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Developing Network Slurry Seal Performance Models Using Pavement Management Systems Data

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Abstract
As a popular pavement preservation treatment, a slurry seal is typically included in agencies' maintenance and rehabilitation toolboxes, in decision trees of pavement management systems (PMS), or both. However, performance prediction models for slurry seals are mostly anecdotal or at undertaken at project level. The goal of this paper is to illustrate a method of developing data-driven performance models for slurry seal applications for use at a network level. A total of 537,891 pavement condition records were collected from 18 different agencies in the United States using the Metropolitan Transportation Commission's PMS program, StreetSaver®. Of these records, 1,195 slurry seal projects met the requirements to be utilized in the development of slurry seal performance models. The development of slurry seal performance models includes grouping project-level modeling results into functional classes, and testing and validating the slurry seal performance models with test cases as well as on actual data produced by agencies. The performance models for slurry seals placed on an asphalt concrete pavement vary depending mainly on the existing pavement's performance, the timing of the slurry seal application, the functional class, and surface type. The data-driven slurry seal models improved the accuracy of predicting slurry seal performance using PMS. The models could also be used to develop beneficial area curves, which are useful in estimating the cost-effectiveness of slurry seals constructed at various pavement condition index values and in identifying the optimal timings for slurry seal applications at a network level.

Keywords
infrastructure, infrastructure management and system preservation, pavement management systems, decision making: pavement management, pavement management, pavement performance, performance modeling, pavement preservation, performance-related

A slurry seal is a popular pavement preservation treatment that consists of mixtures of polymer-modified or conventional emulsified asphalt, graded aggregates, water, and other additives such as mineral filler (*1, 2*). Agencies around the world use slurry seal as a cost-effective maintenance treatment for public roads, highways, airport runways, parking lots, and a variety of other projects. Slurry seals are generally used to treat minor surface defects, such as surface voids, weathering and raveling, and minor cracks, and to improve friction and reduce water damage to the underlying pavement (*3*). A slurry seal can also be applied on top of a chip seal layer to form a cape seal, which is popular in many local agencies, especially on city streets (*4*). As a surface treatment, a slurry seal generally does not add structural capacity to the existing pavement, but it can extend the pavement service life and increase the pavement

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condition index (PCI) of treated pavement sections. PCI is defined as a numerical rating of the pavement condition based on the type and severity of distresses observed on the pavement surface. The PCI value of a pavement condition is represented by a numerical index between 0 and 100, where 0 is the worst possible condition and 100 is the best (*5*). The development of slurry seal performance models plays a key role in the reliability of a pavement management system (PMS). For example, performance models can be utilized to predict deterioration in the condition of pavements over time that have been treated with slurry seals.

Current Study and Problems

The literature review covers national practices for slurry seal performance modeling. Most agencies have not developed network performance models for slurry seal treatments based on real data. At project level, multiple researchers have investigated the performance of slurry seal treatment. Hajj et al. created slurry seal performance models to evaluate the cost-effectiveness of slurry seal applied to new and existing flexible pavement at 0, 1, 3, 5, 7, and 9 years after construction. The goal of this study was to obtain an optimum timing window for slurry seal application (*6*). The collation of data is necessary for the construction of slurry seal performance models. Ozer et al. collected several years of performance data, then evaluated the performance of preservation treatments used. After treatments were applied, pavement condition prediction models were developed for the treatments (*7*). According to an evaluation of the cost-effectiveness and optimal timing of pavement preventive-maintenance treatments in wet–freeze climates, cost-effectiveness depends on the time of application. The benefit cutoff value predefines the performance of the application (*8*). However, at the network level, not many models are derived from real data and analysis.

Frequently, maintenance treatments are delayed because of budget constraints and the lack of methods to model and quantify the treatment impact on performance and the consequences of delaying maintenance. After treatment, there is an improvement in the pavement condition and a reduction in the deterioration rate. Performance models can incorporate these changes by analyzing condition survey data before and after the application of the treatment. The importance of modeling preventive maintenance and communicating the consequences of not applying treatments at the right time have been documented in previous studies by Chang et al. (*9*).

The accuracy of performance models in predicting posttreatment pavement condition and in quantifying treatment effectiveness relies heavily on the quality and quantity of pavement data. The reliability of performance models can also be affected by the accuracy of data sources, including pavement condition assessment records and treatment history. Finding the optimal timing for a treatment is also difficult, given the lack of reliable records that document changes in pavement condition or the potential life extension following a specified treatment. The main limitation in modeling maintenance treatment effectiveness is in the quality and quantity of available pavement performance data (*10*); most local agencies do not collect traffic loading, -speed, or pavement structural information for their PMS, and sometimes the data on maintenance and rehabilitation (M&R) activities and inspections are inaccurate or even missing.

Therefore, the lack of posttreatment performance models for pavement preservation treatments is a major obstacle. Chen et al. used pretreatment performance models and other factors such as traffic and the environment to establish posttreatment performance models (*11*). This paper presents a method based on historical pavement condition inspection data to develop a network-level slurry seal performance model using real pavement survey data and treatment information.

Objective

The objective of this study was to create slurry seal performance models capable of predicting the deterioration of asphalt pavement treated with slurry seal over time. There are many factors that can affect the performance of slurry seal treatments, including existing pavement structural strength, pavement condition, traffic loading, environmental impact, and maintenance activities. Although most of the current network-level performance models for pavement preservation treatments are empirical, this research aimed to develop performance models based on real pavement condition survey data and M&R history.

Modeling Procedure

To develop reliable data-driven network-level slurry seal performance models, the modeling process shown in Figure 1 was developed and followed. The following describes the key steps in this modeling process:

- Data collection was completed, totaling 537,891 records from 18 agencies across states such as California, Oregon, and Washington. These west coast local agencies are in dry no-freeze or wet no-freeze climatic regions, as defined by FHWA LTPP program (*12*). The records included data on

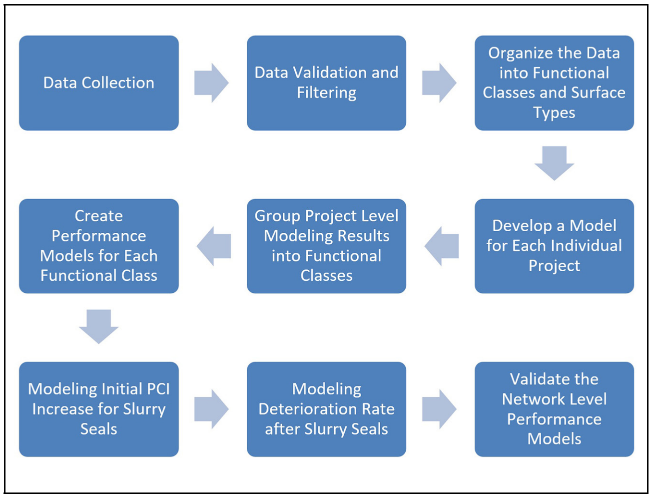


Figure 1. Flow chart of slurry seal performance modeling procedure.

all treatments undertaken by these agencies, but only slurry seal data were used for this study.

- Data validation and filtering were carried out to extract useful slurry seal records. Of 537,891 records, 32,056 records were found to be related to slurry seals. The slurry seal projects selected for this study had known dates for asphalt pavement construction and slurry treatment. These slurry seal projects needed to have undergone prior inspection and had at least two inspections following the slurry with no intervening maintenance treatments. The data were further filtered owing to poor surveying quality on some slurry seal projects. For example, a PCI should neither increase over time without any records of M&R activities, or drop more than 10 points a year for a normal pavement section. After the filtering process, the number of useful slurry seal records was reduced to 5,619 for a total number of 1,195 of slurry seal projects.
- Slurry seal data were classified into functional classes and surface types as follows: residential/local with asphalt concrete (AC) and AC over AC (AC/AC); collector with AC and AC/AC; and arterial with AC and AC/AC.
- Slurry seal performance models for individual projects were developed. The models were created with real data provided by agencies.
- Project-level modeling results were grouped into functional classes and network-level performance models were developed.
- Slurry seal performance models were tested and validated with test cases as well as using actual data produced by agencies.

Strategy to Model Individual Slurry Seal Projects

Individual project data were extracted from the data set. These data included the PCI inspection results of the project and M&R history. For the modeling of each selected slurry seal project, there needed to be at least two validated inspection points. A project-level, best-fit nonlinear performance model was then generated based on real project data. As an example, as shown in Figure 2, a slurry seal project was constructed on a 10-year-old AC pavement. The blue curve represents the predicted project performance curve without the slurry seal maintenance. The orange squares represent PCI survey results after the slurry seal construction. A nonlinear performance model (orange curve) was developed for slurry seal based on the PCI survey points after the slurry seal construction.

The nonlinear model used to represent the project performance curve in Metropolitan Transportation Commission's (MTC) PMS was based on Equation 1 (*13*). Chi (χ) was added to the equation to modify the slope or deterioration rate of the performance curve.

$$PCI_{PRO} = 100 - \frac{\rho}{\left(\ln\left(\frac{\alpha}{AGE}\right)\right)^{\frac{1}{\beta}}} \qquad (1)$$

where
PCI_{PRO} is projected PCI value as a function of age;
AGE is age of the pavement since last rehabilitation or reconstruction; and
α, β, and ρ are regression constants for the pavement family (with the same functional class and surface type) in the appropriate climatic zone in MTC's PMS program.

Initial PCI Jump and Change of Deterioration Rate

Performance models for each slurry seal project were developed using two new parameters: $\triangle$PCI and $\triangle$Chi. $\triangle$PCI represents the initial PCI jump or PCI increase right after a slurry seal treatment. As shown in Figure 3, $\triangle$PCI can be calculated as the PCI differences between the PCI right after- and the PCI immediately before slurry seal. Note that $\triangle$PCI is the calculated PCI difference using the slurry seal performance curve and the preexisting project performance curve at the age of slurry seal construction. Because cracks and other distress types will reflect through the slurry relatively quickly, to see the true impact of the slurry on performance, the slurry seal inspection generally should be delayed until after at least the first subsequent weather climatic cycle. $\triangle$Chi is used to model the change in deterioration rate or the slope of the

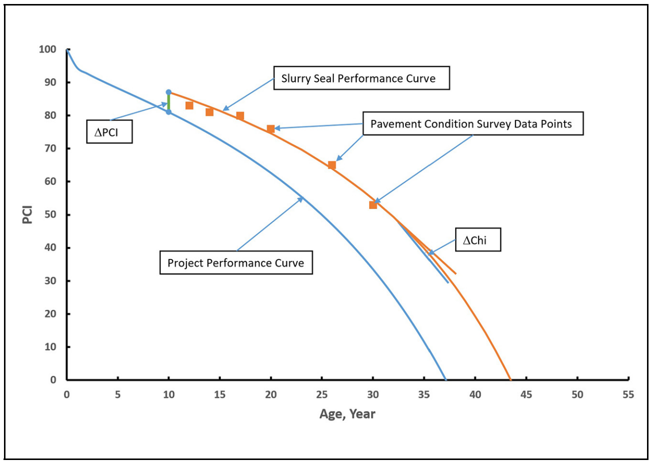
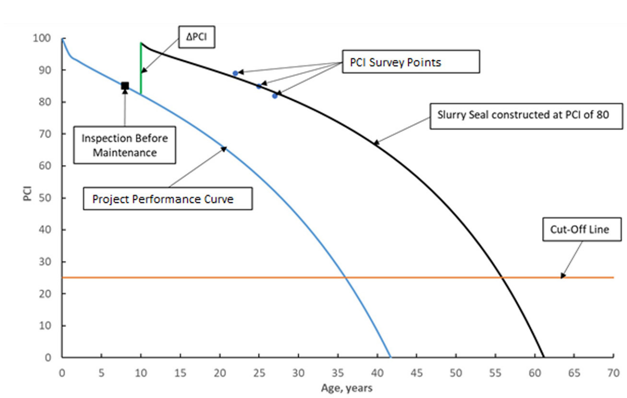


Figure 2. Modeling of an individual slurry seal project.



AGE_{Maint}	PCI_BM	PCI_AM	ΔPCI	Chi_BM	Chi_AM	ΔChi
10	**82**	**98**	**16**	**1.4**	**0.8**	**-0.6**

Figure 3. Example on residential asphalt concrete over asphalt concrete (AC/AC) curve.

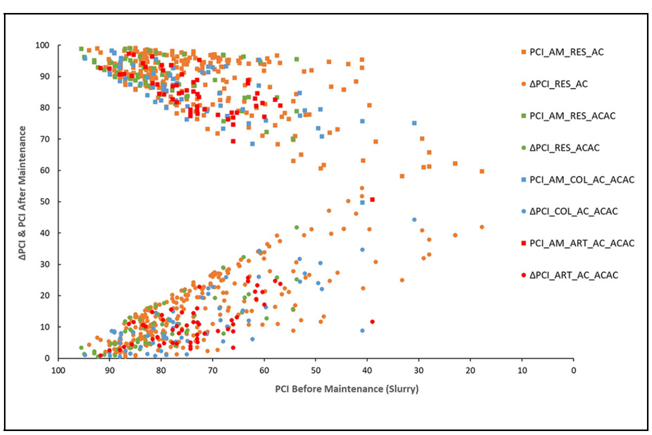


Figure 4. Summary of slurry seal project modeling results.

performance curve. A negative △Chi means the deterioration rate of the pavement is reduced.

An Example of Slurry Seal Project-Level Performance

This section illustrates the procedure to obtain the two parameters △PCI and △Chi. Figure 3 shows an example on a residential street AC with AC overlay (AC/AC) with a Chi of 1.4 for the preexisting PCI performance curve. The black square represents an inspection undertaken at Year 8 after the overlay and before maintenance; its PCI value was 85. Generally, nonlinear regressions were performed on pavement performance data both before and after the slurry seal. The best-fit curve, the blue line in Figure 3, represents the pavement performance curve before slurry seal, whereas the black line represents the pavement performance curve after slurry seal. The △PCI and △Chi can then be calculated from these two curves. The PCI had an initial jump from 82 to 98 after the age of maintenance (AGEMaint) at Year 10, represented by the green line. The △PCI, or jump, is obtained by subtracting the PCI before maintenance (PCI_BM) from the PCI after maintenance value (PCI_AM). In this case 98 − 82 obtaining a △PCI of 16. The three inspections after slurry seal maintenance had PCIs of 89, 85, and 82 as shown in the performance curve after maintenance (the black line), which predicts slurry seal pavement deterioration over time. The △Chi is calculated by subtracting the Chi before maintenance (Chi_BM) from the Chi after maintenance (Chi_AM). In this case 0.8 − 1.4 obtaining a △Chi of −0.6. The negative value of △Chi meant that the slope of deterioration was reduced. The cutoff line (orange-colored) represents the end of the pavement service life.

Network-Level Slurry Seal Model Development

This section covers the process for combining the data of individual projects slurry seal performance results to achieve a network-level slurry seal data set.

Figure 4 Summarizes the PCI values after maintenance and △PCI results of individual projects for different functional classes and surface types. Every point on the network-level model indicates a project-level result. The squares are the PCIs after maintenance and the round points represent the △PCIs. This summary includes the PCI after maintenance of every functional class and every surface type that used slurry seal applications. The orange squares on the upper section of Figure 4 represent the PCI values after maintenance of the 265 projects utilized on residential AC. The orange points on the lower section represent the 271 projects utilized for the △PCI on residential AC pavement. The green

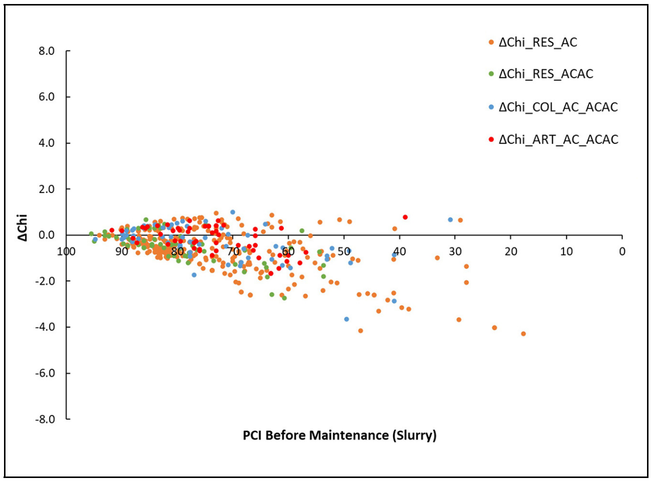


Figure 5. Summary of △Chi for slurry seal projects.
Note: △Chi is the change of deterioration rate or the slope of the performance curve.

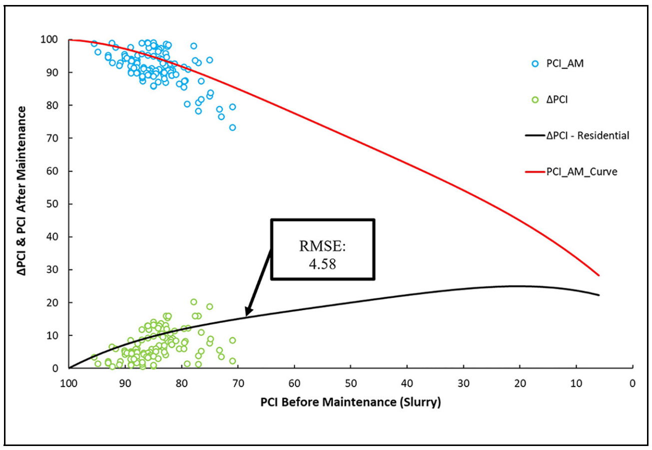


Figure 6. △PCI and PCI after maintenance for slurry seal on residential.
Note: PCI = pavement condition index.

squares on the upper section represent the 57 projects utilized for the PCI after maintenance on residential AC/AC. The green points on the lower section represent the 57 projects utilized for the △PCI on residential AC/AC. The blue squares on the upper section represent the 63 projects utilized for the PCI after maintenance on collector AC and AC/AC. The blue points on the lower section represent the 63 projects utilized for the △PCI on collector AC and AC/AC. The red squares on the upper section represent the 55 projects utilized for PCI after maintenance on arterial AC and AC/AC. The red points on the lower section represent the 55 projects utilized for the △PCI on arterial AC and AC/AC.

Figure 5 summarizes the △Chi for the four functional classes and surface types. Each point on the network represents a result from an individual project. The orange points are the △Chi for residential AC. The green points are the percent △Chi for residential AC/AC. The blue points are the percent △Chi for collector AC and AC/AC. The red points are the percent △Chi for arterial AC and AC/AC.

The goal of this research was to develop network-level performance models for each functional class, that is, residential streets, collectors, and arterials. Therefore, the project modeling results were grouped into three separate functional classes, and △PCI and △Chi models were developed for each functional class.

For example, Figure 6 shows the △PCI and PCI after maintenance for slurry seal on residential AC and AC/AC. The individual projects totaled 114. The blue circles represent the PCI after maintenance and the green circles represent the △PCI. The red line represents the projected PCI values after maintenance. The black line represents the projected △PCI performance curve for slurry seal on residential AC and AC/AC. The root mean square error of the line was calculated using Equation 2 (*14*),

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (\hat{y}_i - y_i)^2}{n}} \tag{2}$$

where

RMSE = root mean square error, defined as the standard deviation of the residuals;

$(\hat{y}_i - y_i)^2$ = square of the difference between estimated and sample value; and

N = number of sample points.

Figure 7 shows the network model for the △Chi for slurry seal on residential streets. The percent △Chi was calculated by obtaining the difference between Chi after maintenance and Chi before maintenance and dividing the result by the Chi before maintenance. The x-axis represents the PCI before maintenance and the y-axis the △Chi in percent. At this stage, the two surface types of AC and AC/AC were combined making a total of 145 individual projects represented by the blue circles. The black line is the predicted △Chi in percent with an RMSE of 0.21.

Figure 8 compares the predicted △PCI versus the PCI before maintenance on slurry seal for all surface types. Residential (the red curve) had the best performance with the highest △PCI; collector represented by the blue curve was the next best performing; and lastly, the arterials (black curve) performed poorly, as expected, especially given the poor preexisting pavement conditions (ie., low PCI before maintenance).

Figure 9 summarizes the predicted △Chi versus PCI before maintenance for the three funtional classes. Overall, all △Chi were negative, which means that slurry seals slowed down the deterioration rate of the pavement for all three functional classes. Residential, represented

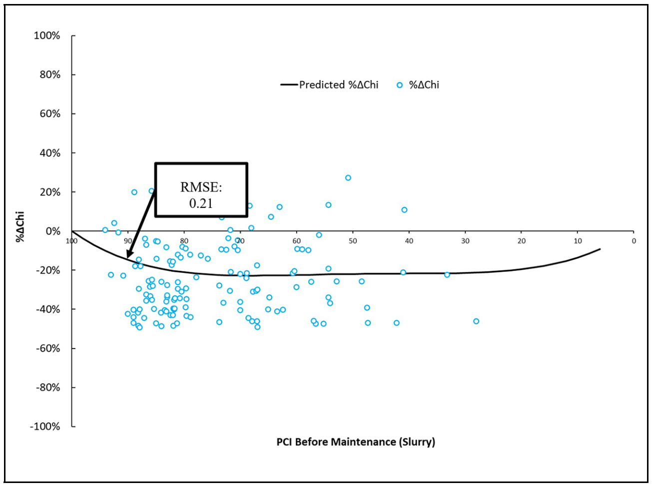


Figure 7. Summary of change of Chi for slurry seal on residential.

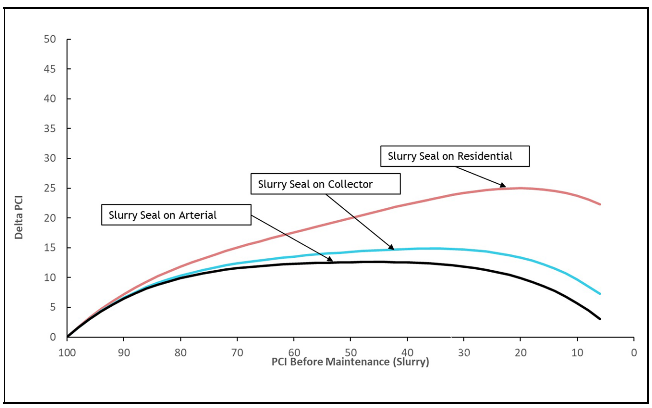


Figure 8. △PCI for slurry seal summary.
Note: PCI = pavement condition index.

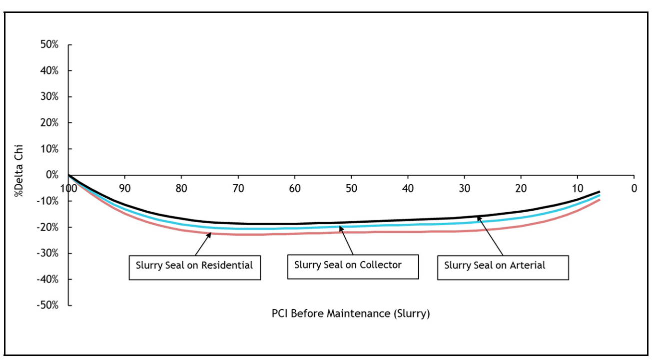


Figure 9. Percent in △Chi for slurry seal summary.
Note: △Chi is the change of deterioration rate or the slope of the performance curve.

by the red curve, performed the best, demonstrating high negative △Chi values; collectors (blue curve) were next best; and the arterials (black curve) again showed the poorest performance of the three, as expected.

Testing and Validation of the Performance Models

Data validation and model calibration were conducted multiple times to improve the models for the residential, collector, and arterial nonlinear regression curves. As stated, the performance curves for slurry seals placed on an AC pavement depend on the existing pavement's performance curve and the timing of the slurry seal application. As illustrated in Figure 10, slurry seal performance was highly dependent on the PCI value of the existing pavement immediately before the slurry seal application. In Figure 10, the red curve represents a slurry seal model constructed at a PCI of 90; the green curve represents a slurry seal model constructed at a PCI of 80; the blue curve represents a slurry seal model constructed at a PCI of 70; the purple curve represents a slurry seal model constructed at a PCI of 45. The black line at PCI 25 represents the cutoff line, below which the pavement is considered to have failed. The purple curve's initial PCI jump, △PCI, was higher than that of the green line. However, the benefit of a slurry seal application, in relation to the improvement of PCI over time, is not only dependent on the △PCI, but on the change in the deterioration rate and the timing of the application. The benefit, or effectiveness, of a slurry seal can be represented by the beneficial area (BA), which is the area bound by the project performance curve, △PCI, the slurry seal performance curve, and the cutoff line.

An example of BA for the slurry seal constructed at a PCI of 45 is shown by the shaded area in Figure 10. Although the △PCI for a slurry seal constructed at a PCI of 45 was higher than that of a slurry seal constructed at a PCI of 80, the BA at a PCI of 80 was much larger than at a PCI of 45.

The BA for a slurry seal constructed at any PCI value before maintenance can be calculated using △PCI and △Chi and preexisting pavement performance curves. The BAs on residential, collectors, and arterials were plotted against before-maintenance PCI values, as shown in Figure 11. The BAs of slurry seals constructed on residential, collectors, and arterials are represented by green-, red-, and blue curves, respectively. By looking at the trend of each curve, BA was higher for a slurry seal constructed on a section of pavement in good condition than on a pavement section in excellent or poor condition. This observed trend was consistent with common pavement engineering knowledge, that slurry seal should not be applied too early or too late.

Slurry seals generally have higher BAs on residential streets than on collectors or arterials. It was found that applying slurry seals at a PCI of 70 on residential streets had a benefit factor approximately 1.6 times higher than on collectors based on the data set in this study. This could be a result, in part, of the lower traffic loading and

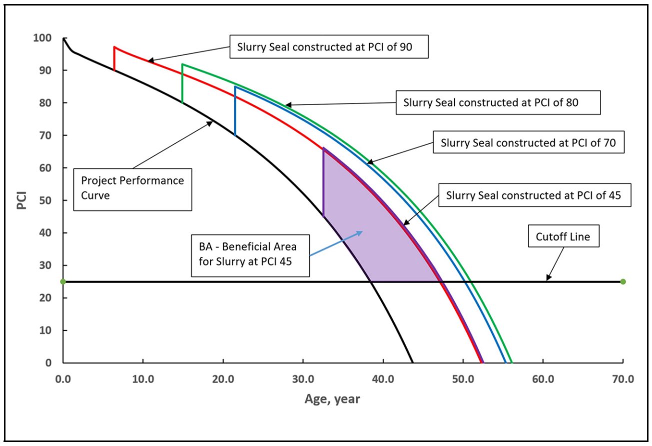


Figure 10. Network performance predictions of slurry seals and beneficial area concept.

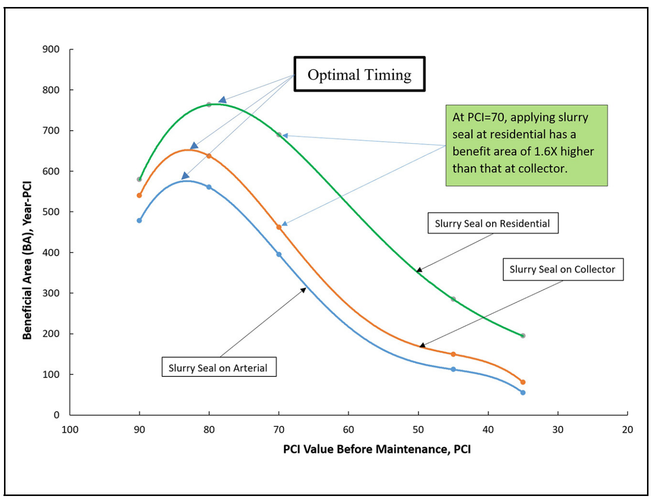


Figure 11. Beneficial area on residential, collectors, and arterials.

-volumes on residential streets. Other valuable information that can be derived from this graph is the optimal time to place a slurry seal. Based on Figure 11, the optimal times for applying slurry seals were at PCI_BM 75-85, 73-83, and 71-81 for arterials, collectors, and residential, respectively.

Conclusions and Recommendations

Conclusions

The following conclusions can be drawn from this study:

- The slurry seal performance models were developed based on real pavement condition survey data from MTC's PMS databases. These slurry seal models could improve the accuracy of predicting slurry seal performance at the network level.
- Development of performance models for individual slurry seal projects was done using data extracted from the real pavement condition survey data set. During this process new parameters, △PCI (initial PCI jump) and △Chi (change in deterioration rate), were used for each of the individual slurry seal project performance models.
- Data validation and calibration were conducted to improve the reliability of the slurry performance models and to improve the parameters. The model-predicted results were consistent with expert knowledge of slurry seals, specifically, they should not be applied too early (high preexisting PCI) or too late (low preexisting PCI).
- The slurry seal performance models were used to develop BA curves, which are useful for estimating the cost-effectiveness of slurry seals constructed at various PCI values and for identifying the optimal timings for slurry seal applications.

Recommendations

The following are the recommendations from this study:

- To develop a reliable network-level slurry seal performance model, significant amounts of data are needed. Agencies should improve the input accuracy of the pavement condition survey. Poor-quality data or contradictory survey information should be filtered out.
- Agencies should improve the accuracy of the inputs to M&R activities. They should also closely monitor M&R activity performance. With enough data, agencies could generate their own network-level performance models for their M&R treatments.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: D. Cheng, R. E. Smith, S. G. Tan, M. Jaquiz, C. M. Chang; data collection: D. Cheng, R. E. Smith, S. G. Tan, M. Jaquiz, C. M. Chang; analysis and interpretation of results: D. Cheng, R. E. Smith, S. G. Tan, M. Jaquiz, C. M. Chang; draft manuscript preparation: D. Cheng. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

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