Analysis of Emulsion and Hot Asphalt Cement Chip Seal Performance

Douglas D. Gransberg, M.ASCE,[1] and Musharraf Zaman, M.ASCE[2]

Abstract: The study collected both design and performance data on 342 chip seal projects worth nearly $30 million that had been completed in the Texas Department of Transportation's Atlanta District since 1996. One hundred sixty five of these projects were emulsion projects utilizing CRS-2P as the binder and 177 were asphalt cement projects using AC15-5TR binders. The external variables were minimized as Atlanta District had used the same seal coat contractor, Area Office, construction season, asphalt suppliers, and aggregate on all its districts chip seal projects for the past 12 years. The one difference in the aggregate was that the AC15-5TR used a lightweight aggregate that was precoated unlike the emulsion seals' lightweight aggregate that was not precoated. Thus, the comparison of the two binders can be made in a very direct manner, and the results can be viewed as specific to the engineering properties of the binders themselves without the need to qualify the conclusions based on independent parameters that could not be mathematically removed from the data. The study found that the emulsion chip seals performed as well as the hot asphalt cement seals and were the more cost effective of the two alternatives. Emulsion chip seals also furnished a better long-term friction course as measured by the skid number.

DOI: 10.1061/(ASCE)0733-947X(2005)131:3(229)

CE Database subject headings: Asphalt pavements; Sealing; Emulsions; Asphalt cement; Pavement management; Performance evaluation.

Background

The purpose of this research study is to identify the design and construction elements that contribute to chip seal success or failure based on actual project performance and to conduct a comparative analysis of various binder–aggregate combinations used during the past five years in the Texas Department of Transportation's (TxDOT) Atlanta District chip seal program. The analyses are undertaken to determine if there are objective, quantifiable differences between chip seal applied using asphalt emulsions and those applied using hot asphalt cements.

Chip seals, which are also called seal coats or surface treatments, have more than a 50 year recorded history in the United States (Jackson et al. 1990). The first uses were limited to surface treatments as wearing courses in the construction of low-volume roads. Since then, maintenance chip seals have become increasingly popular due to a number of factors including increased maintenance needs of existing pavements and the lack of sufficient funds earmarked for maintenance (Jackson et al. 1990). In 1960, McLeod provided definitions for surface treatments and seal coats (McLeod 1960). He defined a surface treatment as "a single application of asphalt binder, followed by a single application of cover aggregate, both placed on a prepared gravel or crushed stone base." He defined a seal coat as "a single application of asphalt binder followed by a single application of cover aggregate, both placed on an existing bituminous surface." These definitions are consistent with what is currently being used by TxDOT. A maintenance seal coat is identified as a preventive maintenance (PM) activity. The National Cooperative Highway Research Program (NCHRP) defined preventive maintenance as " a program strategy intended to arrest light deterioration, retard progressive failures, and reduce the need for routine maintenance and service activities" (NCHRP 1989). On the other hand, routine maintenance was defined as "a program to keep pavements …. in good condition by repairing defects as they occur" (NCHRP 1989). As a PM activity, chip seals may provide a number of enhancements to the pavement performance including sealing of the pavement to moisture, enrichment of the surface, provide or restore adequate skid resistance, preserve existing structural strength, and improve visibility for night driving (Shuler 1990; Elmore et al. 1995). The planned preventive maintenance activities are not expected to enhance the structural capacity of the pavement (MnDOT 1991; Janisch 1995).

Chip Seal Design

The very early practitioners of surface treatments or chip seals appear to have used a purely empirical approach to their design (Hanson 1935; Hank and Brown 1949; Harris 1955). Sealing a pavement was considered then, as it is now in many circles, an art (Connor 1984). The design of a chip seal involves the calculation of correct amounts of a bituminous binder and a cover aggregate to be applied over a unit area of the pavement. There are two major components of chip seal design process. These are to decide the type and amount of binder and aggregate. Aggregates

---

[1] Associate Professor, Construction Science Division, Univ. of Oklahoma, 830 Van Vleet Oval, Room 162, Norman, OK 73019.

[2] Professor, School of Civil and Environmental Engineering, Univ. of Oklahoma, 202 W. Boyd St., Room 334, Norman, OK 73019.

Note. Discussion open until August 1, 2005. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on February 20, 2003; approved on March 15, 2004. This paper is part of the ***Journal of Transportation Engineering***, Vol. 131, No. 3, March 1, 2005. ©ASCE, ISSN 0733-947X/2005/3-229–238/$25.00.

used in chip seal are expected to transfer the load to the underlying surface. They should provide a good skid resistant surface while it is durable against abrasion effects of the traffic as well as resist weathering (TxDOT 1993). The TxDOT recognizes two types of chip seal aggregates: natural aggregates, covered by Item 302 of TxDOT standard specification and lightweight aggregates, covered by Item 303 (TxDOT 1993). Both aggregates may be used with and without a precoating substance.

Precoated aggregates are essentially designed to enhance the binding properties between aggregate and binder (Benson and Gallaway 1953). Precoating an aggregate's surface with a specified bituminous material reduces bonding problems due to presence of dust on aggregate surfaces. Good bonding can minimize the amount of windshield cracking due to dislodged pieces of aggregate and enhance the final quality of the pavement by preventing debonding between the binder and the aggregate. The additional cost of precoated aggregates is justified in many projects due to these benefits as well as reduced public complaint. Another way to reduce windshield damage complaints due to loose aggregate is to use lightweight aggregates (Epps et al. 1974; Shuler 1990). The main advantage of using lightweight aggregate is due to their superior skid resistance values when compared to natural stone (Gallaway and Harper 1966). However, they do not possess good abrasion durability like the harder rock aggregates (Epps et al. 1974).

Use of Lightweight Aggregates

Various factors should be evaluated before making a selection between lightweight and natural aggregates. Lightweight aggregates have high skid values and are less likely to cause windshield cracks. However, they are more expensive than natural aggregate and have less abrasion resistance. It is also more difficult to control gradation and lightweight aggregate has a high rate of water absorption. On the other hand, natural cover rocks provide a superior abrasion resistance, and are less expensive. Unlike the lightweight aggregates, they have lower skid values, are more likely to crack windshields, and can have poor bonding performance with binders due to dust and mineral properties (Epps et al. 1974; Shuler 1990).

The TxDOT first used lightweight aggregate in chip seals in the Abilene District where a test section was constructed in 1962 (Epps et al. 1974). Around the same time, Brownwood District also started using it in surface treatment work. A comprehensive study of lightweight aggregates was undertaken at the Texas Transportation Institute in which the researchers evaluated the suitability of lightweight aggregate as cover stone for chip seals and surface treatments (TTI 1981). This study indicated that "under a variety of construction and service conditions, the lightweight material has, so far, proved to be highly successful cover aggregate for chip seals and surface treatments." It was highlighted that lightweight aggregate did not show potential for significant degradation under freeze–thaw conditions and an accelerated freeze–thaw test in place of the specified magnesium sulfate soundness test was recommended. Of particular interest were the definite advantages of lightweight aggregate in minimizing windshield breakage problems, enhancing skid resistance and its availability as a uniformly graded material.

Application of Chip Seals

Chip seals are applied to existing pavement surfaces for various reasons: to seal the cracked surface against air and water intrusion, to enhance skid values of the pavement, to obtain a uniform looking surface that would improve visibility of traffic lanes and to rejuvenate dry and raveled surfaces (Epps et al. 1980; Ksaibiti et al. 1996). Chip seals have no additional load carrying capability when applied on a surface since they are effectively one rock thick. However, they do affect the performance of the pavement by increasing the life of the pavement surface as a preventive maintenance application. They protect the underlying pavement structure against weathering effects. Chip seals are generally effective in sealing the existing cracks on roadway surface, unless there are indicators of heavy base distresses. Chip seal applications should be considered in low to mid-volume roads where there is no significant accelerating and decelerating traffic (such as in intersections) and serious rutting or corrugation problems (Jackson et al. 1990; Ksaibiti et al. 1996). One of the major difficulties in chip seal design is the nonuniformity of the pavement. Almost all of the chip seal sections have patches laid at different times and with different materials and bleeding and raveling sections observed at different parts of the pavement. All of these conditions necessitate an alteration in the binder application rate, which can make the design much more detailed than desired. However, these alterations can be performed with an experienced field crew changing the rates as required.

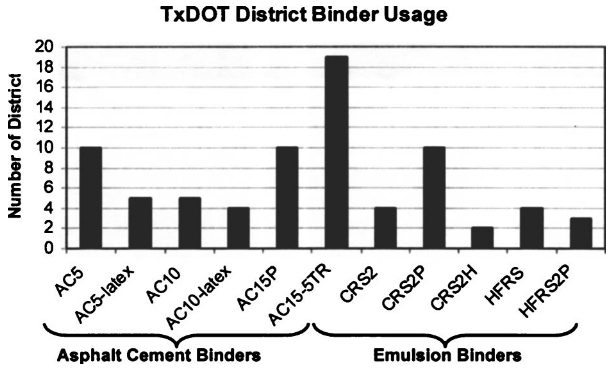

Fig. 1. Texas Department of Transportation district asphalt cement and emulsion use [adapted from Gransberg et al. (1999)]

Texas Statewide Seal Coat Constructability Review

In 1997, the author began a statewide review of the TxDOT seal coat program. All 25 districts were visited and over 125 test sections of typical chip seal projects were surveyed. The results of that study were published in 1999 (Gransberg et al. 1999). Generally it was found that TxDOT districts used both emulsions and hot asphalt cements. There was a bias to use emulsions on seals applied by TxDOT crews and the hot asphalt cements for contract projects (Garcia-Diaz and Cediel-Franco 1988; Gransberg et al. 1999). Figs. 1 illustrate the usage of the various binder options across the state. Asphalt cement (AC) and emulsion usage by the districts is presented in Fig. 1. It lists the common AC and emulsion binder types used by the districts. The most popular AC binder was found to be AC15-5TR. This is asphalt cement with a viscosity grade of 15 (AC15) and modified by the addition of 5% tire rubber (5TR) (USACE 1991). Most of these binders are used in combination with precoated aggregates. Asphalt cements are most popular in hot weather construction. They provide satisfactory seals with good adhesion. CRS-2P is the most commonly used emulsion statewide. This is a cationic (*C*) rapid setting (RS) emulsion that has been polymer (P) modified (Janisch and Gaillard 1998). Precoated aggregates are not normally used in combination with emulsions.

When emulsion use is compared to the AC usage, one can see that emulsions are not as commonly used as hot asphalt cements. Emulsions are generally preferred during cooler weather conditions and when there is a possibility of rain occurring during construction (Holmgreen et al. 1985). One of the major concerns with emulsion is the increased time between application and the removal of traffic control on a newly sealed portion of road. Thus, hot AC binders were often selected because traffic control could be removed earlier and the districts were reluctant to keep traffic waiting longer than the minimum (Gransberg et al. 1999).

Table 1 shows the average statewide aggregate and binders rates used for different binder/aggregate combinations. It shows the variable binder rates used to accommodate for the difference between the area on the wheel paths (WP) and outside the WPs. This is an effort to control wheel path flushing after chip seal application due to the additional embedment of the aggregate in the binder due to traffic.

Research Methodology

The researchers approached the study by collecting both design and performance data on 342 chip seal (also referred to as “seal coat”) projects worth nearly $30 million that had been completed in TxDOT’s Atlanta District since 1996. One hundred sixty five of these projects were emulsion projects utilizing CRS-2P as the binder, while 177 were asphalt cement projects using AC15-5TR binders. The external variables were minimized as Atlanta District had used the same chip seal contractor on all its districts chip seal projects for the past 12 years. Additionally, the same Area Office had been responsible for the district chip seal program during the same period providing both design and construction inspection. The asphalt binders had come from the same supplier and both types of seals had utilized the same type and size of aggregate from the same supplier. The one difference in the aggregate was that unlike the emulsion seals’ aggregate, the AC15-5TR used a lightweight aggregate was precoated with SS-2. All the seals had been shot during the same chip seal season, and a majority of them were completed before July 15 of each year per district policy. Thus, the comparison of the two binders can be made in a direct manner, and the results can be viewed as specific to the engineering properties of the binders themselves without the need to qualify the conclusions based on independent parameters that could not be mathematically removed from the data.

The research team reviewed chip seal performance data collected by Atlanta District in its ongoing Pavement Management Information System (PMIS) program database (TxDOT 2001). Atlanta District uses an outside consultant to do all their PMIS scoring to both enhance the completeness of the data by ensuring that PMIS data collection does not compete with other in-house work for constrained personnel resources and to ensure the objectivity of the input data (Baker personal Communication, 2003). Additional information was sought from the literature to aid in explaining the meaning of both trends and comparative results. The research team made a trip to Atlanta, Tex. in June 2002 to collect the data assembled by the Area Office in charge of the district chip seal program. After data reduction, the researchers developed a series of project performance metrics and conducted a statistical analysis of project performance. The following data were collected for each project, as available from the Atlanta District:

- type of binder,
- type of aggregate,
- specifications for emulsion and asphalt cement,
- average rate shot in the main lanes,
- specifications for aggregate,
- year of installation,
- contract requirements,
- contract amount,
- amount of material used,
- location of project,
- length in feet,
- length in miles,
- area of main lanes shot,
- area of intersections and miscellaneous locations such as drives and turnouts shot,
- average daily traffic,
- visible pavement distresses (shelling and/or flushing), and
- long term performance of underlying pavement.

The following data were collected from the PMIS database for each project:

Table 1. Typical Texas Department of Transportation Binder/Aggregate Combination Rates (Gransberg et al. 1999)

Binder grade	Average daily traffic (vehicles/day)	Binder rate on wheel path (gal/yd^2)	Binder rate on wheel path (L/m^2)	Binder rate outside wheel path (gal/yd^2)	Binder rate outside wheel path (L/m^2)	Aggregate rate on wheel path (yd^2/yd^3)	Aggregate rate on wheel path (m^2/m^3)
Average rates for grade 4 (1/2 in.) aggregate							
AC10	1228	0.28	1.52	0.28	1.52	124	136
AC15-5TR	6176	0.34	1.85	0.35	1.90	139	152
AC5	2507	0.37	2.01	0.37	2.01	126	138
AC5 w/latex	1248	0.35	1.90	0.35	1.90	119	130
CRS-2	960	0.50	2.72	0.61	3.32	125	137
CRS-2H	170	0.59	3.21	0.68	3.70	111	121
CRS-2P	1600	0.43	2.34	0.43	2.34	125	137
Average rates for grade 3 (5/8 in.) aggregate							
AC10	2500	0.38	2.07	0.38	2.07	119	130
AC5 w/latex	4025	0.38	2.07	0.38	2.07	109	119
CRS-2P	6130	0.44	2.39	0.44	2.39	120	131

Table 2. Underlying Pavement Condition in Study Area

Binder	Average distress score	Average RD	Average rut SH	Average rut DP	Average rut sum	Average pat
CRS-2P	95.85	3.57	6.09	1.23	6.66	0.94
AC15-5TR	99.48	3.53	4.80	0.65	4.83	1.81

- type of underlying pavement,
- percent deep and shallow rutting,
- patching percent,
- base failure percent,
- block cracking percent,
- alligator cracking percent,
- longitudinal cracking length per station,
- transverse cracking number per station,
- raveling score,
- flushing score,
- average 18 kip wheel loads,
- average annual maintenance cost,
- distress score,
- ride score,
- surface index,
- skid number, and
- pavement condition score.

The complete PMIS information was not available for all projects. However, the pavement condition (PC) score information was present for 150 emulsion projects and 157 asphalt cement projects. Skid numbers (SNs) were available for 62 of the emulsion jobs and 104 of the asphalt cement jobs. So, a sufficient sample size was obtained to conduct statistically significant analyses on both types of projects for the two major PMIS performance indicators. As a result, the data were divided into three base populations as follows: total population data set, PC data set, and SN data set.

Project Performance Metrics

The research team sought to develop as many performance measures as possible for the given data. Three types of metrics were created. The first contains standard averages for each category of PMIS performance ratings. The second category uses weighted averages based on total measures of area. These were used to develop a better idea of how the performance measures were actually distributed. Area weighted averages capture the salient physical aspect of a chip seal as it is by nature a technology based on area of coverage design. These were needed because the Atlanta District tended to use more AC15-5TR on four lane roads than they used the CRS-2P. Thus, the two binders are compared on the basis of the same physical unit.

The final category of metrics comes from a variant of utility theory called cost index number theory (West and Riggs 1986). As PMIS is itself is based on utility theory (TxDOT 2001), using cost index number theory is a logical choice for this type of analysis. The method seeks to combine cost and engineering measurements into a single index that can permit the direct comparison of two or more alternatives simultaneously and thus provide a measure of cost effectiveness on an engineering property basis. This theory allows the research team to compare a more expensive technology with a less expensive technology to determine if the incremental cost difference between the two alternatives is offset by enhanced engineering performance. To account for time value of money issues between the individual projects in the population, the 2002 bid costs for CRS-2P, AC15-5TR, and the aggregates were used. A hypothetical 2002 contract cost was computed using the actual quantity data from each project multiplied by the 2002 unit cost for each material. Thus, the cost metrics are all normalized to the present value without the need to assume a discount rate.

Table 3. Traffic Conditions and Maintenance Expenditures in Study Area

Binder	Average daily traffic (ADT)	Average \$/ADT	Average 18 kip (8,165 kg) axle loads	Average \$/18 kip (\$/8,165 kg)
CRS-2P	1074	\$88.50	322	\$347.30
AC15-5TR	4060	\$46.85	2908	\$159.71

Table 4. Raveling and Flushing in Study Area

Binder	Average high raveling score	Average low raveling score	Average raveling score	Average high flushing score	Average low flushing score	Average flushing score
CRS-2P	0.24	0.00	0.12	1.05	0.18	0.61
AC15-5TR	0.14	0.00	0.07	0.88	0.13	0.51

The PMIS data did not exactly coincide with the project data in that there were projects that spanned more than one PMIS data collection section. Therefore, when this was the case, the high and low values for the given PMIS ratings were recorded and a simple average of all values was also entered into the data set. Mathematical averages were computed for the following data items:

- percent deep rutting,
- percent shallow rutting,
- sum of deep and shallow rutting percents,
- patching percent,
- base failure percent,
- block cracking percent,
- alligator cracking percent,
- longitudinal cracking,
- transverse cracking,
- raveling score: high, low, average,
- flushing score: high, low, average,
- average 18 kip (8,165 kg) wheel loads,
- average annual maintenance cost,
- distress score,
- ride score,
- surface index,
- skid number: high, low, average, and
- pavement condition score: high, low, average.

Table 5. Skid Number Score Comparison

Binder	Average high skid number	Average low skid number	Average skid number	Weighted average skid number mile	Weighted average skid number area	Skid number cost index
CRS-2P	63	44	54	54	54	1640
AC15-5TR	60	34	57	47	45	2607

Table 6. Pavement Condition Score Comparison

Binder	Average high pavement condition score	Average low pavement condition score	Average pavement condition score	Weighted average pavement condition score mile	Weighted average pavement condition score area	Pavement condition score cost index
CRS-2P	63	44	54	54	54	1640
AC15-5TR	60	34	57	47	45	2607

Discreet Metrics

Discreet metrics were developed directly from the data and basically consist of mathematical averages of the PMIS information and the cost information for each project. The study computed 27 discreet metrics from the data set. Examples of these are average high flushing score, average low flushing score, and project average flushing score, average cost of binder, average cost of aggregate, average number of square yards on main lane, etc.

Weighted Average Metrics

As previously mentioned, the use of AC15-5TR on four-lane roads exceeded the use of CRS-2P and vice versa. As a result, the appropriate physical parameter on which to base a comparative analysis is the unit of area rather than on a unit of length. The following formulas were used to compute the weighted averages.

$$\text{WT PC} = \frac{3\text{SY}_i(\text{PC}_i)}{3\text{SY}_i} \tag{1}$$

where WT PC=square yard weighted average of the pavement condition score; SY_i=area in square yards of project "*i*" (1 yd^2 =0.836 m^2); and PC_i=pavement condition score of project "*i*."

$$\text{WT SN} = \frac{3\text{SY}_i(\text{SN}_i)}{3\text{SY}_i} \tag{2}$$

where WT SN=square yard weighted average of the skid number; SY_i=area in square yards of project "*i*" (1 yd^2=0.836 m^2); and SN_i=skid number of project "*i*." Twelve weighted average metrics were computed in this study. See Tables 2–6 for details.

Cost Index Number Metrics

The purpose for developing cost index numbers is to permit a direct comparison of a more expensive technical system, in this case, AC15-5TR with precoated lightweight aggregate, to a less expensive system, CRS-2P with nonprecoated aggregate that is designed to perform the same technical purpose. In effect, it is an objective method to measure how much "bang" TxDOT is getting for its chip seal "buck." During the statewide constructability review, the authors found two pavement maintenance philosophies. One espoused sealing as many lane miles each year as possible using a less expensive chip seal system on the idea that any seal would effectively extend the life of the pavement and thereby reduce overall system life cycle cost. The other approach maintained that the use of the best quality chip seal system was warranted to ensure a good surface wearing course and minimize the need for spot seals and other routine maintenance.

The other reason for developing these types of metrics is to address the cost/technical tradeoff issue between the two products. One major attraction is hot asphalt cement's ability to open a newly sealed road to traffic more quickly than emulsion seals. While there is some intangible safety benefit that might be accrued from this, faster opening to traffic is really a matter of convenience. Reducing the disruption of the traveling public reduces the number of complaints that must be addressed by a severely manpower-constrained public agency. Therefore, to select a specific technology solely on the basis of its short-term benefits effectively suboptimizes the purpose for chip seal projects in the first place. Thus, if one product or the other can be shown to be clearly more cost effective in the long term, then state personnel may be more willing to deal with short term disbenefits to obtain long term benefits.

In this study, two PMIS data categories effectively portrayed the salient reasons for conducting chip seal operations in the first place. The first is the PC score, and the second is the SN. The PC is computed using a utility theory algorithm and is a function of distress score (DS), RS, average daily traffic (ADT), and speed limit. It serves as an indicator of the need to perform maintenance on a given pavement. The DS for asphalt pavements is computed using the following equation (TxDOT 2002):

$$\begin{aligned}\text{DS} = 100(&U_{\text{SRut}} \times U_{\text{DRut}} \times U_{\text{Patch}} \times U_{\text{Fail}} \times U_{\text{Block}} \times U_{\text{Alg}} \\ &\times U_{\text{LCrack}} \times U_{\text{Tcrack}})\end{aligned} \tag{3}$$

where DS=distress score; U_{SRut}=utility value for shallow rutting; U_{Drut}=utility value for deep rutting; U_{Patch}=utility value for patching; U_{Fail}=utility value for failures; U_{Block}=utility value for block cracking; U_{Alg}=utility value for alligator cracking; U_{LCrack}=utility value for longitudinal cracking; and U_{Tcrack}=utility value for transverse cracking.

It should be noted that raveling (shelling) and flushing are not included in the DS as they have no utility factors in PMIS. It is also must be noted that PC score is influenced by road roughness which would yield a lower score for pavements covered by chip seals using a coarser aggregate. However, all the projects in the sample population utilized the same aggregate gradation. Thus, this is not a factor in this analysis. The PC score is computed using the following equation:

$$\text{PC} = \text{DS} \times U_{\text{Ride}} \tag{4}$$

where PC=pavement condition score (TxDOT manuals use the abbreviation CS); DS=distress score; and U_{Ride}=utility value for ride quality (based on serviceability index, ADT, and speed limit).

To evaluate the impact of binder selection on pavement condition, a cost index number was developed to measure the cost of each pavement condition score point. The metric will be called the Pavement Condition Cost Index and is shown in the following equations:

$$\text{PCCI}_i = \frac{\text{TC}_i}{\text{Ave PC}_i} \tag{5}$$

and

$$\mathrm{PCCI}_B = \frac{3\ \mathrm{PCCI}_i}{\mathrm{TP}_B} \tag{6}$$

where PCCI_i=pavement condition cost index of project "*i*"; Ave PC_i=average pavement condition score of project "*i*"; TC_i=total cost of project "*i*"; PCCI_B=pavement condition cost index binder "*B*"; and TP_B=total number of projects using binder "*B*."

The second cost index seeks to measure the cost effectiveness of each binder in creating a good friction course and will be called the skid number cost index. A recent report by the TxDOT Construction Division (TxDOT 2001) states: "FM (farm to market) roads are typically surfaced with high-macrotexture seal coats which give higher skid scores than roads surfaced with hot-mix asphalt or Portland cement concrete."

In this study, sampled chip seal projects were not confined to FM roads but included any surface that was covered by a chip seal. Thus, analyzing SN is extremely valuable to determine the extent to which this technology is achieving one of its design purposes, the development of a friction course on the road's surface. The following equations are used to complete this analysis:

$$\mathrm{SNCI}_i = \frac{\mathrm{TC}_i}{\mathrm{Ave\ SN}_i} \tag{7}$$

and

$$\mathrm{SNCI}_B = \frac{3\mathrm{SNCI}_i}{\mathrm{TP}_B} \tag{8}$$

where SNCI_i=skid number cost index of project "*i*"; Ave SN_i=average skid number score of project "*i*"; TC_i=total cost of project "*i*"; SNCI_B=skid number cost index binder "*B*"; and TP_B=total number of projects using binder "*B*."

Results of Quantitative Comparative Analysis

The first step is to measure the quality of the pavements that lie under the chip seals to establish if there is a relationship between the structural pavement and the performance of the seals. As neither asphalt cement nor emulsion chip seals are structural in nature, the PMIS data relating to distress score, rut depth, and patching are the best measure of the condition of the underlying pavements (TxDOT 2001). Examination of Table 2 shows that the emulsion seals are being placed on roads that are more heavily rutted and that have a lower distress score meaning that they are less structurally sound. The hot asphalt seals are placed on roads with more patching, and the two types of binders are over roads with roughly equal ride scores.

The second step is to examine if there are any differences in the traffic conditions and maintenance expenditures that might impact the performance of the seals. During the interview with Atlanta District personnel, they indicated that they tend to use the AC15-5TR on the higher ADT roads and the CRS-2P on the less traveled roads. Inspection of Table 3 confirms that fact with the hot asphalt cement projects being applied on roads with an average of four times the traffic of the of the roads that receive an emulsion chip seal. It also shows that the AC15-5TR roads experience nearly nine times more equivalent 18 kip (8,165 kg) equivalent single axle loads which would lead one to infer that truck traffic is heavier on those roads with hot asphalt cement chip seals. The additional traffic would normally coincide with a heavier pavement structural cross section to accommodate the additional load (Huang 1993). Thus, the relationship between traffic load and maintenance cost would not be linear. Table 3 shows that the average cost for emulsion chip sealing per ADT ($/ADT) and per 18 kip (8,165 kg) wheel load ($/18 K) are about twice the cost of asphalt cement. Nevertheless, one would expect that given the facts of Table 2 above, that maintenance costs would be higher on the emulsion roads as they are placed on pavement sections with greater inherent distress. Additionally, as the AC15-5TR is used on higher ADT roads, one would presume that those highways would also have a higher priority for maintenance funding.

The next pavement condition issue deals directly with the performance of the chip seals themselves with regard to raveling (also called shelling) and flushing (also called bleeding). Table 4 shows the average PMIS scores for both conditions. These distresses are optional ratings and are rated as none, low, medium, and high with corresponding values of 0, 1, 2, and 3, respectively, in the PMIS system (TxDOT 2001). Table 4 shows that while emulsion seals have both a higher average raveling score (Ave RAV) and flushing score (Ave FL) that both are less than one which indicates that on average less than 10% of the road's surface is either raveled or flushed. Therefore it seems that no specific conclusion can be drawn between the two binders with regard to the major chip seal distresses. However, one can say that the use of chip seals appears to be quite effective in the Atlanta District and that the majority of the sealed lane miles have been effectively sealed. This is an especially important conclusion as it sets the foundation on which to compare skid resistance between the two binders and overall pavement condition after sealing. If a high degree of flushing had been present in either of the binder types, it would have skewed the skid score and a correction would have had to be made to account for this issue. As the flushing and raveling scores for both the binders types are roughly equal and in the "none to low" score range, the comparison of binder performance can be made directly.

This leads to the discussion of skid resistance as measured by the SN. The TxDOT report "Managing Texas pavements" (TxDOT 2002) states (emphasis added by the authors):

> "The skid score does not indicate the stopping characteristic of any one vehicle, driver, or climatic condition, but *it is useful to engineers in evaluation of surface friction properties* of aggregate types, asphalt mix design, and pavement construction methods. Although higher skid scores are preferable to lower skid scores, it is not possible to select a single value which can be considered adequate for all sites and traffic conditions."

Table 5 shows the results of the analysis for the three types of metrics in this category. It can be seen that emulsion chip seals have consistently higher SNs regardless of the way in which the SN-related metric was computed. The average high SN, average low SN, overall average SN, and square yard weighted average SN was higher for emulsion projects than AC projects. Some of this SN difference can be possibly be explained as being due to the higher traffic that is experienced on the roads with hot AC seals detailed in Table 3. The remainder is probably due to the use on precoated lightweight aggregate in the hot AC seals. Gallaway found that lightweight aggregates abrade as they wear rather than polish, and this characteristic accounts for their superior frictional characteristics when compared to natural stone (Gallaway and Harper, 1966). Precoating this very porous material must decrease its skid resistance as compared to aggregate that has not been precoated. It must be noted that this result with respect to relative SNs is purely a function of the lightweight aggregate and should not be imputed to seals that use natural aggregate as cover stone.

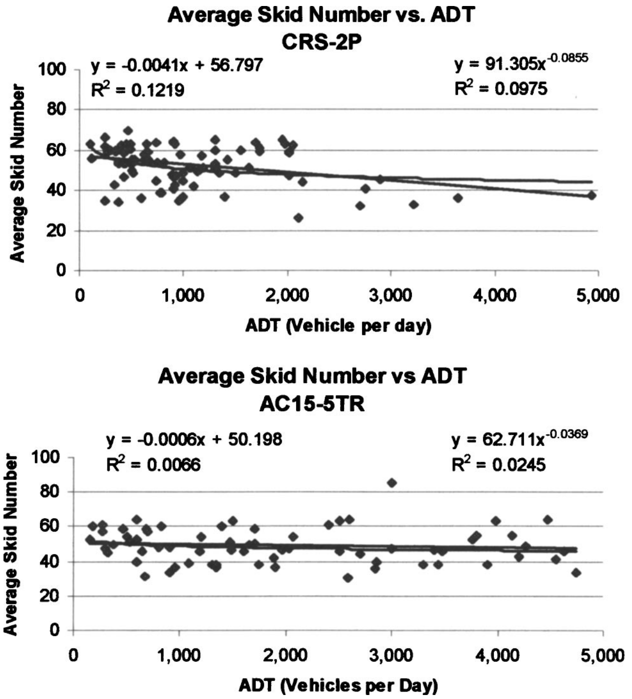

Fig. 2. Relationship between average skid number and average daily traffic with linear and nonlinear regression results

Additionally, this characteristic should not be construed to any inherent engineering property of the emulsion binder

Most telling of all the metrics is the skid number cost index (SNCI) that seeks to measure the "bang for the buck" aspects of the two processes. The SNCI for emulsions is half the number for the hot asphalt cement. This leads one to infer that the use of emulsion chip seals as a means to deliver a friction course with good skid resistance is much more cost effective than the use of AC15-5TR. This is particularly illustrative in light of the fact that emulsions are generally used on roads that are in worse underlying condition than the ones on which hot asphalt seals are applied. Again, the use of a binder that does not require precoated aggregate to attain adequate adhesion eliminate one element of cost and enhances the cost effectiveness of the emulsion seals. The raveling and shelling results shown in Table 4 indicate that emulsions perform about as well as hot asphalts after placement.

The final direct comparison utilizes the PMIS pavement condition (PC) score. This seeks to measure the current condition of the pavement. Table 6 outlines the results of the analysis. One can see that the two binders are pretty much equal in all metrics except the pavement condition cost index (PCCI). The square yard weighted average pavement condition shows the AC15-5TR to be slightly better in terms of overall performance than the CRTS-2P, but when the PCCI is considered, that advantage appears to be at about a 30% cost index premium. This conclusion must be tempered by the fact that the hot asphalt cement chip seals tended to be applied to higher volume roads with a greater number of equivalent 18 kip (8,165 kg) wheel loads.

Because it would seem that there must be a relationship between traffic volume and PMIS average scores, this possibility must be analyzed. Intuitively, one would assume that some direct relationship should exist between higher traffic levels and lower pavement condition and skid scores. This might then translate to higher expenditures for annual maintenance and subsequently more costly chip seals. The research team chose to search for these relationships graphically. Average skid number, average pavement condition score, average annual maintenance cost, and the total cost in dollars per square yard were all graphed against ascending average daily traffic (ADT) for each type of binder.

Fig. 2 illustrates the graphical relationships between the average skid number and ADT for each binder. It can be easily seen that other than a slight downward trend as ADT increases, there appears to be no direct mathematical relationship between these two parameters. Both linear and nonlinear regression analysis were tried to determine if the downward trend was significant. However *R*-squared values in both cases of less that 0.2 show that neither approach was able to closely fit the field data. Therefore, it must be concluded that while it might seem intuitive to attribute a correlation between skid number and ADT, there is no such mathematical relationship. The same approach was used to test for possible relationships between ADT and the three other parameters: average pavement condition score, average maintenance cost, and total unit cost. Again no clear trend was found to exist between these variables and ADT.

Another way to assess the impact of traffic volume on PMIS average scores between the two types of binders is to compare the metrics at the same ADT levels for both categories. A look at the CRS-2P shows that for the SN data set, maximum ADT is 4,930 vehicles per day, and for the pavement condition score data set, the maximum ADT is 8,130 vehicles per day. Selecting all the AC15-5TR projects with ADT's less than these two respective ADT's eliminates those roads from the comparison with much higher traffic volumes. The AC15-5TR data set has ADT volumes up to 19,300 vehicles per day. Table 7 contains the results of comparing the two binders on average skid number and average pavement condition score. It is evident that very little has changed from the numbers shown in Tables 5 and 6. The average SN for AC15-5TR increased two points. The corresponding average PC dropped one point.

Finally, the two binders should be compared on equal service life terms to ascertain if there is a detectable change in performance as the chip seal ages. To this end, the data was arranged by year of construction. Table 8 shows the results of comparison of projects constructed in the same year. The reader must be careful to not read any type of trend into these results as the projects are all different roads with different levels of traffic and underlying conditions. This thought is best illustrated by looking at the

Table 7. Skid Number and Pavement Condition Score Comparison at Equal Average Daily Traffic

CRS-2P				AC15-5TR			
Average skid number	Projects in sample	Average pavement condition score	Projects in sample	Average skid number	Projects in sample	Average pavement condition score	Projects in sample
54	90	87	150	49	67	87	128

Table 8. Skid Number and Pavement Condition Averages by Project Year

Project year	Average skid number CRS-2P	Average skid number AC15-4TR	Average pavement condition score CRS-2P	Average pavement condition score AC15-4TR
1997	57	48	76	85
1998	57	42	88	94
1999	44	45	86	89
2000	50	47	90	92
2001	52	51	84	83

change in average SN and average PC between the 1999 projects and the projects in 1998 and 2000.

If one were looking for a trend, it would seem that SN's on CRS-2P projects go down and back up over time. This is not the case as the projects in each year group in the table are different projects constructed in each year not a set of annual measurements on a single set of projects. So Table 8 must be interpreted on a comparative basis between the two binders in each project year category. It is interesting to note that the relative differences in SN's becomes greater in year groups 1997 and 1998 than in the more recent year groups. The emulsion projects seem to have a better ability to retain their higher SN over time than do the AC15-5TR projects. With regard to PC, it seems that the reverse it true. Average PCs seem to be roughly equal in the more recent year groups with a significant difference occurring in the later year groups.

As the SNCI and PCCI seem to be the significant metrics in this analysis the average SNCI and PCCI is then computed for all the projects in each year group. Figs. 3 and 4 illustrate a comparison on a year-by-year basis. One can see that the relative differences between the two are roughly the same as the same metrics calculated for the entire population as tabulated in Table 8.

Conclusions

The following conclusions can be drawn from the above analysis.

1. The Atlanta District's policy to use AC15-5TR hot asphalt cement chip seals on high volume roads and CRS-2P emulsion chip seals on lower volume roads is being followed. The roads in these two binder categories were skewed as expected with regard to average daily traffic. The use of the hot AC binders on the higher volume roads is primarily due to the faster curing time (i.e., reduced traffic control period) and indicates the District's higher confidence in that system's probability to be successfully applied (Baker, private communication 2003).
2. Because the emulsions were generally used on the lower volume roads, those roads were generally in poorer condition with regard to rutting, cracking, and as measured by the PMIS distress score.
3. Loss of aggregate after sealing (raveling or shelling) is not a problem for either binder type as the average PMIS raveling score is less than 1 in both cases. A rating of 1 corresponds to low, which is less than 10% of the road's surface affected. The same conclusion can be reached for flushing.
4. The average distress score for emulsions was roughly 4% worse than that of hot asphalt cements, and there was about 38% more rutting as measured by the average sum of the rutting scores. However, the emulsion's average pavement condition score was only 2% lower than the AC15-5TR. Therefore, even though the roads' surfaces were in worse condition, the overall pavement condition was not proportionately worse. This is not to infer that some engineering property of the emulsion chip seals is responsible for retarding pavement degradation. However, since the PMIS pavement condition score is computed by multiplying the distress score by the utility value for ride quality, it does indicate that the use of the emulsion binder has a positive effect on the ride quality score.
5. The CRS-2P pavement condition cost index was 949, and the AC15-5TR PCCI was 1281. This index was developed to measure the cost impact of pavement condition. The result shows that it costs less to maintain a unit of pavement condition score with the emulsions than it does with the hot asphalt cement binder.
6. When the binders were compared on a basis of the cost versus traffic volume, hot AC seals furnished the lower cost per unit of annual daily traffic. This conclusion combined with conclusion 5 above validates the Atlanta District policy with regard to the use of the two binders detailed in conclusion 1 above.
7. The same conclusion as conclusion 5 can be drawn with the skid number cost index. The SNCIs were 1,640 and 2,607 for emulsions and asphalt cements, respectively. Thus, it costs less to maintain a friction course as measured by the skid number with emulsions.
8. The CRS-2P emulsion chip seals appear to be the more cost effective of the two alternatives. Even though the emulsion chip seals are generally used on roads that are in poorer condition, the result was a surface that on average had higher skid resistance and a marginally better ride quality at a lower total cost. Over 30 metrics were used to compare the two

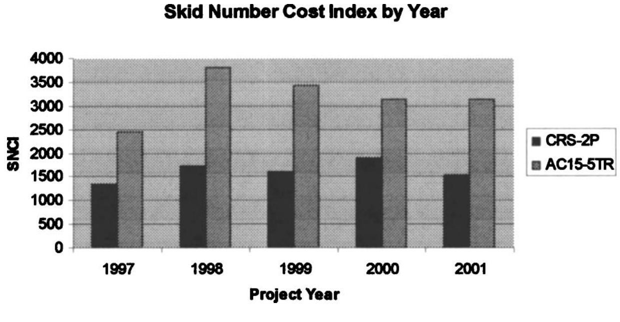

Fig. 3. Skid number cost index comparison by project year

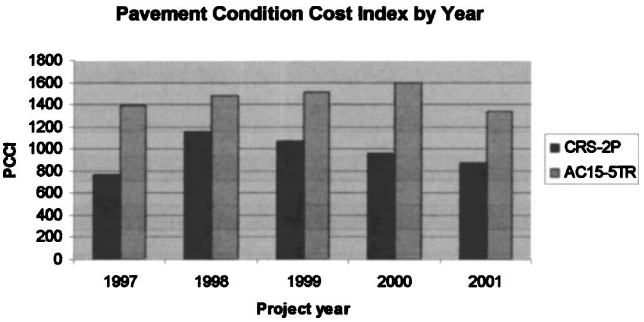

Fig. 4. Pavement condition cost index comparison by project year

binders. Significant differences were found as discussed above.

It should be noted that the results with regard to chip seal performance are a testimony to the quality of the Atlanta District's execution of its chip seal program (Gransberg et al. 1999). It also validates the most significant finding of the statewide chip seal constructability review. That review indicated that chip seal performance was a function of the experience of the state and contractor personnel involved and that consistently using the same approach to chip seal operations furnishes the long-term benefit of enhanced performance of those projects.

In summary, it can be concluded that when compared on a basis of equal traffic conditions, the emulsion chips seals performed every bit as well as the hot asphalt chip seals in the overall pavement condition score category even though they seem to be used on roads with a poorer underlying condition. The CRS-2P seals were markedly better than the AC15-5TR in the skid number category. The cost index metric analysis for pavement condition and skid number showed the emulsion chip seals to be convincingly more cost effective. While the differences between the two binders do not justify a sweeping recommendation to switch all chip seal projects to emulsion binders, it does show that the use of emulsion chip seals is warranted in those situations where its technical advantages make it appropriate. Additionally, in a constrained pavement maintenance budget scenario, it appears that the use of emulsion chip seals will permit a public agency like TxDOT to stretch those scarce resources with no apparent loss in performance.

Acknowledgments

The writers would like to warmly acknowledge the support provided for this study by the Asphalt Emulsion Manufacturer's Association, especially the efforts by AEMA members Alan James of Akzo Nobel Surface Chemistry, LLC and Bill O'Leary, of Prime Materials without whom the study would never have gotten off the ground. They reserve a special thanks to E. John Baker, Jr., PE, Area Engineer for the TxDOT Atlanta District who assembled the data, helped them in its proper interpretation, and ensured that the report was consistent with TxDOT practice and terminology.

Notation

The following symbols are used in the paper:

Ave PC_i = average pavement condition score of project "*i*";
Ave SN_i = average skid number score of project "*i*";
DS = distress score;
L = liters;
m^3 = cubic meters;
PC_i = pavement condition score of project "*i*";
PCCI_B = pavement condition cost index binder "*B*";
PCCI_i = pavement condition cost index of project "*i*";
SN_i = skid number of project "*i*";
SNCI_B = skid number cost index binder "*B*";
SY_i = area in square yards of project "*i*" (1 yd^2 0.836 m^2)
TC_i = total cost of project "*i*";
TP_B = total number of projects using binder "*B*";
U_{Alg} = utility value for alligator cracking;
U_{Block} = utility value for block cracking;
U_{Drut} = utility value for deep rutting;
U_{Fail} = utility value for failures;
U_{LCrack} = utility value for longitudinal cracking;
U_{Patch} = utility value for patching;
U_{Ride} = utility value for ride quality;
U_{SRut} = utility value for shallow rutting;
U_{Tcrack} = utility value for transverse cracking;
WP = wheel path;
WT PC = square yard weighted average of pavement condition score; and
WT SN = square yard weighted average of skid number.

References

Benson, F. J., and Gallaway, B. M. (1953). "Retention of cover stone by asphalt surface treatments." *Bulletin 133*, Texas Engineering Experiment Station, Texas A&M Univ. System, College Station, Tex.

Connor, B. G. (1984). "Asphalt surface treatment and sealing parameters."*Rep.*, Alaska Department of Transportation and Public Facilities, Fairbanks, Alaska.

Elmore, W. E., Solaimanian, M., McGennis, R. B., Phromson, C., and Kennedy, T. W. (1995). "Performance-based seal coat specifications." *CTR Research Rep. No. 1367-1*, CTR, Austin, Tex.

Epps, J. A., Chaffin, C. W., and Hill, A. J. (1980). "Field evaluation of a seal coat design method." *Research Rep. No. 214-23*, Texas Transportation Institute, Texas A&M Univ. System, College Station, Tex.

Epps, J. A., Gallaway, B. M., and Brown, M. R. (1974). "Synthetic aggregate seal coat research." *Rep. No. 83-2F*, Texas Transportation Institute, Texas A&M Univ. System, College Station, Tex.

Gallaway, B. M., and Harper, W. J. (1966). "A laboratory and field evaluation of lightweight aggregates as coverstone for seal coats and surface treatments." *Research Rep. No. 51-2*, Texas Transportation Institute, Texas A&M Univ. System, College Station, Tex.

Garcia-Diaz, A., and Cediel-Franco, F. (1988). "Evaluation of in-house maintenance contract costs for guardrail, rest areas, pavement marker, striping, and seal coats." *Research Rep. No. 380-1F*, Texas Transportation Institute, College Station, Tex.

Gransberg, D. D., Senadheera, S., and Karaca, I. (1999). "Analysis of statewide seal coat constructability review." *Texas Dept. of Transportation Research Rep. No. TX- 98/0-1787-1R*, Texas Tech Univ., Lubbock, Tex.

Hank, R. J., and Brown, M. (1949). "Aggregate retention studies of seal coats." *Proc., Association of Asphalt Paving Technologists*, Vol. 18, Minneapolis.

Hanson, F. M. (1935). "Bituminous surface treatments of rural highways." *Proc., New Zealand Society of Civil Engineers*, Christschurch, New Zealand, Vol. 21.

Harris, J. R. (1955). "Surface treatments of existing bituminous surfaces." *Proc., Symp. on Seal Coats and Surface Treatments for Existing Bituminous Surfaces*, Technical Sessions of the Associations of Asphalt Paving Technologists, Vol. 24, New Orleans.

Holmgreen, R. J., Epps, J. A., Hughes, C. H., and Gallaway, B. M. (1985). "Field evaluation of the texas seal coat design method." *Research Rep No. 297-1F*, Texas Transportation Institute, Texas A&M Univ. System, College Station, Tex.

Huang, Y. H. (1993). *Pavement analysis and design*, Prentice–Hall, Edgewood Cliffs, N. J., 546–582.

Jackson, D. C., Jackson, N. C., and Mahoney, J. P. (1990). "Washington state chip seal study," *Transportation Research Record, 1259*, Transportation Research Board, Washington, D.C.

Janisch, D. W. (1995). "Reevaluation of seal coating practices in Minnesota, in seal coats and asphalt recycling." *Transportation Research Record*, *1507*, Transportation Research Board, Washington, D.C.

Janisch, D. W., and Gaillard, F. S. (1998). *Minnesota seal coat handbook*, Minnesota Local Road Research Board, Office of Minnesota Road Research, Maplewood, Minn., 3.2–3.4.

Ksaibiti, K., Cole, M., and Farrar, M. (1996). “Evaluation of surface treatment practices in the United States.” *Transportation Research Record*, *1545*, Transportation Research Board, Washington, D.C., 26–34.

McLeod, N. W. (1960). “Basic principles for the design and construction of seal coats and surface treatments with cutback asphalts and asphalt cements.” *Proc., Technical Sessions*, The Association of Asphalt Paving Technologists, Supplement to Vol. 29, Memphis, Tenn.

Minnesota Department of Transportation (MnDOT). (1991). *Design and construction of seal coats*, Materials and Research Lab, Maplewood, Minn.

National Cooperative Highway Research Program (NCHRP). (1989). “Evolution and benefits of preventative maintenance strategies.” *Synthesis of highway practice No. 153*, NCHRP, Transportation Research Board, National Research Council, Washington, D.C.

Shuler, S. (1990). “Chip seals for high traffic pavements.” *Transportation Research Record*, *1259*, Transportation Research Board, Washington, D.C., 24–34.

Texas Department of Transportation (TxDOT). (1993). “Standard specifications for construction of highways, streets, and bridges.” TXDOT, Austin, Tex.

Texas Department of Transportation (TxDOT). (2001). *Analysis of PMIS skid data*, *Rep.*, Construction Division, Pavements Section, Texas Department of Transportation, Austin, Tex.

Texas Department of Transportation (TxDOT). (2002). Managing Texas pavements: Basic concepts and data interpretation for TxDOT’s pavement management information system (PMIS), *Rep. Prepared for Design Division, Pavements Section*, TXDOT, Austin, Tex.

Texas Transportation Institute (TTI). (1981). “Field manual on design and construction of seal coats.” *Research Rep. No. 214-25*, Texas A&M Univ. System, College Station, Tex.

United States Army Corps of Engineers (USACE). (1991). *Hot mix asphalt paving handbook*, Vol. UN-13, Washington, D.C., 1–10.

West, T. M., and Riggs, J. L. (1986). *Engineering economics*, 3rd Ed., TxDOT, McGraw-Hill, New York, pp. 781–789.