An Analysis of Two Leading Chip Seal Design Methods

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Two of the most commonly used chip seal design procedures are compared in this study. One method published by the Asphalt Institute (Asphalt Institute 1979) is based on work originally done by Hanson (Hanson 1953) and later refined by McLeod (McLeod 1969). This method is widely used by many agencies around the world. The other method was developed in Texas by Kearby (Kearby 1953) and later refined by Benson (Benson and Gallaway 1955) and Epps (Epps 1981). This method is used by some U. S. agencies. Both methods evaluate the asphalt and aggregate chip application rates by conducting certain quantitative laboratory tests on the aggregate and estimating the embedment depth of the aggregate based on traffic volume. However, although both methods are based on similar principles, they often do not provide the same aggregate or asphalt application rates. This paper is an analysis of these differences and provides conclusions to explain the reasons for the differences.

Keywords: Chip seal, chip seal design, preventive maintenance, pavement preservation

LITERATURE REVIEW

Chip seals have been widely used around the world as a pavement preservation treatment for over fifty years (Hanson 1953, Kearby 1953, McLeod 1969, Marais 1981, Abdullah, et al 1994, Chen et al 2003, Croteau et al 2005). They are considered one of the most cost effective preventive maintenance treatments as long as proper design and construction practices are followed (Davis et al 1991, Shuler 1998, Gransberg 2005). However, since the beginning of chip seal use the proper application rate for asphalt and aggregate chips has been debated. Two chip seal design procedures (Asphalt Institute 1979 and Mcleod 1969, Epps et al 1981) have evolved from early work by Hanson in New Zealand (Hanson 1953) and Kearby in Texas (Kearby 1953). These two methods both evaluate the asphalt and aggregate chip application rates by conducting certain quantitative laboratory tests on the aggregate and then providing a calculated estimate of the application rates of the asphalt and aggregate chips based on a specific embedment depth. However, the quantities of material obtained by these methods often do not agree eventhough the theoretical basis for each procedure is essentially the same. Furthermore, when the design material quantities obtained by these procedures are compared with actual material quantities applied in the field more differences become apparent (Shuler 1998).

BACKGROUND

The objective of this study was to compare the aggregate and asphalt binder application rates for both the Texas design (Epps 1981), referred to as Procedure One herein, and the Asphalt Institute design (Asphalt Institute 1979), Procedure Two herein. These two chip seal design procedures

are the most widely used in the world but often do not provide the same material quantity estimates. The reasons for this have never been published and therefore, selecting which design procedure to use, has largely been left to personal preference or tradition. However, both procedures can misrepresent appropriate material quantities when compared to successful application rates on real pavements (Shuler 1998). Therefore, an experiment was developed to provide material application quantities for four different aggregates, compare the results and analyze the reasons for any differences. By understanding the reasons why the procedures sometimes produce differing results, the most appropriate design procedure might better be matched to specific field conditions and a more accurate estimate of material quantities might result.

METHOD

Four aggregate chips were selected for testing from basalt, granite, limestone and alluvial deposits. The physical properties of these materials are shown in Table 1.

Table 1. Physical Properties of Aggregate Chips

Sieve	Passing, %			
	Limestone	Granite	Basalt	Alluvial
½ inch	100	100	100	100
3/8 inch	100	99	100	99
5/16 inch	100	50	79	73
¼ inch	48	9	30	33
No. 4	1	1	1	2
No. 8	1	1	1	2
No. 16	1	1	1	2
No. 30	1	1	1	2
No. 50	1	1	1	2
No. 100	1	1	1	2
No. 200	1	0.6	1	2
Flakiness Index	33.78	5.77	13.08	10.49
Avg Least Dimension, in	0.170	0.265	0.218	0.222
Loose Unit Wt, pcf	78.3	84.0	92.2	86.1
Board Weight, psy	11.0	15.6	14.5	14.1
Bulk Specific Gravity	2.615	2.612	2.773	2.566

Both design procedures were performed on the four test aggregates with the following assumptions:
- Traffic correction factor is based on over 1000 vehicles per day.
- Surface condition correction is based on a smooth and non-porous surface.
- In calculating bulk specific gravity (BSG), it is assumed that the natural state of the applied aggregate is the oven dry state (as stored).

- The residual content of the asphalt emulsion is 70%
- Where initial embedment, or initial voids, is referred to, this indicates the loose condition before mechanical compaction (as opposed to final embedment or final voids).

Both the Texas (Procedure One) and the Asphalt Institute (Procedure Two) design methods were performed for the four aggregates shown in Table 1. Results of the four designs for aggregate application rate and emulsion spray rate are shown in Tables 2 and 3 below.

RESULTS

Texas Design

Table 2. Aggregate and Asphalt Emulsion Rates for TX Design

Aggregate	Aggregate Spread Rate, psy	Asphalt Spray Rate, gsy
Limestone	10.97	0.20
Granite	15.55	0.26
Basalt	14.45	0.20
Alluvial	14.14	0.21

Asphalt Institute Design

Table 3. Aggregate and Asphalt Emulsion Rates for AI Design

Aggregate	Aggregate Spread Rate, psy	Asphalt Spray Rate, gsy
Limestone	16.48	0.18
Granite	26.11	0.27
Basalt	22.95	0.21
Alluvial	21.73	0.21

ANALYSIS

Clearly, the Texas design estimates lower aggregate spread rates than the Asphalt Institute design while the asphalt emulsion quantities are very similar.

In the Texas (TX) design, the technician physically fits the aggregate, in the board test, to arrive at maximum coverage mass. In the Asphalt Institute (AI) design, however, a formula that

considers the shape (elongation or flakiness) of the particles and accounts for the likelihood of particles to lay flat when compacted is utilized.

Additionally, the AI design formula makes the assumption that the final compaction of the aggregate is such that the voids in the applied aggregate are reduced to 40 percent of their initial (or applied) volume. As a result of this assumption, the AI design allows for more aggregate to be placed in the same area in a more compact condition than does the TX method.

It is important to note the relative void volumes assumed by the procedures: AI calculates the required mass of compacted aggregate (with assumed final void volumes as low as 18.5% (**0.4*46%**) for the test aggregates); and TX board test positions the aggregate in a semi-compacted state (void volumes as low as 46%). For the board test procedure also note that the mat depth formula (d=4Q/3W) implies that the board weight (Q) is based on a loose condition of the aggregate (as is the denominator, W) with percent initial voids (in the loose aggregate) equal to **1-(W/62.4G)** (between 52% and 46% for the test aggregates).

To determine whether the Texas and Asphalt Institute designs would match more closely if the 40 percent void reduction were removed, the AI design was repeated but without consideration for aggregate void volume reduction. The results are shown in Table 4.

Table 4. Aggregate Spread Rate for AI Design without Void Reduction

Aggregate and Asphalt Quantities:
　Aggregate: Procedure Two Modified for No Reduction of void volume

Flakiness Index (FI)

Agg.	Sieve sizes (passing - retained)	slot width (mm)	wt. ret. On slot (g)	wt. passing slot (g)	total wt. tested (g)	FI (%)
LSTN	1/2" - 3/8"	0.263"	0.0	0.0	0.0	0.00%
	3/8" - 1/4"	0.184"	620.1	410.3	1030.4	39.82%
	1/4" - no.4	0.131"	678.2	252.0	930.2	27.09%
			1298.3	662.3	1960.6	**33.78%**
GRNT	1/2" - 3/8"	0.263"	14.1	1.3	15.4	8.44%
	3/8" - 1/4"	0.184"	1706.5	106.4	1812.9	5.87%
	1/4" - no.4	0.131"	152.8	7.1	159.9	4.44%
			1873.4	114.8	1988.2	**5.77%**
BSLT	1/2" - 3/8"	0.263"	5.1	0.9	6.0	15.00%
	3/8" - 1/4"	0.184"	837.6	147.4	985.0	14.96%
	1/4" - no.4	0.131"	520.5	56.8	577.3	9.84%
			1363.2	205.1	1568.3	**13.08%**
ALLVL	1/2" - 3/8"	0.263"	10.4	3.5	13.9	25.18%
	3/8" - 1/4"	0.184"	1191.3	151.4	1342.7	11.28%
	1/4" - no.4	0.131"	568.6	52.5	621.1	8.45%
			1770.3	207.4	1977.7	**10.49%**

Average Least Dimension (ALD) of Aggregate

	LSTN	GRNT	BSLT	ALLVL
Flakiness Index (%)	33.78%	5.77%	13.08%	10.49%
Median Size (mm.)	6.412	7.993	7.023	7.047
Median Size (in.)	0.252	0.315	0.277	0.277
H: ALD (in.)	0.170	0.265	0.218	0.222

Vol of measure = 14,284.3 g　　=　　0.014330237 c.m.　=　0.506068 c.ft.
　　　　　　　996,794.4 g/c.m.

Dry Loose Unit Weight (W)

	LSTN	GRNT	BSLT	ALLVL
mass of agg (g)	17,974.2	19,274.4	21,163.1	19,751.7
mass of agg (lb.)	39.63	42.50	46.66	43.55
vol. of agg (c.m.)	0.014	0.014	0.014	0.014
vol. of agg (c.ft.)	0.506	0.506	0.506	0.506
loose unit weight (kg/c.m.)	1,254.28	1,345.02	1,476.81	1,378.32
W: loose unit weight (lb/c.ft.)	**78.31**	**83.97**	**92.20**	**86.05**
V: init'l void volume = [1 - (W / 62.4G)]	0.52010	0.48479	0.46715	0.46257

M: multiplying factor =	1.00
E: wastage factor =	1.00

Aggregate Quantity (C)

	LSTN	GRNT	BSLT	ALLVL
G: Bulk Specific Gravity	2.615	2.612	2.773	2.566
C: cover aggregate (lb/sy)	**9.98**	**16.69**	**15.04**	**14.33**

K: multiplying factor	1.00			
T: traffic corr. factor =	0.65	0.50	0.40	0.30
SC: surface corr. factor =	0.00	gal/sy		
A: corr. for absorption =	0.00	gal/sy		
RC: residual content =	0.70			

Asphalt Quantity (A)

	LSTN	GRNT	BSLT	ALLVL
B1: emulsified asphalt (gal./sy)	**0.461**	**0.669**	**0.529**	**0.535**
B2: emulsified asphalt (gal./sy)	**0.354**	**0.515**	**0.407**	**0.411**
B3: emulsified asphalt (gal./sy)	**0.283**	**0.412**	**0.326**	**0.329**
B4: emulsified asphalt (gal./sy)	**0.213**	**0.309**	**0.244**	**0.247**

Note: Here, B1, B2, B3 & B4 are asphalt quantities that would fill, respectively, 65%, 50%, 40% and 30% of the initial (and final) voids. These voids are not reduced by compaction.

Table 5. Aggregate Rates for TX and AI Design Before and After Void Reduction

Aggregate	TX Aggregate Spread Rate, psy	AI Aggregate Spread Rate w/o Void Reduction, psy	AI Aggregate Spread Rate w/ Void Reduction, psy
Limestone	10.97	9.98	16.48
Granite	15.55	16.69	26.11
Basalt	14.45	15.04	22.95
Alluvial	14.14	14.33	21.73

Texas Design: **Asphalt Quantity**

The formula for asphalt emulsion quantity tells us what quantity of emulsion will fill the embedment portion of the **initial void volume** between particles.

In procedure one, the designed *asphalt* quantity (A_d) is first calculated. This is then corrected for temperature (A_t). The volume of *emulsion,* required to give us this much asphalt, is then calculated (A_e). Finally this volume may be corrected, as recommended, for installations done during different seasons of the year **(A_R)**.

A_d is the designed quantity of asphalt that is to be applied to the surface at a temperature of 60 degrees Fahrenheit.
    Units: gallons per square yard (gal./SY)
For each SY of surface area:
[% of initial void volume to be asphalted] * [initial void volume]
                                        = asphalt volume (volume/sy)
And since % embedment of aggregate   =   % of initial void volume to be asphalted,
[% embedment(e)] * [% initial void vol.(V) * avg. mat depth (*d inches*) * 1 SY Area]
                                        = asphalt volume (*in. * SY / SY area*)
Therefore, asphalt volume (*in. * SY / SY area*) = V*e*d
And since: 1 in. SY = 0.75 c. ft. = 5.61 gallons,
    The required asphalt volume = 5.61*V*e*d (gal./SY)
Notice that this has the same structure as procedure one's formula:
    $A_d = 5.61E(1-(W/\gamma_w G)(T) + (SC) = 5.61edV(T) + (SC)$
(Note: Actual final % embedment may be greater than (*e*) due to compaction of the aggregate and reduction of the initial void volume.)
To this theoretical asphalt volume, the traffic correction factor (T) and the surface condition correction (SC) are applied.

Note, since the void Volume $V = \{1 - (W/62.4G)\}$, if the designed quantity of asphalt is called A_d:

      Formula: $A_d = [5.61E \{1-(W/62.4G)\}*\{T\}] + [SC]$
      Formula: $A_t = A_d / F_t$
      Formula: $A_e = A_t / RC = A_d / (F_t * RC)$
      Therefore: $(RC*A_e) = A_d / F_t = A_t$
      Formula: $A_R = A_t + K(A_e - A_t)$
            $= (RC*A_e) + K(A_e - \{RC*A_e\})$
            $= A_e (RC + K - \{K*RC\})$

Therefore, $A_R = \left(\dfrac{[5.61E \{1-(W/62.4G)\}*\{T\}] + [SC]}{F_t * RC} \right) * \left(RC + K - \{K*RC\} \right)$

Where: $E = ed$ Units: inch (in.)
        e = percent embedment (decimal percent)   Units: dimensionless
        d is the average mat depth $= 4Q/3W$ Units: inch (in.)

        T is the traffic correction factor
        SC is the surface condition correction

        F_t is the correction factor for the application temperature.
        RC is the residual content of the asphalt emulsion (a decimal percent).
        K is the seasonal factor and may carry the following values:
        K: 0.6 (Spring)   0.4 (Summer)   0.7 (Fall)   0.9 (Winter)

Therefore, $A_R = \left(\dfrac{[5.61*e*d*V*T] + [SC]}{F_t * RC} \right) * \left(RC + K - \{K*RC\} \right)$

For our research purposes, the following factors will be used.
      F_t: 0.98 (at 60 degrees Celcius or 140 degrees Fahrenheit)
      T: 1.0 (over 1000 vpd) See **EEEC**, Ta. 7
      SC: -0.03 gal/SY (smooth non-porous surface) See **EEEC**, Ta. 8
      RC: 0.70 (70% residual content)
      K: 1.0
These factors cause our formula to reduce to:
      $A_R = \left(\dfrac{[5.61*e*d*V*1.0] + [-0.03]}{0.98 * 0.7} \right) * \left(0.7 + 1.0 - \{1.0*0.7\} \right)$

      $A_R = \left(\dfrac{[5.61*e*d*V*1.0] + [-0.03]}{0.686} \right) * \left(1.0 \right) = 8.1778edV - 0.0437$ gal./sy

In summary, at the particular sizes of the test aggregates, procedure one assumes asphalt to fill approximately 30% of the initial void volume (the embedment depth, e), less a surface condition

correction for smooth non porous surfaces of -0.03 gal./sy. Assuming an average A_d of 0.150 gal./sy, the surface correction is some 20% of the 30% initial void volume. The result is that the initial void volume is only required to be approximately 24% (30% -{30%*20%}) filled with asphalt (before compaction).

Note that the author of procedure one does not directly comment on the expected final compacted volume, the expected percent reduction of initial voids or on the volume of the final voids to be asphalted.

Asphalt Institute: Asphalt Quantity

In procedure two, the *asphalt emulsion* quantity (B) is calculated without correcting for temperature. Just as factors and corrections are applied in procedure one, so too in procedure two a traffic correction factor, a surface condition correction and an absorption correction are applied.

The main body of procedure two's asphalt formula is very similar to that of procedure one's except that procedure two assumes that the initial void volume is reduced by 40% due to compaction and that, based on traffic conditions, between 85% (under 100 vpd) and 60% (over 2000 vpd) of this final void volume should be filled with asphalt to avoid bleeding.

B is the designed quantity of asphalt that is to be applied to the surface.
        Units: gallons per square yard (gal./SY)
For each square yard of surface area:
        [% of final void vol. to be asphalted] * [final void vol.] = asphalt vol. (volume/sy)
i.e.:   [T] *[% initial void vol.(V) * % (final void vol./initial void vol.)(c) * avg. least
                                                            dim. (*H inches*) * 1 SY Area]
                                        = asphalt volume (*in. * SY / SY area*)
Therefore, asphalt volume (*in. * SY / SY area*) = T*V*c*H
And since: 1 in. SY   =   0.75 c. ft.   =   5.61 gallons,

The required asphalt volume = 5.61*c*H*T*V
        (**compare the above formula to procedure one's asphalt volume = 5.61edVT**)
In procedure two, the void volume is assumed to be finally compacted to 40% (*c*) of the initial void volume, thus reducing the above as follows:
        The required asphalt volume = 2.244*H*T*V
        Where the initial void Volume V = {1 – (W/62.4G)}
To this theoretical volume, the surface condition correction (SC), the Absorption correction (A) and a multiplying factor are applied.
        Formula: **B** = K [(2.244*H*T*V) + (SC) + (A)]
                                        RC
        Where: K is a multiplying factor that must be evaluated by experience with local
        conditions of climate, traffic, cover aggregate, etc., and may have a value either less than
        or greater than 1.0, which may be its normal value. However experience has shown that
        for emulsions used in colder northern areas, "K" can have a value of about 1.2.

H is the average least dimension of the aggregate.

T is a traffic factor = % of final void space to be filled with asphalt.

SC is a correction for the texture of the surface on which the treatment is to be placed.   Units: gallons per square yard (gal./SY)

A is a correction for the absorption of asphalt into the cover stone. (disregard except for obviously porous stone).
                          Units: gallons per square yard (gal./SY)

RC is the residual content of the asphalt emulsion (a decimal percent).

For our research purposes, the following factors will be used.

   K: 1.0
   T: 0.65 (1,000 to 2,000 vpd) See **AEM** Ta. VI-4
   SC: 0.00 gal/SY (smooth non-porous surface) See **AEM** p. 55
   A: 0.00 gal/SY
   RC: 0.70 (70% residual content)

These factors cause our formula to reduce to:

$$\mathbf{B} = K \left[\frac{(2.244*H*T*V) + (SC) + (A)}{RC} \right]$$

$$\mathbf{B} = 1.0 \left[\frac{(2.244*H*0.65*V) + (0.00) + (0.00)}{0.7} \right] = 2.08371 \; HV \; gal./sy$$

In summary, for 1000 to 2000 vpd, procedure two assumes asphalt to fill 26% (0.4*0.65) of the initial void volume and applies no surface condition correction for smooth non porous surfaces.

Overall Analysis of Asphalt Results

In comparing procedure one and procedure two we find that their asphalt formulas are similar and give similar results when no flakiness exists. However, for my test aggregates, flakiness caused a significant decrease in procedure two's results for aggregate size (**H**) and this reduced the asphalt quantity significantly, in comparison to procedure one, even though procedure two's aggregate results are greater than procedure one's (See asphalt emulsion results of <u>procedure two modified for no reduction of initial void volume</u>).

Procedure two assumes that compaction reduces the initial void volume to 40% of its value. Additionally it fills 65% of the final void volume with asphalt (or 0.65 *40% = 26% of the initial volume). Procedure one, however, arrives at approximately the same final asphalted void volume (22% to 25%, after applying the surface condition correction), although the procedure makes no mention of how this embedment decision has been made.

In our research, we will prepare our stored (dry) aggregates such that our tests are performed on these aggregates at actual moisture contents of 0.5% and 2.5%. Since actual absorptions of the test aggregates range between 0.76% (GRNT) and 1.86% (LSTN), for those aggregates that are

tested at 0.5% moisture content, this water will be located within the permeable pores. However, for aggregates tested at 2.5% moisture content, most of this water will be located in the voids between aggregate particles.

Granite (BSG = 2.612), for example, with absorption of 0.76%, and initial void volume of 46.7%, will have 9.7% of its initial voids filled with water (or 24.26% of the final void volume filled with water, assuming a compacted void volume of 40% of the initial void volume). This will cause temporary displacement of the asphalt until the water evaporates.

Proof: Water in voids = % free water mass*G* γ_w = (2.5% - 0.76%)*2.612*0.997g/cm^3
$= 0.04531$g/cm^3 $= 0.04531$ cm^3 water/cm^3 aggregate bulk volume
(since water has a density of 1g/ cm^3)

And since each cubic centimeter of bulk aggregate volume has an initial void volume of 46.7%, the above reduces to 0.04531 cm^3 water /0.467cm^3 of initial void volume, or 9.7% of initial void volume.

If we further assume that compaction brings the final void volume to 40% of initial void volume, the above would become: 0.04531 cm^3 water /(0.40*0.467cm^3 of initial void volume), or 0.04531 cm^3 water /(0.1868cm^3 of final void volume), or 24.26% of final void volume.

CONCLUSIONS

1. The Texas and Asphalt Institute chip seal design procedures provide different aggregate spread rates. The Texas procedure produces lower aggregate spread rates than the Asphalt Institute design. The reason is because the Asphalt Institute design assumes the void space between the aggregates will be reduced during compaction in the field, allowing for more aggregates to be placed.

2. The asphalt emulsion quantity estimated by the two procedures is very similar if assumptions about surface texture, traffic, and climate are considered equal.

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