Comparing the Performance of Emulsion versus Hot Asphalt Chip Seal Projects in the Texas Department of Transportation's Atlanta District

Abstract

The study collected both design and performance data on 342 chip seal projects worth nearly $30 million that had been completed in the Atlanta District since 1996. 165 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 seals for the past 12 years. The one difference in the aggregate was that unlike the emulsion seals' aggregate, the AC15-5TR used a lightweight aggregate that was precoated with SS-2. Thus, the comparison of the two binders can be made is 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 form the data. The study found that the emulsion chip seals performed as well as the hot asphalt cement seals and were more cost effective of the two alternatives. Emulsion chip seals also furnished a better friction course as measured by the skid number.

Objective

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.

Background

Seal coats or surface treatments have more than a 50-year recorded history in the United States. The first uses were limited to surface treatments as wearing courses in the construction of low-volume roads. Since then, maintenance seal coats 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.

In 1960, McLeod provided definitions for surface treatments and seal coats (26). 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. 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" (28). On the other hand, routine maintenance was defined as "a program to keep pavements.... in good condition by repairing defects as they occur." As a PM activity, seal coats 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, improve ride quality, preserve existing structural strength, and improve visibility for night driving. The planned preventive maintenance activities are not expected to enhance the structural capacity of the pavement.

Seal Coat Design

The very early practitioners of surface treatments or seal coats appear to have used a purely empirical approach to their design. Sealing a pavement was considered then, as it is now in many circles, an art. The design of a seal coat 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 seal coat design process. These are to decide the type and amount of binder and aggregate.

Aggregates used in seal coat 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. They should also resist weathering. Texas State Department of Transportation classified the aggregate types as follows (29):

- Item 302: Aggregate for surface treatments
- Item 303:Aggregate for surface treatments (Lightweight)

Precoated aggregates are essentially designed to enhance the binding properties between aggregate and binder. The precoated aggregate surface with specified bituminous material prevents the poor bonding problem due to presence of dust on aggregate surfaces. Good bonding can eliminate flying stones that cause windshield cracks and ensure final quality of the pavement by preventing disintegrating of binder and aggregate. Additional cost of precoated aggregates is justified in many projects due to these benefits as well as reduced public complaint. Another way to prevent flying stones is to use lightweight aggregates. The main advantage of using lightweight aggregate is their superior skid resistance values (12). However, they do not possess the good abrasion durability unlike the hard rock aggregates. Several design approaches outlined in the literature are briefly described below.

Selection of cover stone aggregates is directly affected by the local availability of aggregates. Whatever the selected aggregate is, caution should be exercised with the aggregate size distribution. Gradation of the aggregate is desired to be as uniform as possible. One-size cover aggregate can be understood if there is an 85 weight percent passing from a specified size sieve. This will provide a better interlocking of particles and better aggregate detention on the surface. Also, the same embedment depth will be provided throughout the surface.

The shape of cover aggregate is also crucial to obtain a good interlocking pattern of aggregates. Angular aggregate shapes such as cubical or pyramidal surfaces have demonstrated satisfactory service. Rounded, elongated and flat gravels should be avoided. Flakiness index defined as the ratio of smallest size of aggregate to the average aggregate size can indicate the suitability of the aggregate. In practice such undesired particle shapes are avoided by specifying a maximum percentage of aggregates having a 0.6 flakiness index (11).

There are mainly 2 gradations used in seal coat applications in Texas. These are Grade 3 and Grade 4 aggregates. In addition to these gradations, Grade 5 and Grade 4 modified aggregates are also used. Grade 3 aggregate applications provide a thicker seal in terms of cover rock and binder. Hence these thicker seals will enable a better protection to the underlying surface. However, Grade 3 aggregates are susceptible to cause windshield cracks and rough riding surfaces that creates noise for the driver. Grade 3 seal coat applications can also be more expensive than other gradations due to higher amount of aggregate and binder utilized. As a remedy to these problems, lightweight and precoated aggregates can be used. One other advantage of Grade 3 aggregate is the relative tolerance of binder application rates. If the design rate is exceeded during construction, excess asphalt can be adsorbed easily without causing flushing problems due to larger voids between aggregates. Therefore binder rates should be more closely monitored when Grade 4 and Grade 5 aggregates are used. Coarser cover rock surfaces are preferred for high volume roads but good results can also be obtained with Grade 4 rock if the asphalt rate and type of rock are properly selected. Drainage properties of Grade 3 are better than Grade 4 cover rock that reduces the risk of hydroplaning.

Use of Lightweight Aggregates

Various factors can be evaluated before making a selection between precoated, lightweight aggregates. Lightweight aggregates have high skid values and are less likely to cause windshield cracks. However, they are more expensive than natural rocks, have less abrasion resistance, more difficult gradation control and high water absorption. On the other hand, natural cover rocks provide superior abrasion resistance, and are less expensive. Unlike the lightweight aggregates they have less skid values, likely to crack windshields, poor bonding performance with binders due to dust and mineral properties.

TxDOT first used lightweight aggregate in seal coats in the Abilene district where a 1000 ft. test section was constructed in 1962 (12). Around the same time, Brownwood district also started using it in surface treatment work. A comprehensive study undertaken at the Texas Transportation Institute studied the suitability of lightweight aggregate as coverstone for seal coats and surface treatments (32). 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 seal coats 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 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.

Hanson Method (New Zealand)

The first recorded effort at developing a design procedure for seal coats appear to be made by Hanson (19). His design method was developed primarily for liquid asphalt, particularly cutback asphalt, and was based on the average least dimension (ALD) of the cover aggregate spread on the pavement. Hanson calculated ALD by manually calipering a representative aggregate sample to obtain the smallest value for ALD that represents the rolled cover aggregate layer. He observed that when cover aggregate is dropped from a chip spreader on to a bituminous binder, the voids between aggregate particles is approximately 50 percent. He theorized that when it is rolled, this value is reduced to 30 percent and it further reduces to 20 percent when the cover aggregate is compacted by traffic. Hanson's design method involved the calculation of bituminous binder and aggregate spread rates to be applied to fill a certain percentage of the voids between aggregate particles. Hanson specified the percentage of the void space to be filled by residual binder to be between 60 and 75 percent depending on the type of aggregate and traffic level.

Kearby Method (Texas)

One of the first efforts at designing seal coat material application rates in the United States was made by Jerome P. Kearby, then Senior Resident Engineer at Texas Highway Department (24). He developed a method to determine the amounts and types of asphalt and aggregate rates for one-course surface treatments and seal coats. He developed a nomograph that provided an asphalt cement application rate in gallons per square yard for the input data of average mat thickness, percent aggregate embedded and percent voids in aggregate. The percent voids in aggregate used correspond to the percent voids in a bulk loose volume of aggregate and not to the aggregate spread on a pavement. If liquid asphalt were to be used, he recommended that the rate of bituminous material application should be increased such that the residual asphalt content is equal to the asphalt content given by the design nomograph. In order to determine the aggregate spread rate, for most aggregates, and especially for aggregates containing flat and elongated particles, Kearby recommended the laboratory Board Test method where aggregate is spread over a one square-yard area.

In addition to the nomograph, Kearby recommended the use of a uniformly graded aggregate by outlining eight grades of aggregate based on gradation and associated average spread ratios. Each gradation was based on three sieve sizes. He also recommended that combined flat and elongated particle content should not exceed ten percent of any aggregate gradation requirement. Flat particles were defined as those with thickness less than half the average width of particle, and elongated particles were defined as those with length greater than twice the other minimum dimension. Kearby was quick to point out that "computations alone cannot produce satisfactory results and that certain existing field conditions require visual inspection and the use of judgment in the choice of quantities of asphalt and aggregate." He suggested that when surface treatments are applied over existing hard-paved surfaces or tightly bonded hard base courses, the percentage of embedment should be increased for hard aggregates and reduced for soft aggregates. He also mentioned that some allowance should be made for highway traffic. It was suggested that for highways with high counts of heavy traffic, the percent embedment should be reduced along with using larger-sized aggregates and for those with low traffic, it should be increased with the use of medium-sized aggregates. However, Kearby did not recommend any specific numerical corrections.

Kearby also elaborated on the following construction aspects of surface treatments and seal coats based on his experience at the Texas Highway Department.

- Seal coats had been used satisfactorily on both heavy-traffic primary highways and low-traffic farm roads, with the degree of success largely depending on the structural strength of the pavement rather than the surface treatment itself.
- Thickness of the surface treatment range from ¼ in. to 1 in. with the higher thickness being preferred. However, lighter treatments have, in general, proven satisfactory when the pavement has adequate structural capacity and drainage.
- In general, most specification requirements for aggregate gradation are very broad, resulting in considerable variations in particle shape and size as well as percent voids in the aggregate.
- It is better to err on the side of a slight deficiency of asphalt to avoid a fat, slick surface.
- Considerable excess of aggregate is often more detrimental than a slight shortage.
- Aggregate particles passing the #10 sieve acts as filler, thereby raising the level of asphalt appreciably and cannot be counted on as cover material for the riding surface.
- Suitable conditions for applying surface treatments are controlled by factors such as ambient, aggregate, and surface temperatures as well as general weather and surface conditions.
- Rolling with both flat wheel and pneumatic rollers is virtually essential.

During the same period, two researchers from the Texas Highway Department (5) published a paper on their aggregate retention studies on seal coats. They conducted tests to determine the aggregate retention under a variety of conditions including source of asphalt cement, penetration grade of asphalt, number of roller passes, binder type (AC vs. cutback), aggregate gradation and binder application temperature.

All their tests were conducted under the same conditions with only the test parameter being variable. The authors concluded that aggregate retention was not significantly different in asphalt cements picked from five different sources commonly used by the Texas Highway Department at the time. A commentary made in the early 1950's by the authors on the subject of asphalt quality strikes a familiar theme commonly used by practitioners even today.

> " There has long been a perhaps natural but unjustified tendency to attribute a large variety of job failures to the *quality* or source of the asphalt without adequate investigation of the other factors involved. Ironically, this was as true back in the days of almost universal use of Trinidad natural asphalt ... now often referred to as standards of *quality* in demonstrating the inferiority of some *modern* product, as it is today" (5).

This study also highlighted the inter-relationship between the binder type, binder grade and the temperature of the pavement during the asphalt shot and during rolling. In one set of laboratory experiments, the aggregate loss from an OA-230 penetration grade asphalt cement (close to an AC-2.5) reduced from 44 percent to 11 percent when the number of roller passes increased from one to three. In the same study, the effect of aggregate gradation on the performance of seal coats was investigated. An OA-135 asphalt cement (close to an AC-5) applied at a rate of 0.32 gallons per square yard was used under different aggregate treatments and the corresponding aggregate loss values are reproduced in Table 1 below. These results highlight the authors' contention that increased #10-sized aggregate content pose aggregate retention problems in seal coats. In addition, these researchers showed that a smaller portion of aggregate smaller than ¼ in. size will result in better performance of the seal coat.

Table 1. Effect of Aggregate Gradation and Aggregate Treatment on Retention (5)

Test Condition for Aggregate	Aggregate Loss as a % of Original
12.6% passing #10 sieve	72.0
6.7% passing #10 sieve	57.4
0% passing #10 sieve	30.5
12.6% passing #10 sieve & rock pre-heated to 250°F	17.7
12.6% passing #10 sieve & rock precoated with MC-1	33.6

In 1953, more research findings on aggregate retention were published by Benson and Galloway of Texas Engineering Experiment Station (5). The intent of this research was to study the effects of field factors that usually affect the surface treatments as an extension of the Kearby design method. A comprehensive laboratory test program was conducted to study a number of factors including the material application rates, aggregate gradation, moisture and dust in the aggregate as well as the elapsed time between the application of binder and aggregate for different binder types. Some of the notable conclusions made by Benson and Galloway are listed below.

- A ten percent upward correction is needed to the aggregate quantity calculated from the Board Test recommended by Kearby (24) to account for spreading inaccuracy.
- For average mat thickness less than 0.5 in., a higher percentage embedment is needed to hold the smaller aggregate particles together. As a result, the authors proposed an alteration to the curve proposed by Kearby.
- When asphalt cement is used as the binder, aggregate should be spread as soon as possible after the asphalt is sprayed.
- Harder asphalt cements hold cover stone more tightly, but initial retention is more difficult to obtain.
- Cover stone with a limited variation in grading will give the highest retention.
- Wet aggregates give poor retention with asphalt cement.

- Dust in aggregate result in poor retention. However, wetting the dry aggregate before application and by allowing it to dry before rolling reduced the negative effect from dust.
- Aggregate retention increased with increased quantity of asphalt.
- When a 24-hour curing period was allowed, the retention of wet stone by RS-2 emulsion was slightly greater than that for dry stone.
- The retention of wet dusty stone was slightly less than for dry stone.

During the 1940's and 1950's, research work indicated that sufficient curing time is needed for seal coats constructed using liquid asphalt. The recommendation from researchers was that at least 24 hours of curing is required before opening the road for traffic. J. R. Harris (20) of the Texas Highway Department proposed, based on his experience, that precoated aggregate should be used to increase the performance of the seal coat as well as to expedite the construction process. Harris' contention was that precoated aggregates considerably shorten the required curing time by eliminating the problems associated with aggregate dust and moisture, and that traffic can be allowed to use the roadway within one hour after a seal coat is placed with precoated aggregate. Also, the report said that this would allow using seal coats on high traffic roadways where shorter lane closure times due to the use of precoated aggregates would make the traffic control problem a lot more manageable.

Modified Kearby Method (Texas)

In 1974, Epps et al. proposed a further change to the design curve developed by Kearby for use in seal coats using synthetic aggregates (12). Due to high porosity in synthetic aggregates, a curve showing approximately 30 percent more embedment than the Benson-Gallaway curve was proposed. The rationale for this increase was that high friction lightweight aggregate may overturn and subsequently ravel under the action of traffic.

In a separate research effort, Epps et al. (12) continued the work done in Texas by Kearby (24) and Gallaway and Benson (14) by undertaking a research program to conduct a field validation of Kearby's design method. Actual pre-construction and post-construction data of 80 different projects were gathered and analyzed for this purpose. It was observed that Kearby design method predict less asphalt rates than what is used in Texas practice and the study proposed two changes to the design procedures. First one is a correction to the asphalt application rates based on level of traffic and existing pavement condition. Second is the justification of the shift of the original design curve proposed by the Kearby and Benson-Gallaway methods, as suggested for lightweight aggregates.

The following equation was used to calculate the asphalt application rate (in gallons per square yard), which included two correction factors determined for traffic level and existing surface condition.

$$A = 5.61\frac{E}{d}\left(1 - \frac{W}{62.6G}\right)T + V \qquad \text{Equation 1}$$

Where *W* and *G* are the dry unit-weight and dry bulk specific gravity of the aggregate, respectively, and *d* is the mat thickness that can be measured in the laboratory. Also, *E* is the depth of embedment and *T* and *V* are traffic correction factor and surface correction factor, respectively, for the asphalt application rate (*A*). The proposed correction factors were projected from the actual mat thickness-embedment combinations that were proven to be working well in the field. Tables 2 and 3 show the asphalt application rate correction factors corresponding to traffic level and existing surface condition, respectively. Epps et al. (11) also suggested that consideration should be given to varying the asphalt rate both longitudinally and transversely as reflected by the pavement surface condition. Since then, practitioners and researchers have labeled this design approach as the "Modified Kearby Method."

Table 2. Asphalt Application Rate Correction Factor for Traffic (11).

	Traffic Level – Vehicles Per Day Per Lane				
	Over 1000	500 to 1000	250 to 500	100 to 250	Under 100
Traffic Factor (*T*)	1.00	1.05	1.10	1.15	1.20

Table 3. Asphalt Application Rate Correction Factor for Existing Surface Condition (11).

Description of Existing Surface	Asphalt Application Rate Correction (Gallons per Square Yard)
Flushed asphalt surface	-0.06
Smooth, nonporous surface	-0.03
Slightly porous, slightly oxidized surface	0.00
Slightly pocked, porous, oxidized surface	+0.03
Badly pocked, porous, oxidized surface	+0.06

Since the publication of this design procedure, TxDOT Brownwood district (17) has expanded on the asphalt application correction factors for ADT and existing surface condition. In addition, correction factors to incorporate the effects of truck traffic and aggregate gradation were also developed.

Application of Seal Coats

Seal coats are applied to existing pavement surfaces for various reasons: sealing the cracked surface against air and water intrusion, enhance skid values of the pavement, obtain a uniform looking surface that would improve visibility of traffic lanes and rejuvenate the dry and raveled surface. Seal coats have no additional load carrying capability when applied on a surface since they are effectively one rock thick sealing coatings. 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. If there exists a base failure or the pavement is very rough, seal coats cannot be used to improve the pavement quality. Therefore, seal coat applications should not be applied against badly cracked, and weathered pavement surfaces where a rehabilitation or overlaying activity is needed. In some cases, seal coats may be recommended on such poor surfaces as a temporary maintenance measure until the corrective action is taken. This may be needed because of inadequate funding or other technical constraints.

Seal coats are generally effective in sealing the cracks existing on roadway surface, unless they are the indicators of heavy base distresses. Seal coat 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 and corrugation problems. Flushing or bleeding surfaces that are considered for seal coat applications should be treated carefully because flushing is generally reflected to the new seal if the aggregate and binder rates are not designed accordingly. In such surfaces, binder rates should be decreased than what is normally used and coarser aggregate should be selected. One of the major difficulties in seal coat design is the non-uniformity of the pavement. Almost all of the seal coat sections have patches laid at different times and with different materials and flushing and shelling 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 detailed than desired. However, these alterations can be performed with an experienced field crew changing the rates as needed basis.

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 seal coat projects were surveyed. The results of that study were published in 1999 (17). Generally it was found that TxDOT districts used both emulsions and hot asphalt cements. There was a bias to use emulsions on seal applied by TxDOT crews and the hot AC's for contract projects. Figures 1 and 2 below illustrate the usage of the various binder option across the state.

Asphalt cement and emulsion usage by the districts is presented in Figure 1. It lists the common asphalt cement and emulsion binder types used by the districts. The most popular AC binder is found to be AC15-5TR. The others are AC15P and AC5. Most of these binders are used in combination with precoated aggregates. Asphalt cements are most popular in hot weather construction during summer months. They provide satisfactory seals with good adhesion. CRS-2P is found to be the most common emulsion used statewide. Precoated aggregates are not normally used in combination with emulsions.

When emulsions are compared to the AC usage chart it is realized that emulsions are not as commonly used as asphalt cements. Emulsions are generally preferred during cooler weather conditions and when there is the possibility of rain occurring during construction. One of the major concerns with emulsion is the spreading time of aggregate after the emulsion is applied. The Asphalt Institute says that aggregate should not be spread until the emulsion breaks or its color changes. However, this was not always implemented by the districts due to the districts' reluctance to keep traffic waiting for a long time.

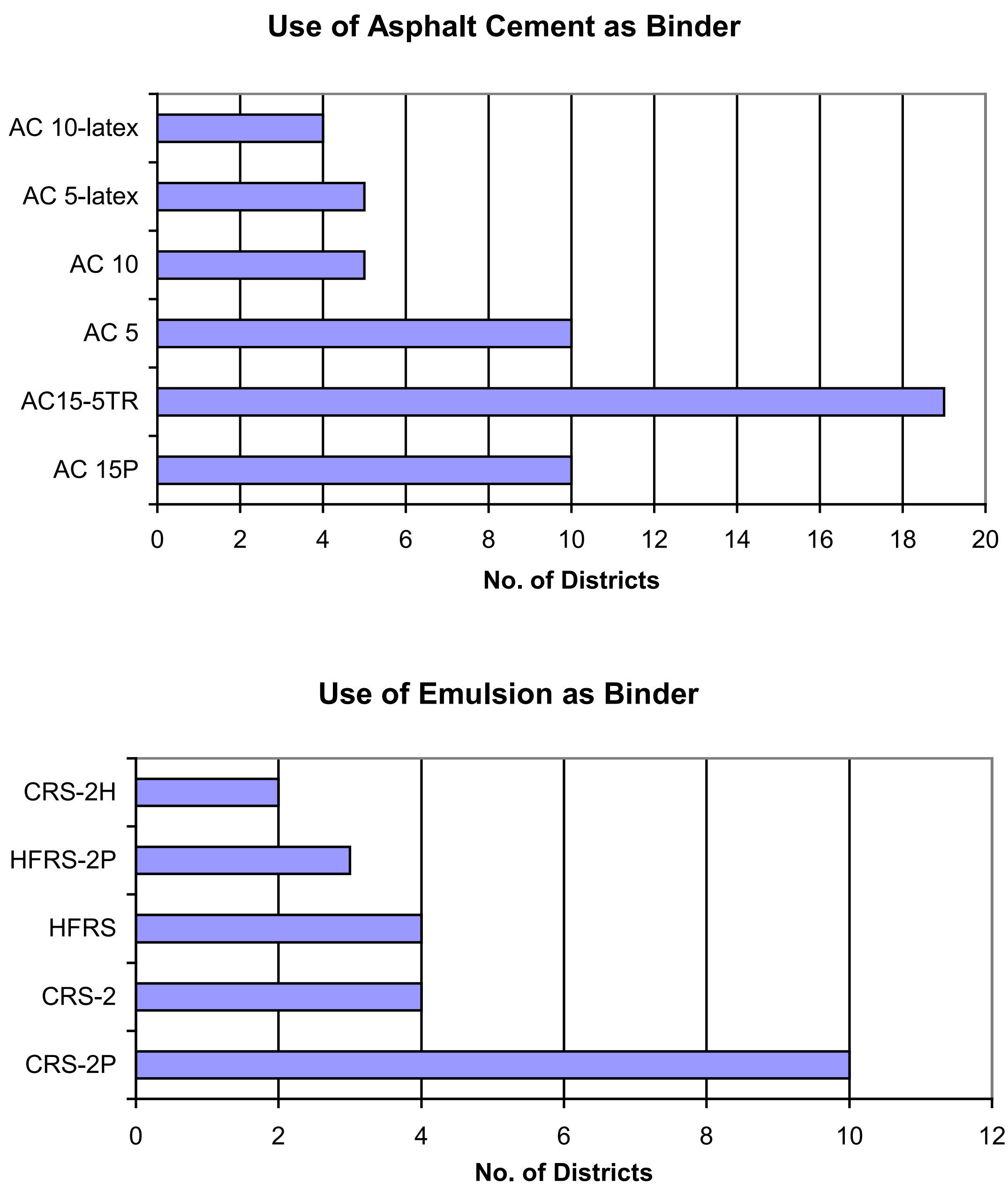

Figure 1: TxDOT District Asphalt Cement and Emulsion Use (17).

Table 4 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 and outside the wheel paths. This is an effort to control wheel path flushing after seal coat application due to the additional embedment of the aggregate in the binder due to traffic.

Table 4: Typical TxDOT Binder/Aggregate Combination Rates (17)

AVERAGE RATES FOR G4 AGGREGATE

Binder Grade	ADT	Binder Rate on WP (gal/sy)	Binder Rate Outside WP (gal/sy)	Agg.Rate on WP (sy/cy)
AC10	1228	0.28	0.28	124
AC15-5TR	6176	0.34	0.35	139
AC5	2507	0.37	0.37	126
AC5 w/ latex	1248	0.35	0.35	119
CRS-2	960	0.50	0.61	125
CRS-2H	170	0.59	0.68	111
CRS-2P	1600	0.43	0.43	125

AVERAGE RATES FOR G3 AGGREGATE

Binder Grade	ADT	Binder Rate on WP (gal/sy)	Binder Rate Outside WP (gal/sy)	Agg.Rate on WP (sy/cy)
AC10	2500	0.38	0.38	119
AC5 w/ latex	4025	0.38	0.38	109
CRS-2P	6130	0.44	0.44	120

Research Methodology

The researchers approached the study by collecting both design and performance data on 342 chip seal projects worth nearly $30 million that had been completed in the Atlanta District since 1996. 165 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 on all its districts seal cost projects for the past 12 years. Additionally, the same Area Office had been responsible for the district seal coat 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 that was precoated with SS-2. All the seals had been shot during the same seal coat season, and a majority of them were completed before July 15th of each year per district policy. 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 form the data.

The research team reviewed chip seal performance data collected by Atlanta District in its ongoing Pavement Management Information System (PMIS) program database (30). Additional information was sought in the literature to aid in explaining the meaning of both trends and comparative results. The Asphalt Emulsion Manufacturers Association coordinated the survey of Atlanta District. Based on this coordination, the research team made a trip to Atlanta, Texas in June 2002 to collect the data assembled by the Area Office in charge of the District seal coat program. The research assistant then reduced the data. The researchers developed a series of project performance metrics and conducted the statistical analysis of project performance. The following data points 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
- Average temperature, rainfall and freeze-thaw cycles during project life (National Weather Service)
- 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 shot
- Area of miscellaneous locations such as drives and turnouts shot
- Average daily traffic
- Visible pavement distresses (shelling and/or flushing)
- Long term performance of underlying pavement

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

- Type of underlying pavement
- Percent deep and shallow rutting
- Patching percent
- Base failure percent
- Block cracking percent
- Alligator cracking percent
- Longitudinal cracking percent
- Transverse cracking percent
- Raveling percent
- Flushing percent
- Average 18 kip wheel loads
- Average annual maintenance cost
- Date of last surface

- Distress score
- Ride score
- Surface index
- Skid number
- 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 (SN) were present 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 was 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 are 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 (34). As PMIS itself is based on Utility Theory (30), 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 a 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 researcher 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 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 of assuming a discount rate.

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 points:

- 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 percent
- Transverse cracking percent
- Raveling percent: high, low, average
- Flushing percent: high, low, average
- Average 18 kip wheel loads
- Average annual maintenance cost
- Date of last surface
- Distress score
- Ride score
- Surface index
- Skid number: high, low, average
- Pavement condition score: high, low, average

Discreet Metrics

Discreet metrics are developed directly from the data and in this study, they basically consist of mathematical averages of the PMIS information and the financial information for each project. The study computed 27 discreet metrics from the data sample. 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.

$$WT\ PC = \frac{3SY_i(PC_i)}{3\ SY_i} \qquad \text{Equation 2}$$

where: $WT\ PC$ = Square yard weighted average of the pavement condition score
SY_i = Area in square yards of project "i"
PC_i = Pavement condition score of project "i"

$$WT\ SN = \frac{3SY_i(SN_i)}{3\ SY_i}$$ Equation 3

where: WT SN = Square yard weighted average of the skid number
SY_i = Area in square yards of project "i"
SN_i = Skid number of project "i"

Twelve weighted average metrics were computed in this study. See Tables 5 through 9 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 non-precoated aggregate that is supposed to perform the same technical purpose. In effect, it is an objective method to measure how much "bang" TxDOT is getting for its seal coat "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 seal coat system on the idea that any seal would effectively extend the life of the pavement and thereby reduce overall life cycle cost. The second approach maintained that the use of the best quality seal coat 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 trade-off issue between the two products. Hot asphalt cements' major attraction is the 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 because of this, the 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 seal coat 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 points effectively portrayed the salient reasons for conducting seal coat operations n the first place. The first is the Pavement Condition (PC) score, and the second is the Skid Number (SN). PC is computed using a utility theory algorithm and is a function of Distress Score, Ride Score, ADT, and speed limit. It furnishes an indicator of the need to perform maintenance on a given pavement. The Distress Score for asphalt pavements is computed using the following equation:

$$DS = 100(U_{SRut} \times U_{DRut} \times U_{Patch} \times U_{Fail} \times U_{Block} \times U_{Alg} \times U_{LCrack} \times U_{Tcrack}) \quad \text{Equation 4}$$

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
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. The PC score is computed using equation 5 below:

$$PC = DS \times U_{Ride} \quad \text{Equation 5}$$

Where: PC = Pavement Condition Score (TxDOT manuals use the abbreviation CS)
DS = Distress Score
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 equations 6 and 7.

$$PCCI_i = \frac{TC_i}{\text{Ave } PC_i} \quad \text{Equation 6}$$

and

$$PCCI_B = \frac{3\, PCCI_i}{TP_B} \quad \text{Equation 7}$$

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"
TP_B = Total number of projects using Binder "B"

The second cost index seeks 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 (31) states:

> "FM 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, seal coats were not confined to Farm to Market (FM) roads but included any surface that was covered by a seal coat. 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. Equations 8 and 9 are used to complete this analysis.

$$SNCI_i = \frac{TC_i}{Ave\ SN_i} \qquad \text{Equation 8}$$

and

$$SNCI_B = \frac{3\ SNCI_i}{TP_B} \qquad \text{Equation 9}$$

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"
TP_B = Total number of projects using Binder "B"

Results of the Quantitative Comparative Analysis

The first step is to measure the quality of the pavements that lie under the seal coats to establish if there is a relationship between the structural pavement and the performance of the seals. As neither asphalt cement nor emulsion seal coats 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 (30). Examination of Table 5 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 covering more patching, and the two types of binders are over roads with roughly equal Ride Scores.

Table 5: Underlying Pavement Condition in Study Area

Binder	Ave DIS	Ave RD	Ave Rut SH	Ave Rut DP	Ave Rut Sum	Ave 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

The second step is to look and see 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 6 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 and emulsion chip seal. It also shows that the AC15-5TR roads experience nearly nine times more equivalent 18 kip 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. Thus, the relationship between traffic load and maintenance cost would not be linear. Table 6 shows that the average cost for seal coating per ADT ($/ADT) and per 18 kip wheel load ($/18K) are about twice the cost of asphalt cement. Nevertheless, one would expect that given the facts of Table 5 above, that maintenance costs would be higher on the emulsion roads as they are lighter pavement sections with greater inherent distress. Additionally, as the AC15-5TR is used on higher ADT roads, one would also presume that those highways would also have a higher priority for maintenance funding.

Table 6: Traffic Conditions and Maintenance Expenditures in Study Area

Binder	AVE ADT	$/ADT	AVE 18K	$/18K
CRS-2P	1074	$88.50	322	$347.30
AC15-5TR	4060	$46.85	2908	$159.71

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 7 shows the average PMIS scores for both conditions. These distresses are optional ratings (30) and are rated as none, low, medium, and high with corresponding values of 0, 1, 2, and 3, respectively. Table 7 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 been made to account for this issue. As both flushing and raveling are roughly equal, the comparison can be made directly.

Table 7: Raveling and Flushing in Study Area

Binder	Ave RAV hi	Ave RAV lo	Ave RAV	Ave FL hi	Ave FL lo	Ave FL
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

This then leads to the discussion of skid resistance as measured by the Skid Number (SN). The TxDOT report *Managing Texas Pavements* (30) 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 8 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 SN's 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. The most important point to not from all the metrics is the Skid Number Cost Index 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 telling in light of the fact that emulsions are generally used on roads that are in worse underlying condition than the hot asphalts. The raveling and shelling results shown in Table 7 indicate that emulsions perform about as well as hot asphalts after placement.

Table 8: Skid Number Score Comparison

Binder	Ave Hi SN	Ave Lo SN	Ave SN	Wt SN mi	Wt SN sy	SNCI
CRS-2P	63	44	54	54	54	1640
AC15-5TR	60	34	47	47	45	2607

The final direct comparison utilizes the PMIS Pavement Condition Score (PC). This seeks to measure the current condition of the pavement. Table 9 outlines the results of the analysis. One can see that the two binders are about equal in all metrics except the Pavement Condition Cost Index. The square yard weighted average pavement condition shows the AC15-5TR to be slightly better in 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 wheel loads.

Table 9: Pavement Condition Score Comparison

Binder	Ave Hi PC	Ave Lo PC	Ave PC	Wt PC mi	Wt PC sy	PCCI
CRS-2P	98	76	87	86	86	949
AC15-5TR	98	78	88	86	88	1,281

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 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.

Figure A1 in Appendix A 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 analyses were attempted to determine if the downward trend was significant. Figures A6 and A7 in Appendix A shows 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 evident. The same approach was used to test for possible relationships between ADT and three other parameters: average pavement condition score, average maintenance cost, and total unit cost. Figures A2, A3, and A4 graphically demonstrate that no clear trend exists 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 form the comparison with much higher traffic volumes. The AC15-5TR data set has ADT volumes up to 19,300. Table 10 contains the results of comparing the two binders on average skid number and average pavement condition score. One can see that very little has changed from the numbers shown in Tables 8 and 9 above. The average SN for AC15-5TR increased two points. The corresponding average PC dropped one point.

Table 10: Skid Number and Pavement Condition Score Comparison at Equal ADT's

CRS2P Ave Skid #	CRS2P # Projects In sample	AC15-5TR Ave Skid #	AC15-5TR # Projects In sample	CRS2P Ave PC	CRS2P # Projects In sample	AC15-5TR Ave PC	AC15-5TR # Projects In sample
54	90	49	67	87	150	87	128

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 address this, the data was arranged by year of construction. Table 11 shows the results of comparison of projects constructed in the same year. The reader must be careful to not extract 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 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 physically impossible. So Table 11 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 SN's gets 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 PC's seem to be roughly equal in the more recent year groups with a significant difference occurring in the later year groups.

Table 11: Skid Number and Pavement Condition Averages by Project Year

Project Year	Ave SN CRS-2P	Ave SN AC15-5TR	Ave PC CRS-2P	Ave PC AC15-5TR
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

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. Figures 2 and 3 below illustrate the 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 Tables 8 and 9 above.

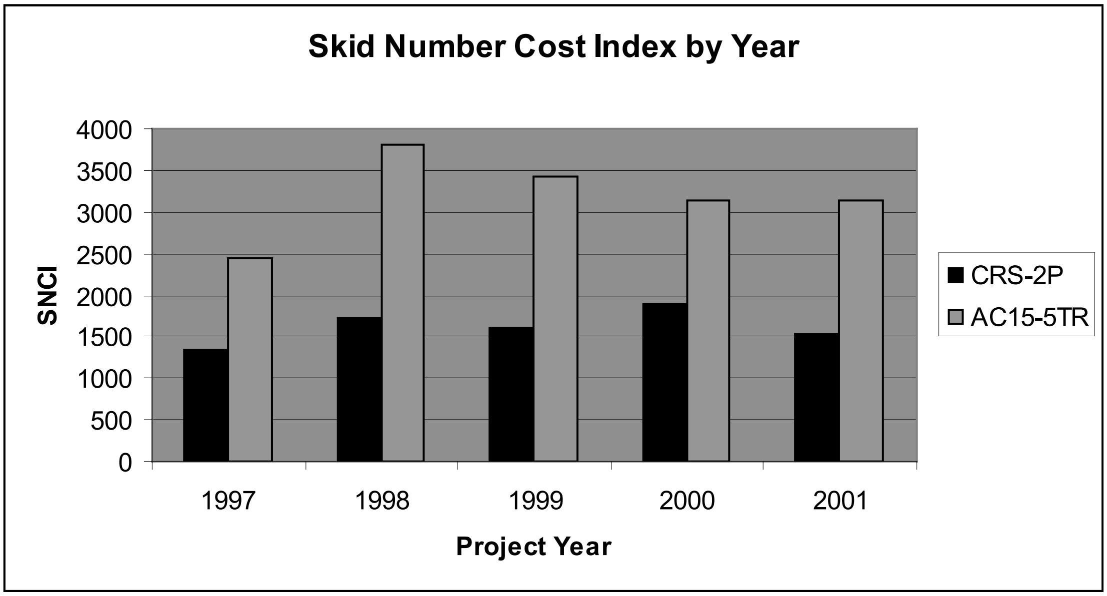

Figure 2: Skid Number Cost Index Comparison by Project Year

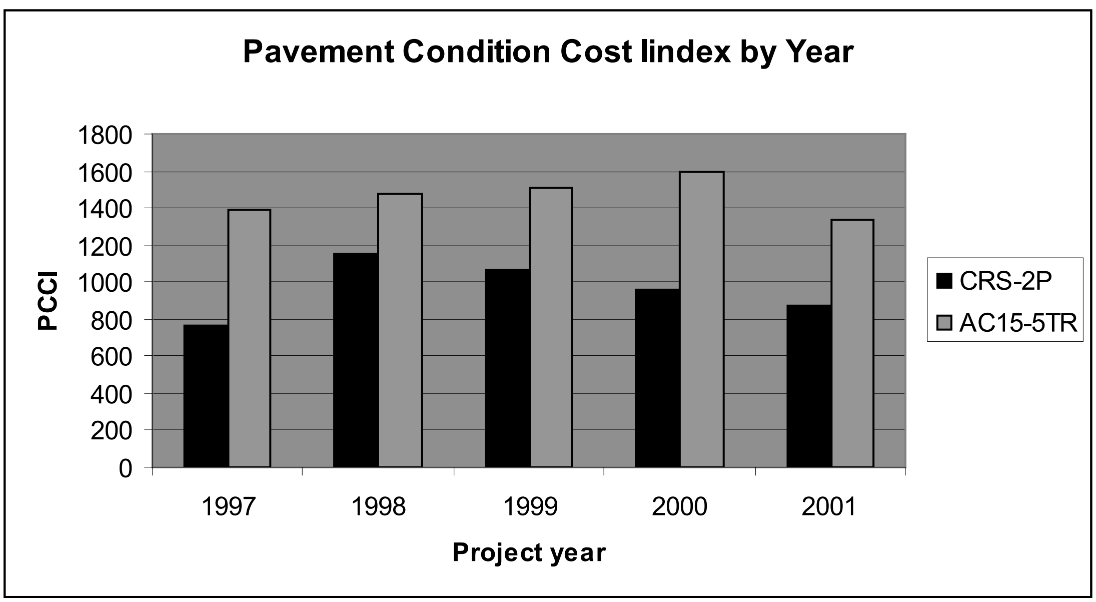

Figure 3: Skid Number Cost Index Comparison by Project Year

Conclusions

The following conclusions can be drawn from the above analyses.

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.
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 1.0 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. The same conclusion can be drawn with the Skid Number Cost Index. The SNCI's were 1640 and 2607 for emulsions and asphalt cements, respectively. Thus, it costs less to maintain a friction course as measured by the skid number with emulsions.
7. The CRS-2P emulsion chip seals appear to be the more cost effective of the two alternatives. Even though the emulsion chip seal 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 thirty metrics were used to compare the two binders. Significant differences were found as discussed above.

It must 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 (17). It also validates the most significant finding of the statewide seal coat constructability review. That finding was that seal coat 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 furnish the long term benefit of enhanced performance of those projects.

In summation, it can be concluded that the emulsion chips seals performed 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 stretch those scarce resources with no apparent loss in performance.

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