Reevaluation of Seal Coating Practices in Minnesota

David W. Janisch, *Minnesota Department of Transportation*

Seal coating of bituminous pavements, referred to as chip sealing in this paper, is a common type of routine maintenance done by local government agencies in Minnesota. Most cities, counties, and rural Minnesota Department of Transportation (Mn/DOT) districts construct at least some seal coats annually. Over the years, Mn/DOT has received calls from local agencies concerned about poorly performing seal coats. This, along with recent developments from the Strategic Highway Research Program (SHRP), led to the development of a seal coat research study. The goal of this study is to find the factors involved in constructing a quality seal coat, including examining the current Mn/DOT specifications and studying the performance of seal coats designed using the procedure found in the Asphalt Institute's asphalt emulsion manual (MS-19), which was used by SHRP. In all, eight local agencies participated in this study: five municipalities and three counties. The test sections were constructed during the summer and fall of 1993. Experiment variables include application rate, sweeping time, aggregate type, and gradation and binder type. These sections will be monitored over the next several years to evaluate their performance. This paper presents an overview of the study, examines the preliminary data, and summarizes the findings. This study will likely lead to changes in the current Mn/DOT bituminous seal coat specification.

The Minnesota Department of Transportation (Mn/DOT) specification for bituminous seal coating (Specification 2356) is found in the 1988 edition of *Standard Specifications for Construction* (*1*). It states that the aggregate shall be spread "at the rate of one pound per square yard for each 0.01 gallon of bituminous material applied" (13.1 kg/m^2 for each liter of bituminous material). This aggregate application rate has been contained in every edition of the standard specifications since 1959. The amount of bituminous material required is outlined in the Mn/DOT *Bituminous Manual* (*2*) and is based on the average particle diameter of the aggregate. The specification does not adjust the application rate to account for the gradation, shape, or specific gravity of the aggregate. Further compounding the problem is the fact that many agencies skip the design procedure altogether and simply assume application rates based on the specified aggregate size and experience.

In contrast, recent chip seals constructed by SHRP (*3*) required the use of the design procedure contained in the Asphalt Institute's MS-19, 1979 edition (*4*). This design procedure was developed by McLeod in the 1960s. It is outlined in proceedings from the 1960 and 1969 annual meetings of the Association of Asphalt Paving Technologists (*5,6*). This procedure is called the McLeod procedure for the remainder of this paper.

Over 160 km (100 mi) of pavement was chip-sealed as part of this study. Five agencies constructed chip seals using both their standard application rates and application rates determined by the McLeod procedure. Test sections were also constructed using various aggregates (granite, trap rock, limestone, pea rock), binders (CRS-2, CRS-2P, HFMS-2, RC 800), construction techniques (standard seal and choke seal), and curing times (early and late sweeping).

Mn/DOT Design Procedure

The Mn/DOT design procedure is based on a measurement termed the average particle diameter (APD), sometimes called the spread modulus. The APD provides a measure of the average seal coat thickness. It is defined as the weighted average of the mean size in millimeters of the largest 20 percent, the middle 60 percent, and the smallest 20 percent of the aggregate particles. The mean size is determined by projecting a vertical line from the 10 percent, 50 percent, and 90 percent passing line. The APD is then determined using the following equation:

$$\begin{aligned} APD &= (0.20)(90\% \text{ passing size}) \\ &\quad + (0.60)(50\% \text{ passing size}) \\ &\quad + (0.20)(10\% \text{ passing size}) \end{aligned} \tag{1}$$

Once the APD is known, the binder application rate is determined by using one of the following equations:

For cutbacks and asphalt emulsions:

$$\text{Binder application rate} = \begin{cases} (\mathrm{L/m^2}) \\ (\mathrm{gal/yd^2}) \end{cases} = \begin{cases} (0.177)(APD, \text{ mm}) \\ (1.0)(APD, \text{ in.}) \end{cases} \tag{2}$$

For asphalt cements:

$$\text{Binder application rate} = \begin{cases} (\mathrm{L/m^2}) \\ (\mathrm{gal/yd^2}) \end{cases} = \begin{cases} (0.124)(APD, \text{ mm}) \\ (0.7)(APD, \text{ in.}) \end{cases} \tag{3}$$

For example, suppose we are using an aggregate that has the gradation shown in Figure 1. The mean sizes of the largest 20 percent, middle 60 percent and smallest 20 percent are 9.0 mm (0.354 in.), 6.3 mm (0.248 in.), and 3.5 mm (0.138 in.), respectively. From Equation 1,

$$\begin{aligned} APD &= (0.20)(9.0 \text{ mm}) + (0.60)(6.3 \text{ mm}) \\ &\quad + (0.20)(3.5 \text{ mm}) = 6.28 \text{ mm } (0.247 \text{ in.}) \end{aligned} \tag{4}$$

Assuming that an asphalt emulsion is to be used, the binder application rate is determined using Equation 2:

$$\text{Binder application rate} = \begin{cases} (0.177)(6.28 \text{ mm}) \\ (1.0)(0.247 \text{ in.}) \end{cases} = \begin{cases} 1.11\mathrm{L/m^2} \\ 0.247(0.25) \text{ gal/yd}^2 \end{cases} \tag{5}$$

As mentioned earlier, Mn/DOT specifications state that the aggregate shall be spread at the rate of 1 lb/yd^2 for each 0.01 gal of bituminous material applied (13.1 kg/m^2 for each liter of bituminous material). This results in the following aggregate application rates:

Aggregate application rate =

$$\begin{cases} (1.11 \text{ L/m}^2) \times \left(\dfrac{13.1 \text{ kg/m}^2}{1 \text{ L/m}^2}\right) = 14.5 \text{ kg/m}^2 \\[2ex] (0.25 \text{ gal/yd}^2) \times \left(\dfrac{1 \text{ lb/yd}^2}{0.01 \text{ gal/yd}^2}\right) = 25 \text{ lb/yd}^2 \end{cases} \tag{6}$$

McLeod Design Procedure

The McLeod procedure also determines the aggregate and binder application rates. Aggregate application rates depend on gradation, shape (measured by the flakiness index), and specific gravity. Binder application rates depend on the aggregate gradation and shape, traffic volume, existing pavement condition, and binder properties. The procedure is based on the following factors:

1. There is a certain amount of a given aggregate that can be spread one stone thick over 1 m^2 of pavement.
2. The voids in this aggregate layer need to be 70 percent filled with asphalt binder for good performance.

Some key components of the design procedure are

- Loose unit weight of the cover aggregate,
- Voids in the cover aggregate in a loose condition,
- Flakiness index,
- Mean aggregate size, and
- Average least dimension.

The loose unit weight of the cover aggregate is determined according to ASTM C 29 and is needed to calculate the voids in the aggregate in a loose condition. There was a wide range of loose unit weights for the samples from this study due to the different gradations and aggregate types. Average loose unit weights were

90, 95, and 100 lb/ft^3 for granite, trap rock, and pea rock, respectively. The loose unit weight depends more on the gradation of the aggregate than it does on specific gravity.

The voids in the cover aggregate in a loose condition approximates the voids present when the chips are dropped from the spreader onto the pavement. This value will be near 50 percent for a one-sized aggregate (4), less for graded aggregate. The voids in the samples from this study averaged 45 percent and ranged from 37 to 50 percent. After initial rolling, the voids are assumed to be reduced to 30 percent, and finally to 20 percent after sufficient traffic has oriented the stones on their flattest side.

The flakiness index is a measure of the percentage by weight of flat particles. It involves testing a small sample of aggregate particles for their ability to fit through a slotted plate. They will fit through the plate if they have a flat side smaller than 70 percent of the sieve opening on which they were retained. For example, any chip retained on the 12.5-mm (0.5-in.) sieve that has a flat side thinner than 8.75 mm (0.35 in.) will pass through the plate opening. The plate contains slots for material retained on the 19.0, 12.5, 9.5, 6.3, and 4.75 mm (3/4 in., 1/2 in., 3/8 in., 1/4 in., and No. 4) sieves.

The median aggregate size is determined from the gradation chart. It is the theoretical sieve size through which 50 percent of the material passes. The median aggregate size represents the mean thickness of the seal coat and is found by projecting a vertical line at the 50 percent passing size (see Figure 1).

The average least dimension is determined from the median aggregate size and the flakiness index. It is a reduction of the median aggregate size after accounting for flat particles.

Samples of the aggregate and binder were submitted to Mn/DOT's Materials Research and Engineering Laboratory for testing. The aggregates were tested for gradation, bulk specific gravity, loose unit weight, and flakiness index determination. The binder was tested for compliance with specifications and determination of the residual asphalt content.

The aggregate application rate (C) is determined from the following equations:

$$C = \begin{cases} (1 - 0.4V)HGE \\ 46.8(1-0.4V)HGE \end{cases} \tag{7}$$

where

C = cover aggregate application rate (kg/m^2) (lb/yd^2),
V = voids in the loose aggregate, in percentage expressed as a decimal:

$$V = \begin{cases} 1 - \dfrac{W}{1000G} \\ 1 - \dfrac{W}{62.4G} \end{cases} \tag{8}$$

H = average least dimension (mm) (in.),
G = bulk specific gravity of the aggregate,
E = wastage factor for traffic whip-off (ex: 1.10 for 10 percent wastage),
W = loose unit weight of the cover aggregate, ASTM Method C 29 (kg/m^3) (lb/ft^3).

For example, assume that the aggregate used in the previous example (Figure 1) also has the properties given in Table 1. Using these values and Equations 7 and 8, the aggregate application rate is calculated as follows:

$$C = \begin{cases} [1 - (0.4)(0.48)] \times (4.7\text{ mm}) \times (2.71) \\ \times (1.10) = 11.3\ (11\text{ kg/m}^2) \\ (46.8) \times [1 - (0.4)(0.48)] \times (0.185\text{ in.}) \\ \times (2.71) \times (1.10) = 20.8\ (21\text{ lb/yd}^2) \end{cases} \tag{9}$$

The binder application rate (B) depends not only on the properties of the aggregate mentioned above but also on the existing pavement condition, traffic volume, aggregate absorption, and residual asphalt content of

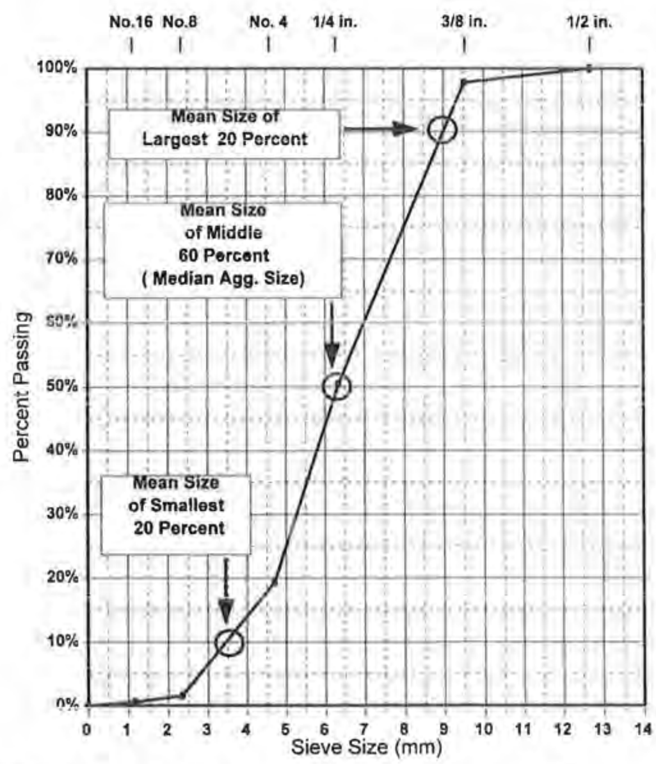

FIGURE 1 Gradation of aggregate in design example (1 mm = 0.039 in.).

TABLE 1 Input for McLeod Aggregate Application Rate Design Example

Type of Test	S.I. Metric Units
Median Particle Size	6.3 mm
Flakiness Index	20.8 percent
Average Least Dimension	4.7 mm
Loose Unit Weight of Aggregate	1,396.50 kg/m³
Voids in the Cover Aggregate	0.48
Bulk Specific Gravity	2.71
Wastage Factor Due to Traffic Whip-Off, E	1.10

1 mm = 0.039 in., 1 kg/m³ = 0.062 lb/ft³

the binder. The binder application rate is determined as follows:

$$B = \begin{cases} \dfrac{(0.40)(H)(T)(V) + S + A}{R} \\[2ex] \dfrac{(2.244)(H)(T)(V) + S + A}{R} \end{cases} \tag{10}$$

where

B = binder application rate (L/m^2) (gal/yd^2),
H = average least dimension (mm) (in.),
T = traffic factor (based on expected vehicles per day),
V = voids in the loose aggregate, in percentage expressed as a decimal (Equation 8),
S = surface condition factor (L/m^2) (gal/yd^2) (based on the "dryness" of the existing surface),
A = aggregate absorption factor (L/m^2) (gal/yd^2) (equal to zero unless aggregate is porous), and
R = residual asphalt content of binder, in percentage expressed as a decimal.

Typical values for determining the binder application rate are shown in Table 2. Using these values, the binder application rate, B, is calculated from Equation 10.

$$B = \begin{cases} \dfrac{(0.40)(4.7\text{ mm})(0.70)(0.48) + 0.27\text{ L/m}^2 + 0)}{0.67} = 1.35\text{ L/m}^2 \\[2ex] \dfrac{(2.244)(0.185\text{ in.})(0.70)(0.48) + 0.06\text{ gal/yd}^2 + 0}{0.67} = 0.30\text{ gal/yd}^2 \end{cases} \tag{11}$$

Comparison of Design Application Rates

For this example, the binder application rate is 1.11 L/m^2 (0.25 gal/yd^2) for the Mn/DOT procedure and 1.35 L/m^2 (0.30 gal/yd^2) for the McLeod procedure. The aggregate application rate is 15 kg/m^2 (25 lb/yd^2) for the Mn/DOT procedure and 11 kg/m^2 (21 lb/yd^2) for the McLeod procedure. This is the common trend found when comparing the two design procedures. Most of the time, the Mn/DOT procedure recommends more aggregate and less binder than the McLeod procedure. A comparison of the aggregate and binder application rates for all 40 samples tested is shown in Figures 2 and 3.

Problems With Current Mn/DOT Design Procedure

Several problems are believed to contribute to the poor performance of seal coats in Minnesota. Among them are the following.

- The Mn/DOT procedure recommends the same binder application rate for all emulsions and cutbacks. A typical RC-800 cutback contains 85 percent residual asphalt compared with only 67 percent for a CRS-2 emulsion. As a result, if these two binders are applied at the same rate, the emulsion will contain 21 percent less asphalt than the cutback once the cutter or water has evaporated. Since the residual asphalt bonds to the stone particles, having the binder application rate based on this residual asphalt content is vital for proper embedment of the aggregate particles.

TABLE 2 Input for McLeod Binder Application Rate Design Example

Type of Test	S.I. Metric Units
Surface Condition Factor, S	0.27 liter/m² (slightly pocked, porous and oxidized surface)
Traffic Factor, T	0.70 (500 to 1,000 vehicles per day)
Aggregate Absorption Factor, A	0.0 (disregarded except for obviously porous stone)
Residual Asphalt Content of Binder, R	0.67 (Typical value for CRS-2 in Minnesota)

1 liter/m² = 0.22 gallon/yd²

• The Mn/DOT FA-3 (AASHTO M43, Size No. 8) gradation does not require the 9.5-mm (1/4-in.) sieve. Requirements are given for the 9.5-mm (3/8-in.) and 4.75-mm (No. 4) sieves. This gap in successive sieves sizes (4.75 mm, 0.188 in.) results in large differences in material considered to be the same. For example, one sample of FA-3 material had 100 percent passing the 6.3-mm (1/4-in.) sieve, whereas another had only 30 percent passing. This large difference was not detected using the normal sieve nest and will lead to problems when agencies use the same application rates from year to year.

• The Mn/DOT procedure recommends the same amount of cover stone for all aggregate types and gradations as long as the average particle diameter is the same. This is a problem because a given mass of trap rock will not cover as large an area as the same mass of pea rock because of differences in specific gravity (2.98 for trap rock, 2.66 for pea rock).

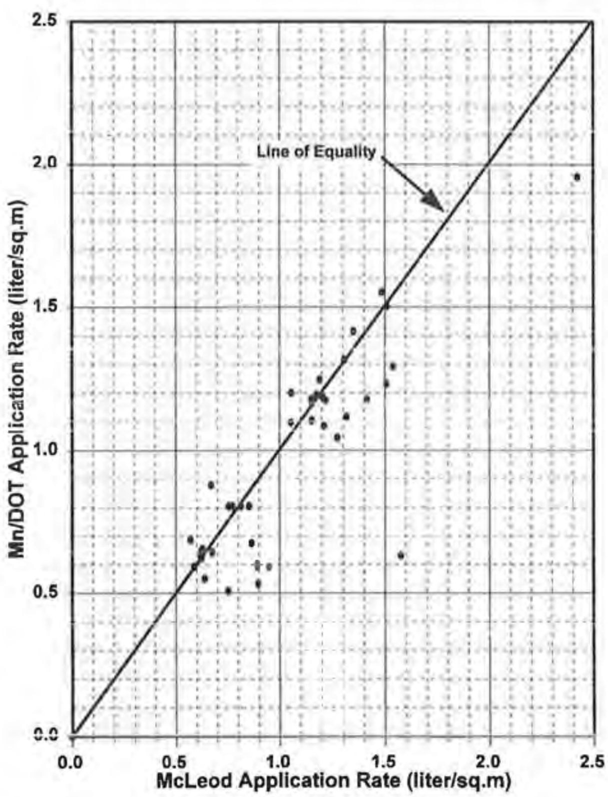

FIGURE 2 Comparison of binder design application rates (1 L/m² = 0.22 gal/yd²).

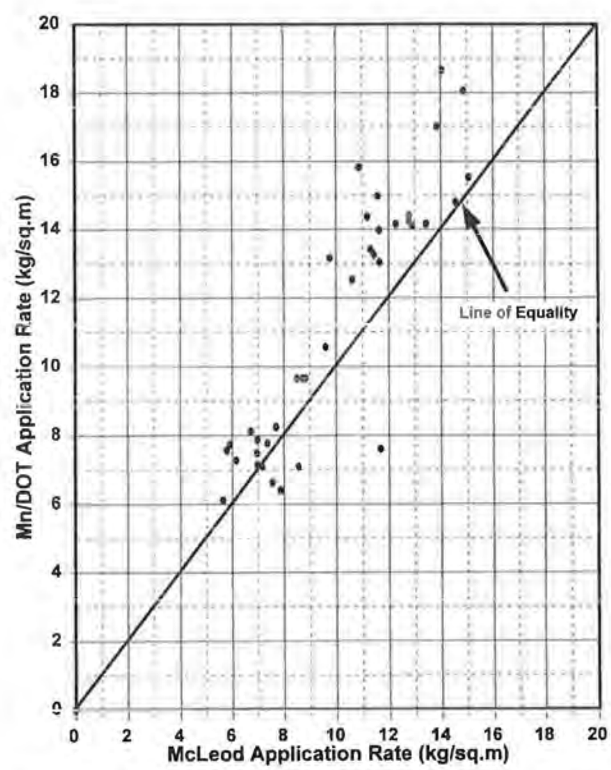

FIGURE 3 Comparison of aggregate design application rates (1 kg/m² = 1.84 lb/yd²).

• The Mn/DOT procedure makes no adjustments for one-sized aggregates. It is quite possible to have two aggregates with the same average particle diameter and very different gradations. An aggregate that is one-sized will have more void space to fill with binder than a graded aggregate.

• No adjustments are made in the Mn/DOT procedure for flat aggregate. Samples from this study ranged from a low of 9 to a high of 36 percent flat particles by weight (flakiness index). It is assumed that over time, traffic will cause the chips to lie on their flattest side. As a result, the chip seal will be thinner when using flat aggregate than it will when using cubical aggregate. To obtain the proper embedment, this thickness and its corresponding void content must be known.

• No adjustments are suggested in the Mn/DOT procedure for adjusting the binder application rate to account for traffic or surface condition other than experience.

• The Mn/DOT procedure usually results in more aggregate and less binder than the McLeod procedure. This combination has the potential for large amounts of premature aggregate loss.

• The Mn/DOT procedure usually results in seal coats with a multiple-stone thickness rather than the desired one-stone thickness. If the large amount of loose stone is not swept soon after it is placed, traffic will cause it to act like an abrasive, grinding off and/or wedging between the stones that are properly embedded. In addition, the surface often has so much loose aggregate, the rolling operation does not orient the stones on their flat side as is needed. This is because the roller is not in contact with the stones that are touching the existing road and embedded in the binder.

Observations Made During Construction

Several observations were made by the author during the construction of the chip seals sections:

• While some agencies calibrated the distributor before construction, no calibration of the aggregate application rate was being done by any of the contractors or agencies. In addition, the same application rate was being applied to all of the sections provided the weather conditions did not change. No corrections in binder application rates were made to adjust for traffic or existing pavement condition.

• The projects that used three rollers did a much better job of achieving full coverage before the emulsion "broke." When two rollers were used, they had difficulty keeping up with the distributor. Usually these rollers were exceeding the specified 8.3 km/hr (5 mi/hr). In one extreme case, the rollers were so far behind the distributor, in an attempt to catch up they were traveling close to 33 km/hr (20 mi/hr), leaving a wake of loose chips in their path.

• The bituminous distributor operator plays a vital role in the success or failure of the project. The difference between experienced and inexperienced operators was obvious. The inexperienced operators had large overlaps, long delays (particularly on culs-de-sac). Some delayed so much that the binder "broke" long before any chips were placed.

• There does not appear to be a standard way to seal-coat culs-de-sac. Nearly every agency and/or contractor sealed them differently. Some sprayed the entire cul-de-sac with binder before spreading any chips; some drove the distributor, spreader, and roller in circles; some started at the far end of the cul-de-sac, while others started at the radius.

Current Condition of Test Sections

Most of the sites were visited in February and November of 1994 to find out how well the sections held up to snowplow blades over the winter and traffic over the summer. There is little or no damage from plow blades on any of the sections to date. In addition, both the designed and undesigned sections appear to have a very high degree of chip retention despite aggregate type or size. However, the undesigned sections have a much more irregular-looking surface than the designed sections. A more in-depth condition assessment will be made in subsequent years.

Conclusion

Since the projects described in this paper were constructed in 1993, there are no long-term performance data. However, several conclusions are felt to be appropriate at this time.

• Very few of the agencies run gradations before seal-coating. As a result, no design procedure is used. Depending on the specified size (FA-3, FA-2, etc.), the binder rates are chosen based on experience. The aggregate is then applied at the specified rate of 1 lb/yd^2 for each 0.01 gallon of bituminous material applied (13.1 kg/m^2 for each liter of bituminous material). This often results in as much as 16 to 19 kg/m^2 (30 to 35 lb/yd^2) of aggregate.

• Aggregate application rates were reduced by as much as 50 percent when using the McLeod design procedure instead of the agencies' standard rate. The McLeod procedure always reduced the amount of aggregate recommended when compared to the agencies' standard.

- Usually, the Mn/DOT design procedure recommended more aggregate and less binder than the McLeod procedure.
- Sweeping time was significantly reduced when using the design application rates rather than the agencies' standard rate. This is due to the designed seal coats being only one stone thick. As a result, there is very little loose, nonembedded aggregate to sweep up.
- To date, seal coats designed using the McLeod procedures perform as well as or better than undesigned seal coats.

Recommendations

- Mn/DOT's current seal coat aggregate gradation requirements should include the 6.3-mm sieve (U.S. No. 3, 0.25 in.) in the nest to better characterize the gradation of FA-3 material. This will provide for a more uniform product from year to year.
- Aggregate samples submitted for design should be taken from several areas of the stockpile after it is on the job site rather than submitted from the source pit due to considerable variability in the material.
- Calibration of the equipment, particularly the chip spreader, is crucial, easy to do, and should be required as part of the specification. Calibration of the chip spreader should be done whenever the design application rate changes. The ASTM draft method for chip spreader calibration is recommended. This procedure involves placing 10 to 12 one-foot-wide (30.5-cm) ribbed rubber mats side by side and driving the spreader over them as it drops chips. The longitudinal spread rate is then determined by weighing the amount of aggregate retained on each mat. The transverse spread rate is determined by comparing the amount of stone on each of the mats. Adjustments are then made to the gate openings so they apply a uniform spread rate.
- Sweeping should occur as soon as possible after construction, normally the day after sealing. Leaving loose stones on the roadway is dangerous and is believed to be detrimental to seal coat life.
- The Minnesota DOT should continue to monitor the performance of these sections and modify the existing seal coat specification (2356) and *Bituminous Manual* accordingly.

References

1. *Standard Specifications for Construction.* Minnesota Department of Transportation, 1988.
2. *Bituminous Manual.* Section 5-693.600 Minnesota Department of Transportation, 1990.
3. Bullard, D. J., R. E. Smith, and T. J. Freeman. Development of a Procedure to Rate the Application of Pavement Maintenance Treatment. *Strategic Highway Research Program.* Report No. SHRP-M/FR-92-102. 1992.
4. *A Basic Asphalt Emulsion Manual.* Manual Series No. 19 (MS-19). Asphalt Institute, 1979.
5. McLeod, N. W. Basic Principles for the Design and Construction of Seal Coats and Surface Treatments With Cutback Asphalt and Asphalt Cements. *Proc., Association of Asphalt Paving Technologists,* Supplement to Vol. 29, 1960.
6. McLeod, N. W. A General Method of Design for Seal Coats and Surface Treatments. *Proc., Association of Asphalt Paving Technologists,* Vol. 38, 1969.