although it may have been referred to in the written paper. It is also relevant to the question about the use of rounded aggregates. This factor is that chippings become embedded into the existing surface whether this is gravel or bituminous. The degree of embedment affects the total amount of asphalt that should be sprayed. In the case of a rounded cover aggregate there is little embedment and the quantity of asphalt required is high, whereas in the case of crushed cover stone there is more embedment and less asphalt is required to prevent flushing.

DR. MCLEOD: The point you make is a very important one. If the cover aggregate is going to be forced part way into the existing surface, this in effect reduces the Average Least Dimension of the cover aggregate particles. This in turn means that there is less void space for asphalt binder. Consequently, the quantity of asphalt binder to be applied should be reduced, otherwise as Mr. Edwards has stated, flushing or bleeding will occur.

In cases where this partial penetration of cover aggregate into an existing surface is likely to occur, the quantity of asphalt binder to be applied should be based on the *effective* Average Least Dimension of the cover stone, which is its Average Least Dimension minus its anticipated depth of partial penetration into the existing surface.

MR. W. H. CAMPEN: Dr. McLeod, the type of surface treatment we have been talking about at times is designated as of two types, seal coats and armor coats. What distinction do you make between the two, if you make any at all?

DR. MCLEOD: The paper defines only two types, which however are intended to cover the many different names that are currently given to this class of asphalt surface. If this type of asphalt surface construction is applied over a consolidated gravel or similar base it is called a single or multiple surface treatment. If it is applied to a paved surface of any kind, it is referred to as a single or multiple seal coat. Consequently, the term "armor coat" and similar designations would be covered by one or the other of these two definitions.

MR. W. J. KARI (by letter): It has been suggested that the rate of application of emulsions for surface treatments be increased over that used for asphalt cement. The theory is that the total asphalt content for both emulsion surface treatments and for those using asphalt cements should be the same. The purpose of this discussion is to present another approach to the design and construction of emulsion surface treatments, one which holds that the rate of application should be the same, on a gallon-for-gallon basis, as that used with asphalt cement.

In emulsion surface treatments, the water in the emulsion has three major functions: lowers application viscosity so the emulsion can be applied at a lower temperature than the asphalt cement from which it was made, serves as a carrier for adhesion agents to insure a good bond between asphalt, pavement, and aggregate, and to effect a volume change (or "film collapse") to insure bond yet minimize subsequent bleeding. This volume change, illustrated in Figure A, permits use of emulsions at the same application rate as asphalt cement. The emulsion level immediately after application of the aggregate is high on the stone. When the emulsion sets, there is a 30 to 35 per cent volume reduction due to evaporation of water. The film collapses due to this volume change. The asphalt film forms a saddle, i.e., remains high on the stone and low in the spaces between the aggregate. This insures a high surface contact area between the asphalt and stone to prevent aggregate whip-off by traffic. Also, the amount of asphalt in the spaces between the stones is kept low to prevent bleeding should the aggregate embed into the pavement due to heavy traffic or show wear due to use of tire chains or studded tires during winter.

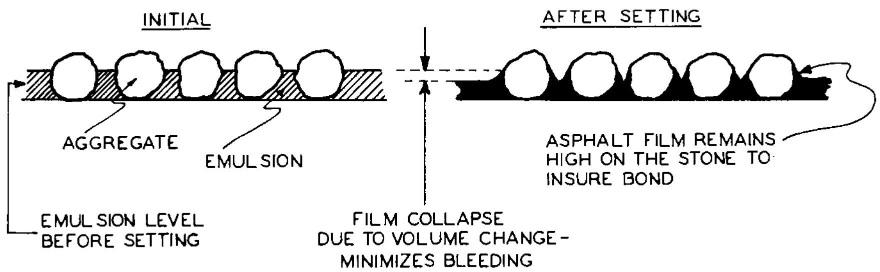

Fig. A. Emulsified Asphalt Seal Coat.

To make maximum use of the volume change, the following construction practices should be followed for emulsion surface treatments:

1. Apply the emulsion at the same rate of application as you would use with penetration grade paving asphalt. If the emulsion content is increased, the benefits of film collapse are lost.
2. Apply damp aggregate as soon as possible. This insures maximum embedment of rock into the emulsion.
3. Roll with a pneumatic roller as soon as possible. This permits the stone particles to orient to their most stable position while the emulsion is still at a fluid viscosity.
4. Avoid use of excess aggregate. This is not needed to blot up excess binder as with other types of surface treatments. The emulsion volume change minimizes bleeding.

AUTHOR'S CLOSURE: The author would like to thank Mr. Holberg for his instructive comments, and Mr.. Chaffin for his useful and generous remarks.

Mr. Holberg has referred to the very extensive use of cutback asphalts and asphalt cements in Australia and New Zealand for surface treatments and seal coats, relative to the wide use of asphalt emulsions in Canada for this purpose. In reply, it might be pointed out that asphalt emulsions are manufactured in New Zealand and Australia, and that serious efforts have been made to have asphalt emulsions adopted for surface treatments and seal coats. Consequently, Australia and New Zealand are quite familiar with both anionic and cationic asphalt emulsions, and some asphalt emulsion is used for surface treatment and seal coat construction. However, it would appear that as a result of many years of experience with each of these types of binders, asphalt cements and cutback asphalts are so firmly established as binders for surface treatments and seal coats, that Australia and New Zealand seem unlikely to change over to asphalt emulsions in any major way, at least in the immediate future.

Mr. Holberg has stated that the method of design suggested in the paper is my own recommendation. This is only partly correct, for the method of design recommended is largely a modification of the design method that has been used with such outstanding success for many years in Australia and New Zealand, to make it applicable to the conditions that exist in North America and in many other parts of the world. Both New Zealand and Australia have for many years insisted on the use of cover stone that is much more nearly one-size than is ordinarily available in North America and other countries where only graded cover aggregates can usually be obtained. As shown in the paper, the ultimate voids between the aggregate particles in a surface treatment or seal coat made with a graded cover aggregate are normally much less than are assumed in Australia when one-size cover aggregate is employed. Consequently, for surface treatments and seal coats to be made with graded cover aggregates, it has been necessary to develop the modified design equations (5) and (6) for the required quantities of cover aggregate and asphalt binder per unit area. As indicated in the paper itself, these equations are of general application, and can be applied even when one-size cover stone is employed, since one-size cover stone is only a special case of cover aggregates in general. It has been shown in the paper, that for the one-size cover stone and design assumptions employed in Australia, that the general design equations (5) and (6) revert to equations (3) and (4) which represent Australian design. Consequently, the general design equations (5) and (6) recommended in the paper, make it possible to apply the Australian principles of design to surface treatments and seal coats that are to be made with either graded or one-size cover aggregates.

Reading between the lines of the last paragraph of Mr. Holberg's prepared discussion, I would gather that he questions the use of the same equations to design surface treatments or seal coats with asphalt cements, cutback asphalts, or asphalt emulsions. During the past 15 years I have examined many surface treatments made with asphalt emulsions, cutback asphalts, and asphalt cements. In every case, when the surface treatment or seal coat has been providing satisfactory service for several years, the cover aggregate particles have been embedded in asphalt binder to from approximately two-thirds to three-quarters of their depth. Consequently, in my opinion at least, whether a seal coat or surface treatment is to be constructed with asphalt cement, asphalt emulsion, or cutback asphalt, *the same amount of residual asphalt* must be provided. Equations [4], [6], and [8] recognize this principle.

In his paper published nearly 35 years ago, Hanson referred to a rule of thumb often cited in connection with the quantity of asphalt emulsion to be applied per unit area for a surface treatment or seal coat, namely, apply asphalt emulsion at the same rate per unit area as asphalt cements or cutback asphalts. Hanson commented in effect, that this rate of application was often satisfactory for asphalt emulsions only because far too much asphalt cement or cutback asphalt was normally applied, with resulting flushing or bleeding.

As pointed out in the paper itself, the need for basing the design of seal coats and surface treatments *on the quantity of residual asphalt required,* appears to have been clearly recognized by many organizations and individuals including the British Road Research Laboratory, Country Roads Board, Idaho Department of Highways, Utah Department of Highways, Kerr, Hanson, Tagle, Nevitt, Kearby, Winnitoy, and Benson. When surface treatments and seal coats are designed on the basis of the *same residual asphalt requirement*, because of the current composition of asphalt binders, this will always require the application of more finished asphalt emulsion in gallons per unit area, than of cutback asphalt or asphalt cement.

The information contained in Mr. Chaffin's prepared discussion, which is based on the very extensive experience of the Texas Highway Department with surface treatments and seal coats, provides a highly useful addition to the paper itself. Mr. Chaffin's reference to precoated cover aggregate for improved adhesion, and to the use of lightweight cover aggregate to avoid windshield damage from flying cover aggregate particles, should be particularly noted.

The suggestion in the paper, that consideration should be given to splitting the asphalt binder application for even single surface treatments or seal coats into two applications, with the second application being covered with the minimum amount of clean coarse sand to avoid pick-up by traffic, was prompted by two observations:

(a) the serious damage to motor vehicles that can result from flying cover stone particles during the first few days after a new single seal coat or surface treatment is opened to traffic.

(b) the complete loss of cover aggregate that frequently occurs from the portions of a seal coat along the outside edges, and sometimes from the centre of the pavement, which are areas that ordinarily receive little traffic, and the cover aggregate is therefore often poorly embedded in asphalt binder.

By splitting the bitumen requirement into two applications, the second application being applied over the layer of cover stone, the cover stone particles would be firmly bonded to the surface. This would avoid motor vehicle damage due to flying particles, and loss of cover stone from the outside edge and centre of the pavement. The second application of asphalt binder would of course have to be followed by an application of clean coarse sand, and rolling, in order to carry traffic.

Mr. Chaffin points out that the coarse sand used for the second application might tend to fill the voids and cause flushing or bleeding. On the other hand, for double surface treatments, the Country Roads Board of Victoria, Australia, indicates that clean coarse sand all passing 1/8 inch can be used as cover aggregate for the second layer of a double surface treatment when the cover stone employed for the first layer is 1/2 inch or larger. Consequently, provided the amount of clean coarse sand that is applied for the second application is held to a minimum that will avoid pick-up by traffic, it should not result in flushing or bleeding. The problems presented by current single seal coat construction are so serious, particularly vehicle damage due to flying particles, that some modification of present construction practice is necessary, if single seal coats are to be considered for heavily travelled pavements. However, we are in agreement with Mr. Chaffin that in this case, it would be highly preferable to employ the standard design procedure for a double surface treatment.

Dr. McLeod's (concluding final comment): With respect to Mr. Kari's prepared discussion I would like to make the following comments: The attached Figure B leads to a quite different conclusion than that illustrated in Mr. Kari's Figure A. Mr. Kari's Figure A appears to assume that no difference in the void space in the cover aggregate occurs between the end of rolling, and after the reorientation of the cover aggregate particles into their final position as a result of a considerable volume of traffic. It was one of Hanson's principle conclusions more than 35 years ago (6), that at the end of the rolling operation the void space between the aggregate particles is approximately 30 per cent, and that this void space eventually closes up to about 20 per cent after considerable traffic. The service performance of seal coats and surface treatments verifies this at least in principle. Figure B (1) illustrates the 30 per cent voids after rolling, and Figure B (2) the 20 per cent of cover aggregate voids after substantial traffic.

Figure B (1) demonstrates that the height of the *residual* asphalt, "b", immediately after rolling (30 per cent voids) is just 2/3 of its height "a", after considerable traffic (20 per cent voids), Figure B (2). A cationic asphalt emulsion consists of approximately 2/3 asphalt and 1/3 water, and this is also true of RS 2 anionic emulsions, Table VI.

Consequently, if the original asphalt emulsion contains 1/3 water, *the height of the originial emulsion* at the end of the rolling operation will be at level "a" in Figure B (1). However, because of the decrease in aggregate voids from 30 per cent to 20 per cent resulting from several weeks of warm weather traffic, and assuming that the emulsion has lost its water during this time, at the end of this period of traffic, as illustrated by Figure B (2), the height of the *residual* asphalt will have risen from level "b" to level "a", and there will be no meniscus. That is, the height of the *residual* asphalt after substantial traffic, level "a", is the same as the height of the original *asphalt emulsion* at the conclusion of rolling, level "a". Therefore, the meniscus situation illustrated in Mr. Kari's Figure A could at best be of only brief temporary duration, depending upon the relative speeds at which the emulsion loses water,

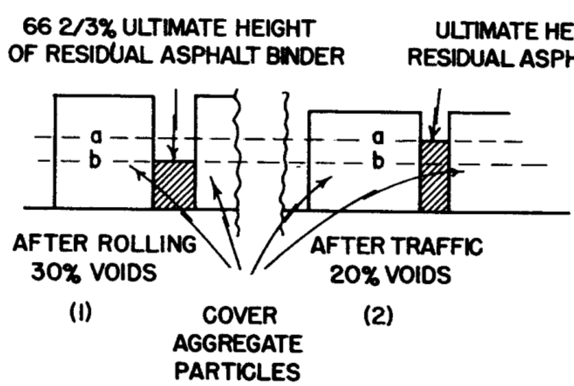

Fig. B. Illustrating Behaviour of Asphalt Emulsions in Seal Coats or Surface Treatments.

and at which the voids in the cover aggregate close up under traffic from about 30 per cent when rolling is complete, to their final value of approximately 20 per cent. However, the principal point that is emphasized by Figure B, is that the same amount of residual asphalt is required for a seal coat or surface treatment, regardless of whether the original asphalt binder is an asphalt emulsion, a liquid asphalt, or an asphalt cement.