Reevaluation of Seal Coating Practices in Minnesota

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Seal coating bituminous pavements, also called chip sealing, is a common type of routine maintenance done by local governmental 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 poor 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 high-quality seal coat. This includes an examination of the current Mn/DOT specifications and studying the performance of seal coats designed using the procedure found in the Asphalt Institute MS-19 *A Basic Asphalt Emulsion Manual*, 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. An overview of the study is presented, the preliminary data are examined, and the findings are summarized. The study will likely lead to changes to the current Mn/DOT bituminous seal coat specifications.

The Minnesota Department of Transportation (Mn/DOT) specification for bituminous seal coating (Specification 2356) is found in the 1988 edition of the *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 is 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. This specification does not adjust the application rate to account for the gradation, shape, or specific gravity of the aggregate. In addition most 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 the Strategic Highway Research Program (SHRP) (*3*) required the use of the design procedure contained in the Asphalt Institute's MS-19, 1979 edition (*4*). This design procedure was reported by Norman McLeod in the proceedings from the 1960 and 1969 Annual Meeting of the Association of Asphalt Paving Technologists (*5,6*). The procedure is called the "McLeod procedure" for the remainder of this report.

More than 160 km (100 mi) of pavements were 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).

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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 the weighted average of the mean size (millimeters or inches) of the largest 20 percent, the middle 60 percent, and the smallest 20 percent of the aggregate particles. These mean sizes are 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:

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

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

- For cutbacks and asphalt emulsions:

–S.I. metric units

$$\text{Binder application rate (L/m}^2) = (0.177)(\text{APD, mm}) \quad (2)$$

–U.S. customary units

$$\text{Binder application rate (gal/yd}^2) = (1.0)(\text{APD, in.}) \quad (3)$$

- For asphalt cements:

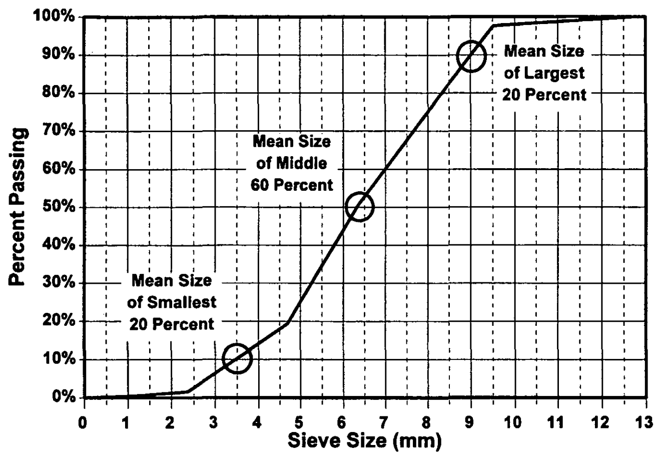
–S.I. metric units

$$\text{Binder application rate (L/m}^2) = (0.124)(\text{APD, mm}) \quad (4)$$

–U.S. customary units

$$\text{Binder application rate (gal/yd}^2) = (0.7)(\text{APD, in.}) \quad (5)$$

An example of this procedure is shown in Figure 1. For comparison purposes, another design procedure was investigated. The design procedure most widely accepted is the procedure reported by Norman McLeod in the late 1960s. This procedure, or some adaptation of it, is found in several sources including the Asphalt Institute's MS-19 Manual (*4*). The procedure described in the 1979 Edition of MS-19 is the one used by SHRP for the SPS-3 sections.



S.I. Metric Units

Average Particle Diameter = (0.2)(3.5) + (0.6)(6.3) + (0.2)(9.0) = 6.28 mm (0.247 in.)

For Asphalt Emulsion, the Binder Application Rate = (0.177)(6.28) = 1.11 liter/sq.m

Aggregate Application Rate = (1.11/1)(13.1) = 14.5 kg/sq.m

U.S. Customary Units

Average Particle Diameter = 0.247 inches

For Asphalt Emulsion, the Binder Application Rate = (1.0)(0.247) = 0.25 gal/sq.yd

Aggregate Application Rate = (0.25/0.01)(1) = 25 lbs/sq.yd

FIGURE 1 Example of Mn/DOT design procedure (25.4 mm = 1 in.).

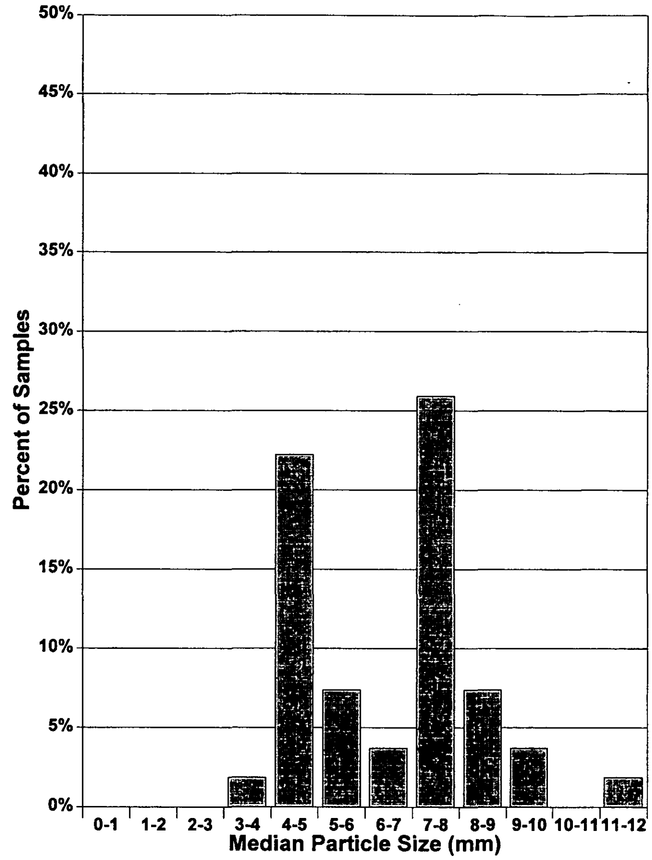


FIGURE 2 Distribution of median particle size (25.4 mm = 1 in.).

McLEOD DESIGN PROCEDURE

In the McLeod procedure, the aggregate application rate depends on the aggregate gradation, shape, and specific gravity. The binder application rate depends on the aggregate gradation and shape, traffic volume, existing pavement condition, and binder properties. The key components of the design are as follows.

Median Particle Size

The median particle size is determined from the gradation chart. It is the theoretical sieve size through which 50 percent of the material passes (50 percent passing size). Figure 2 shows the distribution of the median particle size of all of the aggregate samples from this study.

Flakiness Index

The flakiness index is a measure of the percentage, by weight, of flat particles. It is determined by testing a small sample of aggregate particles for their ability to fit through a slotted plate. The aggregate particles will fit through the slots if they have a least dimension smaller than 60 percent of the mean of the coarse sieve fractions. For example, for aggregate passing the 19-mm (0.75-in.) sieve and retained on the 12.7-mm (0.50-in.) sieve, the mean sieve size is 15.85 mm (0.625 in.) and the flakiness index of this particular sieve fraction would be the percentage, by weight, of particles having a least dimension of 9.51 mm or 0.375 in., this being 60 percent of 15.85 mm. The plate contains slots for material retained on the 19.0, 12.7, 9.5, 6.3, and 4.7 mm (3/4, 1/2, 3/8, and 1/4 in., and no. 4) sieves. The lower the flakiness index, the more cubical is the material. Flakiness index results are shown in Figure 3.

Average Least Dimension

The average least dimension (ALD) is determined from the median particle size and the flakiness index. It is a reduction of the median particle size after accounting for flat particles. It represents the expected seal coat thickness and is a key component in both of the McLeod design equations. The ALD results are shown in Figure 4. Comparing Figures 2 and 4 shows the effect the flakiness index has in converting the median particle size to the ALD.

Loose Unit Weight of Cover Aggregate

The loose unit weight, shown in Figure 5, is determined according to ASTM C 29 and is needed to calculate the voids in the aggregate in a loose condition. This test, which simulates dropping chips from

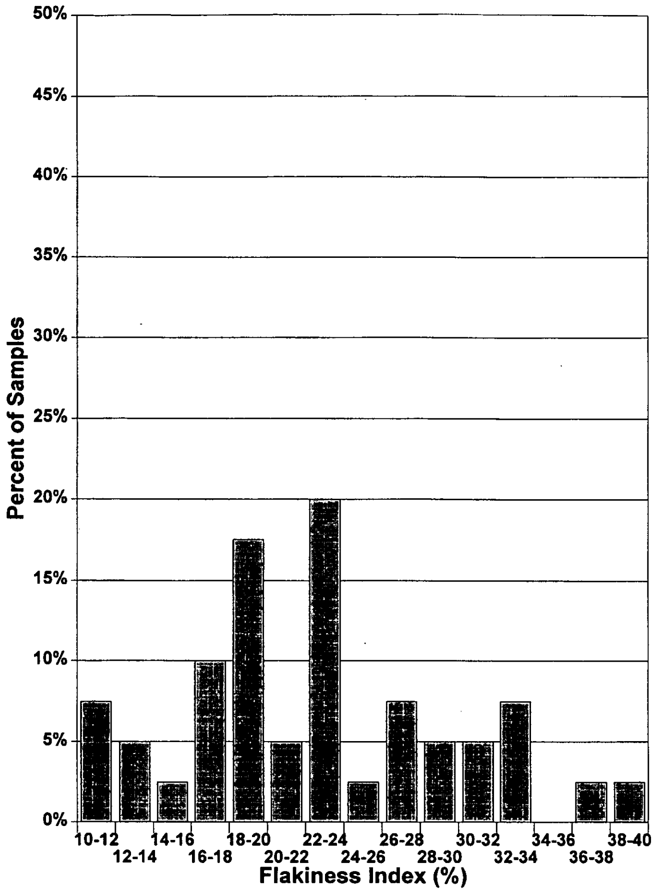


FIGURE 3 Distribution of flakiness index.

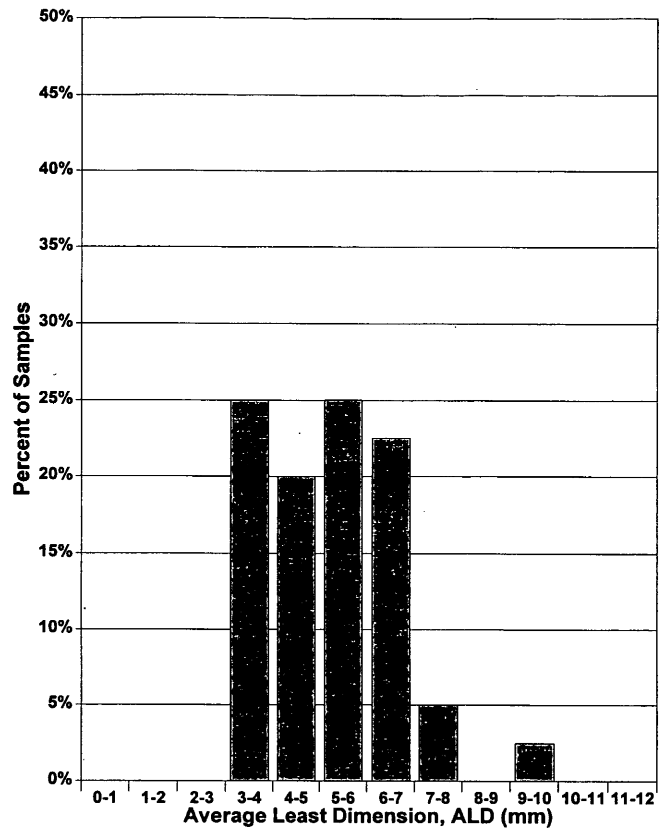


FIGURE 4 Distribution of average least dimension (25.4 mm = 1 in.).

a chip spreader, is used to estimate the space available for the binder. The loose unit weight depends on the gradation and shape of the aggregate more so than its specific gravity. Pea rock, which had the lowest specific gravity of the aggregates tested, typically had the highest loose unit weight.

Voids in Loose Aggregate

The voids in the aggregate in a loose condition, shown in Figure 6, approximate the voids present when the chips are dropped from the spreader onto the pavement. Generally, this value will be near 50 percent for one-size aggregate, less for graded aggregate. 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 voids in most of the samples from this study were less than 50 percent, meaning that they were graded instead of one size.

Samples of the aggregate used on all of the projects were submitted to Mn/DOT's Materials Research and Engineering Laboratory for testing. Aggregates samples were tested for gradation, bulk specific gravity, loose unit weight, and flakiness index determination. Binder samples were tested for specification compliance and determination of the residual asphalt content. The application rates for the aggregate and binder are obtained by using the following equations.

Aggregate Application Rate

The aggregate application rate is determined from the following equations:

- S.I. metric units

$$C = (1 - 0.4V)HGE \tag{6}$$

where C is the cover aggregate application rate, in kilograms per square meter, and V represents voids in the loose aggregate, in percentage expressed as a decimal.

$$V = 1 - \frac{W}{1000G} \tag{7}$$

where

W = loose unit weight of cover aggregate, ASTM Method C29 (kg/m^3);
G = bulk specific gravity of aggregate;
H = average least dimension (mm); and
E = wastage factor for traffic whip-off (Table 1).

- U.S. customary units

$$C = 46.8(1 - 0.4V)HGE \tag{8}$$

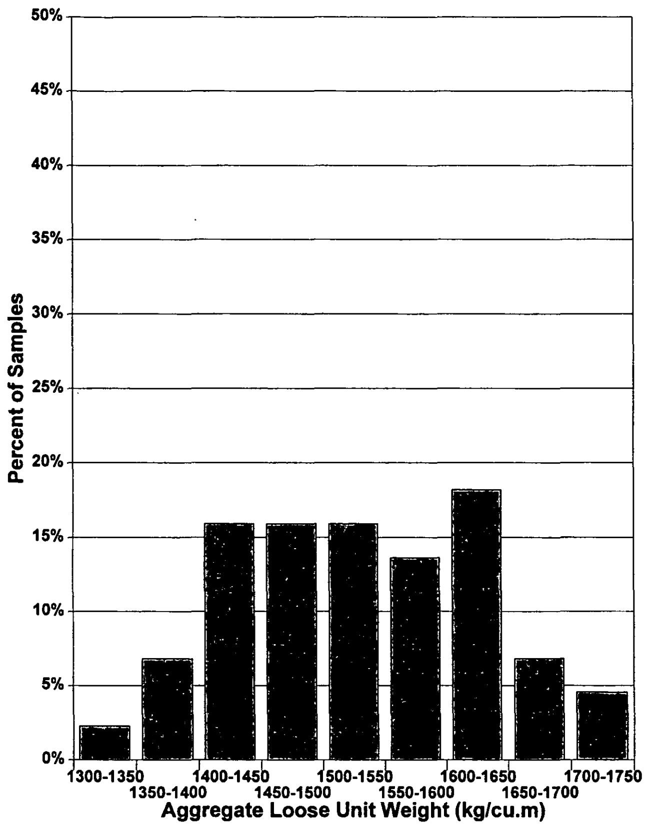


FIGURE 5 Distribution of loose unit weight of cover aggregate ($16.05\ kg/m^3 = 1\ lb/ft^3$).

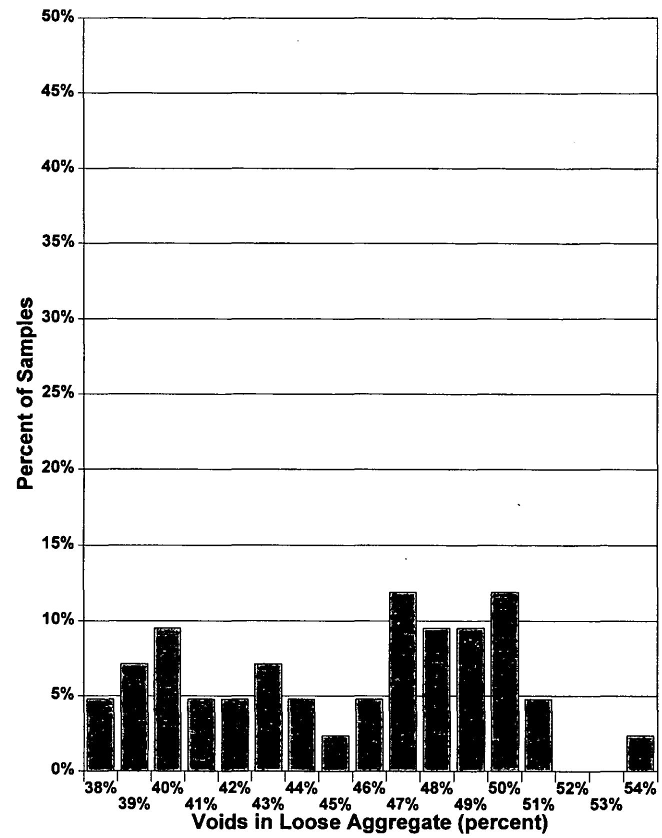


FIGURE 6 Distribution of voids in cover aggregate.

where C is the cover aggregate application rate in pounds per square yard.

$$V = 1 - \frac{W}{62.4G} \qquad (9)$$

where W is the loose unit weight of the cover aggregate, ASTM Method C29, in pounds per cubic yard, and H is the average least dimension in inches.

TABLE 1 Aggregate Wastage Factor, *E* (*4*)

Percentage Waste[a] 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

[a] Due to traffic whip-off and handling

BINDER APPLICATION RATE

The binder application rate depends not only on the properties of the aggregate mentioned above but also the existing pavement condition, traffic volume, aggregate absorption, and residual asphalt content of the binder. Binder application rates are determined from the following equations:

- S.I. metric units

$$B = \frac{(0.40)(H)(T)(V) + S + A}{R} \qquad (10)$$

where

B = binder application rate (L/m^2);
H = average least dimension (mm);
T = traffic factor (based on expected vehicles per day, Table 2);
S = surface condition factor (based on the "dryness" of existing surface, Table 3) (L/m^2);
A = aggregate absorption factor (equal to zero unless aggregate is porous) (L/m^2); and
R = residual asphalt content of binder (% expressed as a decimal).

- U.S. customary units

$$B = \frac{(2.244)(H)(T)(V) + S + A}{R} \qquad (11)$$

TABLE 2 Traffic Correction Factor, *T* (*4*)

Aggregate	Traffic Factor = Percentage (expressed as a decimal) of 20 percent void space in cover aggregate to be filled with asphalt				
	Traffic -Vehicles per Day				
	Under 100	100 to 500	500 to 1,000	1,000 to 2,000	Over 2,000
Recognized Good Type of Aggregate	0.85	0.75	0.70	0.65	0.60

NOTES:

(1) The factors above do not make allowance for absorption by the road surface or by absorptive cover aggregate

(2) **Values in the table are from "Seal Coat and Surface Treatment Design and Construction Using Asphalt Emulsions", by Norman W. McLeod, January 1974.**

where

B = binder application rate (gal/yd^2),
H = average least dimension (in.),
S = surface condition factor (based on the "dryness" of existing surface, Table 3) (gal/yd^2), and
A = aggregate absorption factor (equal to zero unless aggregate is porous) (gal/yd^2).

COMPARISON OF DESIGN PROCEDURES

The McLeod procedure is based on two basic principles:

1. The application rate of a given cover aggregate should be determined so that the resulting seal coat will only be one-stone thick. This amount of aggregate will remain constant, regardless of the binder type or pavement condition.
2. The voids in this aggregate layer need to be 70 percent filled with asphalt cement for good performance on moderately trafficked pavements.

The Mn/DOT procedure is based on the incorrect principle that the asphalt binder application rate must be known before the aggregate application rate can be determined. In addition, the aggregate type is not accounted for, only its size. Granite, limestone, pea rock, and trap rock will all be applied at the same rate if they have the same average particle diameter. This is a problem because a given weight of trap rock will not cover as large an area as the same weight of pea rock due to differences in specific gravity (2.98 for trap rock, 2.66 for pea rock).

Seal coats designed with the Mn/DOT procedure are usually multiple-stones thick instead of the desired one-stone thick. Proper embedment of the aggregate particles is more difficult to achieve with multiple-stone-thick seal coats. The stones on the bottom will be completely embedded in the binder whereas the ones on top will only be partially embedded. In addition, if the excess 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 and contacting the road surface.

Aggregate Gradation

Both procedures account for the aggregate gradation but do so differently. The McLeod procedure uses the *median particle size* whereas the Mn/DOT procedure uses the *average particle diameter*. As shown in Figure 7, both methods give nearly the same results for the samples in this study.

TABLE 3 Surface Correction Factor, *S* (*4*)

Texture	**Correction, S**	
	liter/m^2	**gal/yd^2**
Black, flushed asphalt	-0.04 to -0.27	-0.01 to -0.06
Smooth, non-porous	0.00	0.00
Absorbent		
- Slightly porous, oxidized	0.14	0.03
- Slightly pocked, porous, oxidized	0.27	0.06
- Badly pocked, porous, oxidized	0.40	0.09

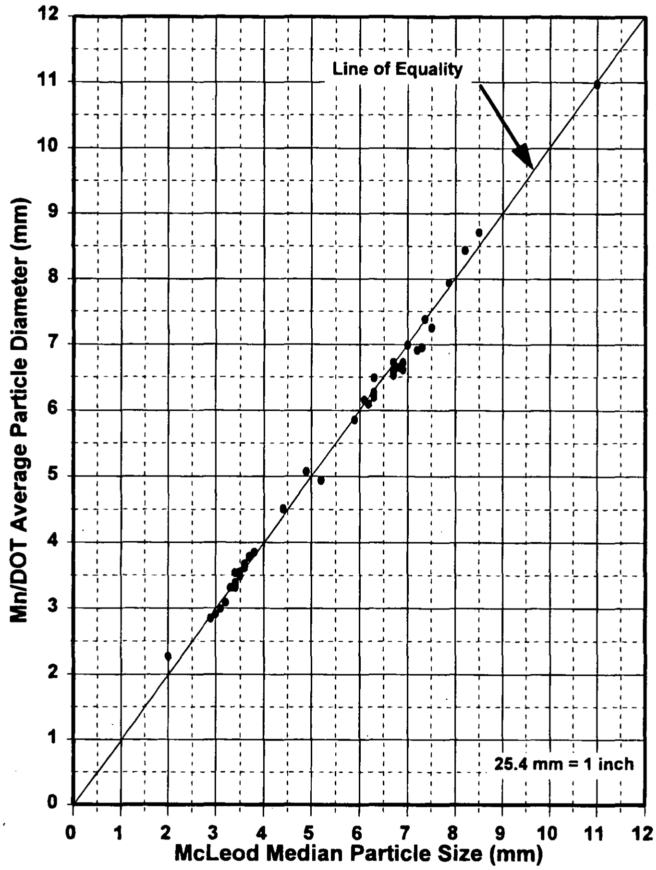


FIGURE 7 Comparison of median particle size and average particle diameter.

One problem with the Mn/DOT FA-3 gradation (AASHTO M43, size no. 8) is that it does not require the 6.3-mm (¼-in.) sieve. Requirements are given for the 9.5-mm (⅜-in.) and 4.75-mm (no. 4) sieves. This large gap in successive sieve sizes (4.75 mm, 0.188 in.) results in large differences in material considered the same. For example, one sample of FA-3 material had 100 percent passing the 6.3-mm (¼-in.) sieve whereas another only had 30 percent passing. This large difference was not detected using the normal Mn/DOT sieve nest and will lead to problems if agencies continue to base the application rate on the aggregate size only.

Another problem with the Mn/DOT procedure is that it does not account for the differences between one-size and graded aggregate. Figure 8 shows two gradations, a one-size aggregate and a graded aggregate both having the same median particle size and average particle diameter (7.5 mm). Since the Mn/DOT procedure bases the binder application rate solely on the average particle diameter, the recommended binder application rate is the same for both aggregates.

By contrast, the McLeod procedure accounts for the difference in these aggregates by incorporating the voids in the loose aggregate into the design equations. The voids in the loose aggregate will be higher for the one-size aggregate than for the graded aggregate. As a result, the binder application rate will be higher for the one-size aggregate than for the graded one. Failure to base the binder application rate on voids could lead to flushing, if the voids are lower than expected (graded aggregate) or loss of aggregate, if the voids are higher than expected (one-size aggregate).

Aggregate Shape

No adjustments are made in the Mn/DOT procedure for flat aggregate. Samples from this study ranged from 10 percent (very cubical) to 40 percent (very flat) flat particles by weight. The McLeod procedure assumes that over time, traffic will cause the chips to lie on their flattest side. As a result, a chip seal will be thinner when using flat aggregate than it will when using cubical aggregate. To obtain the proper embedment, this thickness (average least dimension) and its corresponding void content must be known.

The National Association of Australian State Road Authorities specifies 35 percent as the maximum permissible flakiness index (*4*). The SHRP SPS-3 program specified a maximum flakiness index of 15 percent, resulting in very cubical aggregate (*3*).

Because determining the flakiness index is a time consuming and tedious task, it was hoped that some estimate of ALD could be made without knowing the flakiness index. Figure 9 shows the relationship of median aggregate size, determined from the gradation curve, and the resulting ALD. This covers flakiness index values from 10 to 40 percent and median particle sizes from 3 to 12 mm (0.118 to 0.472 in.). The relationship is quite good and suggests that this may be a way to estimate the ALD without knowing the flakiness index. This relationship will be studied further to determine its applicability.

Surface Condition

No adjustments are suggested in the Mn/DOT procedure for adjusting the binder application rate to account for surface condition other than experience. The Mn/DOT *Bituminous Manual* states that the bitumen application rate "for each job will depend on the average particle size of aggregate used, the type of bitumen used, its rate of absorption into the mat, and the surface texture of the mat. Increases or decreases in the application rate will have to be made from careful observation and consideration of all the factors involved." No guidelines for how much of an adjustment to make or when to make it are given.

The McLeod procedure uses Table 3 to adjust how much binder is required based on the surface condition. The surface condition is rated in one of five categories of texture/porousness and an appropriate adjustment in liters per square meter (or gallons per square yard) is recommended. This table makes it easy to adjust the application rate in the field when pavement conditions change. This adjustment must be made to prevent a dry, porous pavement from absorbing the binder intended for chip retention. Simple field testing procedures for determining which category to use are being investigated.

Traffic Volume

The Mn/DOT procedure makes no recommendations for adjusting the binder application rate to account for traffic volume. As a result, most agencies use the same binder application rate on all roadways sealed in a given year, regardless of traffic. Cul-de-sacs with very little traffic get the same amount of binder as heavily traveled collectors.

The McLeod procedure adjusts the binder application rate to account for the effect traffic will have on the orientation of the chips and the resulting voids. As more traffic travels across the seal coated surface, more chips will lay on their flat side. Eventually, traffic will cause the seal coat to reach its lowest expected void content of

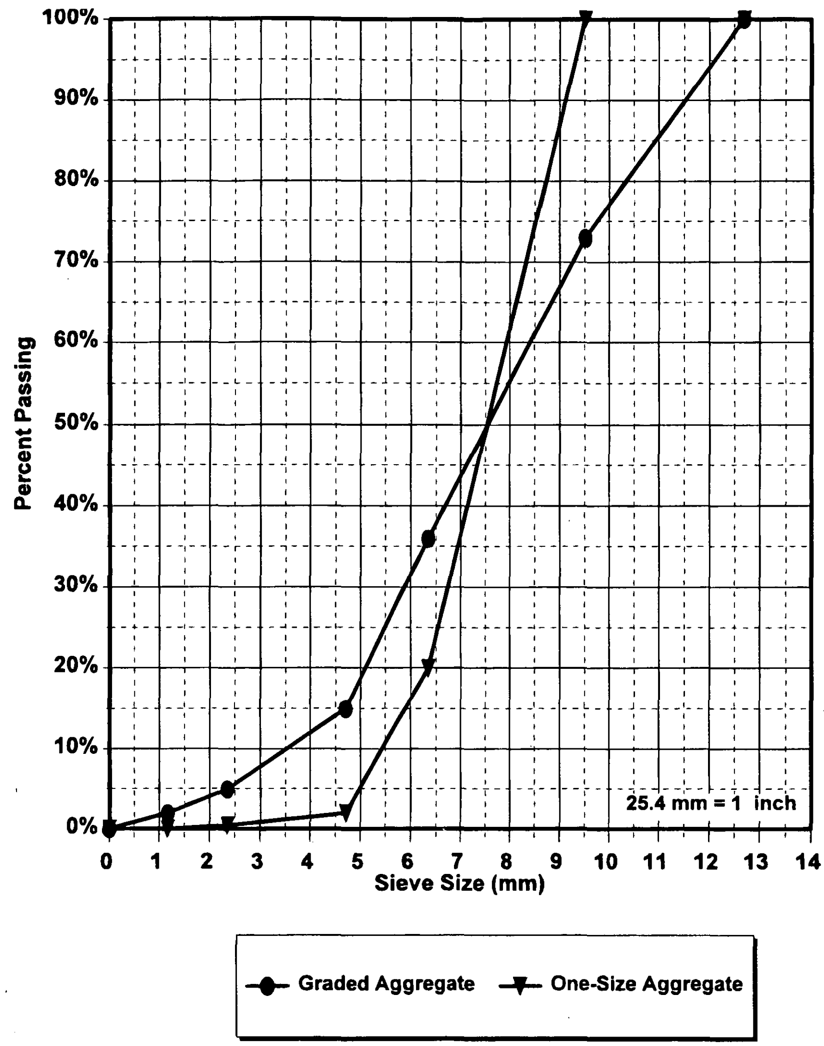


FIGURE 8 One-size and graded aggregate with the same median particle size.

approximately 20 percent. For moderate traffic, this 20 percent void space should be 70 percent filled with asphalt binder. However, as traffic increases, this void space should only be 60 percent filled with asphalt cement. Conversely, in very low traffic areas, such as cul-de-sacs, the void space should be filled more than 70 percent with binder. The percent the voids should be filled based on traffic volume is shown in Table 2.

Binder Properties

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/water has evaporated. Since the residual asphalt is what bonds the stone particles to the pavement, having the binder application rate based on this residual asphalt content is vital for proper embedment of the aggregate particles.

The McLeod procedure accounts for the type of binder by having the residual asphalt content as the denominator in the binder application design equation. The more residual asphalt in the binder, the less binder required.

COMPARISON OF DESIGN APPLICATION RATES

The aggregate and binder application rates were determined using both the McLeod procedure and the current Mn/DOT procedure. Figures 10 and 11 show a comparison of the resulting application rates. Figure 10 shows that with few exceptions, the Mn/DOT procedure recommends more aggregate than the McLeod procedure, sometimes 45 percent more. As mentioned before, this results in multiple-stone-thick instead of one-stone-thick seal coats. Figure 11 shows that the McLeod procedure generally requires more asphalt binder than the Mn/DOT procedure.

CONCLUSIONS

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

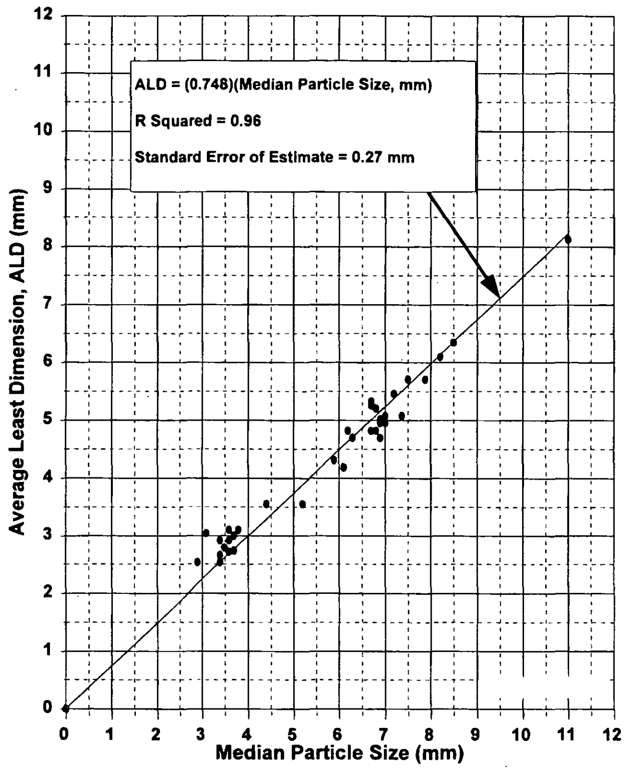


FIGURE 9 Relationship between median particle size and average least dimension.

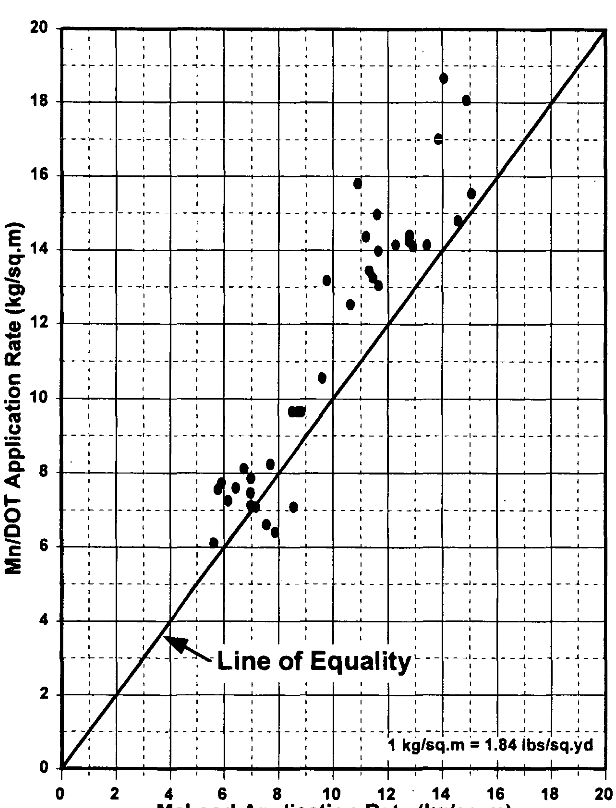


FIGURE 10 Comparison of McLeod and Mn/DOT aggregate application rates.

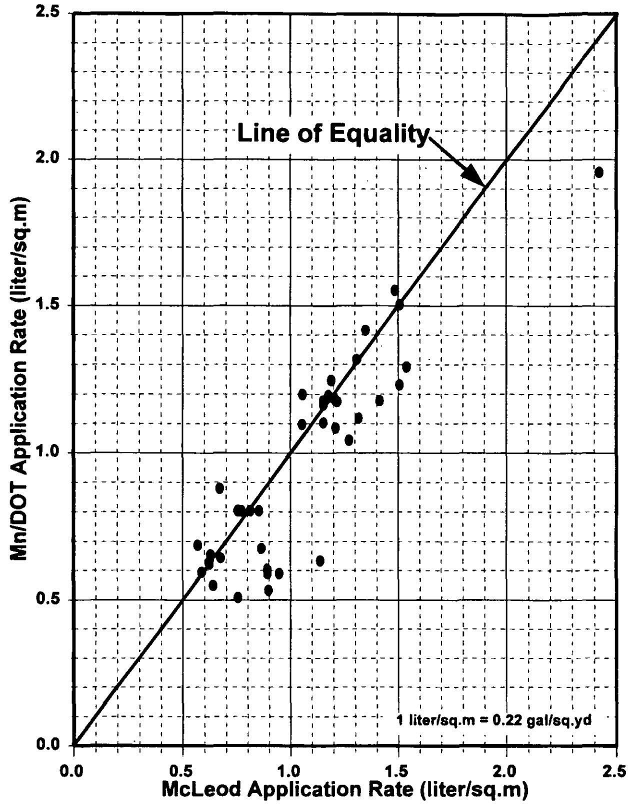


FIGURE 11 Comparison of McLeod and Mn/DOT binder application rates.

1. Most agencies do not use a design procedure for determining binder or aggregate application rates. Instead, the application rates are based on experience and size of aggregate. The most common application rate for FA-3 (Table 4) is 30 lb/yd^2 (16.3 kg/m^2) of aggregate and 0.30 gal/yd^2 (1.4 L/m^2) of binder. The most common application rate for FA-2 (Table 4) is about 25 lb/yd^2 (13.6 kg/m^2) of aggregate and 0.25 gal/yd^2 (1.1 L/m^2) of binder.
2. Aggregate application rates were reduced by as much as 50 percent when using the McLeod design procedure instead of the agency's standard application rate.
3. Sweeping time was reduced significantly when using the McLeod design procedure. Since the seal coat is only one stone thick, very little loose aggregate is left to sweep up.
4. To date, the seal coats designed using the McLeod procedure are performing as well as or better than the undesigned seal coats while using much less cover aggregate and thus costing less.

RECOMMENDATIONS

1. Seal coats should be designed instead of based simply on a previous year's results or the aggregate size used (FA-2, FA-3, etc.). In addition, the binder application rate should be changed whenever the traffic and/or surface conditions change. Failure to account for these changes will likely lead to seal coat failures.
2. 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 characterize the gradation of FA-3 material better. This will provide for a more uniform product from year to year.

TABLE 4 Mn/DOT Seal Coat Gradations

Sieve Size		Total Percent Passing	
		FA-2 Size No. 9 AASHTO M43	FA-3 Size No. 8 AASHTO M43
25.0 mm	(1 in)	100	100
19.0 mm	(¾ in)	100	100
12.5 mm	(½ in)	100	100
9.5 mm	(⅜ in)	100	85-100
4.75 mm	(No. 4)	85-100	10-30
2.36 mm	(No. 8)	10-40	0-10
1.18 mm	(No. 16)	0-10	0-5
300 μm	(No. 50)	0-5	

3. Aggregate samples submitted for design should be taken from several areas of the stockpile after it is on the job site as opposed to submitted from the source pit due to considerable variability in the material.

4. 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 D5624-95 method for chip spreader calibration is recommended. This procedure involves placing ten to twelve 1-ft-wide (30.5-cm-wide) 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 aggregate retained on each mat. The transverse spread rate is determined by comparing the amount of stone on each mat. Adjustments are then made to the gate openings so they apply a uniform spread rate.

5. Dirty aggregate should not be used. The current Mn/DOT specifications do not require washing under any circumstances. It is recommended that the aggregate be washed if the percent passing the no. 200 sieve (75 μm) is 2 percent or higher.

6. Sweeping should occur as soon as possible after construction, normally the day after sealing. Leaving loose stones on the roadway can cause windshield damage and is detrimental to seal coat life.

7. Mn/DOT should continue to monitor the performance of these sections and modify the existing seal coat specifications (2356) and bituminous manual accordingly.

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