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16. Abstract

SMERP (Supplemental Maintenance Effectiveness Research Program) was designed to study the effectiveness of maintenance treatments typically used in Texas. Six maintenance treatments and a control section were applied at 20 locations throughout the state. Treatments included: asphalt rubber chip seal, polymer modified emulsion chip seal, latex modified asphalt chip seal, asphalt chip seal, microsurfacing treatment, and a fog seal section. Researchers inspected the sites annually for the next eight years.
This project provides statistically valid guidance on the performance of the various maintenance treatments for the key variables of initial condition, type of distress, and type of treatment so that the user can select the most appropriate treatment. The documentation will take the form of a manual that describes the expected performance, life extension, and recommendations on timing.

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ANALYSIS AND TREATMENT RECOMMENDATIONS FROM THE SUPPLEMENTAL MAINTENANCE EFFECTIVENESS RESEARCH PROGRAM (SMERP)

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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation (TxDOT) or Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation. Additionally, this report is not intended for construction, bidding, or permit purposes. Thomas J. Freeman was the principal investigator for the project.

ACKNOWLEDGMENTS

Special thanks are given to the project director Joe Leidy; to Elias Rmeili, Larry Buttler, Dr. Andrew Wimsatt, James Brown, and James Sassin of TxDOT for their assistance in the development and construction of the Supplemental Maintenance Effectiveness Research Program (SMERP) experiment; and to the other members of the project monitoring committee. This project was completed in cooperation with TxDOT and FHWA.

This report is dedicated to the memory of Donald A. Pinchott, without whose extraordinary assistance in collecting the data through numerous trips to all of the sites, his assistance in the compilation and analysis of the data, and friendship, the work could not have been completed.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Cont.)

TABLE OF CONTENTS (Cont.)

LIST OF FIGURES

LIST OF FIGURES (Cont.)

Page

LIST OF FIGURES (Cont.)

LIST OF FIGURES (Cont.)

LIST OF FIGURES (Cont.)

Page

LIST OF FIGURES (Cont.)

Page

LIST OF FIGURES (Cont.)

Page

LIST OF FIGURES (Cont.)

Page

LIST OF PICTURES

Page

LIST OF TABLES

LIST OF TABLES (Cont.)

Page

CHAPTER 1. BACKGROUND AND OBJECTIVES

BACKGROUND

Now that most of the new road construction in the United States is complete, the major emphasis has switched to maintaining those roads. In an effort to improve the information available on the performance of maintenance treatments, the Strategic Highway Research Program (SHRP) implemented research on the effectiveness of maintenance treatments. SHRP is gathering field performance data from pavement test sections spread over the various climatic regions of the United States. However, the SHRP data are not applicable to many of the pavement preventive maintenance treatments currently used in Texas.

The SHRP H-101 Maintenance Effectiveness program studied the effects of selected preventive maintenance treatments (Smith, et al., 1993). Texas is in the SHRP Southern region. The SHRP Southern region has test sites throughout Texas, as far north as Tennessee, and as far east as Florida. The SHRP research required that the contractor use the same asphalt and aggregate at each site constructed within the specific SHRP region. In addition, the SHRP research studied the following maintenance treatments only: emulsified asphalt chip seal, crack seal, slurry seal, and a thin overlay. When SHRP personnel were looking for SHRP sites on which to build the Asphalt Maintenance Cost Effectiveness Study, Specific Pavement Study-3 (SPS-3), they offered to state highway agencies the option to build supplemental test sections adjoining the SPS-3 sections under the agreement that SHRP would monitor all test sections constructed. Several Texas districts expressed interest in the SHRP offer. However, a combination of limited funding in the individual district's maintenance allocation and lack of consensus on which treatments to place resulted in a decision by the administration to adjust the state's overall preventive maintenance program and develop a comprehensive preventive maintenance experiment.

In 1990 the Texas Department of Transportation (TxDOT) was spending approximately $450 million per year on its overall maintenance program and approximately $150 million per year on the preventive maintenance program. TxDOT introduced the Texas Preventive Maintenance Research Program at the annual District SHRP Coordinators meeting in October 1990. The name of this program was later changed to the Supplemental Maintenance Effectiveness Research Program

(SMERP). One million dollars was allocated to the experiment to build test sections of preventive maintenance treatments of interest to Texas but not considered in the SHRP national experiment.

The SMERP study was designed to study more closely the types of maintenance treatments typically used in Texas, and it allowed the contractor to use local materials if desired. The treatments constructed in the SMERP study were asphalt rubber chip seal, polymer modified emulsion chip seal (also called CRS-2P), latex modified AC (asphalt cement) chip seal, unmodified AC chip seal, and a microsurfacing treatment. All treatments were placed on test sections that were 500 feet (213.4 m) long. Both lanes were treated and the shoulders were also treated, where they existed. Shoulders were not treated under the SHRP SPS-3 study. State forces treated the fog seal section. A control section was established on which no treatment was placed. In general, the SMERP contractor did not use local materials at each site, but did use local or regional sources of asphalt and aggregate where available.

OBJECTIVES

The goal for the SMERP experiment is to establish the effectiveness of typical and promising maintenance treatments used in Texas to prolong the life of asphalt pavements.

Factors that contribute to increased maintenance effectiveness and optimum pavement life-cycle cost are maintenance planning, spending, and performance monitoring. TxDOT will be able to address these factors by using the pavement management system and the data collected from the SHRP SPS-3 and SMERP studies. By combining the data and analysis of both programs, the department will assure optimal planning strategies in selecting preventive maintenance treatments. Once again, the primary objective is to determine optimum preventive maintenance strategies that prolong pavement life and to demonstrate positive rates of return on preventive maintenance funds.

EXPERIMENT DESIGN

TxDOT decided that the experiment design should incorporate factors considered to be key variables in the analysis and that the basic design matrix should be similar to the one developed for the SHRP study. At that point, the decision was made to fill the matrix with candidate projects that fit the following criteria.

A. Performance Regions:
   West, East, South, Northwest, and Central.

B. Pavement Condition:
   Good and Fair.

C. Traffic:
   Low and High.

After reviewing all of the sites submitted, TxDOT determined that the goal of filling all of the above criteria could not be accomplished without substantial additional work. However, the goal of including all of the performance regions was satisfied. Sections that fit all of the pavement condition and traffic criteria were not available, but the sites selected were typical candidates to receive preventive maintenance treatments. Table 1 provides the final list of sites, and Figure 1 illustrates the geographical distribution of the sites.

Potential SMERP sites were identified by districts that offered to participate in the study. The sites were then approved by the TxDOT Design Division. The districts marked the beginning and end of each treatment and provided signs along the roadway to indicate the location of each of the SMERP treatments.

LAYOUT, MARKING, AND SIGNING TEST SECTIONS

Figure 2 illustrates the typical layout of test sections within each site. All sections were grouped together unless there was a change in pavement structure, traffic, or condition. The monitoring section is 500 feet (152.4 m) long and only in the designated lane. However, some visual distress data have been collected on both lanes.

To alert the public to the existence of a test site, the district installed a sign alongside the test section 6 feet (1.8 m) to the right of the shoulder and 200 feet (61.0 m) before the first test section. This sign reads "TEST SITE NEXT 1 MILE." Signs identifying the specific treatment type are installed near the right-of-way line at the beginning of each section. Each sign listed SMERP, the test section number, and the treatment type. At the one site (site 7) where the district did not install signs, the fog seal and control section were chip sealed by state forces unaware of the test sections. These treatments at these sites were removed from the experiment.

Table 1. Test Sites, Locations, and Section Numbers.

SITE NO.	DIST.	ROAD	COUNTY	REF. MARKER FROM	REF. MARKER TO	LOCATION FROM	LOCATION TO	SITE DESIG.
1	PAR	SH 11	Grayson	600+0.000	600+0.800	2.8 mi S. of FM 637	0.8 mi S.	48A01
2	PAR	SH 19	Hopkins	246+0.000	246+0.760	Sulphur Springs City Limits	0.8 mi S.	48B01
3	AMA	US 385	Deaf Smith	116+0.000	116+1.000	FM 1412	FM 1062	48C04
4	AMA	FM 1061	Potter	102+0.000	104+0.000	0.8 mi E. of FM 2381	2.0 mi E.	48D04
5	ODA	FM 181	Ector	326+0.000	336+0.500	Andrews County Line	Near SH 158	48E06
6	ODA	SH 349	Martin	288+0.000	302+1.850	Near FM 87	Dawson Co.	48F06
7	ABL	SH 36	Taylor	296+7.000	302+3.000	Abilene City Limits	Callahan Co.	48G08
8	ABL	US 84	Scurry	407+1.740	404+4.000	Snyder City Limits	US 180	48H08
9	WAC	FM 933	McLennan	356+1.367	358+0.161	FM 3051	0.8 mi S.	48I09
10	TYL	SH 135	Smith	302+1.962	304+1.752	420 m N.E. of SH 64	0.8 mi N.E.	48J10
11	YKM	SH 35	Calhoun	602+0.000	606+0.260	Jackson Co. Line	FM 1593	48K13
12	YKM	SH 71	Fayette	644+0.283	648+0.310	Baylor Creek	FM 955	48L13
13	SAT	SH 46	Bandera	472+0.442	468+0.042	Kendall Co. Line	SH 16	48M15
14	SAT	FM 484	Comal	462+0.041	464+0.988	FM 32	FM 306	48N15
15	BRY	US 190	Milam	628+0.685	628+1.485	1.9 mi S. of US 77	0.8 mi S.	48O17
16	ATL	SH 49	Titus	700+1.111	700+1.774	1.1mi W. of Morris Co.	Morris Co.	48P19
17	ATL	SH 315	Panola	738+0.709	738+1.370	1.4 mi W. of SH 149	0.3 mi W. of SH 149	48Q19
18	BMT	FM 105	Jasper	424+0.000	424+1.500	US 96	1.5 mi S.	48R20
19	BWD	US 67	Brown	558+0.540	558+1.470	Blanket Creek Bridge	1.0 mi N.	48S23
20	BWD	US 377	McCulloch	472+1.908	474+0.836	1.0 mi N. of FM 2996 S.	FM 2996	48T23

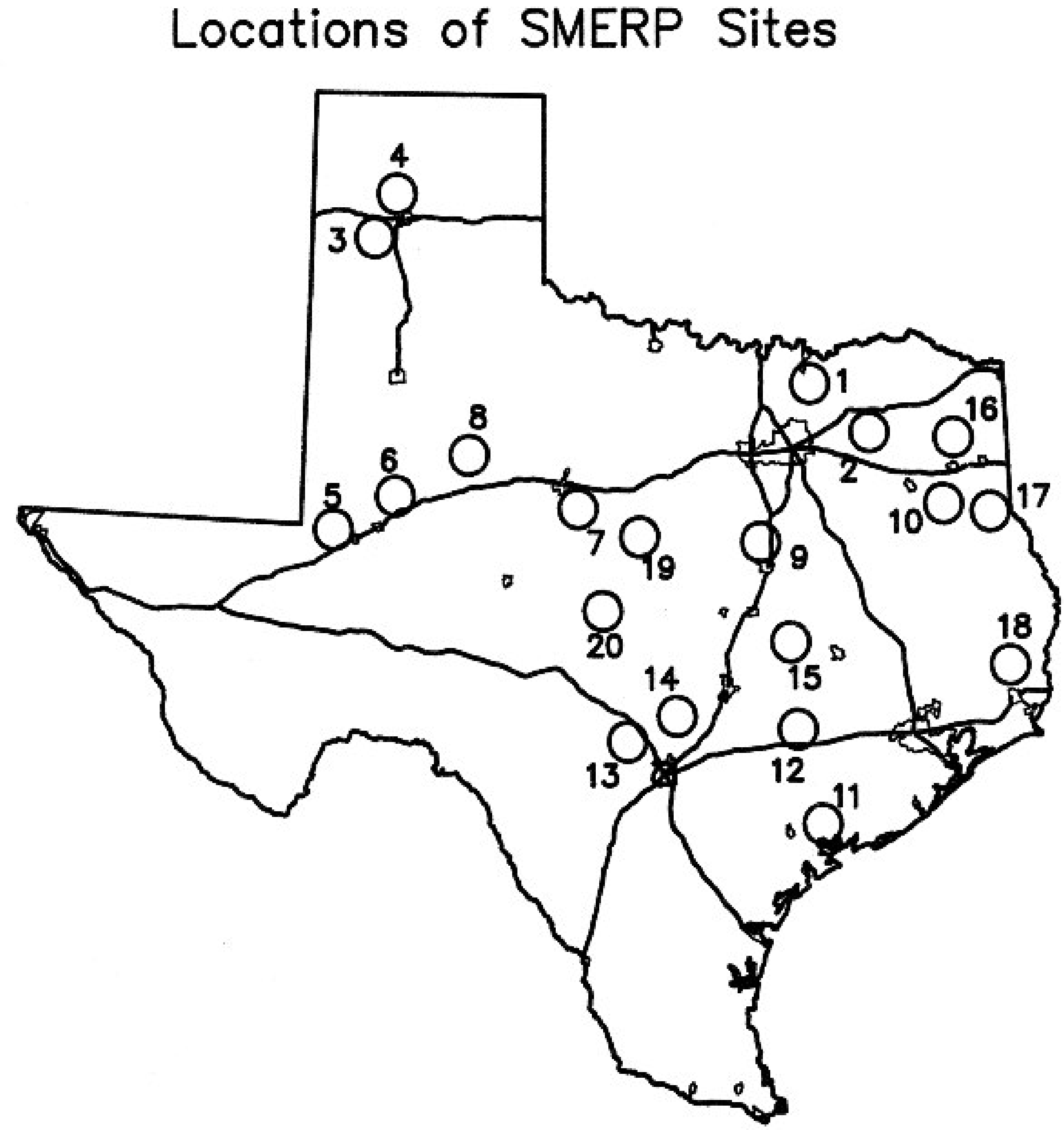
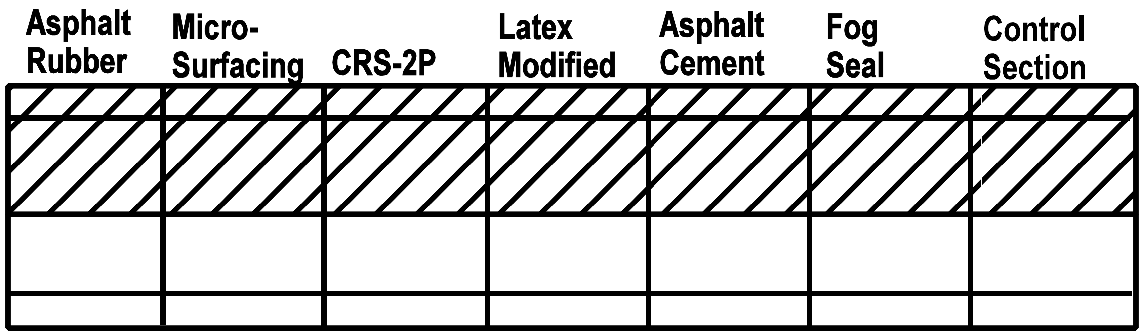


Figure 1. Locations of SMERP Sites.



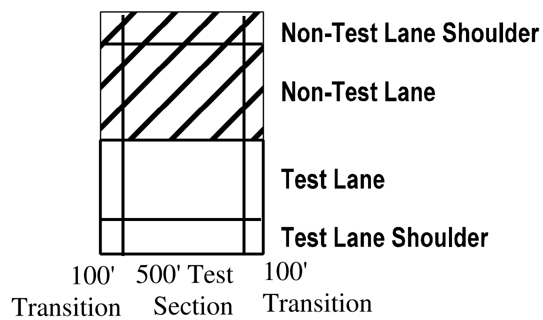


Figure 2. Typical SMERP Site Layout.

On most sites, white, non-reflectorized traffic buttons were placed on the edge of the shoulder at the beginning of every section and at every 100 feet (30.5 m). If a site did not have a shoulder, buttons were not installed.

A white paint stripe 3 to 4 inches (0.076 m to 0.102 m) wide was placed at the beginning and end of each treatment across the treatment lane. A white stripe 3 to 4 inches (0.076 m to 0.102 m) wide was also placed at the beginning and end of the monitoring section across the treatment lane. The stripe at the end of a treatment was placed for the beginning of the next treatment if the two treatments were adjacent.

White crosses were painted at the beginning and end of the monitoring section and at every 100 feet (30.5 m) within the monitoring section. The station numbers (0, 1, 2, 3, 4, and 5) were painted to the right of the crosses to aid in location for distress surveys and other data collection efforts.

The section number was painted to the right of the white stripe at the beginning of the monitoring test section. The numbers and letters were about 5 inches (0.127 m) high. The section numbering scheme of the SMERP sections is similar to that of the SHRP scheme. The numbering of a site consists of four parts. The first two digits (48) represent the state code for Texas. The next character is the site number expressed alphabetically (i.e., A is site 1, B is site 2, C is site 3, etc.). The next two digits signify the number designation of the TxDOT district where the site is located. The final character is the site type. Table 2 lists the site types and their corresponding descriptions.

Table 2. Site Numbering Description.

Example: 48A01H

Abbrev.	Description	Abbrev.	Description
H -	Asphalt Rubber Test Lane	R -	Asphalt Rubber Non-Test Lane
M -	Microsurfacing Test Lane	I -	Microsurfacing Non-Test Lane
E -	Polymer Modified Emulsion Test Lane	U -	Polymer Modified Emulsion Non-Test Lane
L -	Latex Modified Test Lane	T -	Latex Modified Non-Test Lane
C -	Unmodified AC Test Lane	O -	Unmodified AC Non-Test Lane
F -	Fog Seal Test Lane	G -	Fog Seal Non-Test Lane
X -	Control Section Test Lane	N -	Control Section Non-Test Lane

PRE-CONSTRUCTION CONDITION SURVEYS

Prior to construction of the SMERP treatments, researchers conducted a manual condition survey. In the initial survey, only the test lane was surveyed. Subsequent manual distress surveys were conducted on the test lane only, but the first two inspections did survey both lanes. Only the test lane data were analyzed. The manual survey was conducted in accordance with the procedures set up for a SHRP distress survey (SHRP, 1993a). In addition to measuring the number and quantity of each distress at each severity level, researchers drew a crack map showing the location of each distress. Figure 3 shows an example drawing of a completed form.

The distress data from the manual surveys were summarized and entered into a spreadsheet. The data were also placed in an ASCII file in a format that is compatible with the output from the SHRP Long Term Pavement Performance (LTPP) database.

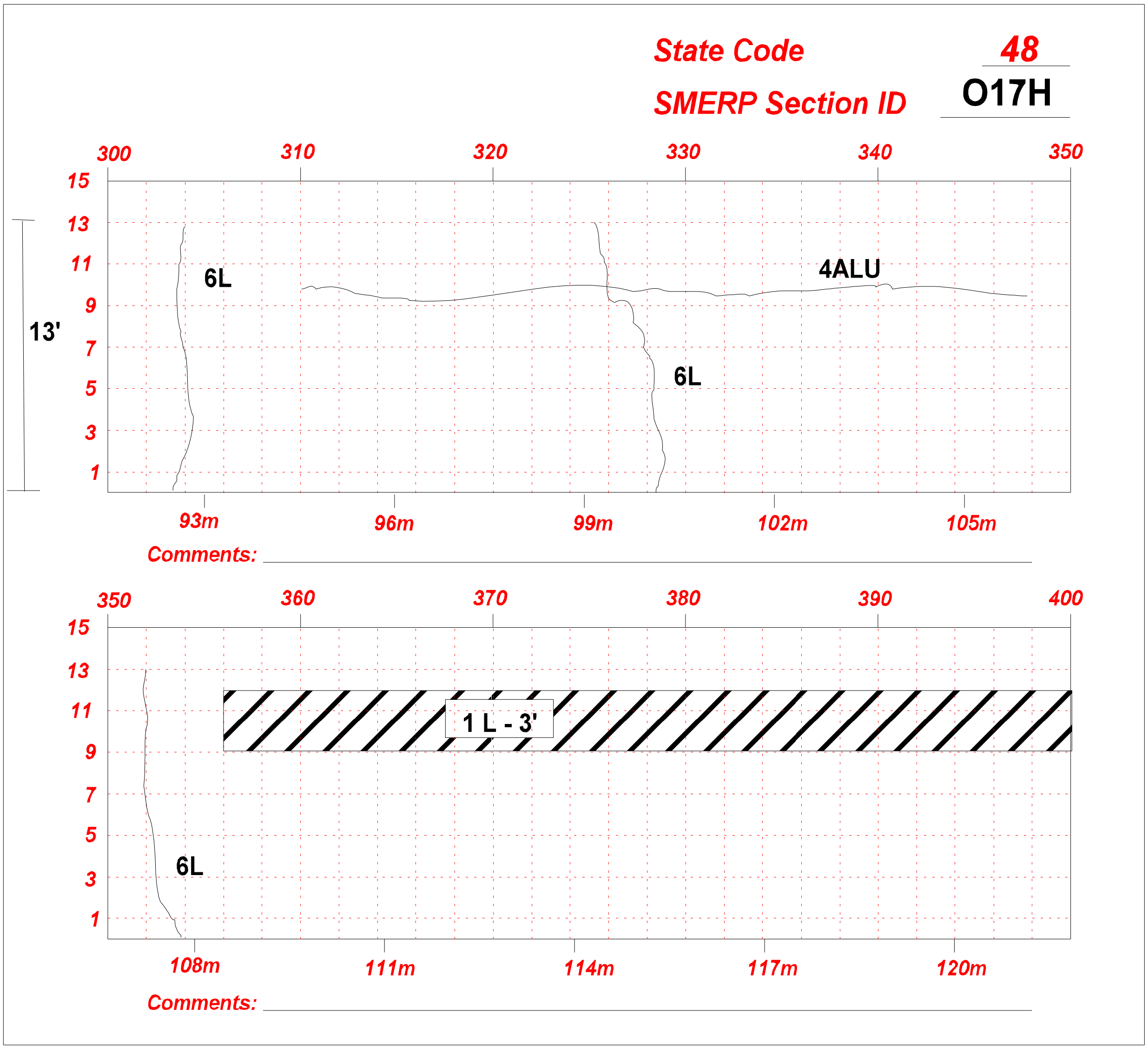


Figure 3. Completed SHRP LTPP Condition Survey Form.

CHAPTER 2. CONSTRUCTION AND POST-CONSTRUCTION DISTRESS SURVEYS

CONSTRUCTION

Twelve districts participated in the research project. The districts were: Paris (PAR), Amarillo (AMA), Odessa (ODA), Abilene (ABL), Waco (WAC), Tyler (TYL), Yoakum (YKM), San Antonio (SAT), Bryan (BRY), Atlanta (ATL), Beaumont (BMT), and Brownwood (BWD). A total of 20 sites were constructed. Each site included a total of seven 500 foot (213.4 m) sections. The sections were microsurfacing (M), fog seal (F), a control section (X), and four chip seal types: asphalt rubber (H), latex modified (L), polymer modified emulsion (E), and unmodified AC seal coat (C). Two sites did not have a fog seal or a control section.

After preparation of the plans, specifications, and special provisions, TxDOT distributed bid documents to interested parties. Upon receipt and opening of the bids, Keystone Services of Bixby, Oklahoma, was selected as the prime contractor to perform the work.

Construction of the SMERP sites began on April 5, 1993, and was completed July 14, 1993. The contractor was Keystone Services, Inc. (KS), and the subcontractor was International Surfacing, Inc. (ISI). KS constructed the microsurfacing section and the polymer modified, latex modified, and unmodified AC seal coat sections. ISI constructed the asphalt rubber chip seal section. Overall, the project was completed with a TxDOT rating of "Good." The fog seal sections were constructed by the local districts. No treatment was applied to the control section, which was used to track the "do nothing" approach.

Construction began on SH 35, Yoakum District. The contractor constructed all five test sections within each site before moving to the next site. The contractor provided all materials and equipment to construct all sections and provided traffic control throughout construction.

Prior to beginning construction at each site, the contractor met with the design division personnel and the local district to review all construction details. After the meeting, the supervision of the site construction was assigned to the local inspector and the site was constructed according to the normal construction procedures of the local district.

Table 3 lists the ranges of target application rates for the individual materials. The actual target rate used for the sites in each district was provided by the local district. Target rates were modified in the field as necessary to ensure a high-quality treatment.

Table 3. Target Application Rates.

Treatment Type	TxDOT Specification	Target Rate
Asphalt Rubber	Item 318	.50 - .60 Gal/SY (1.8 - 2.7 L/m^2)
Polymer Modified Emulsion	Item 316	.30 - .40 Gal/SY (1.4 - 1.8 L/m^2)
Asphalt Cement with Latex	Item 316	.30 - .40 Gal/SY (1.4 - 1.8 L/m^2)
Unmodified Asphalt Cement	Item 316	.30 - .40 Gal/SY (1.4 - 1.8 L/m^2)
Microsurfacing	Special Specification	25 Lb/SY (13.6 Kg/m^2)
Lightweight Grade 4	Item 303	110 - 120 SY/CY Coverage (12 Lb/SY (6.5 Kg/m^2))
Precoat Grade 4	Item 302	110 - 120 SY/CY Coverage (21 - 23 Lb/SY (11.4 - 12.5 Kg/m^2))
Precoat Grade 3	Item 302	80 - 90 SY/CY Coverage (23 - 30 Lb/SY (12.5 - 16.3 Kg/m^2))

The contractor always began work on the non-test lane and shoulder sections. After placing all the sections scheduled on that side for that day, the traffic would be switched to the non-test lane and shoulder and treatments would be placed on the shoulder and test sections. The reason behind treating the non-test lane first was to make sure everything was working properly by the time the test section was constructed. It usually took two days to construct the five treatments on both lanes and shoulders within a site. Usually three sections were treated the first day and the other two sections were treated the next day. Sometimes the contractor was able to construct four treatments the first day.

The first section to be completed was usually the asphalt rubber seal coat section, followed by the unmodified asphalt cement. The next treatment completed was the chip seal with polymer modified cationic rapid set emulsion, typically referred to as CRS-2P.

After both sides of the road were treated with the polymer modified emulsion chip seal, operations were usually halted until the next day. Prior to leaving the site, all chip seal sections except for the polymer modified emulsion chip seal section were swept to remove loose rock. The polymer modified emulsion test section was usually swept the next day.

Operation on the second day typically began with the above construction sequence being performed on the chip seal with the latex modified asphalt cement binder. After completing the latex modified chip seal test section, the contractor began construction of the microsurfacing test section. Table 4 lists the equipment used and Table 5 lists the application rates for each material.

Table 4. Materials and Equipment Used.

TREATMENT	MATERIALS		EQUIPMENT
	Type of Asphaltic Material	**Type of Aggregate**	
Seal Coat, Unmodified	AC-5 and AC-10	Lightweight Grade 4 or Precoat Grade 4	Asphalt distributor, aggregate spreader, and 2 rollers
Seal Coat, Polymer Modified	Emulsion with 2% Polymer	Lightweight Grade 4 or Precoat Grade 4	Asphalt distributor, aggregate spreader, and 2 rollers
Seal Coat, Latex Modified	AC-5 with 2% Latex	Lightweight Grade 4 or Precoat Grade 4	Asphalt distributor, aggregate spreader, and 2 rollers
Seal Coat, Rubber Modified	AC-10 with 20% Rubber	Lightweight Grade 4, Precoat Grade 4, or Precoat Grade 3 Modified	Asphalt distributor, aggregate spreader, and 2 rollers
Microsurfacing	Emulsion with additives	Microsurfacing Grade 2	Microsurfacing mixer and spreading box
Fog Seal	Emulsion	None	Asphalt distributor
Control	None	None	None

Table 5. Asphalt Application Rates in Test Lane, Gal/SY (L/m^2).

Treatment Type	SITE NUMBER																			
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Seal Coat, AC-5 Unmodified	0.31 1.40		0.32 1.45	0.32 1.45	0.36 1.63	0.37 1.68	0.33 1.49	0.27 1.22	0.35 1.58				0.32 1.45	0.32 1.45				0.35 1.58	0.29 1.31	0.31 1.40
Seal Coat, AC-10 Unmodified		0.24 1.09								0.34 1.54	0.27 1.22	0.26 1.18			0.36 1.63	0.32 1.45	0.33 1.49			
Seal Coat, Polymer Modified	0.31 1.40	0.38 1.72	0.46 2.08	0.46 2.08	0.36 1.63	0.37 1.68	0.41 1.86	0.26 1.18	0.49 2.22	0.43 1.95	0.32 1.45	0.31 1.40	0.42 1.90	0.41 1.86	0.37 1.68	0.39 1.76	0.40 1.81	0.41 1.86	0.43 1.95	0.39 1.76
Seal Coat, Latex Modified	0.30 1.36	0.31 1.40	0.35 1.58	0.37 1.68	0.36 1.63	0.36 1.63	0.36 1.63	0.27 1.22	0.36 1.63	0.34 1.54	0.28 1.27		0.40 1.81	0.42 1.90	0.38 1.72	0.31 1.40	0.32 1.45	0.35 1.58	0.31 1.40	0.31 1.40
Seal Coat, Rubber Modified	0.57 2.58	0.59 2.67	0.59 2.67	0.70 3.17	0.59 2.67	0.64 2.90	0.54 2.44	0.59 2.67	0.64 2.90	0.60 2.72	0.56 2.54	0.56 2.54	0.60 2.72	0.64 2.90	0.62 2.81	0.55 2.49	0.49 2.22	0.61 2.76	0.53 2.40	0.59 2.67
Microsurfacing Lbs/SY (Kg/m^2)	23.0 12.5	24.0 13.0	22.9 12.4	26.5 14.4	22.5 12.2	23.1 12.5	17.4 9.4	21.1 11.4	23.5 12.7	28.5 15.5	20.2 11.0	24.8 13.5	21.7 11.8	19.7 10.7	16.2 8.8	25.6 13.9	20.0 10.8	24.2 13.1	22.4 12.1	22.7 12.3

During and immediately after construction, it was noted that the asphalt rubber test sections exhibited significant amounts of bleeding. A statistical test for the equality of variance was conducted to determine whether the percent of target application rate for the asphalt rubber binder was significantly different statistically than the results for the other applications. There was a statistically significant difference between the asphalt rubber percent of target application rate and the percent of target application rates for the other treatments. The means and standard deviations are listed below.

Treatment Type	Mean	Standard Deviation
Asphalt Rubber	105.0	11.93
CRS-2P	101.1	4.30
Latex Modified	102.0	2.34
Asphalt Cement	103.3	5.74

The construction report lists all of the application data. Appendix E contains the plots of the application data (Freeman and Rmeili, 1994).

POST-CONSTRUCTION CONDITION SURVEYS

Researchers have now performed nine post-construction distress surveys. These manual distress surveys were conducted in accordance with the procedures set up for a SHRP distress survey (SHRP, 1993a). In addition to measuring the number and quantity of each distress at each severity level, researchers also prepared a crack map showing the location of each distress. Figure 3 shows an example of a completed distress survey form. The surveys were conducted approximately 6, 12, 24, 36, 48, 60, 72, 84, and 96 months after construction. In addition to the distress surveys, researchers produced a videotape recording of the condition of each site during the 12 and 48 month surveys by either walking through the section or by videotaping from a car being driven down the lane or shoulder on higher traffic or reduced visibility sites.

The distress data from the manual surveys were summarized and entered into a spreadsheet. The data were also placed in an ASCII file in a format that is compatible with the output from the SHRP database. The data are arranged by site and include all inspections, including the construction inspection where all distresses for all treatments were set to zero except for the fog seal and control sections.

OUTPUT FILE FORMATS

The researchers entered the data collected into an Excel® spreadsheet for the purpose of properly formatting the data. The data are contained in ASCII files formatted into the SHRP SPS-3 compatible format (SHRP, 1993b). Data could not be entered directly into the SHRP database because neither the Texas Transportation Institute (TTI) nor TxDOT has access to this database. Therefore, the format used to output data from the SHRP National Information Management System (NIMS) into ASCII files was selected (SHRP 1993b). The data can then be easily combined with the SPS-3 data for analysis.

The data files follow the data sheets quite closely and, since the data sheets include a longer description of the data item, it is advisable to have the data sheets available during analysis.

CHAPTER 3. PERFORMANCE MEASURES

INITIAL RESULTS

Some early results regarding the application process were shown in research report TX-93/1981-1F, "Development and Construction of the Texas Supplemental Maintenance Effectiveness Research Program (SMERP) Experiment" (Freeman and Rmeili, 1994). Actual application rates were reported and compared to the target rates for the treatments. In general, with the exception of the asphalt rubber test sections, the percent differences between proposed and actual application rates were quite small. The previous report discussed possible complications in the application of the asphalt rubber treatment.

SHRP DISTRESS PROPAGATION AS A MEASURE OF PERFORMANCE

Definitions for the distresses used in this analysis are discussed in the SHRP distress manual (SHRP, 1993a). With enough test sections it may have been possible to study the initiation and propagation of each distress type and severity combination, but for this project, certain simplifying assumptions were necessary. For the analysis of SHRP distresses, the researchers combined certain distresses and severity levels as discussed in the following subsections.

Alligator Cracking Plus Patching

We added the quantity of patching to the quantity of alligator cracking (fatigue cracking) to account for large areas of alligator cracking that have recently been patched. Without this correction some treatments would show an increase of alligator cracking for a time and then the quantity would drop dramatically as the area was patched. Only one of the asphalt rubber test sections had an appreciable quantity of patching prior to construction. Since patches were covered by the treatments, all pre-construction patching was eliminated at the time of construction.

Other Cracking

The distress measure called other cracking is composed of the accumulated lengths of longitudinal cracking in the wheel path, non-wheel path longitudinal cracking, a correction for block cracking, edge, and transverse cracking. The area of block cracking was converted to length of cracking by comparing the crack pattern from previous surveys and converting the block cracking into an equivalent length of longitudinal and transverse cracking.

Bleeding (Flushing)

It is relatively easy to meet the definition in the SHRP manual for low severity bleeding, so pavements that appear to be performing well otherwise may meet the SHRP criteria for low severity bleeding. That definition is "an area of pavement surface discolored relative to the remainder of the pavement by excess asphalt" (SHRP, 1993a). Picture 1 is an example of high severity bleeding, while Pictures 2 and 3 are low and medium severity, respectively. The high severity is shown first, as it is the signature example of the distress. The low severity picture illustrates the minimum level of a deficiency that results in a distress.

Picture 1. High Severity Bleeding.

Picture 2. Low Severity Bleeding.

Picture 3. Medium Severity Bleeding.

Raveling

Raveling is defined as the wearing away of the pavement surface (SHRP, 1993a). In this project, sections had very little raveling. Most of the raveling that did exist was either along the centerline or fog stripe where the two passes of the distributor overlap. One other source was scraping of the pavement surface due to equipment being dragged or due to an entrance or driveway in the section where slowly moving, turning traffic caused damage soon after construction. Raveling was not considered in the analysis.

Rutting

Rutting was measured at the same time as the distress data. A stringline was used to approximate a 4 foot straightedge, and the maximum rutting was estimated for each wheelpath at each station and half-station. The data did not reveal any treatment-specific trends. Rutting was not considered in the analysis.

PAVEMENT CONDITION INDEX AS A MEASURE OF PERFORMANCE

The preceding distress data will be used to illustrate how the quantity of an individual distress type varies with time, but will not explain the overall relative condition of the sites. The measure chosen to convert the raw distress and severity data into a single measure of condition was the Pavement Condition Index (PCI), developed by the Corps of Engineers (COE) with the PAVER system (Shahin and Kohn, 1979). The Corps of Engineers PCI was developed to reflect the functional and structural rating that would be assigned by a group of experienced pavement engineers. Because PCI includes both functional and structural parameters, the overall rating can be significantly affected by functional distresses such as bleeding.

The PCI is primarily a ranking and communication tool. It ranks the inspected pavement sections from bad to good (0 to 100) and allows the user to communicate the relative condition to others. By using an "expert witness" based system, the user gets a rating of the pavement equivalent to that of having the group of experienced pavement engineers who developed the system rate the pavement (Shahin and Kohn, 1979). Thus, a few technicians can be trained to rate the pavement and the results are equivalent to having a group of experienced pavement engineers rate the pavement, but at a considerably lower cost. By using appropriate techniques, a properly scaled PCI provides an index that can be used to project future conditions, measure the impact of various maintenance procedures, and determine maintenance and rehabilitation needs.

A deduct concept is used in the procedure. Since 100 is equivalent to a new pavement, each occurrence of a distress decreases the condition rating. The deduct curves developed by the COE indicate the impact of various densities of each distress type and severity on the pavement condition. These deduct curves were based on a comparison of calculated PCIs to the mean subjective ratings by groups of experienced pavement engineers (Shahin and Kohn, 1979).

The deduct curves were developed as if the occurrence of that distress type and severity was the only distress occurrence in the inspected sample unit. When multiple distress type and severity combinations occur within the same sample unit, the researchers discovered that the deducts from each occurrence could not be directly added. As additional distress types and severities occur within the same sample unit, their impact on the PCI decreases. The COE developed correction curves for multiple distress type and severity combinations to account for this. These curves were again based on a comparison of the calculated PCI to the mean subjective rating by groups of experienced pavement engineers rating pavements with multiple distress types and severities (Shahin and Kohn, 1979).

The overall PCI concept from inspection to calculation of the PCI is illustrated in Figure 4. Five steps are involved in the PCI process (Shahin and Kohn, 1979):

1. Inspect the sample unit using the distress identification guide. Determine the quantity of each distress type and severity combination and record it in the field.

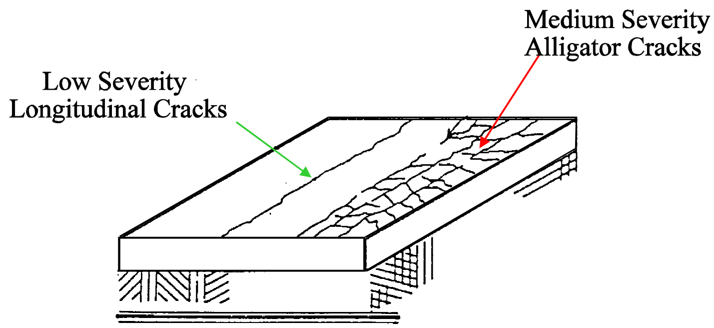
2. Determine the deduct value for each distress type and severity combination from the deduct curves.

3. Compute the total deduct value by summing all deduct values for the individual distress type and severity combinations.

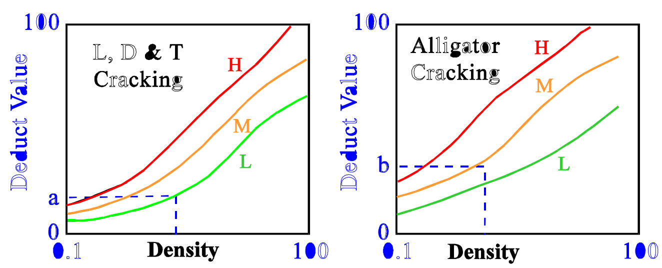
4. Compute the corrected total deduct value when multiple distress type and severity combinations are present. A separate deduct correction curve is used for this purpose.

5. Subtract the corrected deduct value from 100 to determine the inspection unit PCI.

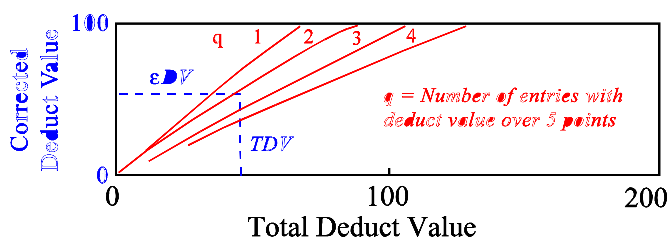
- **Step 1. Inspect sample units to determine type, quantity and severity level of pavement distresses.**



- **Step 2. Determine deduct values.**



- **Step 3. Compute Total Deduct Value, TDV = a + b**
- **Step 4. Adjust Total Deduct Value.**



- **Step 5. Compute Pavement Condition Index, PCI=100-CDV, for each sample unit inspected.**
- **Step 6. Determine Pavement Condition Rating**

Figure 4. PCI Calculation Procedure (Shahin and Kohn, 1979).

This condition measure utilizes most of the SHRP distresses directly, although some measures had to be converted. Rutting was measured, but was not included in the PCI calculation for any of the test sections. The method of measuring rutting for the PCI calculation is to determine the severity (depth) and extent of the rut. For the SMERP experiment, researchers took rut depths only at 50 foot (15.2 m) intervals. This interval makes estimating an equivalent area extremely difficult and imprecise. Another complicating factor is that during construction the contractor typically extended the shoulder treatment into the main lane and double covered this area when placing the treatment in the main lane. This double thickness artificially increases the rutting measurement by the thickness of the treatment. Also, the large size of the coarse seal coat aggregate confounded the results because sometimes the stringline would be on top of aggregates while in other instances it would be at the bottom. Since the COE PCI defines low severity rutting as 0.25 inches (0.635 cm), many pavements were identified as having substantial quantities of rutting which artificially decreased the PCI of the sections. Also since measurements were made at 50 foot (15.2 m) intervals, a minor change in the measurement had a large impact on the severity and extent of the distress.

SITE PROBLEMS

Nine sites lasted throughout the entire eight-year project. For a variety of reasons, 11 sites were taken out of service prematurely, although 17 sites lasted at least five years. Table 6 summarizes the year and reason for the removal of a site.

Table 6. Test Sections Removed from Service.

Site	Dist	Road	Nearby City	Year and Reason
48H08	ABL	US 84	Snyder	Deleted 1996. Rebuilt whole road due to flushing.
48Q19	ATL	SH 315	Carthage	Deleted 1997. Rebuilt whole road. Structural failure of entire roadway.
48P19	ATL	SH 49	Mt Pleasant	Accidently seal coated 1998. Contractor did wrong side
48A01	PAR	SH 11	Sherman	Deleted 1999. Realigned road and bridge.
48F06	ODA	SH 349	Midland	Overlaid 1999. Part of major rehabilitation.
48G08	ABL	SH 36	Abilene	Overlaid 1999. Considerable flushing.
48I09	WAC	FM 933	Waco	Deleted 1999. Accidently seal coated as part of routine seal coat project.
48L13	YKM	SH 71	La Grange	Overlaid 1999. Part of major road improvement
48O17	BRY	US 190	Milano	Seal coated wheelpaths 1999 due to cracking.
48B01	PAR	SH 19	Sulphur Springs	Overlaid 2001. Part of major rehabilitation.
48K13	YKM	SH 35	Port Lavaca	Seal coated 2001.

CATEGORY DESIGNATIONS

It has long been known that the condition of the pavement prior to the application of the maintenance treatment has an effect on the performance of the treatment (Smith et al., 1993). The SMERP experiment design was set up with this in mind and, while sites were not chosen based on a rigid set of existing conditions, researchers did obtain an acceptable distribution of pavement conditions. The analysis of the impact of pre-treatment condition on performance was based on grouping the actual pre-construction conditions into general categories of good, fair, and poor by ranking all pavements by a certain criteria, then looking for logical divisions that would result in nearly equal distributions of the three categories. The values used to categorize the sections and the number of sections in each category are included in Table 7. Membership in a category for one condition state is independent of the other condition states. For example, a pavement may be in good condition with respect to cracking, but in poor condition with respect to bleeding and in fair PCI condition. These categories will be used throughout the remainder of this report.

Table 7. Condition Categories.

Criteria	**G**	**F**	**P**
Total Corrected Cracking (Ft/100Ft)	< 20 (58)	≥ 20, ≤ 100 (42)	> 100 (36)
Bleeding (Percent Area)	< 6% (61)	≥ 6%, ≤ 23% (17)	> 23% (58)
Alligator Cracking plus Patching (Percent Area)	<0.01% (86)	≥ 0.01%, ≤ 4% (31)	> 4% (19)
Pavement Condition Index (PCI)	> 85 (48)	≤ 85, ≥ 70 (50)	<70 (38)

(xx) - Number of sections in this category

CHAPTER 4. STATISTICAL ANALYSIS OF SMERP LONGITUDINAL DATA BY MIXED MODELS

INTRODUCTION TO STATISTICAL METHODOLOGY

Longitudinal studies occupy an important role in contemporary statistics, with applications in medical and sociological research. Many longitudinal studies are designed to investigate and explain the changes over time in several characteristics. To accomplish this, a number of variables over a series of time points are repeatedly measured on the same individuals.

Although analysis of longitudinal data is a fairly new approach in pavement management studies, the data collected for the SMERP study obviously fit the criteria. A total of 20 sites were constructed. Each site included a total of seven 500 foot sections. The sections were applied with one of seven pavement treatments (asphalt rubber, microsurfacing, polymer modified emulsion seal coat, latex modified seal coat, conventional asphalt cement seal coat, fog seal, or control). Data for three basic types of distresses (fatigue or alligator cracking plus patching, all other cracking, and bleeding) were collected on each experiment from the construction date to 2001. Heuristically, each treatment section was similar to a patient taking a specific drug, which is then measured serially on three indices.

From the viewpoint of methodology, longitudinal analysis can be treated as an extension of the combination of repeated measures (RM) model and analysis of covariance (ANCOVA), which were discussed and reported in our preliminary and final research plans (Ren et al., 2001). In that report, we listed four reasons why longitudinal analysis is more appropriate to SMERP data than RM and ANCOVA. These reasons are repeated here:

1. The SMERP study was an unbalanced design. The data contain many missing values, caused by sections dropping out of the study, which results in a different number of inspections for different sections. Even disregarding these missing data, there were 11 inspections for the fog and control sections while other treatments had only 10 inspections. The resulting unbalanced data sets are typically not amenable to analysis using a general RM model.

2. The intervals between any two inspections are unequally spaced. The inspection data were collected at approximately 29, 35, 41, 53, 65, 77, 89, 101, 113 and 125 months after construction for the fog and control sections and -3, 0, 6, 12, 24, 36, 48, 60, 72, 84, and 96 months for the other treatments. In this situation, an RM model is only a simplified approach.

3. In addition to the comparison of treatment performance at different pre-construction conditions (a basic goal of RM), we are interested in finding a functional relationship between the treatment effect (or equivalently, the distress) and its time of application (i.e., the growth curves). The RM technique is not sufficient for curve fitting.

4. The ANCOVA procedure may be helpful, but the distinctive feature of longitudinal data is that the observations on a particular individual value at each time will not be independent. An ANCOVA analysis based on the usual assumptions of regression analysis can not give a precise estimation.

Mixed modeling has become increasingly popular for analysis of longitudinal data because it can include random effects to describe the correlated structure of the serial observations for each subject. We applied this powerful tool throughout the analysis.

As in many situations where missing data occur in longitudinal studies, some experimental sections dropped out of the SMERP inspection, thus providing no data beyond a specific time point. We used pattern-mixture models to account for and impute the missing data. For this approach, we divide the sites into groups depending on their missing-data pattern. Variables based on these groups are used as model covariates. Three possible imputed value models for each missing inspection, which are derived from best linear unbiased prediction (BLUP), expectation conditional on the missing-data pattern, and expectation averaged over the missing-data patterns, respectively, were provided. Then, an expert selected the most appropriate final imputation model.

Strictly speaking, the data have a multivariate nature (consisting of the three distresses and the derived PCI) (Shahin and Kohn, 1979), which greatly complicates the analysis. These data are treated as four univariate response variables, and the following five steps are implemented for each of the variables:

1. exploratory data analysis and simple site curve fitting (before imputation),
2. imputation,
3. site curve fitting with imputed values,
4. multiple comparison to group the treatment at different pre-construction conditions, and
5. family curve fitting.

The "all-other-cracking" response (called cracking in later sections) was selected as an example to illustrate the analysis procedure.

In the next section, we introduce the general mixed models for longitudinal data and the first step of the analysis.

MIXED MODELS FOR LONGITUDINAL DATA

Laird and Ware (1982) first proposed this model. Let the random variable Y_{ij} denote the (possibly transformed) response for the i th individual at time t_{ij} , $i = 1, \cdots, N$, $j = 1, \cdots, n_i$, and let $\mathbf{Y_i}$ be the n_i–dimensional vector of all repeated measurements for the i th subject, i.e., $\mathbf{Y_i} = \left(Y_{i1}, Y_{i2}, \cdots . Y_{in_i}\right)^T$. The general form of the linear mixed-effects model of longitudinal study is

$$\mathbf{Y_i} = \mathbf{X_i}\boldsymbol{\beta} + \mathbf{Z_i}\mathbf{b_i} + \boldsymbol{\varepsilon}_\mathbf{i}, \quad (1)$$

where $\mathbf{X_i} = n_i \times p$ dimensional design matrix of known covariates;

$\boldsymbol{\beta} = p$ -dimensional parameter vector containing the fixed effects;

$\mathbf{Z_i} = n_i \times r$ dimensional design matrix of known covariates;

$\mathbf{b_i} = r$ -dimensional containing the random effects and yielding a combined contribution to $\mathbf{Y_i}$ via the design matrix $\mathbf{Z_i}$; and

$\boldsymbol{\varepsilon}_\mathbf{i} = n_i$ -dimensional vector of residual components.

We further assume the normality and independence:

$$\mathbf{b_i} \sim N(\mathbf{0}, \boldsymbol{\Sigma}_\mathbf{b}),\ \boldsymbol{\varepsilon}_\mathbf{i} \sim N\left(\mathbf{0}, \boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}_\mathbf{i}}\right);\ \mathbf{b_1}, \cdots, \mathbf{b_N} \text{ and } \boldsymbol{\varepsilon}_\mathbf{1}, \cdots, \boldsymbol{\varepsilon}_\mathbf{N} \text{ are independent,}$$

where $\boldsymbol{\Sigma}_\mathbf{b}$ and $\boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}_\mathbf{i}}$ are general $q \times q$ and $n_i \times n_i$ covariance matrices. Then, marginally, the $\mathbf{Y_i}$ are distributed as independent normals with mean $\mathbf{X_i}\boldsymbol{\beta}$ and variance-covariance matrix $\mathbf{Z_i}\boldsymbol{\Sigma}_\mathbf{b}\mathbf{Z_i} + \boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}_\mathbf{i}}$.

Five variables describe cracking data. Let y_{ijk} be the cracking rate measured at inspection time k at SMERP site j , treatment type i . This is the only response, or dependent variable, in our mixed model. We use Trt_i to denote the pavement treatment, which is a classification variable and takes a value of one of the seven pavement treatments: asphalt rubber (H), microsurfacing (M), polymer modified emulsion seal coat (E), latex modified seal coat (L), conventional asphalt cement seal coat (C), fog seal (F), and control (X), for $i = 1, \cdots, 7$, respectively. Let $Site_j$ be A, B, ..., T, the identification symbols for the 20 SMERP sites as $j = 1, \cdots, 20$. Let t_{ijk} denote the value of time for the k th inspection of SMERP site j of pavement treatment type i. There is another independent variable, $Cond_{ij}$, which takes a value of good, fair, or poor to indicate the initial condition of the SMERP section in site j of pavement treatment type i at the time of construction. Theoretically, we want a model in the form of:

$$T(y_{ijk}) = f(Trt_i, Site_j, Cond_{ij}, t_{ijk}) + \varepsilon_{ijk} \qquad (2)$$

where ε_{ijk} = the usual error, T is some normalization transformation, since y = the proportion between the area of cracking and the area of the experimental section (percent area), which is a value between 0 and 1. Before the analysis, we take the routine transformation $T(y) = \sin^{-1}\left(\sqrt{y}\right)$, and still keep the notation y to denote the transformed value. An advantage of this transformation is that the back-transformation can always make the predicted or the fitted values fall in the range $[0,1]$.

In order to apply this general model to cracking data, we have to clarify the data structure, i.e., the layout of the data, as in Table 8.

Table 8. Layout of the Data.

Subj	Trt	Site	Cond	*t* (at month)										
1	H	A	P	y_{111} (0)	y_{112} (6)	y_{113} (12)	y_{114} (24)	…	…	…	…	…	$y_{1,1,10}$ (96)	
2	H	B	G	…	…	…	…	…	…	…	…	…	…	
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
140	X	T	F	$y_{7,20,1}$ (0)	$y_{7,20,2}$ (29)	$y_{7,20,3}$ (35)	$y_{7,20,4}$ (41)	…	…	…	…	…	$y_{7,20,10}$ (113)	$y_{7,20,11}$ (125)

The first stage is site-curve fitting. Our goal is to find a growth curve $y = f(Trt, Site, t)$, which can fit the values with respect to the time, for site j of treatment type i. Diggle, et al. (1994) suggest that an exploratory analysis with the aid of nonparametric regression can help the modeling of longitudinal data. The scatter plots of the transformed cracking rate versus the inspections for each treatment are shown in Figure 5. Figure 6 is an enlarged view of one of the plots.

The dotted lines with the same letters are the (transformed) actual observations. The solid lines represent the nonparametric regression curves intended to capture the main trend. Close observation reveals some interesting properties of the data:

1. There are many zeros and missing values.
2. Routinely, cracking should be increasing with time, however for some reason, the measured values fluctuate.
3. The nonparametric curves depict that the cracking process is slow and somehow nonlinear with respect to time.

Property 3 suggests some nonlinear regression analysis, but it is an unnecessary luxury because of the existence of property 1. The usual approach of polynomial regression fails because of property 2, and we expect an increasing trend extracted from the waved data. A compromise of these two ideas is to introduce some fractional power function as the basis function, which can describe the slow-varying behavior, is nonlinear with respect to time, and can be still handled by linear regression.

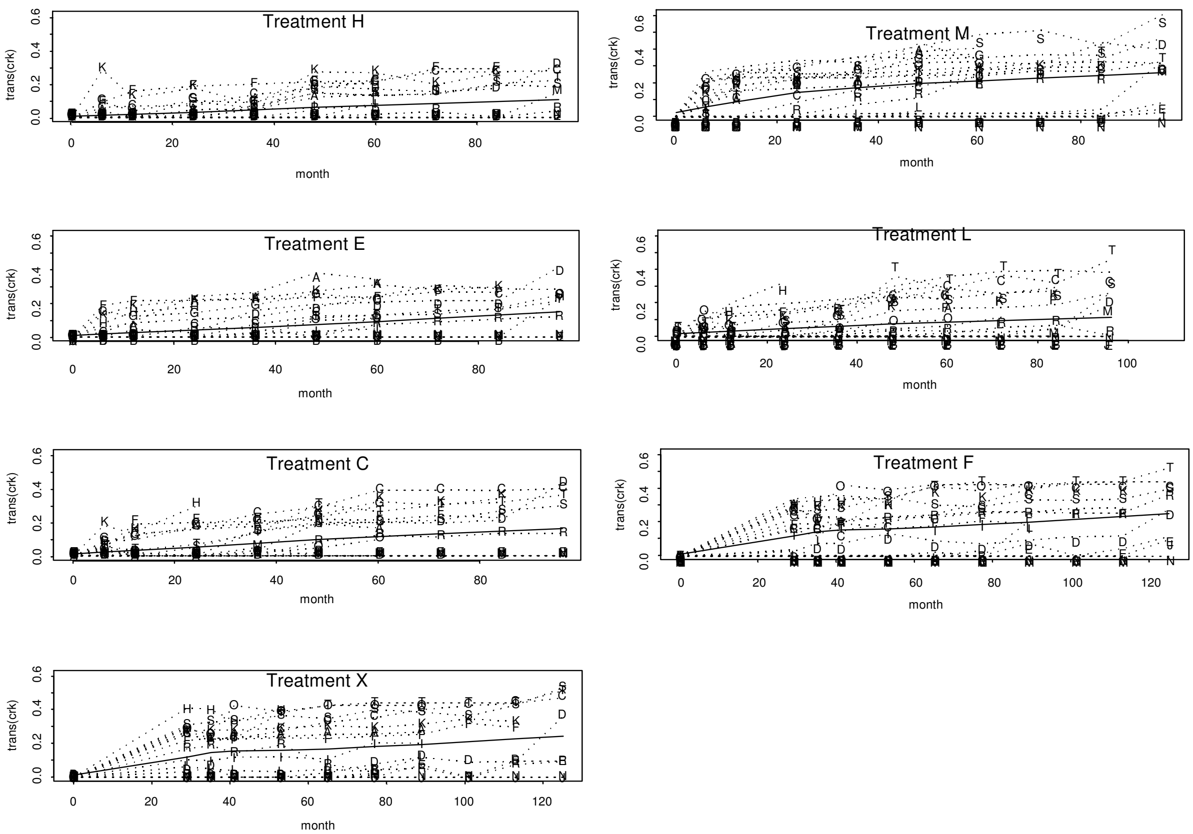


Figure 5. Scatter Plot of the Transformed Cracking Data.

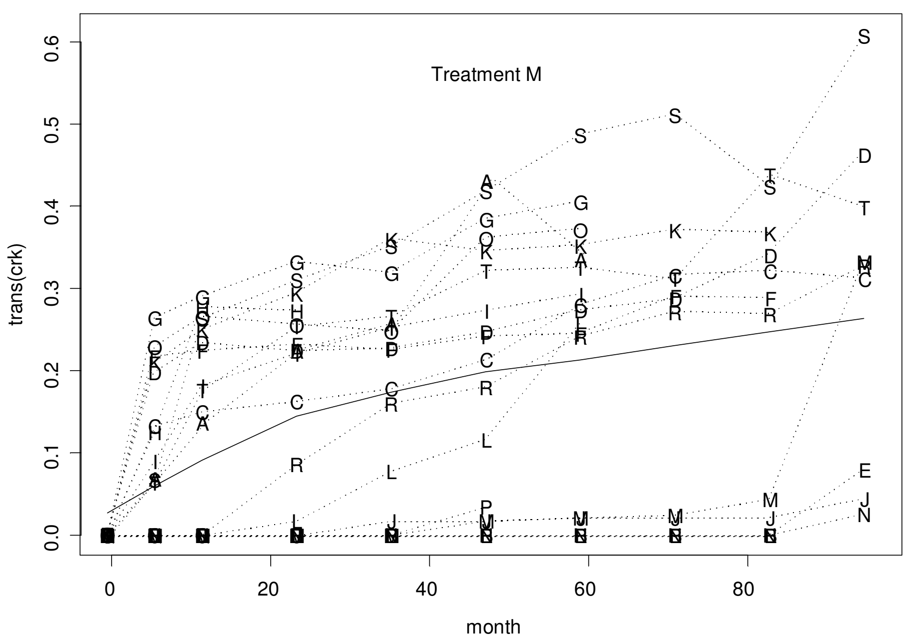


Figure 6. Enlarged View of Site Plot.

After trying many candidate basis functions in the mixed model (Eq. 1), the final model is chosen as:

$$y_{ijk} = \propto_1 Trt_i\sqrt{t_{ijk}} + \propto_2 Site_j\sqrt{t_{ijk}} + \beta_1 Trt_i t_{ijk}^{1/3} + \beta_2 Site_j t_{ijk}^{1/3} + b_{oij}t_{ijk} + b_{1ij}\sqrt{t_{ijk}} + b_{2ij}t_{ijk}^{1/3} + \varepsilon_{ijk}$$

where,

$$\begin{pmatrix} b_{0ij} \\ b_{1ij} \\ b_{2ij} \end{pmatrix} \sim N\left(\begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} \sigma_0^2 & \sigma_{01} & \sigma_{02} \\ \sigma_{10} & \sigma_1^2 & \sigma_{12} \\ \sigma_{20} & \sigma_{21} & \sigma_2^2 \end{pmatrix}\right) \text{ and } \varepsilon_{ijk} \sim N(0, \sigma^2)\,, \qquad (3)$$

whose parameters can be estimated using the subroutine PROC MIXED in the SAS statistical analysis computer program. Figure 7 illustrates the main results output from SAS where we use different variable names in the SAS programming. "Month" is just the inspection time, "smonth" and "ssmonth" are the cubic root and square root of month, respectively, and "type" is equivalent to the treatment. The results show that both the fixed and random effects given in the model are very significant. Figure 8 illustrates how this curve fits the data, and Figure 9 is an enlarged view of one of the plots.

In Figure 9, the circle dots are the actual data and the lines represent the fitted curves from the model (Eq. 2). For the purpose of illustration, only nine cases from 140 treatment-site sections are represented. Generally, the model did a very good job. Except for treatment X at site R (actually, this is the "worst" fitting among all 140 sections), all other curves are monotonic in spite of some deviated and waggled points that deviate somewhat from the representative curves. As seen in treatment F at site H, this model also predicts a reasonable trend despite the presence of many missing data points. Hence, we will extend this model in the imputation.

Estimated G Correlation Matrix

Row	Effect	id	Col 1	Col 2	Col 3
1	month	A01C	1.0000	0.9585	-0.9825
2	smonth	A01C	0.9585	1.0000	-0.9932
3	ssmonth	A01C	-0.9825	-0.9932	1.0000

Covariance Parameter Estimates

Cov Parm	Subject	Estimate	STD. Err	Z Value	Pr Z
UN(1,1)	id	0.000024	5.451E-6	4.40	<0.0001
UN(2,1)	id	0.000724	0.000177	4.09	<0.0001
UN(2,2)	id	0.02379	0.006122	3.89	<0.0001
UN(3,1)	id	-0.00058	0.000135	-4.32	<0.0001
UN(3,2)	id	-0.01861	0.004587	-4.06	<0.0001
UN(3,3)	id	0.01476	0.003464	4.26	<0.0001
Residual		0.000860	0.000044	19.54	<0.0001

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
smonth*type	6	752	8.16	<0.0001
smonth*site	19	752	5.37	<0.0001
ssmonth*type	6	752	5.48	<0.0001
ssmonth*site	19	752	6.26	<0.0001

Figure 7. Output from SAS PROC MIXED.

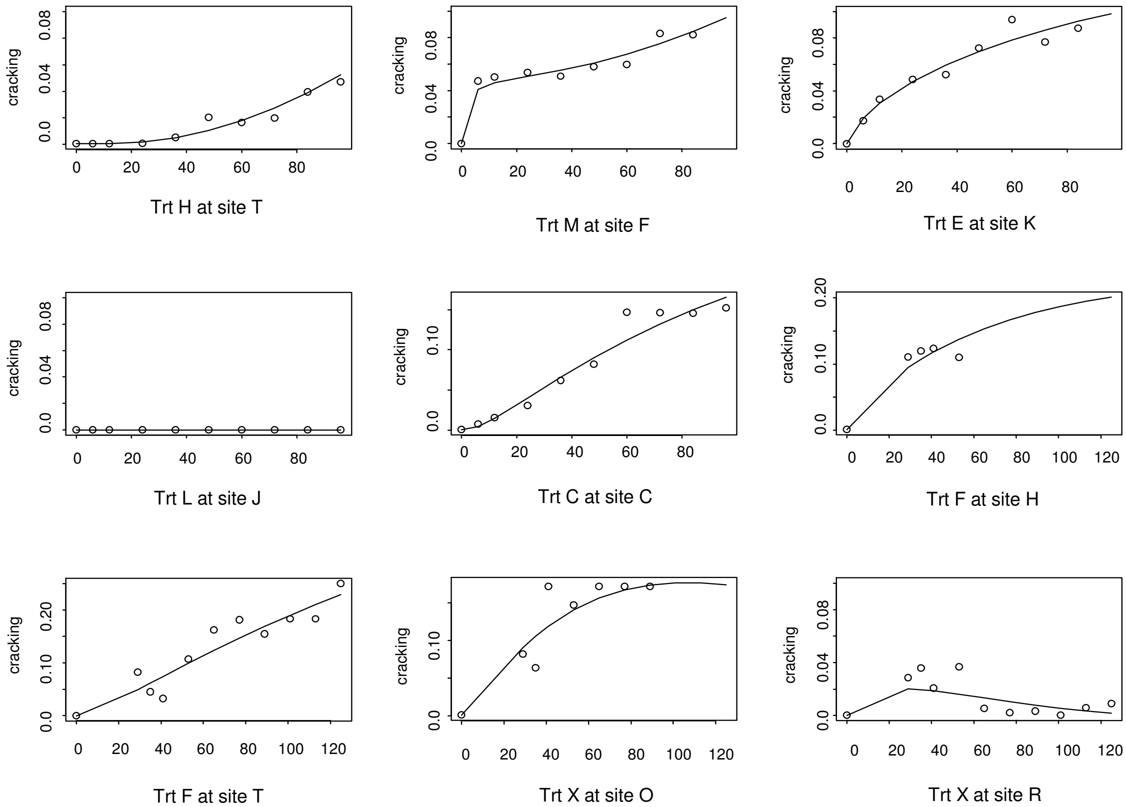


Figure 8. Curve-fitting to the Cracking Data.

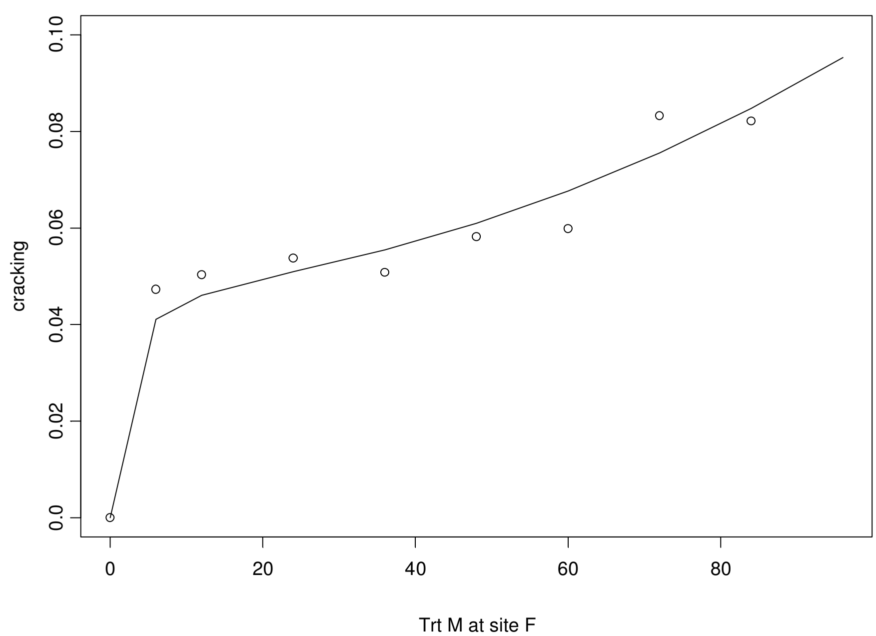


Figure 9. Enlarged View of Treatment M at Site F.

IMPUTATION BY MIXED PATTERN-MIXTURE MODEL

The problem of dealing with missing values is common throughout statistical work and is almost always present in the analysis of longitudinal data. Dropouts are by far the most common reason for missing data, that is, patterns in which once a missing value occurs, they are only followed by missing values.

The standard framework for missing data has been described by Rubin (1976) and Little and Rubin (1987). In the same setting as in the earlier section, we continue to define

$$R_{ij} = \begin{cases} 1 & \text{if } y_{ij} \text{ is observed} \\ 0 & \text{otherwise.} \end{cases} \tag{4}$$

The missing data indicators R_{ij} are grouped into a group $\mathbf{R}_i$ with the same length as $\mathbf{Y}_i$. $\mathbf{Y}_i$ is partitioned into two subvectors such that $\mathbf{Y}_i^o$ is the vector containing those Y_{ij} for which $R_{ij} = 1$, and $\mathbf{Y}_i^m$ contains the remaining components. They are referred to as the observed and missing components, respectively. In the case that missing data are restricted to dropouts, each vector $\mathbf{R}_i$ is of the form $(1,\cdots,1,0,\cdots,0)$ and we can simply introduce a scalar dropout indicator $D_i = \sum_{j=1}^{n_i} R_{ij}$.

Little (1993) described a general class of models dealing with missing data under the name of "pattern-mixture models." Moreover, Little (1995) presented a comprehensive and statistically rigorous treatment of mixed pattern-mixture models for longitudinal data with dropouts. In these models, subjects are divided into groups on the basis of their missing pattern. The idea of pattern-mixture modeling can be expressed simply by the decomposition of the joint probability density of the full data $f(\mathbf{Y}_i, \mathbf{R}_i)$,

$$f(\mathbf{Y}_i, \mathbf{R}_i) = f(\mathbf{Y}_i \mid \mathbf{R}_i) f(\mathbf{R}_i). \tag{5}$$

Restricting attention to the dropouts, we obtain:

$$f(\mathbf{Y}_i, D_i) = f(\mathbf{Y}_i \mid D_i) f(D_i). \tag{6}$$

The first step in applying the pattern-mixture approach to handling missing data is to divide the subjects into groups on the basis of their missing-data pattern. Next, the missing-data pattern is utilized as a grouping variable in the analysis of longitudinal data. The third step is added to conduct the imputation with the aid of the pattern-mixture models. Imputation means the method of substituting some reasonable guess for each missing value and proceeding to conduct the analysis as if there were no missing values. Rubin (1987) proposed multiple imputation with pattern-mixture models to handle some special missing mechanisms. Our case, enlightened by observations from the cracking data, contributed another single imputation approach. First, we provide three possible imputed values for each missing value derived from the above pattern-mixture model:

1. expected value condition on the missing-data pattern, i.e., $E(y_{ij}|D_i)$;
2. the marginal expectation averaged over the missing-data patterns:

$$E(y_{ij}) = \sum_{d \in \text{all patterns}} E(y_{ij} \mid D_i = d)\, p(D_i = d)\,; \tag{7}$$

3. BLUP based on the mixed pattern-mixture model. This is the generalization of the best linear unbiased estimator (BLUE) in the regression model to the mixed model. Based on the model (Eq. 1), the BLUP can be expressed by:

$$\hat{\mathbf{Y}}_\mathbf{i} = \mathbf{X}_\mathbf{i}\hat{\boldsymbol{\beta}} + \mathbf{Z}_\mathbf{i}\hat{\mathbf{b}}_\mathbf{i}\,, \tag{8}$$

where $\hat{\boldsymbol{\beta}}$ and $\hat{\mathbf{b}}_\mathbf{i}$ are estimated coefficients from the model. We then have an expert in pavement management select the final imputation form, which is simply a mean of one, two, or three of the models.

For the cracking data, dropouts occurred in SMERP sections when the site was removed from the experiment. Figure 10 illustrates this for a fog seal treatment section.

The last plot is obviously the complete case. The detailed dropout information is given in Table 9.

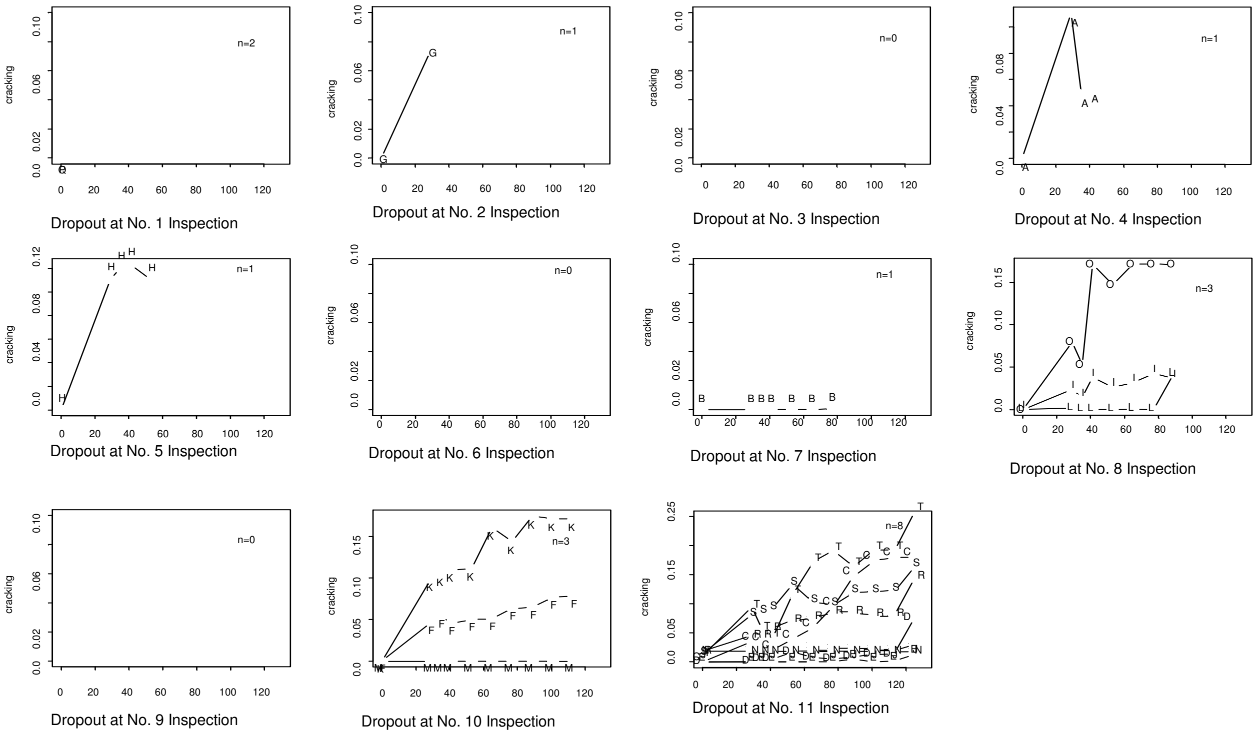


Figure 10. Dropout Plot for Fog.

Table 9. Dropout Distribution.

Site	Inspection Number										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
H	0	0	1	1	0	1	5	0	3	9	
M	0	0	1	1	0	1	5	0	3	9	
E	0	0	1	1	0	1	5	0	3	9	
L	0	0	1	1	0	1	4	1	3	9	
C	0	0	1	1	0	1	5	0	3	9	
F	2	1	0	1	1	0	1	3	0	3	8
X	2	1	0	0	1	0	2	4	0	2	8

Table 9 gives the exact distribution of the numbers of the SMERP sections assigned to treatment type by inspection. The number in each cell indicates the number of sites that dropped out at that inspection. To define a reasonable dropout pattern is difficult because of the nature of the unbalanced design. Part of the difficulty is that fog and control sections have a different number of inspections than do the other treatments. Our definition is based on the grouping result shown in Figure 11.

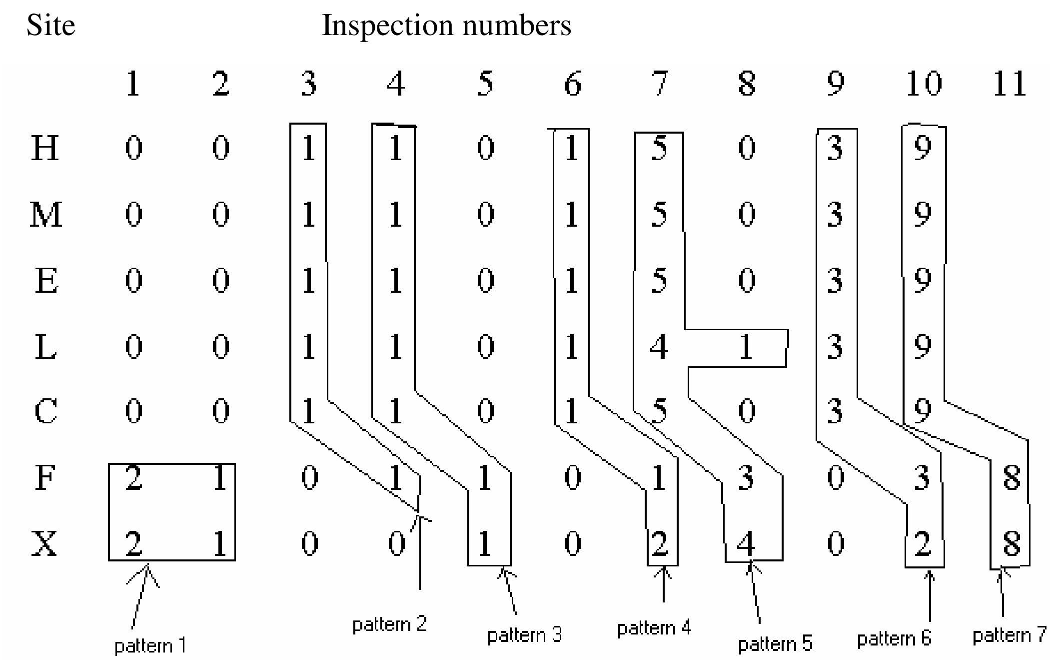


Figure 11. Definition of Dropout Patterns.

Thus, we extract the seven "missing" patterns from the original missing information. Note that pattern seven is the complete case where all treatments have some dropout.

We do not have enough prior information to model the distribution of the dropout mechanism, i.e., the distribution of the "missing" pattern. The easiest way is to assume that it obeys a multinomial distribution. Let D_i = number of SMERP sections belonging to dropout pattern i, and $i = 1, \cdots, 7$. The random vector $(D_1, \cdots, D_7)$ has a multinomial distribution with 140 trials and cell probabilities $\pi_1, \cdots, \pi_7$, which satisfies the requirement that $\sum_{i=1}^{7} \pi_i = 1$. Classical statistics suggest that $\pi_1, \cdots, \pi_7$ can be estimated from the percentages in the output of SAS PROC FREQ, as shown in Figure 12.

Dropout	Frequency	Percent	Cumulative Frequency	Cumulative Percent
1	6	4.29	6	4.29
2	6	4.29	12	8.57
3	7	5.00	19	13.57
4	8	5.71	27	19.29
5	32	22.86	59	42.14
6	20	14.29	79	56.43
7	61	43.57	140	100.00

Figure 12. Output from SAS PROC FREQ.

From Equation 6, the next stage is to model $f(\mathbf{Y}_i \mid D_i)$. We simply add the dropout pattern as a new covariate into the model (Eq. 2) to augment it in the following way:

$$y_{ijk} = \alpha_1 Trt_i \sqrt{t_{ijk}} + \alpha_2 Site_j \sqrt{t_{ijk}} + \alpha_3 Site_j D_{ij} \sqrt{t_{ijk}} + \beta_1 Trt_i t_{ijk}^{\frac{1}{3}} + \beta_2 Site_j t_{ijk}^{\frac{1}{3}} + \beta_3 Trt_i D_{ij} t_{ijk}^{\frac{1}{3}}$$
$$+ \beta_4 Site_j D_{ij} t_{ijk}^{\frac{1}{3}} + b_{oij} t_{ijk} + b_{1ij} \sqrt{t_{ijk}} + b_{2ij} t_{ijk}^{\frac{1}{3}} + \varepsilon_{ijk}. \quad (9)$$

The major results related to the random and fixed effects are calculated from SAS PROC MIXED as shown in Figure 13.

Estimated G Correlation Matrix

Row	Effect	id	Col 1	Col 2	Col 3
1	month	A01C	1.0000	0.9608	-0.9831
2	smonth	A01C	0.9608	1.0000	-0.9938
3	ssmonth	A01C	-0.9831	-0.9938	1.0000

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
smonth*type	6	752	5.86	<0.0001
smonth*site	2	752	8.04	0.0003
ssmonth*type	6	752	5.43	<0.0001
ssmonth*site	2	752	7.03	0.0009
smonth*dropout*type	6	752	0.89	0.4990
smonth*dropout*site	2	752	8.42	0.0002
ssmonth*dropout*site	3	752	5.38	0.0011

Figure 13. Output from SAS PROC MIXED.

The augmented model is significant with the presence of dropouts. All two-way interactions are crucial, since they represent the degree to which treatment and site differences vary across time. The assessment of the three-way interactions is of primary interest. Three possible imputations for each missing inspection as calculated from the model are shown in Figure 14.

For this illustration, only nine SMERP sites are shown. In each plot, A, C, and S indicate marginal expectation (A), conditional expectation (C), and the BLUP from SAS (S), respectively. For most cases, A is the largest with C and S very close to the same value. The expert inspected these imputed candidates and decided which imputed values to use. For example, S was chosen for M-A, L-G, C-F, F-G, X-G, and X-M; C for F-L; the average of A, C, and S for H-I; and the average of A and C for E-A.

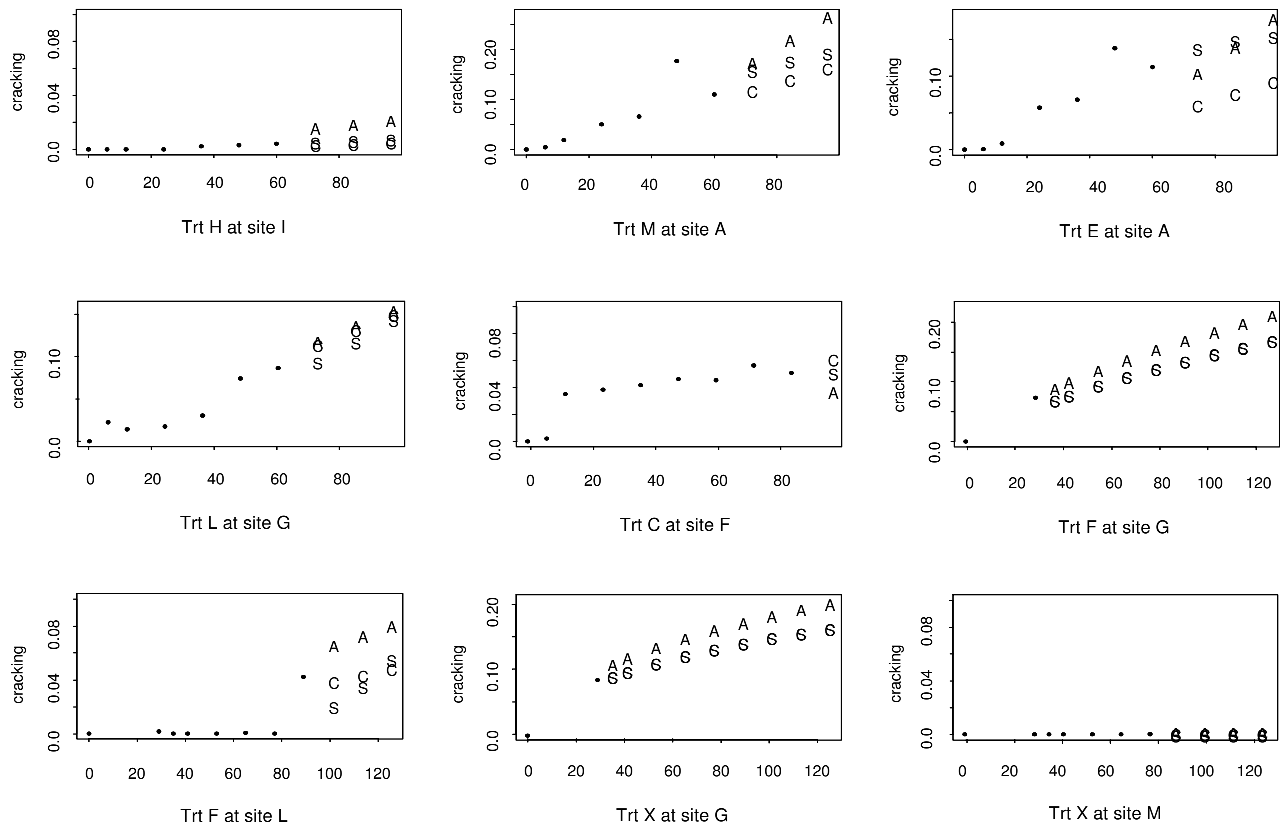


Figure 14. Possible Imputations for Missing Values.

GROUPING AND FAMILY CURVE-FITTING

After imputation, further analysis was conducted based on the supplemented cracking data. For the nine cases shown in Figure 14, after re-calculating the combined version of the possible imputing values based on the expert's determination, the final imputation was calculated. The final curves are shown in Figure 15 with the circle dots representing the imputed values. The objective of this stage is to find a model:

$$T(y_{ijk}) = f(Trt_i, Cond_{ij}, t_{ijk}) + \varepsilon_{ijk} . \qquad (10)$$

Pavement engineers are interested in the treatment, pre-construction, and age effects. It was a natural idea that at the planning stage, the site was designed to confound many effects such as climate and traffic. The site variable was used to calculate the imputation for each subject in the last section. Now we treat the site variable as the replication. Comparing to the first stage, site-curve fitting, we call this stage family-curve fitting. The approach of site-curve fitting is still valid and effective.

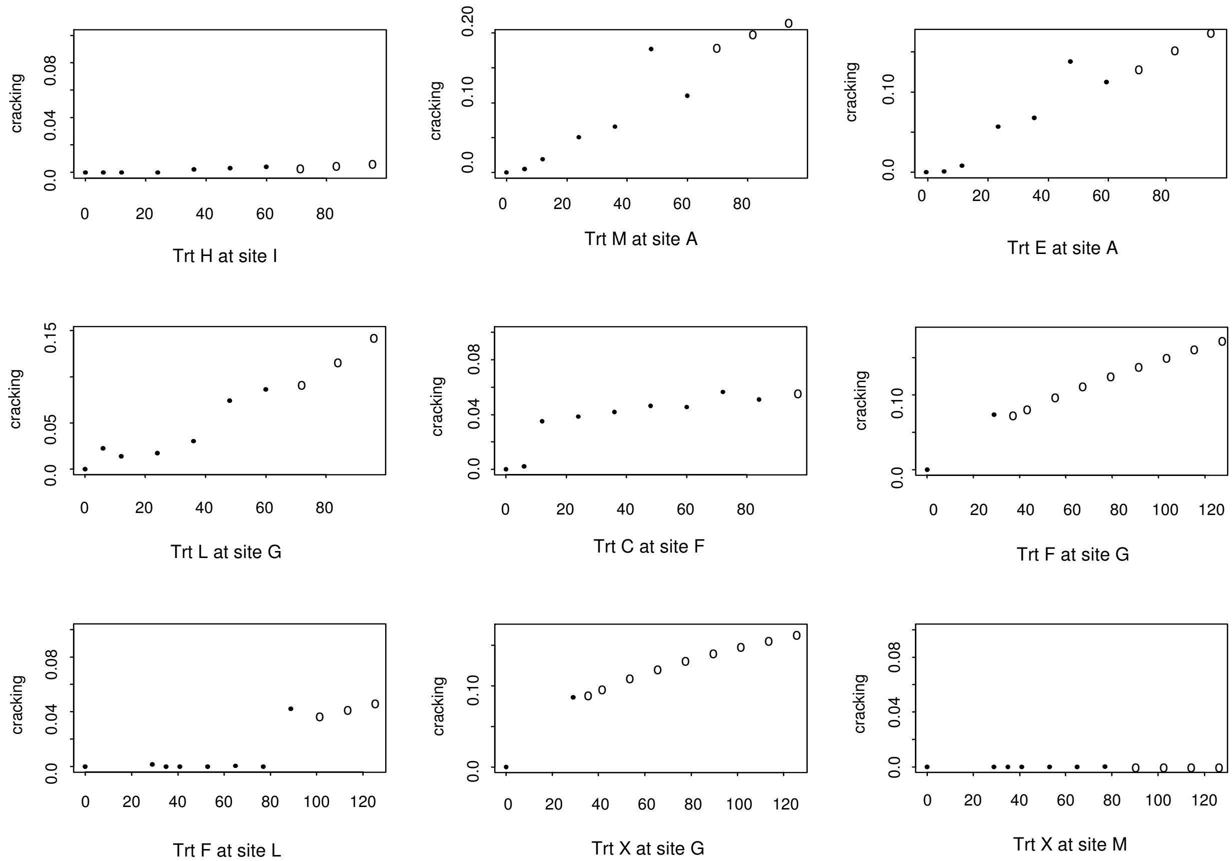


Figure 15. Final Imputations of the Selected Sites in Figure 14.

The exploratory data analyses are shown in Figures 16 and 17. The plots in Figure 16 are very similar to those in Figure 5. Here, the source of each dot is ignored. This growth curve, extracted by the nonparametric regression, is more clearly defined than those in Figure 5. Also, the scatter plot of transformed cracking response versus pavement age for three pre-construction conditions is drawn. These are drawn together in the last plots of Figures 16 and Figure 17.

The model we propose is:

$$y_{ijk} = \alpha_1 Trt_i \sqrt{t_{ijk}} + \alpha_2 Cond_{ij} \sqrt{t_{ijk}} + \beta_1 Trt_i t_{ijk}^{\frac{1}{3}} + b_{oij} t_{ijk} + b_{1ij} \sqrt{t_{ijk}} + b_{2ij} t_{ijk}^{\frac{1}{3}} + \varepsilon_{ijk}, \tag{11}$$

The main SAS output is included in Figure 18.

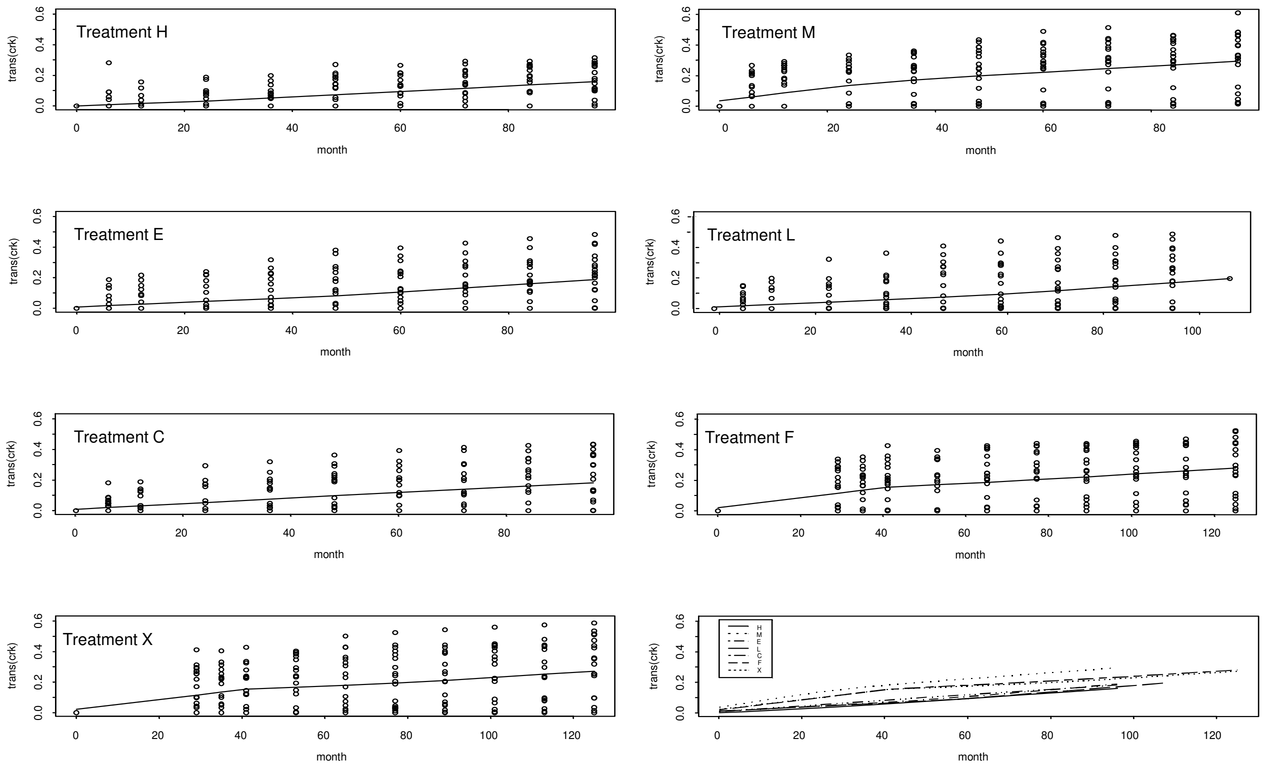


Figure 16. Scatter Plot of the Transformed Imputed Cracking Data by Treatment.

This model provides family curves for all treatment-condition combinations by using different coefficients α_1, α_2 , and β_1 (Eq. 11). For example, the growth curve for treatment H and condition G is:

$$\%cracking\ (t) = \sin^2(0.04506\sqrt{t} - 0.02076\sqrt{t} - 0.04488t^{\frac{1}{3}}), \quad (12)$$

and for treatment F and condition P is:

$$\%cracking\ (t) = \sin^2(0.006933\sqrt{t} + 0.01015\sqrt{t} + 0.05119t^{\frac{1}{3}}). \quad (13)$$

The growth curves are plotted in Figures 19 and 20, respectively.

We are interested in the further grouping, i.e., the possible clustering of similar pavement treatment and pre-construction conditions. To the extent of the authors' knowledge, this classification of longitudinal data has not been well developed. The general multiple comparison methods from the usual experimental design setting reported in our final research plan are applied. Many multiple comparison criterions were tried and all gave the same results. The output from SAS based on Tukey Honestly Significant Difference test (Kuehl, 1994) is included in Figure 21.

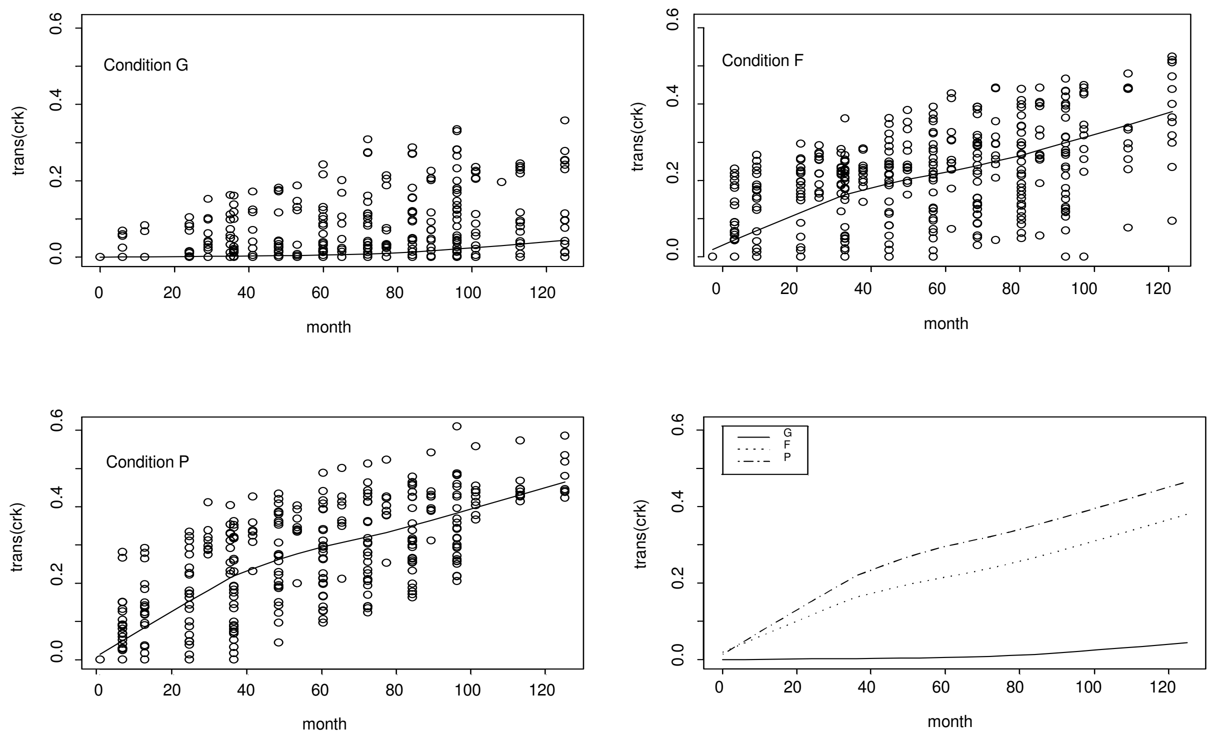


Figure 17. Scatter Plot of the Transformed Imputed Cracking Data by Condition.

Estimated G Correlation Matrix

Row	Effect	id	Col 1	Col 2	Col 3
1	month	1CF	1.0000	0.9298	-0.9690
2	smonth	1CF	0.9298	1.0000	-0.9889
3	ssmonth	1CF	-0.9690	-0.9889	1.0000

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
smonth*type	7	1021	6.42	<0.0001
ssmonth*ckcs	2	1021	141.78	<0.0001
ssmonth*type	6	1021	4.59	0.0001

Figure 18. SAS Output.

Referring to the last plot of Figure 16 and the data structure, the data are grouped as follows:

$$\{(E,C,L,H),(F,X),(M)\}x\{(G),(F),(P)\} \tag{14}$$

that is, nine groups. Equation 11 is still used by substituting grouped treatment for the treatment

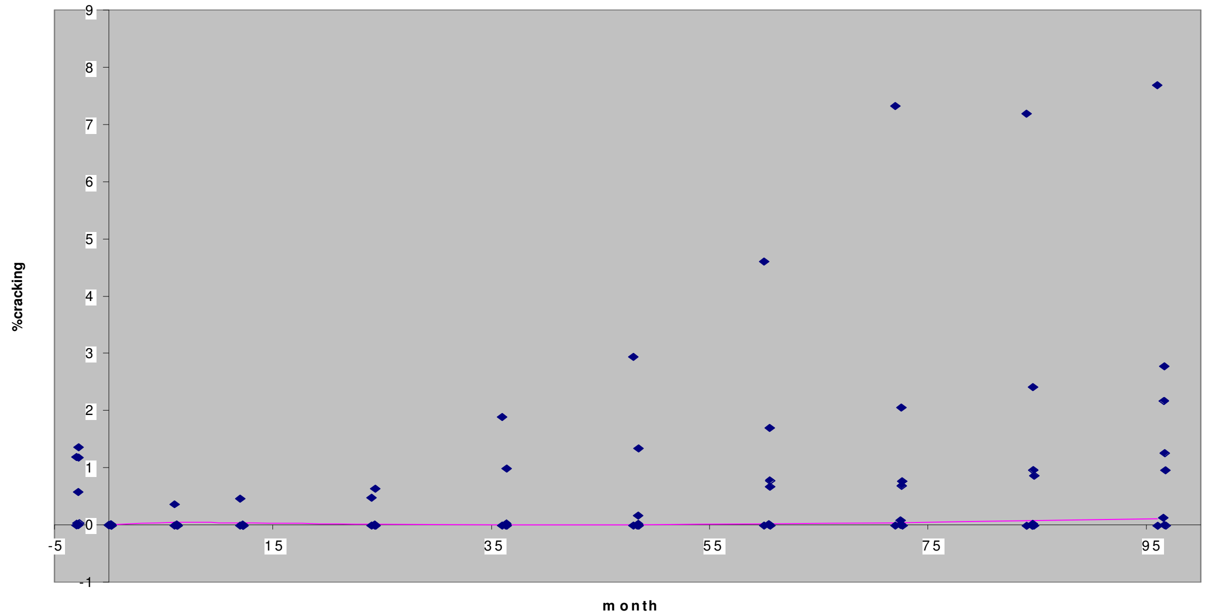


Figure 19. Family Curve for Treatment H, Good Condition.

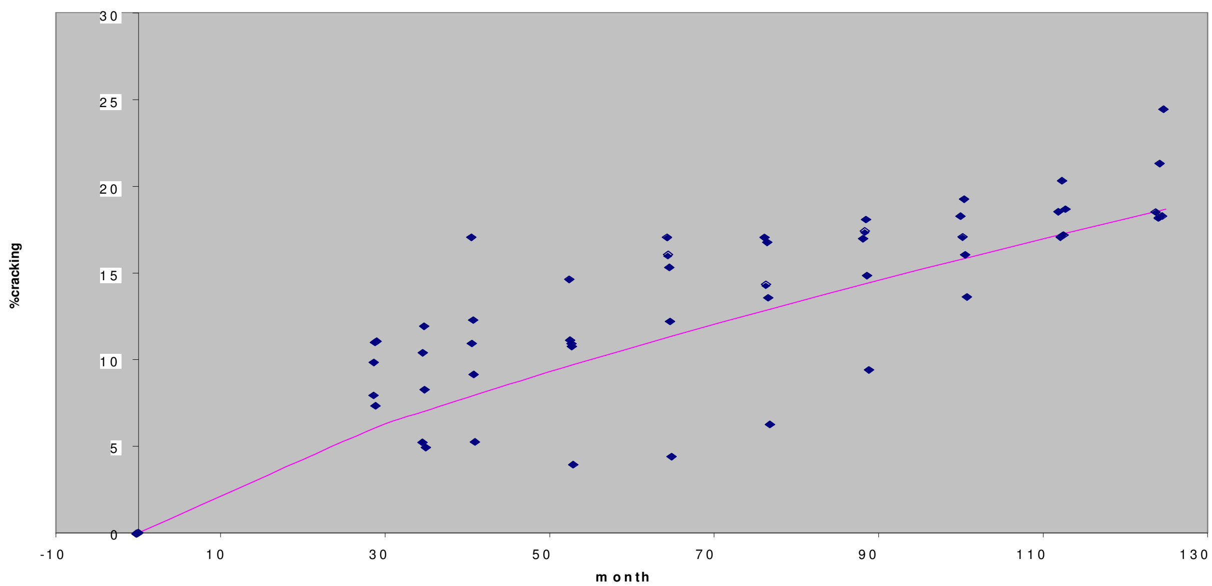


Figure 20. Family Curve for Treatment F, Poor Condition.

variable. The growth curve for treatment group E,C,L,H in condition G is

$$\%cracking\ (t) = \sin^2(0.05647\sqrt{t} - 0.03092\sqrt{t} - 0.04469t^{\frac{1}{3}}), \tag{15}$$

and for treatment combination F,X and condition P is:

$$\%cracking\ (t) = \sin^2(0.01366\sqrt{t} + 0.05966t^{\frac{1}{3}}). \tag{16}$$

The growth curves are plotted in Figures 22 and 23, respectively.

Tukey's Studentized Range (HSD) Test for Trans(crk)			
(Means with the same letter are not significantly different)			
Grouping	**Mean**	**N**	**Type**
A	0.182425	220	F
A	0.179663	220	X
A	0.172488	200	M
B	0.099635	200	E
B	0.099216	200	C
B	0.095971	201	L
C	0.074205	200	H

Grouping	Mean	N	Cond
A	0.237523	369	P
B	0.179348	432	F
C	0.035835	640	G

Figure 21. Output from Tukey Honestly Significant Difference Test.

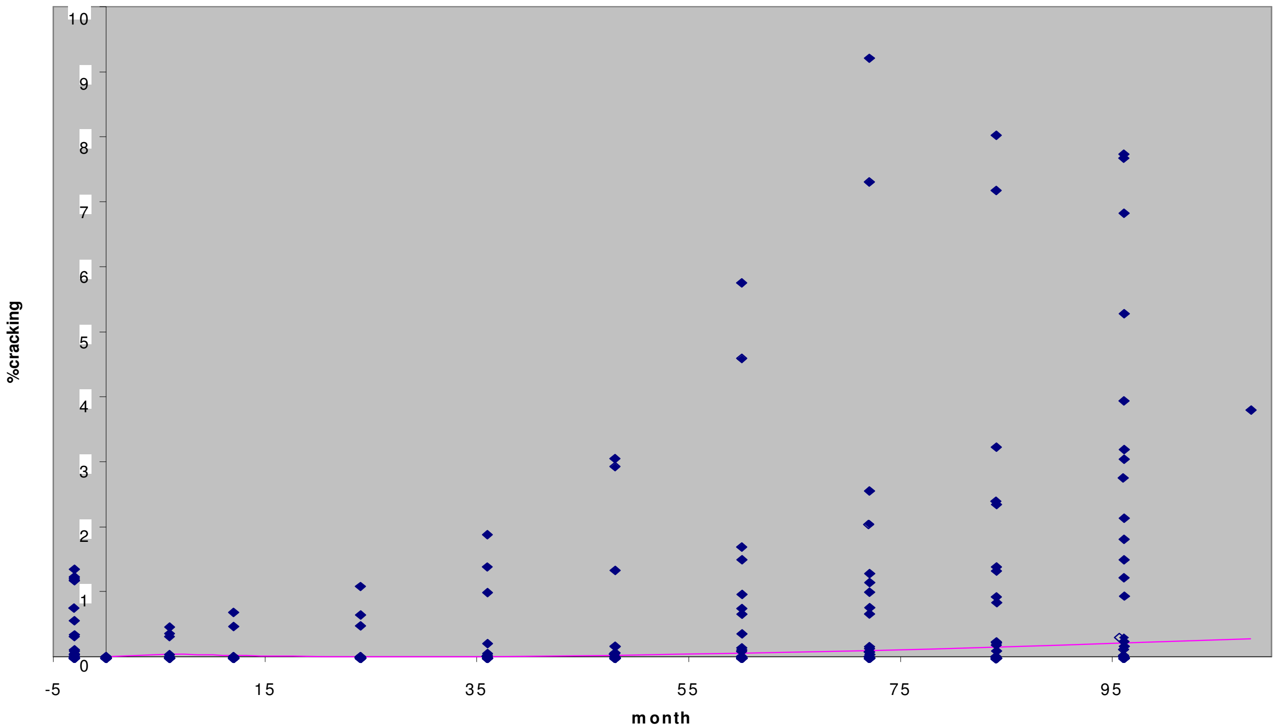


Figure 22. Family Curve for Treatment Group E, C, L, H, Good Condition.

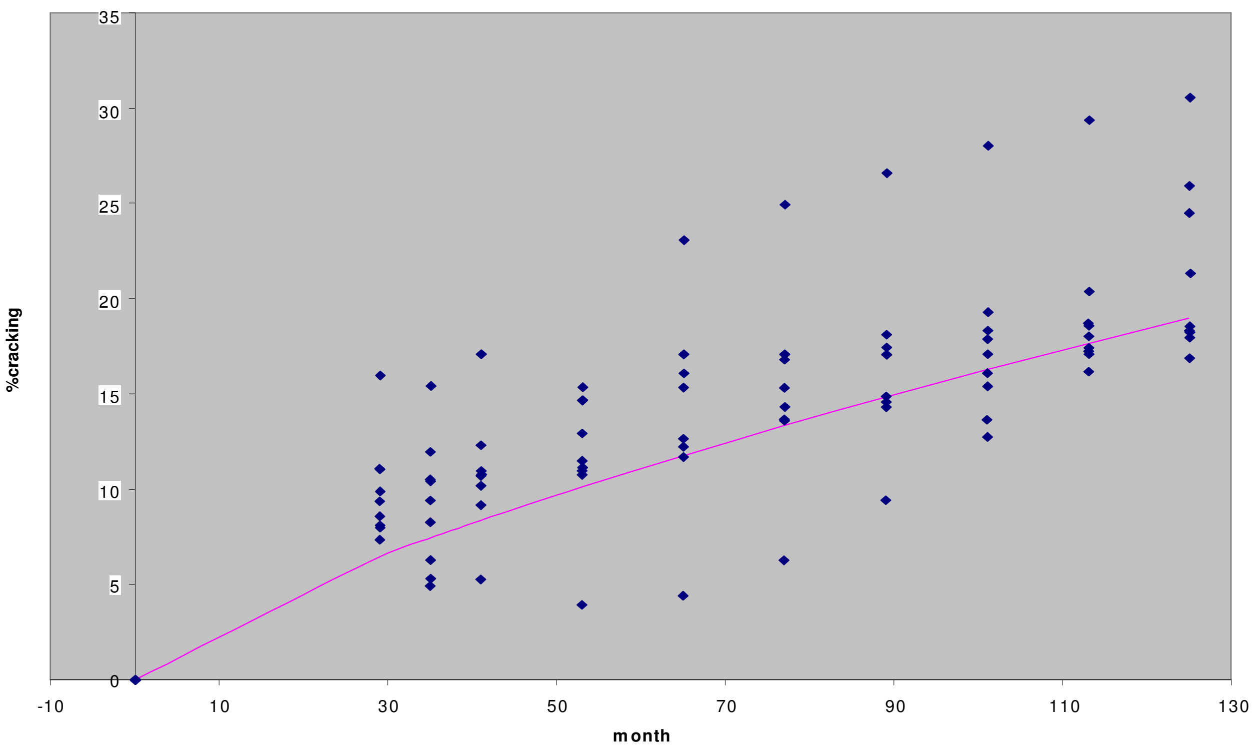


Figure 23. Family Curve for Treatment Group F, X, Poor Condition.

DISCUSSION ITEMS AND CONCERNS

The linear mixed models performed well for the SMERP longitudinal data with dropouts. However, we have the following related issues to discuss.

SPS-3 Data

Although the setting of the SPS-3 project is similar to the SMERP experiment, we could not apply the mixed models to it successfully due to the following reasons:

1. Unclear data collection procedures. The inspection dates for different sections are at many different times and are unbalanced in number. We cannot determine whether some inspections were not conducted or whether they were missed.
2. Strong site effects. The values for cracking and other data oscillate wildly for different sites, and the site effect is much greater than treatment effect. That is, the site designation becomes more important than the treatment type or pre-construction condition. The results were not logical.

Other Factors in SMERP Studies

Climate and traffic are two important environmental factors that affect the performance of pavement, although they do not take part in the SMERP design explicitly. As we pointed out in the initial part of the statistical discussion, they are confounded implicitly in the sites. On the other hand, because of the restriction of the section choices, considering more factors will make the experiment more unbalanced and the reduced replication will dilute the power and accuracy of the analysis. For example, with three treatment conditions and three traffic levels, it would be rare that we would have as many as two sites per cell. For this reason, traffic was not considered. If substantially more sites could be included, the effects of traffic could be isolated.

Calculations of R-square

In classical regression analysis, R-square can indicate the goodness of the fit of the model. Unfortunately, there is no such clear, simple statistic to evaluate the performance of the fitted values in the theory of mixed model. An approximated R-square was calculated for the models used in our analysis and is included on the graphs in the appendices. The values are quite low for good condition compared to that of fair and poor conditions. An obvious reason is that many zeros existed in the original data for good pavements and the R-square is very sensitive to the variations of predicted values around a zero value.

CHAPTER 5. EFFECTIVENESS OF SMERP MAINTENANCE TREATMENTS

The primary question to be answered by this research is "which treatment is most effective in which situation?" To answer this, the researchers performed the previously described comprehensive statistical analysis. The result of this analysis is a complete set of performance curves that are included as the appendices to this report. Appendix A contains the performance curves with respect to cracking, Appendix B contains the performance curves with respect to bleeding, Appendix C contains the performance curves with respect to alligator cracking plus patching, and Appendix D contains the performance curves with respect to Pavement Condition Index.

For each measure of performance, curves for every combination of treatment (except that fog and control sections are always shown as the family performance curve) and for all families are displayed for each initial condition. The results are a mix of the expected and the surprising.

- For all performance measures, treatments placed on sections in good condition performed better than those placed on pavements in fair or poor condition.
- For all performance measures, treatments placed on sections in fair condition performed better than those placed on pavements in poor condition.
- Pavements should be treated while still in good condition.
- Seal coat treatments performed well in reducing cracking.
- For rural roadways with low traffic, unmodified asphalt cement seal coats performed as well as latex and polymer modified seal coats.
- Microsurfacing did reduce bleeding, but did not reduce long-term cracking.
- Seal coat treatments increased bleeding, but the polymer modified emulsion treatment performed better.
- There was very little alligator cracking plus patching, but all treatments appeared to perform well.
- Pavements must be structurally sound. If the alligator cracking is continuous in one wheelpath, the treatment will not perform well without patching. If there is more distress than this, a maintenance treatment should not be used.

- If sections are properly patched at least six months prior to placing the maintenance treatments, the treatments should perform quite well with little distress.

- For PCI, all treatments performed similarly with microsurfacing slightly better and polymer modified emulsion slightly worse than the others.

- Each treatment usually did a very good job of reducing the quantity of distress over the short- and long-term.

- To reduce the effect of bleeding, asphalt application rates should be varied in the wheelpaths. Guidelines from the TxDOT seal coat manual should be followed.

Tables 10 through 13 list the approximate length of time for the specific treatment to accumulate the same quantity of distress that was present at the time of construction. The following key is used in all tables: Rubber - asphalt rubber seal coat (H), Micro - microsurfacing (M), Emuls - polymer modified CRS-2P emulsion seal coat (E), Latex - latex modified seal coat (L), Conv - unmodified asphalt cement seal coat, G - good initial condition, F - fair initial condition, and P - poor initial condition.

Table 10. Time (Years) to Return to Original Condition - Cracking.

Treatment Type	Initial Condition		
	G*	F	P
Rubber (H)	> 8	7	8
Micro (M)	1	3	5
Emuls (E)	7	6	7
Latex (L)	7	6	8
Conv (C)	4	6	8

* - Very little distress

Table 11. Time (Years) to Return to Original Condition - Bleeding.

Treatment Type	Initial Condition		
	G*	F	P
Rubber (H)	< 1	< 1	1
Micro (M)	< 1	3 - 4	> 8
Emuls (E)	< 1	1	3
Latex (L)	< 1	1	2
Conv (C)	< 1	< 1	2

* - Very little distress

Table 12. Time (Years) to Return to Original Condition - Alligator Cracking Plus Patching.

Treatment Type	Initial Condition		
	G*	F	P
Rubber (H)	6	8	> 8
Micro (M)	2	4	5
Emuls (E)	5	6	> 8
Latex (L)	4	> 8	> 8
Conv (C)	4	6	> 8

* - Very little distress

Table 13. Time (Years) to Return to Original Condition - PCI.

Treatment Type	Initial Condition		
	G*	F	P
Rubber (H)	1	3	3
Micro (M)	1	3	5
Emuls (E)	1	3	3
Latex (L)	1	3	4
Conv (C)	1	3	4

* - Very high values

Since the reference pavements (fog and control) were continuing to deteriorate, it is also helpful to determine how the treatments performed with respect to the fog and control sections. Tables 14 through 17 describe that response.

Table 14. Time (Years) to Match Fog and Control - Cracking.

Treatment Type	Initial Condition		
	G*	F	P
Rubber (H)	> 8	> 8	> 8
Micro (M)	3	7	> 8
Emuls (E)	> 8	> 8	> 8
Latex (L)	> 8	> 8	> 8
Conv (C)	> 8	> 8	> 8

* - Very little distress

Table 15. Time (Years) to Match Fog and Control - Bleeding.

Treatment Type	Initial Condition		
	G*	F	P
Rubber (H)	< 1	4	< 1
Micro (M)	> 8	> 8	> 8
Emuls (E)	< 1	< 1	< 1
Latex (L)	< 1	< 1	< 1
Conv (C)	< 1	< 1	< 1

* - Very little distress

Table 16. Time (Years) to Match Fog and Control - Alligator Cracking Plus Patching.

Treatment Type	Initial Condition		
	G*	F	P
Rubber (H)	> 8	> 8	All treatments ended up at or below fog and control, but rates made comparisons difficult
Micro (M)	> 8	> 8	
Emuls (E)	> 8	> 8	
Latex (L)	> 8	> 8	
Conv (C)	> 8	> 8	

* - Very little distress

Table 17. Time (Years) to Match Fog and Control - PCI.

Treatment Type	Initial Condition		
	G*	F	P
Rubber (H)	1	3	3
Micro (M)	1	3	5
Emuls (E)	1	3	3
Latex (L)	1	3	4
Conv (C)	1	3	4

* - Very high values

TREATMENT EFFECTIVENESS FOR CRACKING

Seal coats were very effective in reducing the amount of cracking at all condition levels. However, when there was very little initial cracking (good condition) even a little cracking can be enough to exceed that amount of initial cracking. When this happened, the pavement life extension appears to be minimal. Referring to Table 18, a section in good condition for cracking had less than 20 feet of cracking per station (100 feet). Even a fair section had less than 100 feet of cracking per station, so these pavement sections were in relatively good condition and the seal coat treatments did reduce that cracking for an appreciable length of time. One confounding factor in all of this is that because there was considerable bleeding on many of these seal coat sections, cracks that would have occurred were sealed with the excess asphalt.

The microsurfacing treatment did not perform as well as the seal coat sections in reducing cracking. One explanation for the seeming increase of cracking with treatment is that with this treatment, cracks are much easier to see. However, it may also be that the stiffer layer does not allow for as much healing and resealing during hot weather. The best answer is probably a mix of these two explanations.

Cracking - Good Condition

The seal coat treatments (E, C, L, H) increased the life with respect to cracking of the good condition pavement sections by four to eight years. For pavements in good condition, the asphalt rubber seal coat performed best, but the projected difference in cracking after eight years was only a little more than 3 feet per station.

A good section had less than 20 feet of cracking per station, and 37 of the 58 candidate sections had no cracking. Table 18 illustrates the percent cracking over time compared to the fog and control sections for sections in good condition.

Table 18. Cracking Performance Compared to Fog and Control for Good Sections.

Age (Months)	Feet of Cracking Per Station						Percent of Fog and Control				
	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)	Fog-Control	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)
-3	6.2	0.3	3.1	2.5	0.1						
0	0.0	0.0	0.0	0.0	0.0	10.6	0%	0%	0%	0%	0%
6	0.6	3.0	0.3	0.4	0.6	11.2	6%	27%	3%	3%	5%
12	0.5	5.2	0.1	0.2	0.4	11.7	4%	44%	1%	1%	3%
24	0.1	8.9	0.0	0.0	0.1	12.6	1%	71%	0%	0%	1%
36	0.0	12.3	0.3	0.1	0.0	14.2	0%	87%	2%	1%	0%
48	0.0	15.5	0.8	0.5	0.1	14.1	0%	110%	6%	4%	1%
60	0.2	18.4	1.6	1.1	0.3	14.4	1%	128%	11%	8%	2%
72	0.5	21.3	2.5	1.9	0.6	14.6	3%	146%	17%	13%	4%
84	0.9	24.1	3.6	2.8	1.1	14.8	6%	163%	24%	19%	7%
96	1.4	26.8	4.8	3.9	1.7	14.9	9%	180%	32%	26%	11%

Cracking - Fair Condition

The seal coat treatments (E, C, L, H) increased the pavement life with respect to cracking of the fair sections by six to seven years. Asphalt rubber and conventional treatments performed best, but the projected difference in cracking after eight years was only a little more than 15 feet per station.

A fair section had more than 20 feet and less than 100 feet of cracking per station. Table 19 illustrates the percent cracking over time compared to the fog and control for sections in fair condition.

Table 19. Cracking Performance Compared to Fog and Control for Fair Sections.

Age (Months)	Feet of Cracking Per Station						Percent of Fog and Control				
	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)	Fog-Control	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)
-3	60.9	59.9	59.8	59.7	50.5						
0	0.0	0.0	0.0	0.0	0.0	51.8	0%	0%	0%	0%	0%
6	1.1	13.0	1.7	1.5	1.2	58.9	2%	22%	3%	3%	2%
12	3.7	23.8	5.2	4.9	4.0	65.6	6%	36%	8%	7%	6%
24	10.8	44.1	14.3	13.8	11.4	78.3	14%	56%	18%	18%	15%
36	19.3	63.4	24.9	24.3	20.2	90.0	21%	70%	28%	27%	22%
48	28.7	81.9	36.5	35.9	29.9	101.0	28%	81%	36%	35%	30%
60	38.8	100.0	48.7	48.1	40.1	111.5	35%	90%	44%	43%	36%
72	49.3	117.6	61.4	60.8	50.9	121.5	41%	97%	51%	50%	42%
84	60.1	134.8	74.5	74.0	62.0	131.1	46%	103%	57%	56%	47%
96	71.3	151.7	87.9	87.4	73.4	140.4	51%	108%	63%	62%	52%

Cracking - Poor Condition

The seal coat treatments (E, C, L, H) increased the pavement life with respect to cracking of the poor sections by seven to eight years. For the pavements in poor condition, the asphalt rubber and conventional treatments performed best, but the projected difference in cracking after eight years was only a little more than 15 feet per station.

A poor section had more than 100 feet of cracking per station. Table 20 illustrates the percent cracking over time compared to the fog and control for sections in poor condition.

Table 20. Cracking Performance Compared to Fog and Control for Poor Sections.

Age (Months)	Feet of Cracking Per Station						Percent of Fog and Control				
	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)	Fog-Control	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)
-3	155.6	149.1	148.4	164.4	143.5						
0	0.0	0.0	0.0	0.0	0.0	87.5	0%	0%	0%	0%	0%
6	3.9	20.2	5.0	4.6	4.1	100.6	4%	20%	5%	5%	4%
12	10.3	38.3	13.2	12.0	10.8	112.7	9%	34%	12%	11%	10%
24	26.1	71.9	32.4	30.1	26.9	137.6	19%	52%	24%	22%	20%
36	44.1	103.8	53.7	50.2	45.0	158.7	28%	65%	34%	32%	28%
48	63.0	134.5	76.2	71.5	64.1	178.4	35%	75%	43%	40%	36%
60	82.7	164.3	99.4	93.5	84.0	198.5	42%	83%	50%	47%	42%
72	102.9	193.2	123.0	116.1	104.3	219.5	47%	88%	56%	53%	48%
84	123.4	221.4	147.0	139.0	125.0	238.3	52%	93%	62%	58%	52%
96	144.2	249.0	171.2	162.1	145.9	254.3	57%	98%	67%	64%	57%

TREATMENT EFFECTIVENESS FOR BLEEDING

Seal coats were not effective in reducing the amount of bleeding at any condition level. We cannot ascertain whether this was due to the treatments themselves, the construction method, or the contractor. Proper procedures were followed, though there were some problems with the chip spreader as identified in the report on construction (Freeman and Rmeili, 1994). Part of the situation is that the SHRP distress manual identifies low severity bleeding as "surface discolored relative to the remainder of the pavement by excess asphalt." This definition leads to considerable low severity bleeding on seal coat pavements.

The microsurfacing treatment performed best in all cases. Although most experts do not consider microsurfacing to be an effective method of treating pavements that are bleeding, the data in this study did show it to be effective.

Bleeding - Good Condition

None of the treatments increased the life of the sections with respect to bleeding for the sections in good condition, and some treatments had a negative effect. The situation with definition of low severity bleeding has been discussed previously. The polymer modified emulsion and conventional treatments performed best among the seal coat treatments. Microsurfacing did have a positive effect, but for the pavements in good condition, the bleeding came back fairly quickly. Microsurfacing reduced the long-term bleeding as compared to the fog and control sections. As has been previously noted, these good condition sections had very little bleeding to begin with.

A good section had less than 6 percent bleeding, and 54 of the 61 candidate sections had 0 percent. With these small quantities, even a little bleeding resulted in a large percentage increase. Table 21 illustrates the percent bleeding over time compared to the fog and control for sections in good condition.

Table 21. Bleeding Performance Compared to Fog and Control for Good Sections.

Age (Months)	Percent Bleeding						Percent of Fog and Control				
	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)	Fog-Control	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)
-3	0%	0%	0%	1%	0%						
0	0%	0%	0%	0%	0%	5%	0%	0%	0%	0%	0%
6	18%	0%	6%	6%	7%	5%	348%	5%	109%	108%	137%
12	24%	1%	9%	10%	12%	6%	397%	11%	153%	169%	190%
24	31%	2%	15%	18%	18%	8%	412%	21%	195%	237%	240%
36	36%	2%	19%	24%	23%	9%	401%	27%	215%	273%	262%
48	40%	3%	23%	30%	28%	10%	385%	32%	225%	293%	272%
60	43%	4%	27%	35%	32%	12%	368%	35%	230%	305%	277%
72	45%	5%	30%	40%	36%	13%	352%	38%	232%	313%	278%
84	48%	6%	33%	45%	39%	14%	338%	41%	233%	317%	278%
96	50%	7%	36%	49%	42%	15%	325%	43%	233%	319%	277%

Bleeding - Fair Condition

None of the seal coat treatments increased the life of the sections with respect to bleeding for the sections in fair condition and some treatments had a negative effect. The polymer modified emulsion and conventional treatments performed best among the seal coat treatments. Microsurfacing had a positive effect with a three- to four-year life extension. Long-term, microsurfacing consistently had less bleeding than the fog and control sections.

A fair section had more than 6 percent and less than 23 percent bleeding. Table 22 illustrates the percent bleeding over time compared to the fog and control for sections in fair condition.

Table 22. Bleeding Performance Compared to Fog and Control for Fair Sections.

Age (Months)	Percent Bleeding						Percent of Fog and Control				
	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)	Fog-Control	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)
-3	19%	12%	19%	16%	13%						
0	0%	0%	0%	0%	0%	14%	0%	0%	0%	0%	0%
6	30%	3%	14%	14%	16%	16%	193%	22%	87%	88%	102%
12	38%	5%	20%	21%	23%	17%	224%	31%	115%	125%	134%
24	48%	8%	28%	33%	33%	20%	241%	41%	142%	165%	166%
36	54%	11%	35%	41%	40%	22%	242%	47%	155%	186%	180%
48	58%	13%	40%	49%	46%	25%	238%	51%	163%	198%	188%
60	62%	14%	44%	55%	51%	27%	233%	54%	167%	206%	192%
72	65%	16%	48%	60%	55%	28%	228%	57%	169%	210%	194%
84	67%	18%	52%	64%	59%	30%	222%	58%	171%	213%	195%
96	70%	19%	55%	69%	63%	32%	217%	60%	171%	214%	196%

Bleeding - Poor Condition

The polymer modified emulsion, latex, and conventional seal coat treatments increased the life of the sections with respect to bleeding for the sections in poor condition by two or three years. The asphalt rubber seal coat treatment had a negative effect. Microsurfacing had a positive effect on bleeding, with at least an eight-year life extension. Long-term, microsurfacing consistently had less bleeding than the fog and control sections.

A poor section had more than 23 percent bleeding. Table 23 illustrates the percent bleeding over time compared to the fog and control for sections in poor condition.

Table 23. Bleeding Performance Compared to Fog and Control for Poor Sections.

Age (Months)	Percent Bleeding						Percent of Fog and Control				
	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)	Fog-Control	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)
-3	52%	50%	55%	53%	56%						
0	0%	0%	0%	0%	0%	32%	0%	0%	0%	0%	0%
6	52%	16%	31%	33%	36%	33%	158%	47%	95%	98%	107%
12	61%	19%	40%	43%	45%	35%	177%	56%	114%	123%	129%
24	69%	24%	49%	55%	55%	37%	187%	64%	132%	147%	148%
36	74%	26%	55%	62%	61%	39%	189%	67%	141%	160%	157%
48	77%	28%	59%	68%	66%	41%	189%	69%	146%	167%	162%
60	79%	30%	63%	72%	69%	42%	187%	71%	149%	172%	165%
72	80%	31%	66%	76%	72%	43%	186%	72%	152%	176%	167%
84	82%	32%	68%	79%	75%	44%	184%	72%	153%	178%	168%
96	83%	33%	70%	82%	77%	45%	182%	73%	155%	180%	169%

TREATMENT EFFECTIVENESS FOR ALLIGATOR CRACKING PLUS PATCHING

All treatments were effective in reducing the amount of alligator cracking plus patching at all condition levels. Good and fair sections did not have a lot of distress. The distresses had to be combined for the purpose of analysis; otherwise, the quantities of alligator cracking would fluctuate wildly as alligator cracking occurred and was then patched. The data below do not mean that the treatments will work well **regardless** of the amount of alligator cracking. Pavements must be structurally sound. If the alligator cracking is continuous in one wheelpath, the treatment will not perform well without patching. If there is more distress than this, a maintenance treatment should not be used. However, if sections were properly patched at least six months prior to placing the maintenance treatments, the treatments should behave quite well with little distress. The results are reflected in the following sections and tables.

Alligator Cracking Plus Patching - Good Condition

The seal coat treatments (E, C, L, H) increased the pavement life with respect to alligator cracking plus patching of the good sections by four to six years. Asphalt rubber and polymer modified emulsion treatments performed best, but the amount of distress was always very, very small. The projected difference in cracking after eight years was only a little more than 5 square feet per station. Microsurfacing was not as effective and contributed only two years to life extension.

A good section had no alligator cracking or patching. There were 86 candidate sections. Table 24 illustrates the percent cracking over time compared to the fog and control for sections in good condition.

Table 24. Alligator Cracking Plus Patching Performance Compared to Fog and Control for Good Sections.

Age (Months)	Percent Alligator Cracking Plus Patching						Percent of Fog and Control				
	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)	Fog-Control	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)
-3	0.0%	0.0%	0.0%	0.0%	0.0%						
0	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%
6	0.0%	0.0%	0.0%	0.0%	0.0%	0.7%	2.6%	0.8%	1.1%	0.3%	0.6%
12	0.0%	0.0%	0.0%	0.0%	0.0%	0.9%	2.4%	2.6%	0.7%	0.0%	0.2%
24	0.0%	0.1%	0.0%	0.0%	0.0%	1.3%	1.0%	7.3%	0.0%	0.3%	0.1%
36	0.0%	0.2%	0.0%	0.0%	0.0%	1.7%	0.2%	12.2%	0.2%	1.6%	0.9%
48	0.0%	0.4%	0.0%	0.1%	0.1%	2.3%	0.0%	16.7%	1.1%	3.3%	2.3%
60	0.0%	0.6%	0.1%	0.2%	0.1%	2.9%	0.4%	20.7%	2.4%	5.3%	4.0%
72	0.0%	0.9%	0.1%	0.3%	0.2%	3.6%	1.2%	24.0%	3.8%	7.3%	5.7%
84	0.1%	1.2%	0.2%	0.4%	0.3%	4.4%	2.1%	26.9%	5.3%	9.2%	7.5%
96	0.2%	1.5%	0.4%	0.6%	0.5%	5.2%	3.1%	29.3%	6.7%	11.0%	9.1%

Alligator Cracking Plus Patching - Fair Condition

The seal coat treatments (E, C, L, H) increased the life with respect to alligator cracking plus patching of the fair sections by six to eight years. Asphalt rubber and latex treatments performed best. Microsurfacing was not as effective, but it did contribute four years to life extension.

A fair section had some alligator cracking or patching, but less than 4 percent. Table 25 illustrates the percent cracking over time compared to the fog and control for sections in fair condition.

Table 25. Alligator Cracking Plus Patching Performance Compared to Fog and Control for Fair Sections.

Age (Months)	Percent Alligator Cracking Plus Patching						Percent of Fog and Control				
	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)	Fog-Control	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)
-3	0.7%	0.4%	0.6%	1.7%	0.6%						
0	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%
6	0.0%	0.0%	0.0%	0.0%	0.0%	0.7%	2.7%	0.7%	1.2%	0.4%	0.6%
12	0.0%	0.0%	0.0%	0.0%	0.0%	0.9%	1.9%	3.2%	0.4%	0.0%	0.1%
24	0.0%	0.1%	0.0%	0.0%	0.0%	1.3%	0.2%	11.0%	0.2%	1.4%	0.8%
36	0.0%	0.3%	0.0%	0.1%	0.1%	1.7%	0.3%	19.8%	2.1%	4.9%	3.6%
48	0.0%	0.6%	0.1%	0.2%	0.2%	2.3%	2.0%	28.4%	5.3%	9.4%	7.6%
60	0.1%	1.0%	0.3%	0.4%	0.3%	2.9%	4.5%	36.2%	9.0%	14.2%	12.0%
72	0.3%	1.5%	0.5%	0.7%	0.6%	3.6%	7.5%	43.0%	13.0%	18.9%	16.4%
84	0.5%	2.1%	0.7%	1.0%	0.9%	4.4%	10.6%	48.9%	16.9%	23.4%	20.7%
96	0.7%	2.8%	1.1%	1.4%	1.3%	5.2%	13.8%	53.9%	20.6%	27.6%	24.7%

Alligator Cracking Plus Patching - Poor Condition

All seal coat treatments (E, C, L, H) increased the life with respect to alligator cracking plus patching of the poor sections by more than eight years. Microsurfacing was not as effective, but did contribute five years to life extension. After eight years, most of the distress had returned.

A poor section had more than 4 percent alligator cracking plus patching, but most of these sections did not have large amounts. Table 26 illustrates the percent cracking over time compared to fog and control sections for sections in poor condition.

Table 26. Alligator Cracking Plus Patching Performance Compared to Fog and Control for Poor Sections.

Age (Months)	Percent Alligator Cracking Plus Patching						Percent of Fog and Control				
	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)	Fog-Control	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)
-3	21.6%	13.1%	18.7%	59.9%	23.1%						
0	0.0%	0.0%	0.0%	0.0%	0.0%	1.0%	0.0%	0.0%	0.0%	0.0%	0.0%
6	1.1%	1.6%	1.2%	1.3%	1.3%	1.4%	83.1%	118.8%	90.6%	97.4%	94.7%
12	2.2%	3.1%	2.4%	2.6%	2.5%	1.8%	119.6%	171.6%	130.5%	140.4%	136.4%
24	4.1%	5.9%	4.5%	4.8%	4.7%	3.0%	137.4%	198.2%	150.2%	161.8%	157.1%
36	5.9%	8.5%	6.4%	6.9%	6.7%	4.5%	129.8%	188.0%	142.1%	153.1%	148.7%
48	7.5%	10.9%	8.2%	8.9%	8.6%	6.5%	116.1%	168.8%	127.2%	137.3%	133.2%
60	9.1%	13.2%	9.9%	10.7%	10.4%	8.9%	102.2%	148.9%	112.0%	120.9%	117.3%
72	10.5%	15.4%	11.6%	12.5%	12.1%	11.7%	89.6%	130.8%	98.3%	106.2%	103.0%
84	11.9%	17.4%	13.1%	14.1%	13.7%	15.1%	78.8%	115.3%	86.5%	93.5%	90.7%
96	13.2%	19.3%	14.5%	15.7%	15.2%	18.9%	69.6%	102.1%	76.5%	82.7%	80.2%

TREATMENT EFFECTIVENESS FOR PAVEMENT CONDITION INDEX

All treatments were effective in raising the PCI and in generally lowering the deterioration rate, except that the performance of the seal coat treatments was certainly affected by the extensive bleeding and the microsurfacing was affected by the cracking, as discussed earlier. At the good condition level, the treatments did not have a significant impact, but those pavement sections were already in very good condition, so not much improvement was possible.

Typically, maintenance is performed when the pavements are in a condition that would correspond to fair or poor in this analysis, especially since the PCI is based on a combination of the structural and functional condition.

Pavement Condition Index - Good Condition

All treatments increased the life with respect to PCI for the good sections by approximately one year. While this difference is not a significant increase, to be included in the good condition group meant there was little distress; thus, any reoccurrence or appearance of distress would reduce the score.

A good section had a PCI greater than 85. Twenty-seven of the 48 sections had an initial PCI above 90. Table 27 illustrates the PCI over time compared to the fog and control for sections in good condition.

Table 27. PCI Performance Compared to Fog and Control for Good Sections.

Age (Months)	Pavement Condition Index (PCI)						PCI Increase				
	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)	Fog-Control	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)
-3	93	93	90	91	91						
0	100	100	100	100	100	87	13	13	13	13	13
6	98	98	97	98	98	83	14	15	14	14	14
13	94	94	93	94	94	81	13	13	12	13	13
25	88	89	87	88	88	78	10	11	9	10	10
36	82	83	82	83	82	75	7	8	7	8	7
47	78	80	77	80	78	73	5	7	4	7	5
60	73	76	73	76	74	71	2	5	2	5	3
73	70	73	69	74	71	69	0	3	0	4	1
85	66	70	66	71	68	68	-2	2	-2	3	0
96	64	68	64	70	66	67	-4	1	-4	2	-2

Pavement Condition Index - Fair Condition

All treatments increased the pavement life with respect to PCI for the fair sections by three years. Most treatments, except for the asphalt rubber and polymer modified emulsion, had a positive impact on the PCI for all eight years. For these two treatments, the PCI dropped below that of the untreated sections by more than 3 points. The final inspection for the conventional treatment was also lower.

A fair section had a PCI less than 85 and greater than 70. Table 28 illustrates the PCI over time compared to the fog and control for sections in fair condition.

Table 28. PCI Performance Compared to Fog and Control for Fair Sections.

Age (Months)	Pavement Condition Index (PCI)						PCI Increase				
	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)	Fog-Control	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Con v (C)
-3	52	47	57	52	52						
0	100	100	100	100	100	60	40	40	40	40	40
5	79	80	79	79	80	56	23	24	23	23	24
12	70	71	70	71	71	54	16	17	16	17	17
24	60	61	60	62	61	51	9	11	9	11	10
36	53	55	54	56	54	49	5	7	5	7	6
46	49	51	49	52	50	47	2	4	2	5	3
59	45	48	46	49	47	46	-1	2	-1	3	0
72	42	46	43	47	44	46	-3	0	-3	2	-2
84	40	44	41	46	42	46	-5	-1	-5	0	-3
96	39	43	39	45	41	46	-7	-2	-6	0	-5

Pavement Condition Index - Poor Condition

All seal coat treatments increased the life with respect to PCI for the poor sections by three or four years. Most treatments, except for the asphalt rubber and polymer modified emulsion had a positive impact on the PCI for all eight years. For these two treatments, the PCI dropped below that of the untreated sections by more than 3 points. The final inspection for the conventional treatment was also lower. Microsurfacing was more effective and had a life extension of five years.

A poor section had a PCI less than 70. Table 29 illustrates the PCI over time compared to the fog and control for sections in poor condition.

Table 29. PCI Performance Compared to Fog and Control for Poor Sections.

Age (Months)	Pavement Condition Index (PCI)						PCI Increase				
	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)	Fog-Control	Rubber (H)	Micro (M)	Emuls (E)	Latex (L)	Conv (C)
-3	78	77	78	77	77						
0	100	100	100	100	100	81	19	19	19	19	19
6	94	94	93	94	93	78	15	16	15	16	15
12	88	89	88	89	88	76	12	12	12	13	12
24	81	82	81	83	82	74	8	9	8	9	8
36	76	78	76	78	77	72	5	6	5	7	5
46	73	75	73	75	73	70	2	4	2	5	3
59	69	71	69	73	70	69	0	2	0	3	1
72	66	69	66	71	68	69	-3	1	-2	2	-1
84	64	68	64	69	66	68	-4	-1	-4	1	-2
96	62	66	62	68	64	68	-6	-2	-6	0	-4

CHAPTER 6. TREATMENT SELECTION

TxDOT districts choose specific maintenance treatments for a variety of reasons. The work described in this report adds an important tool in making that decision. Many districts choose a specific maintenance treatment because that is what is historically done in the district, a high-level engineer has had a positive experience with that treatment, or because of material or contractor availability. Less frequently has expected performance been used as a decision-making criterion.

The recommendations below are based on the results of this maintenance research project and the authors' experience. The primary decision criteria are based upon the predominant distress type and quantity. The treatment selection is based upon the short- and long-term performance for that type of distress and on the overall performance of the treatment. Qualifying statements are included for those cases when other distress types are present.

PREDOMINANT DISTRESS TYPE - CRACKING

When longitudinal and transverse cracking is the predominant distress, a seal coat should be the first choice. The asphalt rubber seal coat performed best at reducing the return of the cracking, but other types also performed well. However, since these treatments resulted in bleeding, if high traffic volumes or wet weather skid resistance is a problem, either the polymer modified emulsion or microsurfacing should be used. The microsurfacing treatment will not substantially reduce the cracking, but will provide a good, serviceable pavement. Table 30 contains the full recommendation.

PREDOMINANT DISTRESS TYPE - BLEEDING

When bleeding is the problem, use microsurfacing. However, if there is substantial cracking, the polymer modified emulsion will perform better. Bleeding will still be a concern, but careful attention to application rates may help solve this problem. Table 31 contains the full recommendation.

Table 30. Treatment Selection - Cracking.

Condition Category	Best Treatment	Years until PCI < 70	Good Treatment	If Also Bleeding	If Also Alligator Plus Patch
Less than 20 feet/station	Asphalt Rubber	5	Emuls or other seal coats	Seals increased bleeding so if wet weather skid is a problem, consider Emuls or Micro	Asphalt Rubber
20 to 100 feet/station	Asphalt Rubber	4 - 5	Emuls or other seal coats	Seals increased bleeding so if wet weather skid is a problem, consider Emuls or Micro	Asphalt Rubber
More than 100 feet/station	Asphalt Rubber	4	Latex or Conv, or Emuls	Seals increased bleeding so if wet weather skid is a problem, consider Emuls	Asphalt Rubber

Table 31. Treatment Selection - Bleeding.

Condition Category	Best Treatment	Years until PCI < 70	Good Treatment	If Also Cracking	If Also Alligator Plus Patch
< 6%	Micro	7	Emuls or Conv	For little cracking, use Micro. Otherwise, use Emuls	For little cracking, use Micro. Otherwise, use Emuls or Conv
6 to 23%	Micro	8	Emuls or Conv	For little cracking, use Micro. Otherwise, use Emuls	For little cracking, use Micro. Otherwise, use Emuls or Conv
More than 23%	Micro	5	Emuls or Conv	For little cracking, use Micro. Otherwise, use Emuls	For little cracking, use Micro. Otherwise, use Emuls or Conv

PREDOMINANT DISTRESS TYPE - ALLIGATOR CRACKING PLUS PATCHING

When alligator cracking and patching is present, an asphalt rubber seal coat should be the first choice, then the other types of seal coats. However, since these treatments resulted in bleeding, if high traffic volumes or wet weather skid resistance is a problem, the polymer modified emulsion or conventional seal coat should be used. If substantial alligator cracking is present, none of the treatments will be very effective. Table 32 contains the full recommendation.

When bleeding is also present, use microsurfacing. However, if there is substantial cracking, the polymer modified emulsion will perform better. Bleeding will still be a concern, but careful attention to application rates may help solve this problem.

Table 32. Treatment Selection - Alligator Cracking Plus Patching.

Condition Category	Best Treatment	Years until PCI < 70	Good Treatment	If Also Cracking	If Also Bleeding
None or very little	Asphalt Rubber	5	Emuls or other seal coats	Asphalt Rubber	Emuls then Conv
Less than or equal to 4%	Asphalt Rubber	3	Emuls or other seal coats	Asphalt Rubber	Emuls then Conv
More than 4%	Asphalt Rubber	4	Latex or Conv or Emuls	Asphalt Rubber	Emuls then Conv

GENERAL RECOMMENDATIONS BASED ON PAVEMENT CONDITION

When there is no predominant distress, or when the distresses are not well known, the following table can be used to select the treatment type and determine an approximate life for the treatment. Note that as the initial condition decreases, so does the expected life. Table 33 contains the full recommendation.

Table 33. Treatment Selection - General Condition.

Condition Category	Best Treatment	Years until PCI < 70	Good Treatment	If Also Cracking	If Also Bleeding
Greater than 85	Micro	8	Latex	Latex	Micro
85 - 70	Micro	6	Latex	Latex	Micro
Less than 70	Latex	3-4	Micro	Latex	Asphalt Rubber

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APPENDIX A

CRACKING PERFORMANCE CURVES

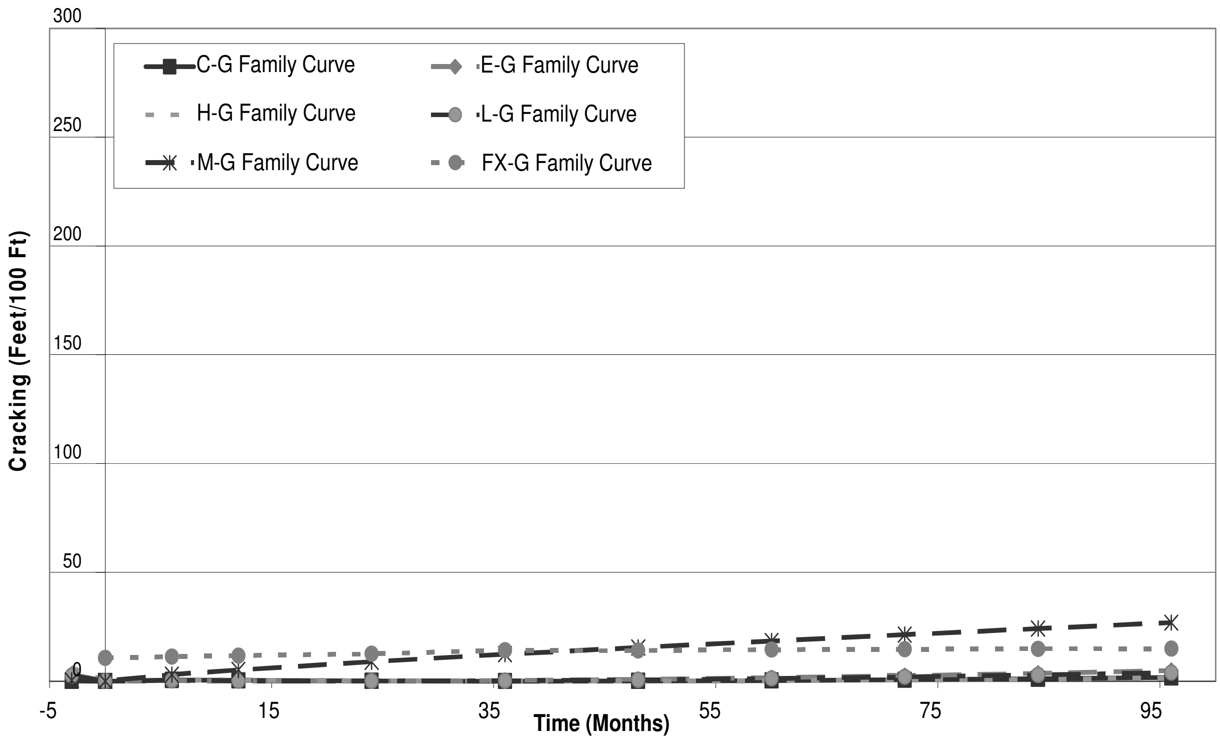

Figure A - 1. Cracking for All Treatments, Good Initial Condition.

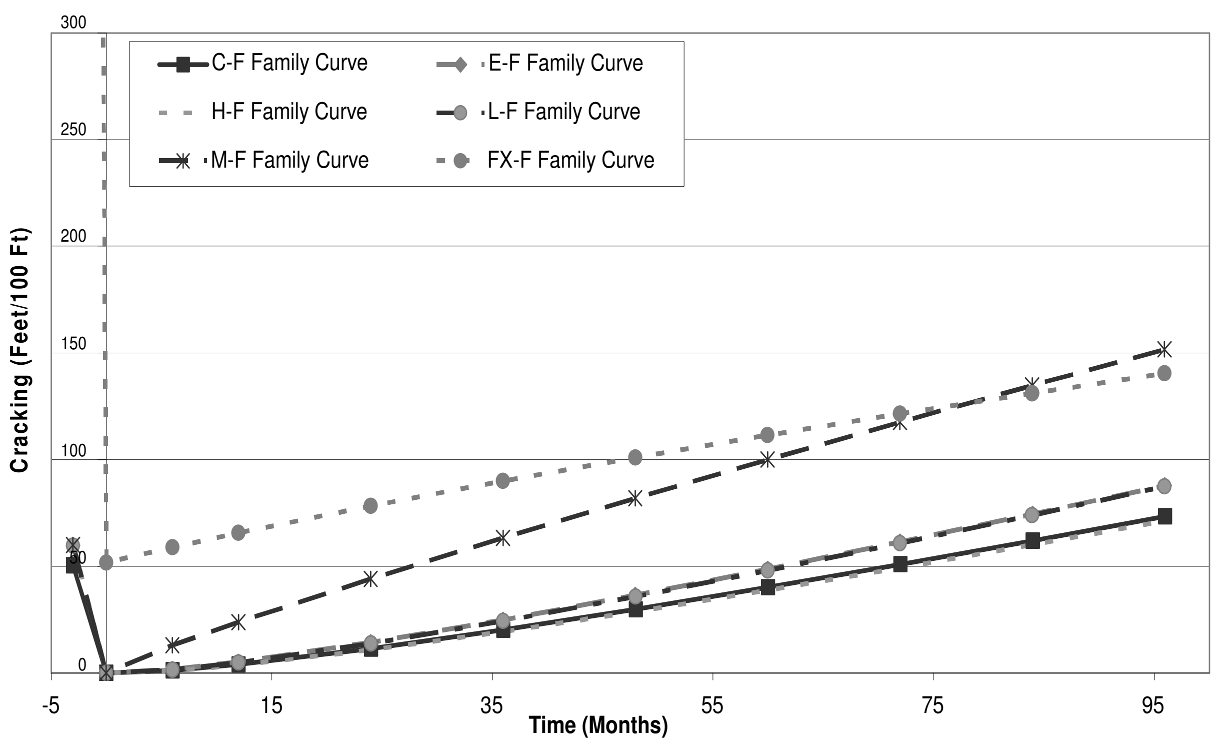

Figure A - 2. Cracking for All Treatments, Fair Initial Condition.

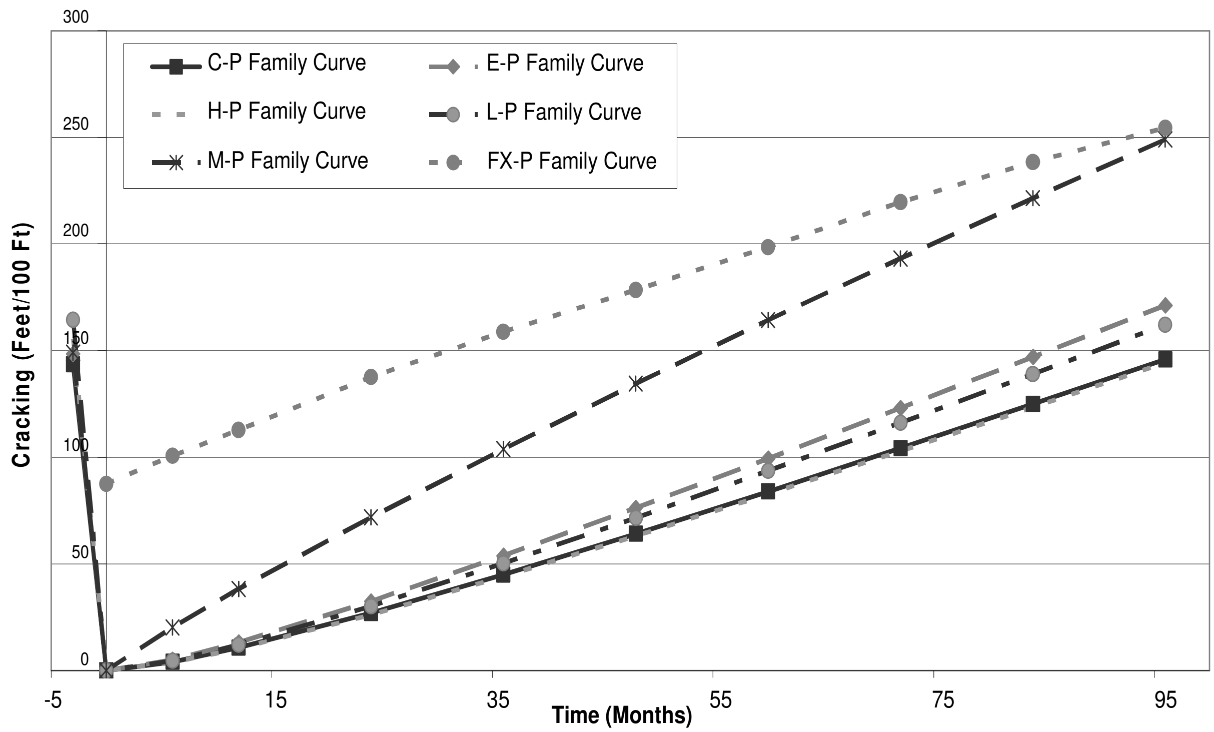

Figure A - 3. Cracking for All Treatments, Poor Initial Condition.

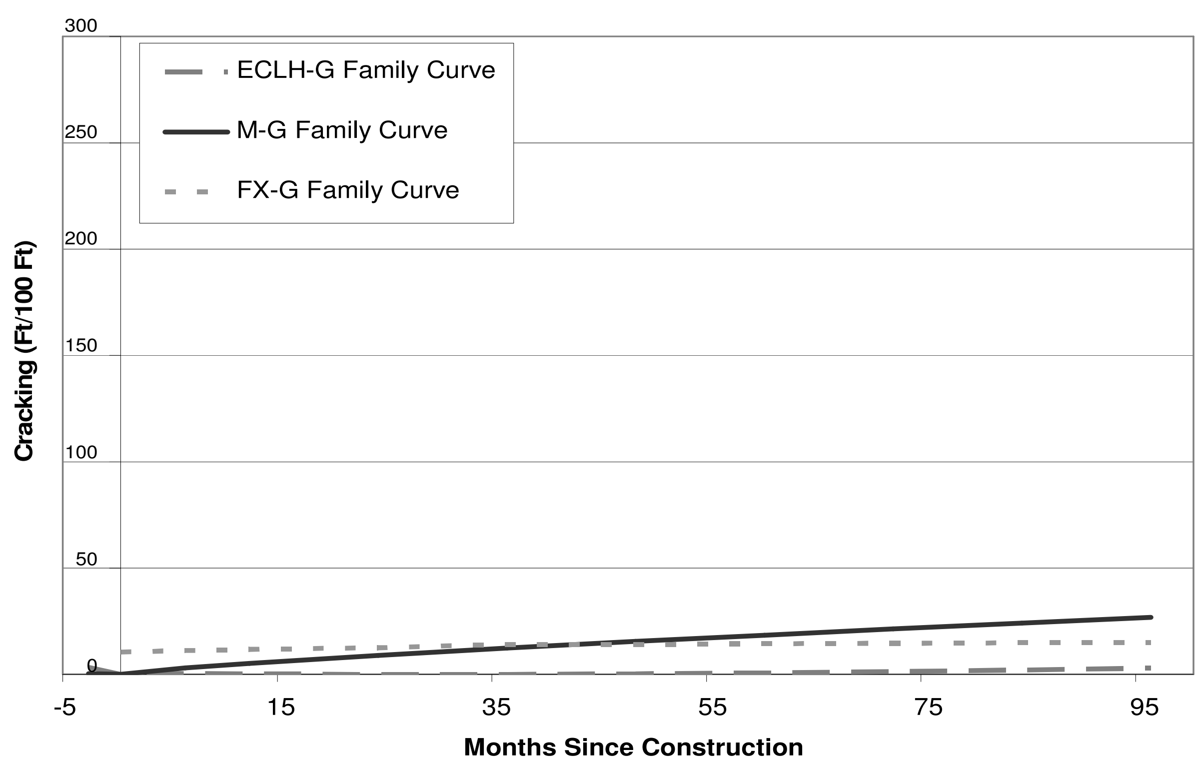

Figure A - 4. Cracking for All Families, Good Initial Condition.

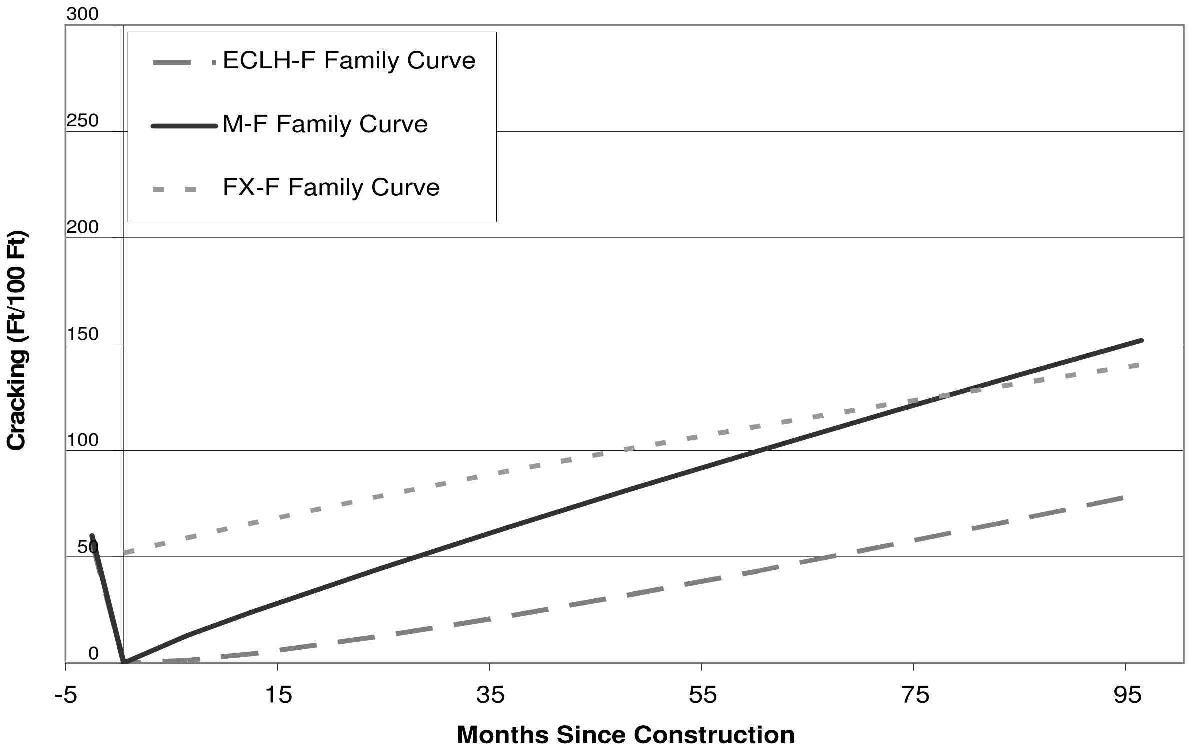

Figure A - 5. Cracking for All Families, Fair Initial Condition.

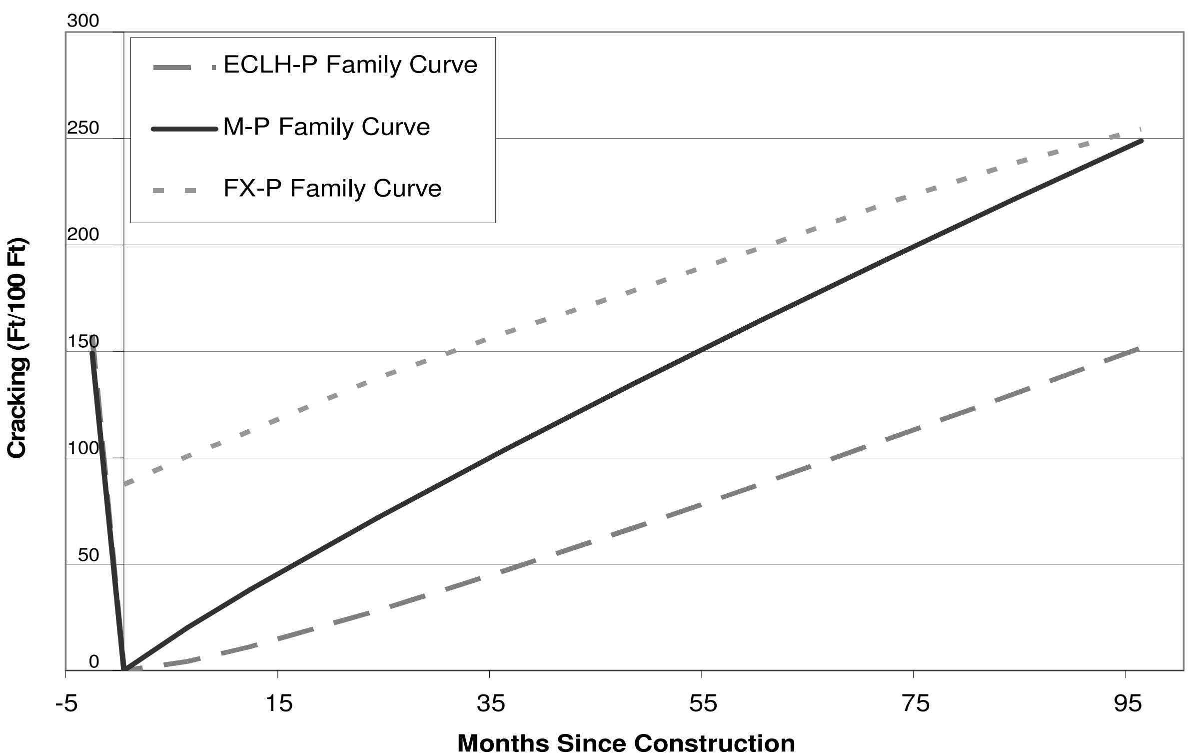

Figure A - 6. Cracking for All Families, Poor Initial Condition.

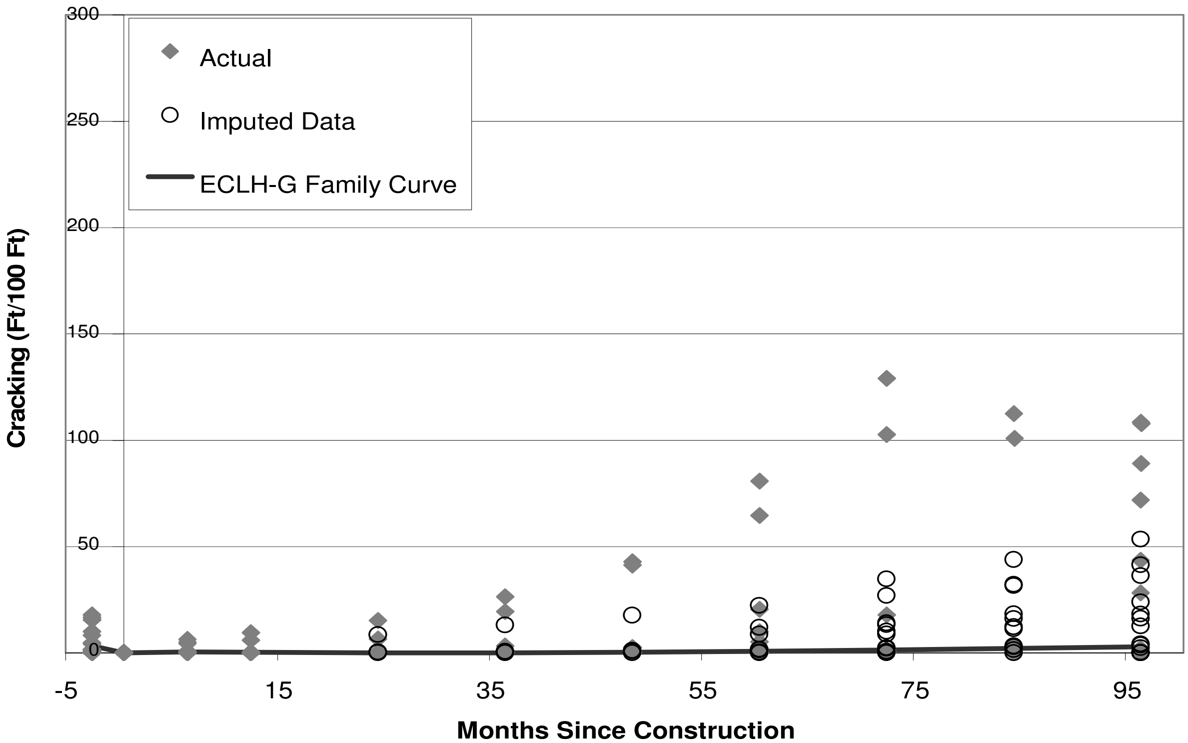

Figure A - 7. Cracking for ECLH Family, Good Initial Condition (R^2 = 0.283).

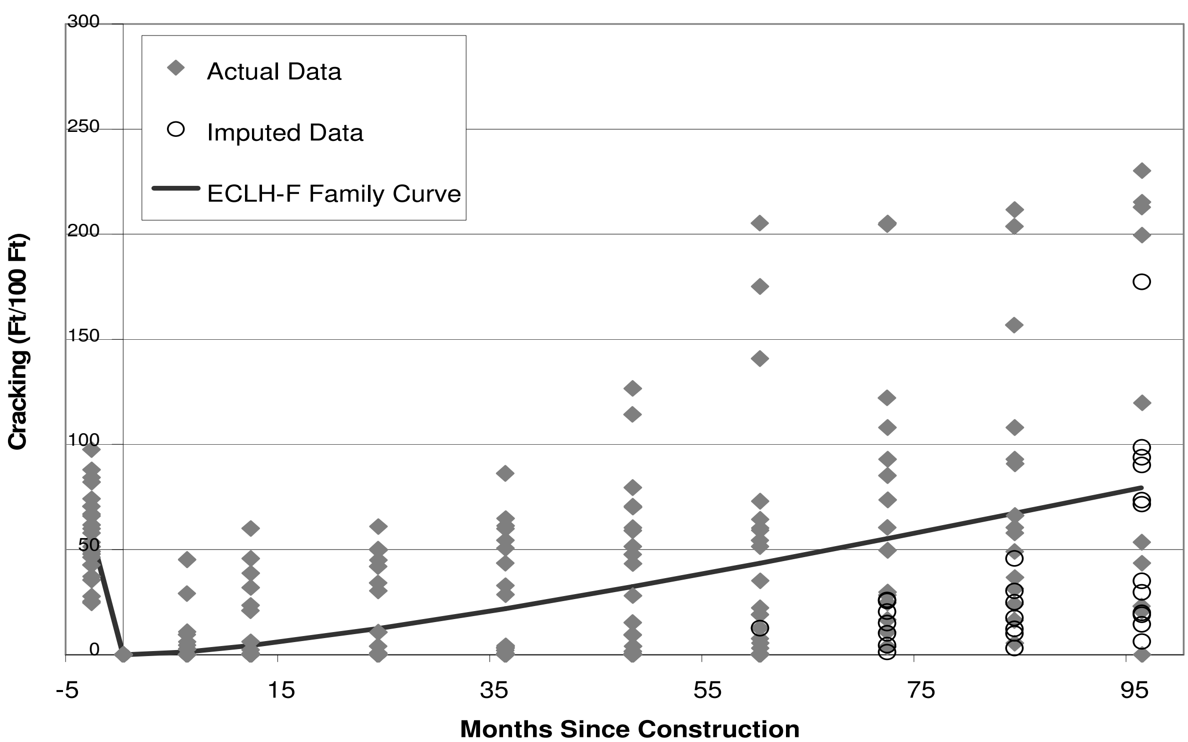

Figure A - 8. Cracking for ECLH Family, Fair Initial Condition (R^2 = 0.682).

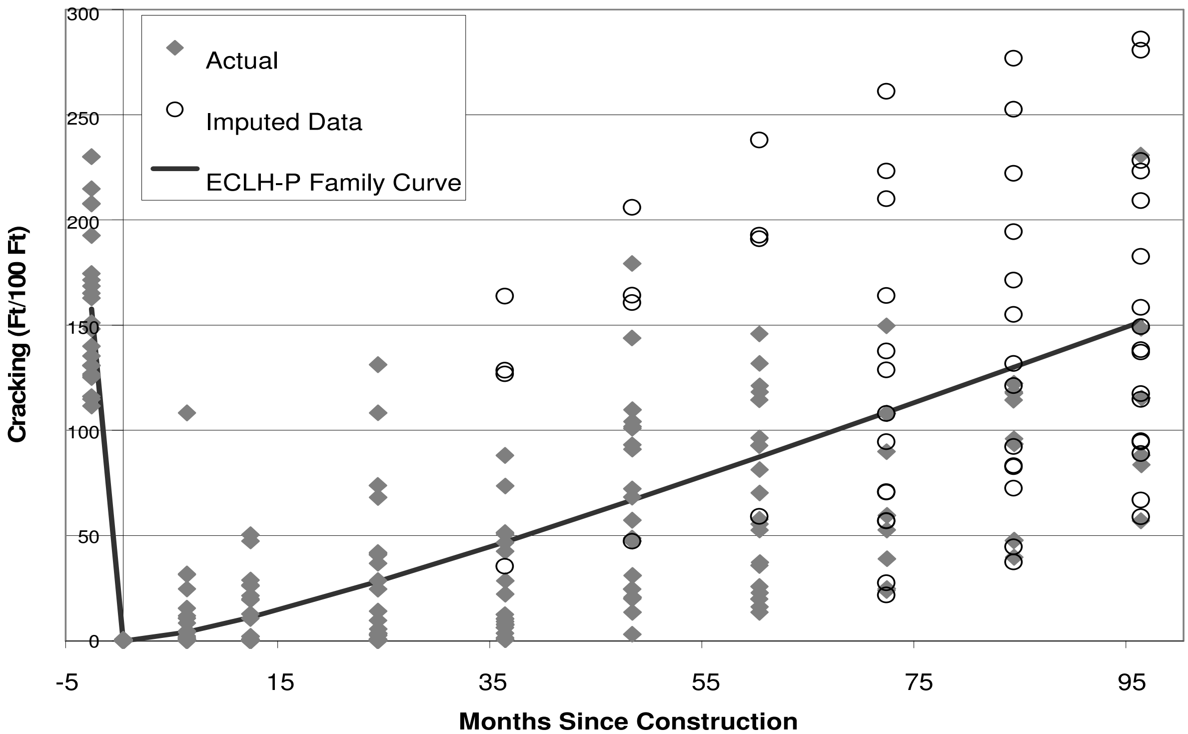

Figure A - 9. Cracking for ECLH Family, Poor Initial Condition (R^2 = 0.851).

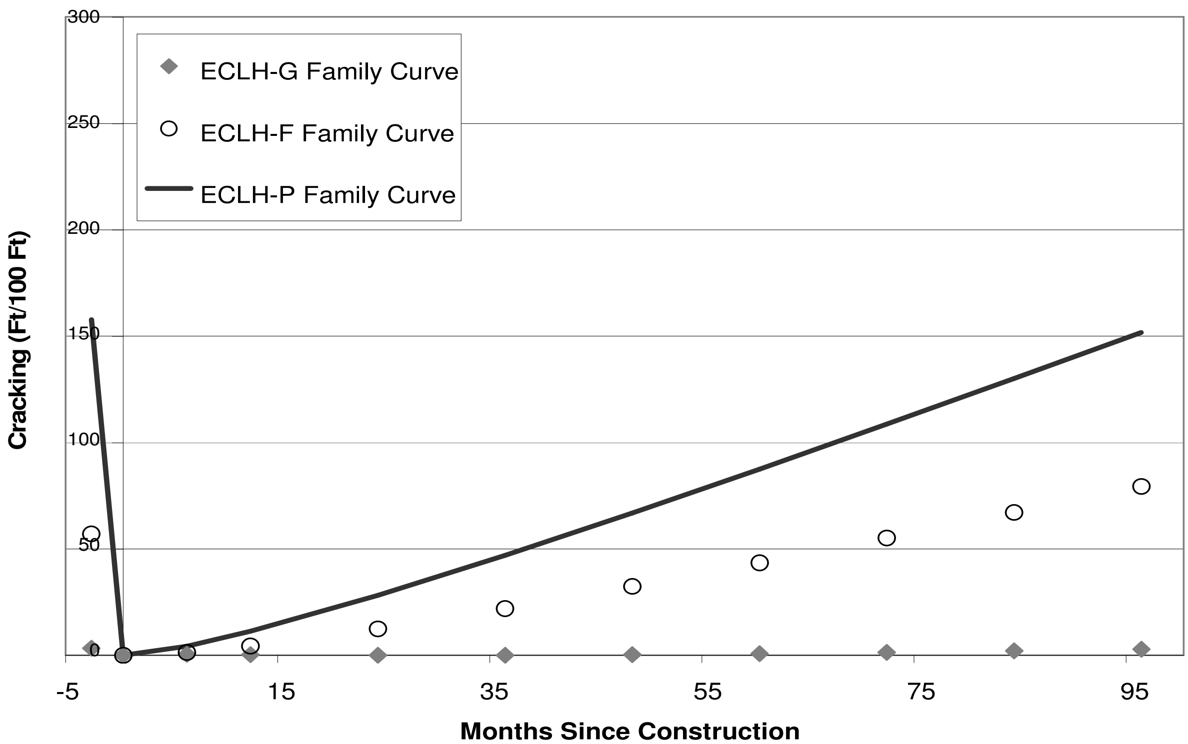

Figure A - 10. Cracking for ECLH Family, All Initial Conditions.

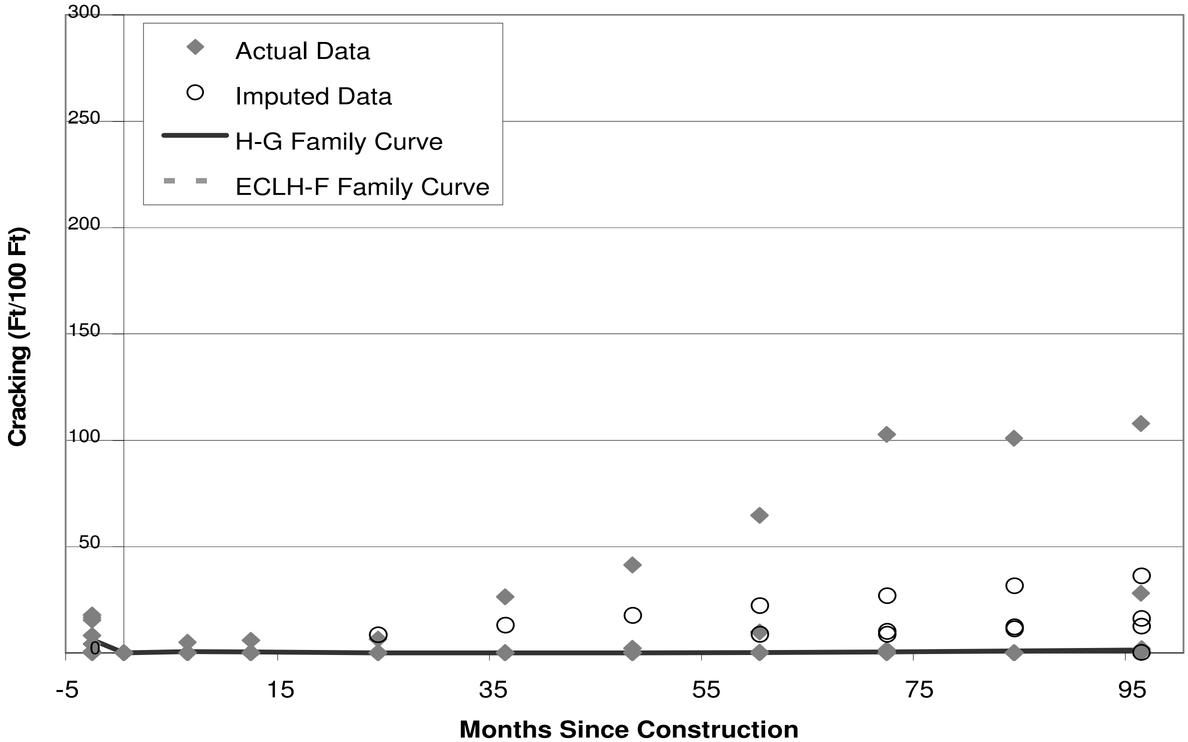

Figure A - 11. Cracking for Asphalt Rubber Seal Coat, Good Initial Condition (R^2 = 0.353).

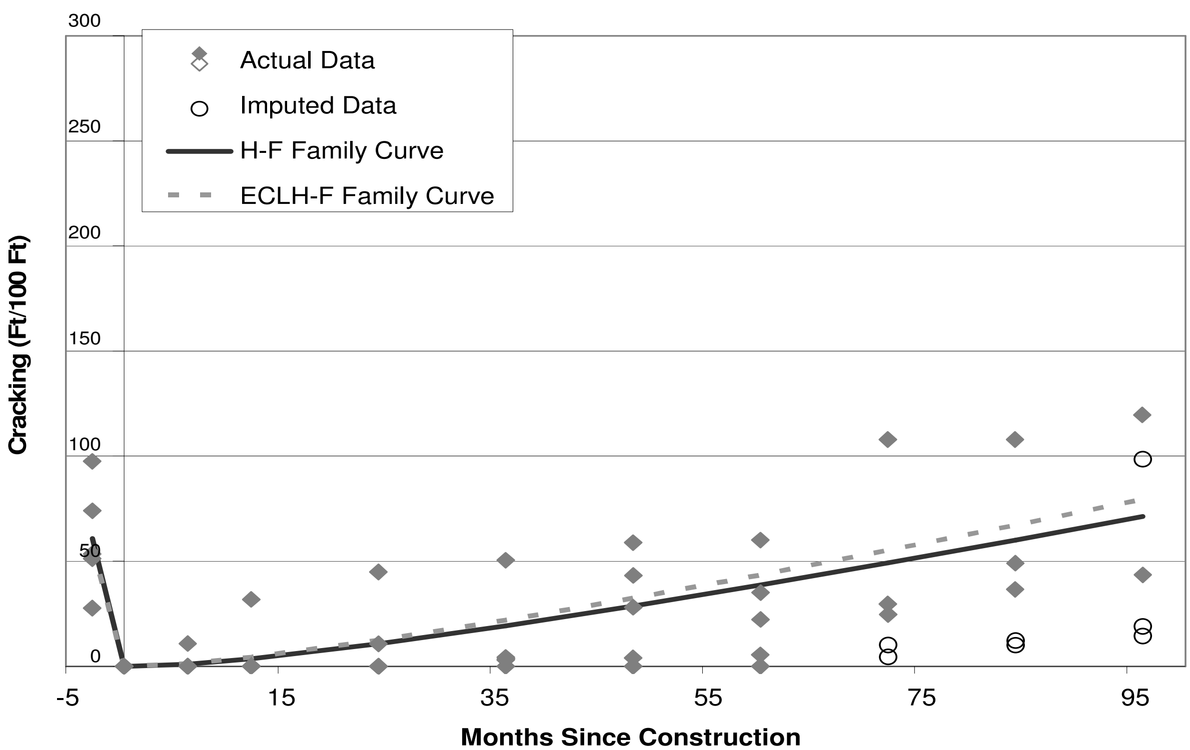

Figure A - 12. Cracking for Asphalt Rubber Seal Coat, Fair Initial Condition (R^2 = 0.724).

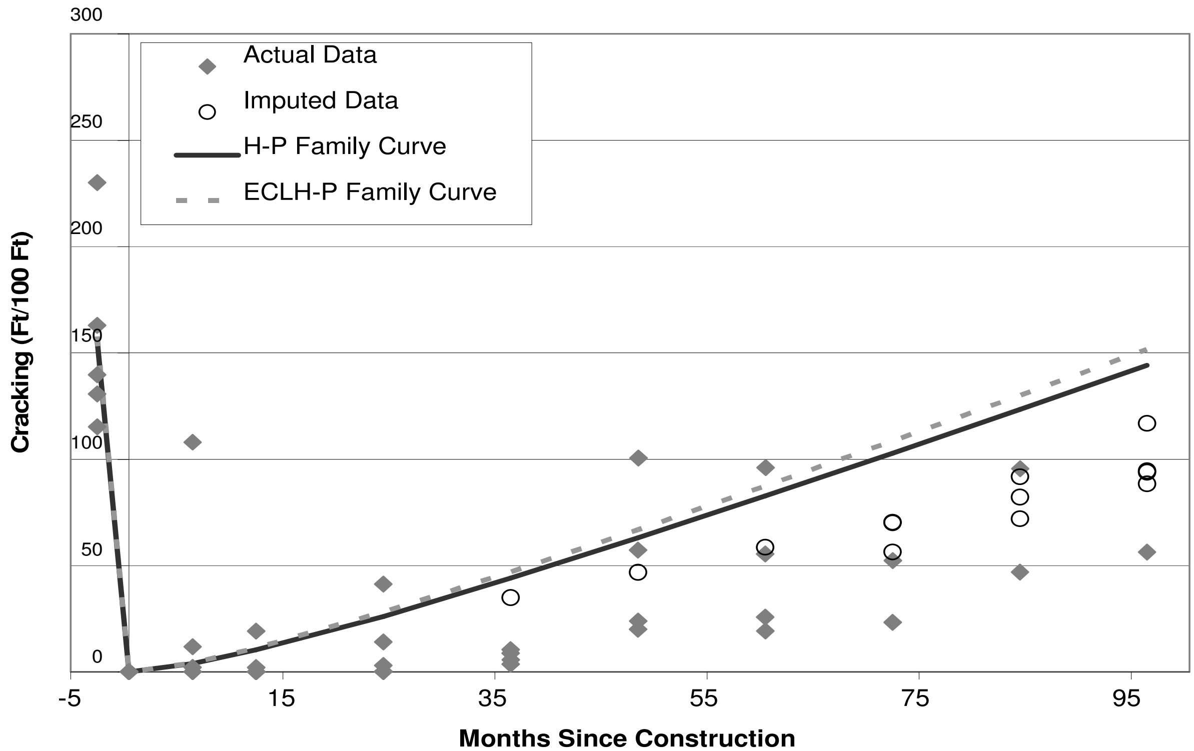

Figure A - 13. Cracking for Asphalt Rubber Seal Coat, Poor Initial Condition (R^2 = 0.883).

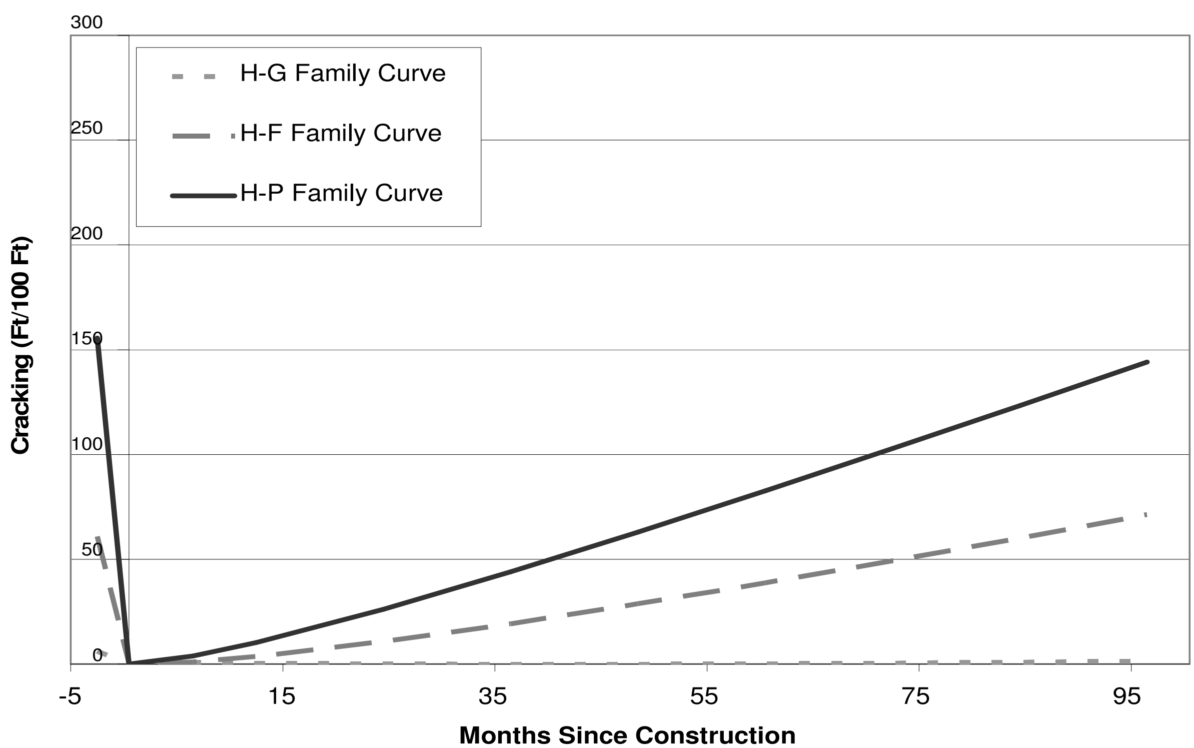

Figure A - 14. Cracking for Asphalt Rubber Seal Coat, All Initial Conditions.

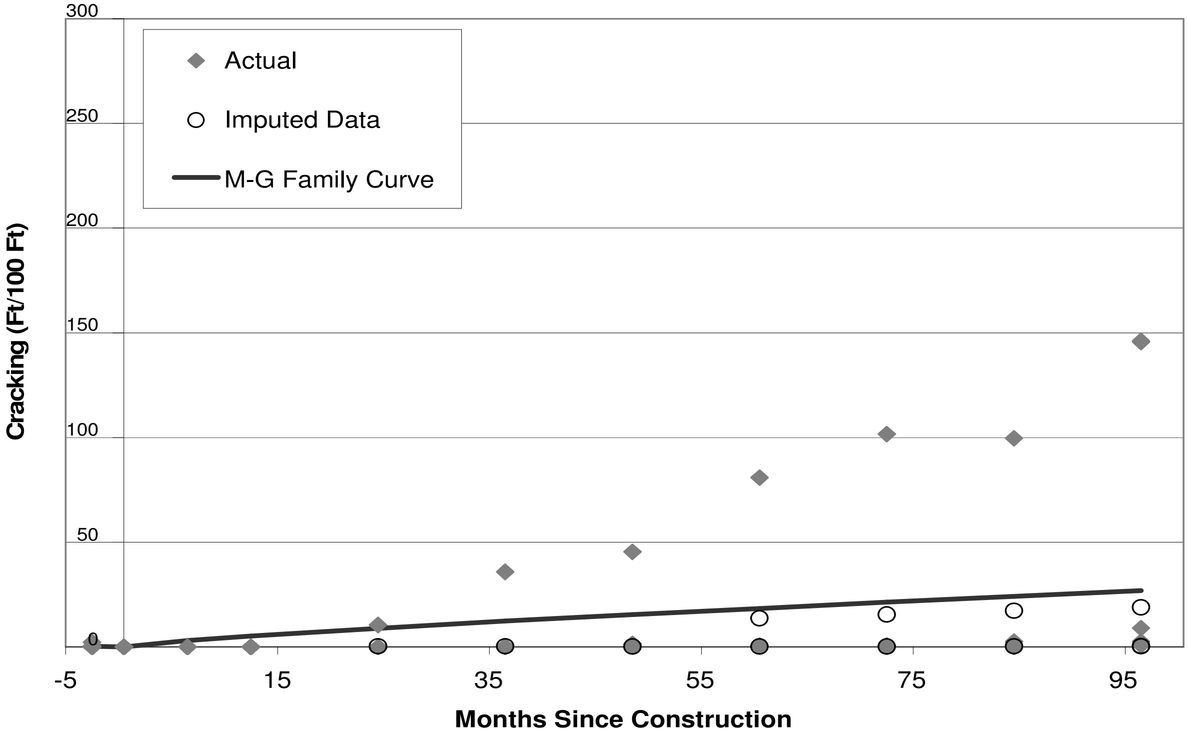

Figure A - 15. Cracking for Microsurfacing, Good Initial Condition (R^2 = 0.338).

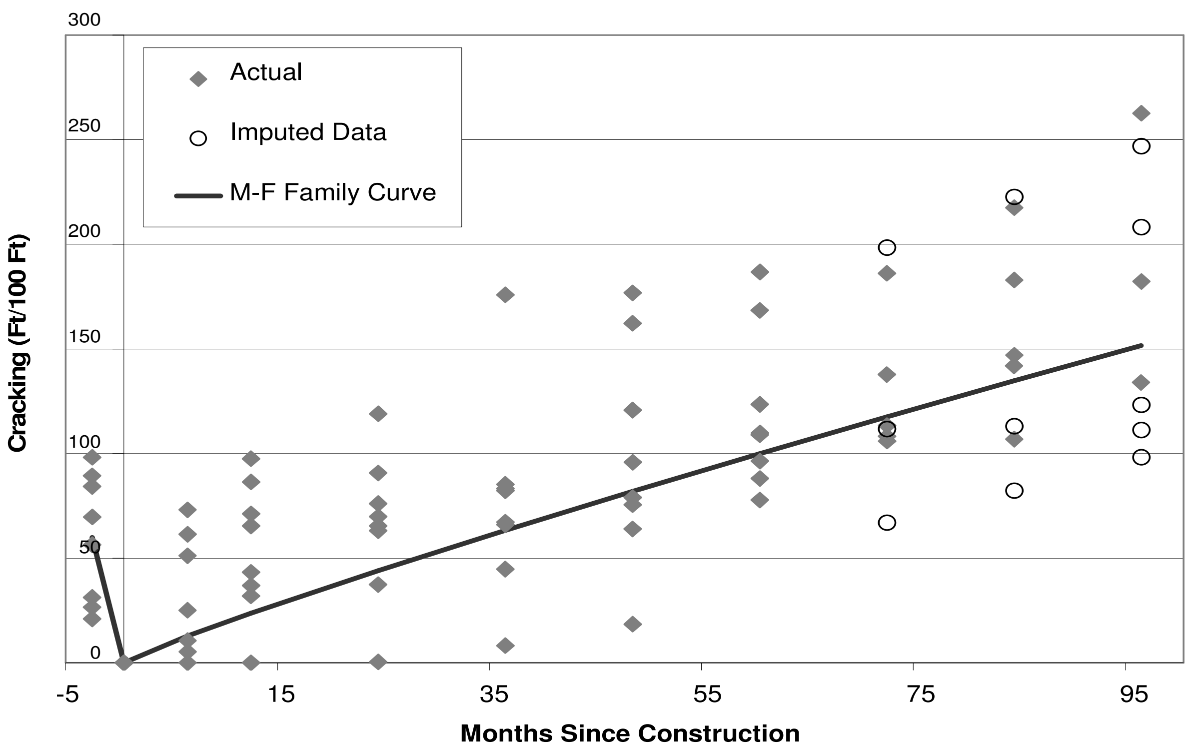

Figure A - 16. Cracking for Microsurfacing, Fair Initial Condition (R^2 = 0.938).

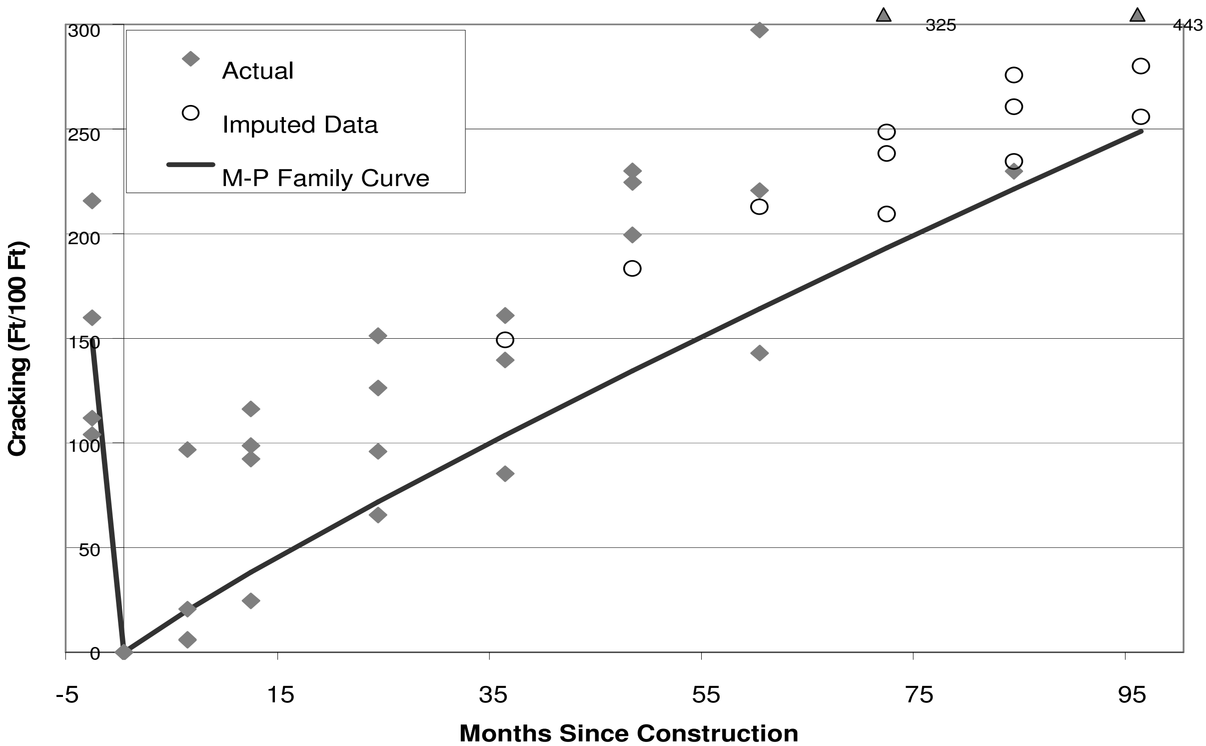

Figure A - 17. Cracking for Microsurfacing, Poor Initial Condition (R^2 = 0.980).

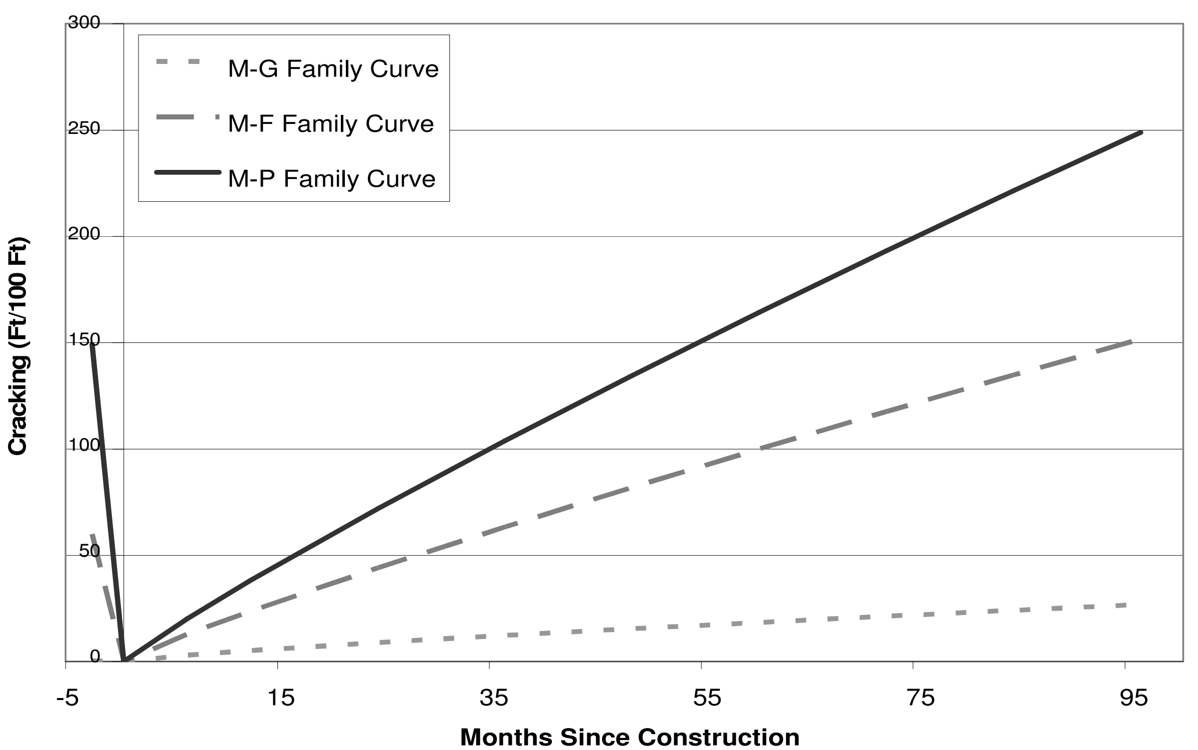

Figure A - 18. Cracking for Microsurfacing, All Initial Conditions.

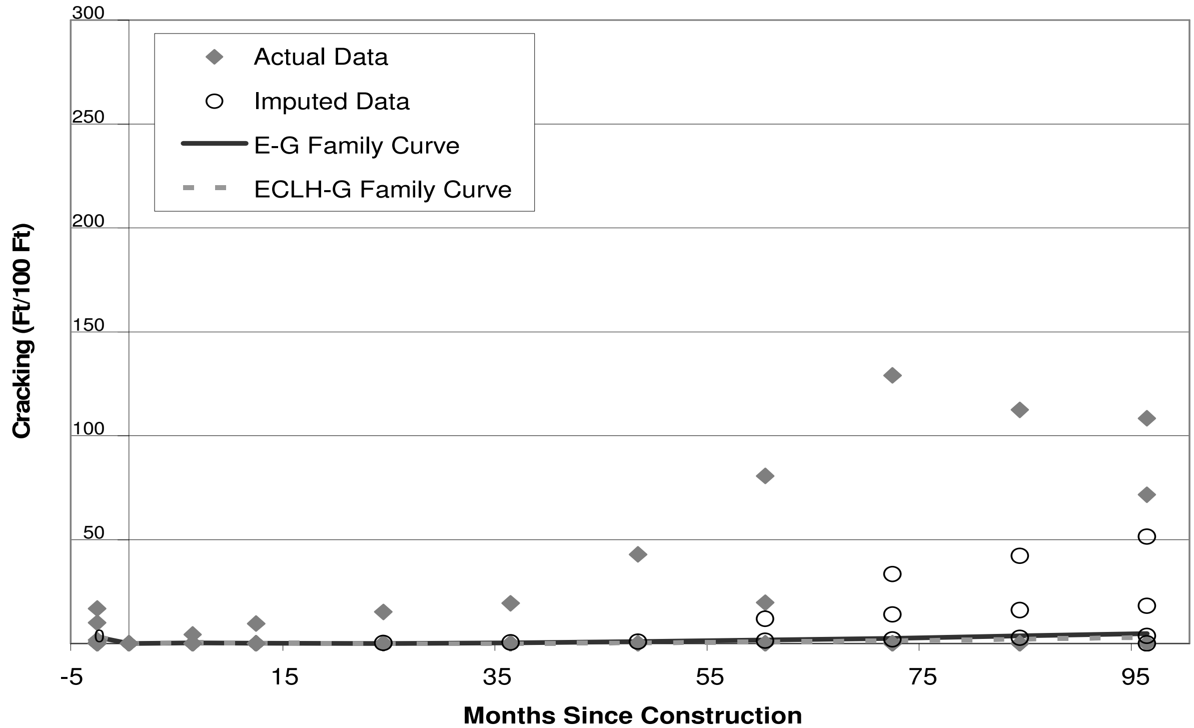

Figure A - 19. Cracking for Polymer Modified Emulsion Seal Coat, Good Initial Condition (R^2 = 0.330).

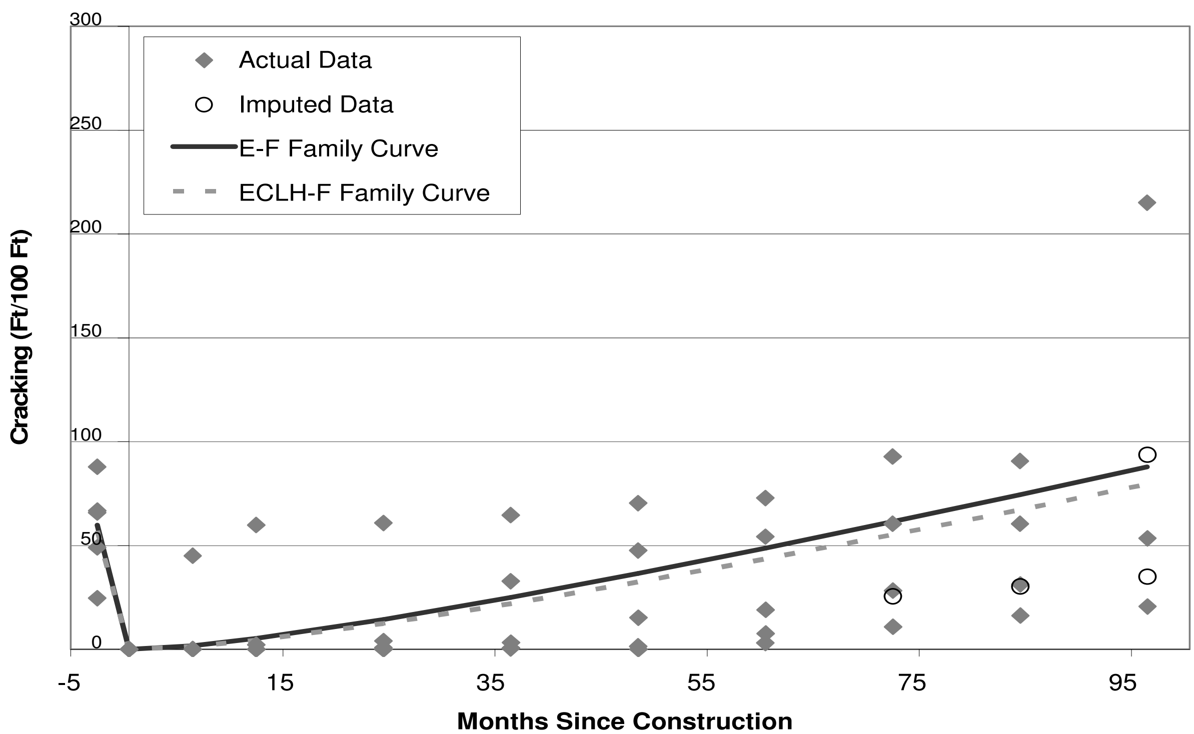

Figure A - 20. Cracking for Polymer Modified Emulsion Seal Coat, Fair Initial Condition (R^2 = 0.735).

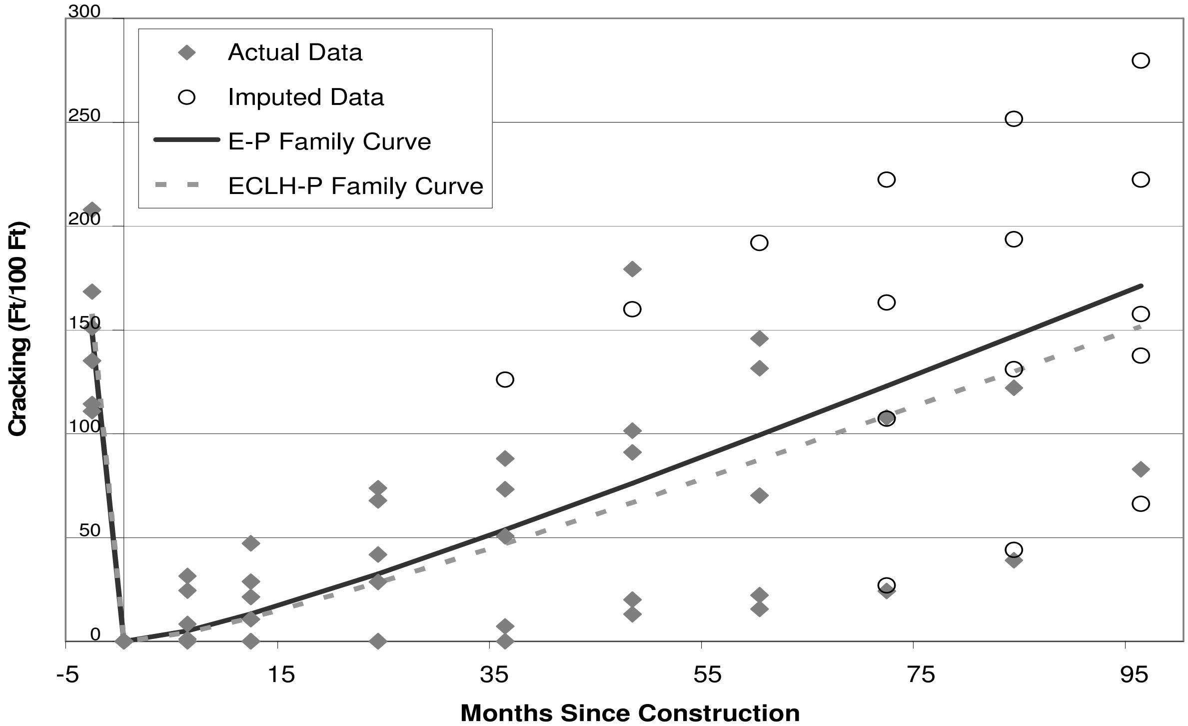

Figure A - 21. Cracking for Polymer Modified Emulsion Seal Coat, Poor Initial Condition (R^2 = 0.845).

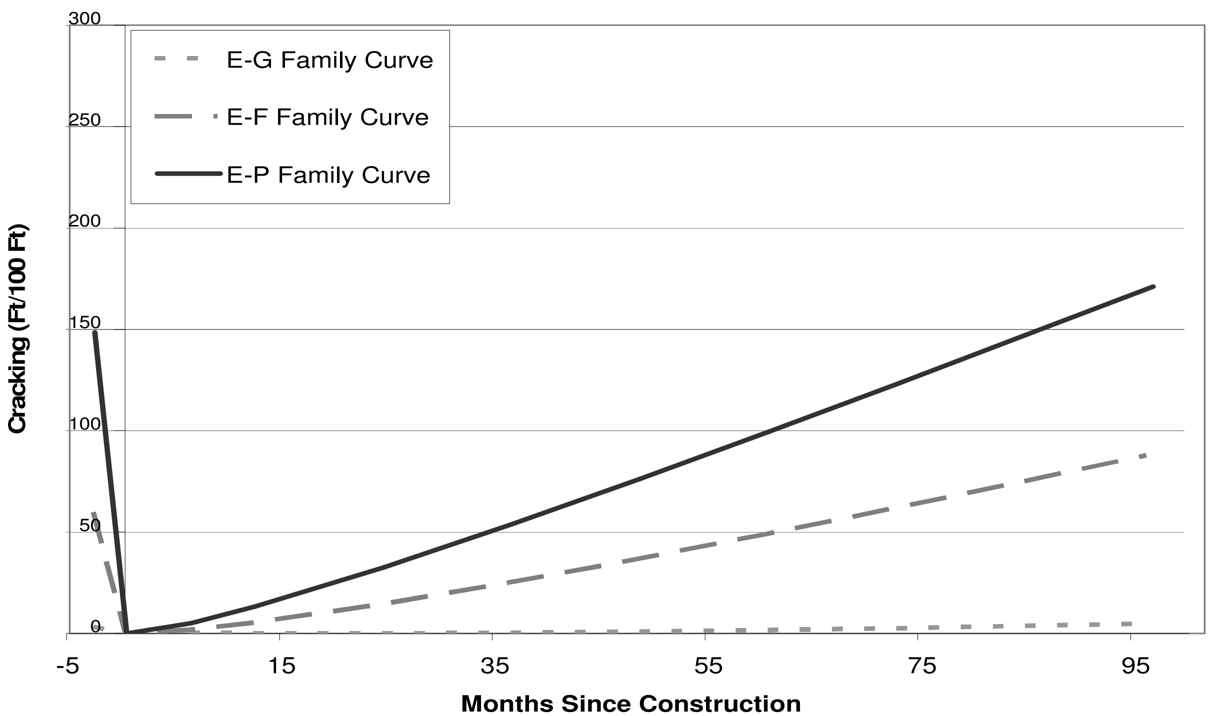

Figure A - 22. Cracking for Polymer Modified Emulsion Seal Coat, All Initial Conditions.

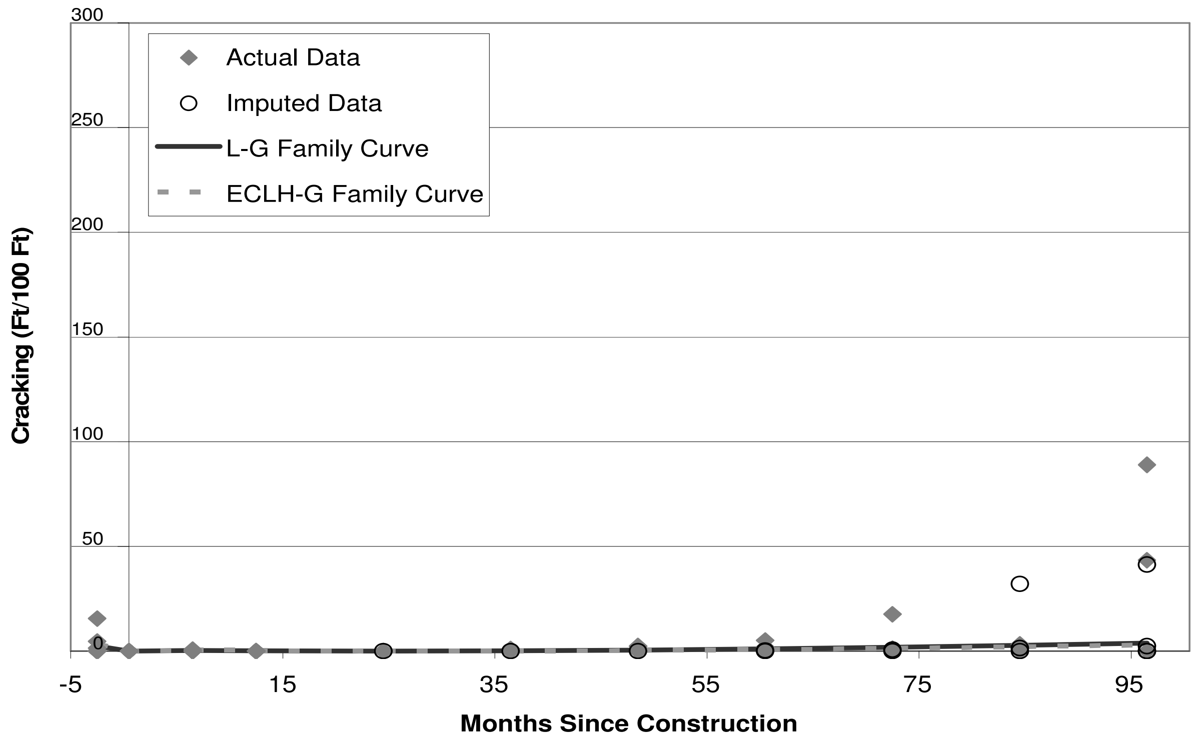

Figure A - 23. Cracking for Latex Modified Seal Coat, Good Initial Condition (R^2 = 0.302).

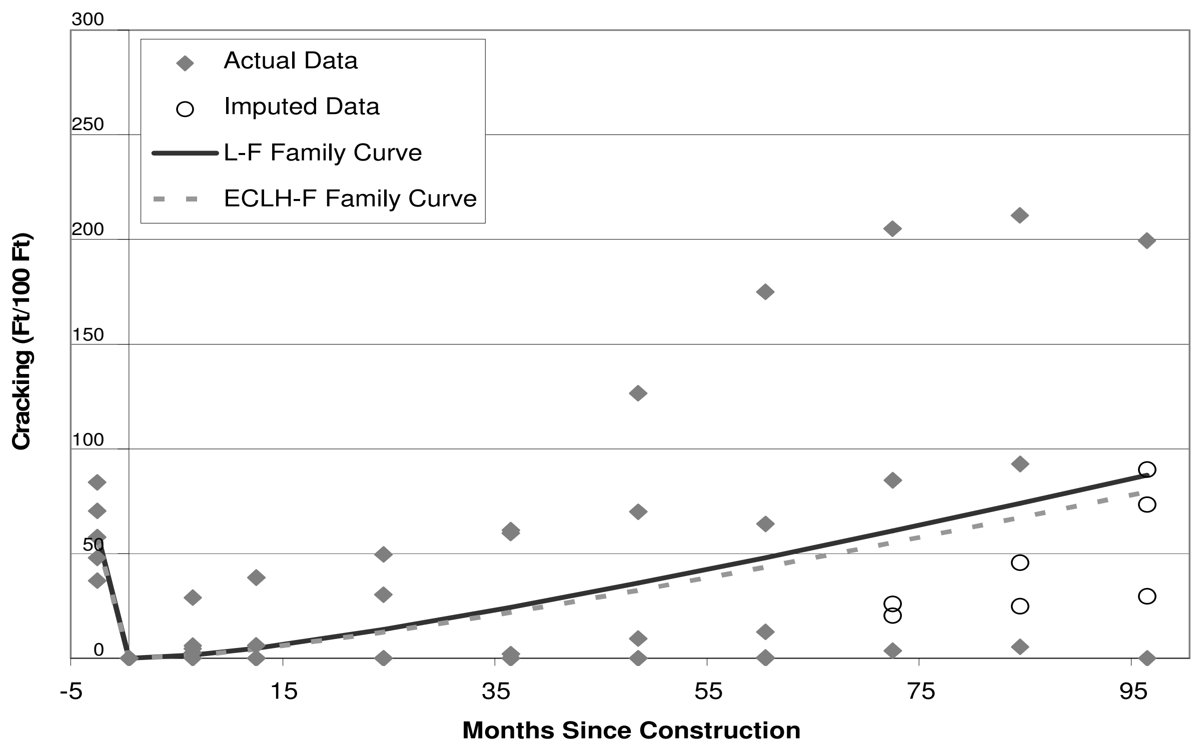

Figure A - 24. Cracking for Latex Modified Seal Coat, Fair Initial Condition (R^2 = 0.626).

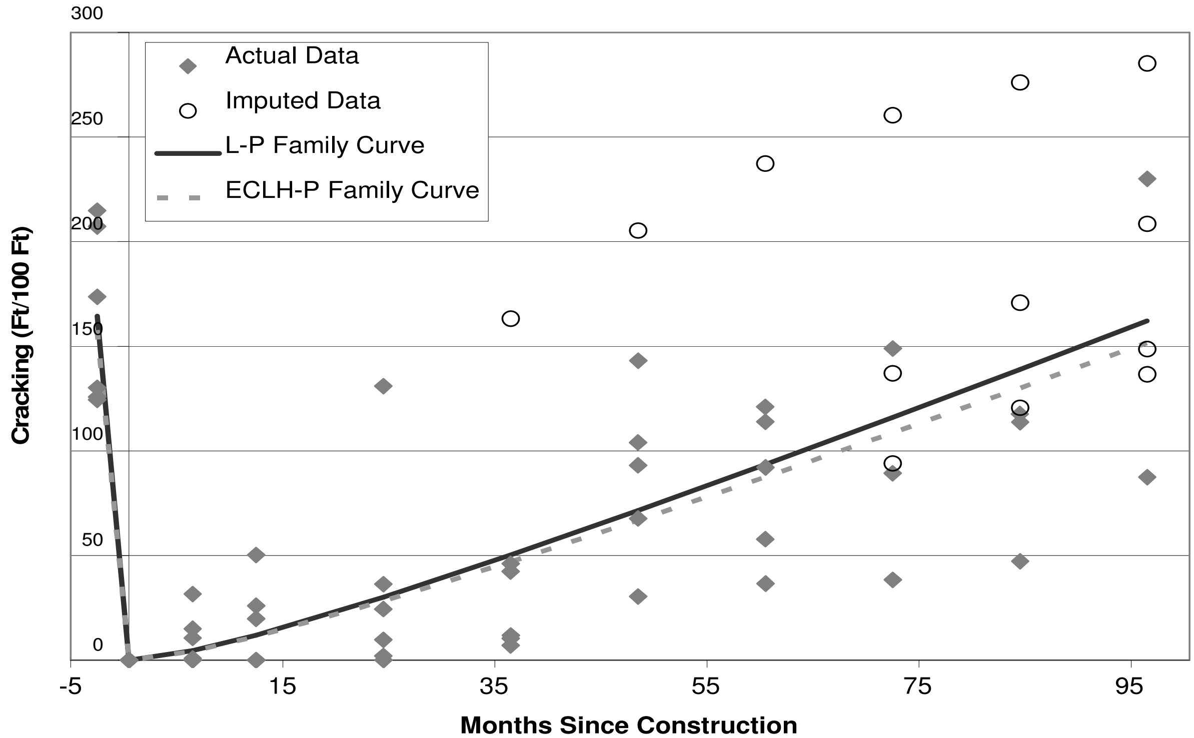

Figure A - 25. Cracking for Latex Modified Seal Coat, Poor Initial Condition (R^2 = 0.886).

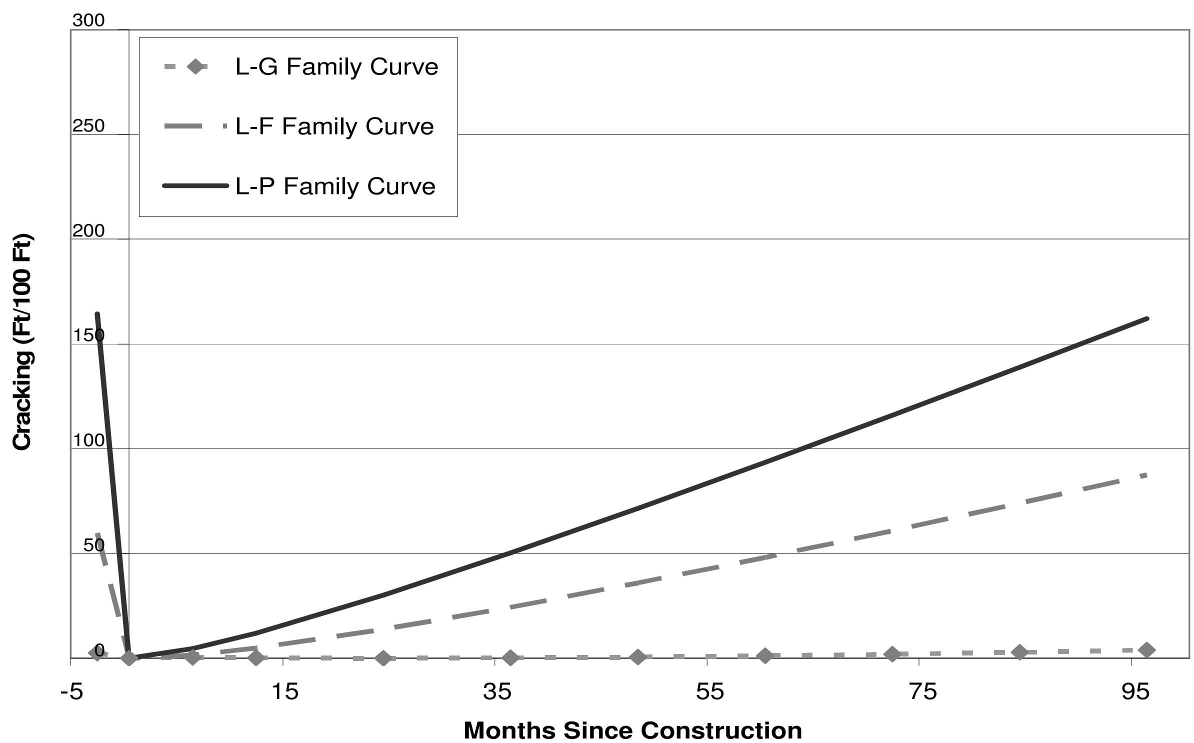

Figure A - 26. Cracking for Latex Modified Seal Coat, All Initial Conditions.

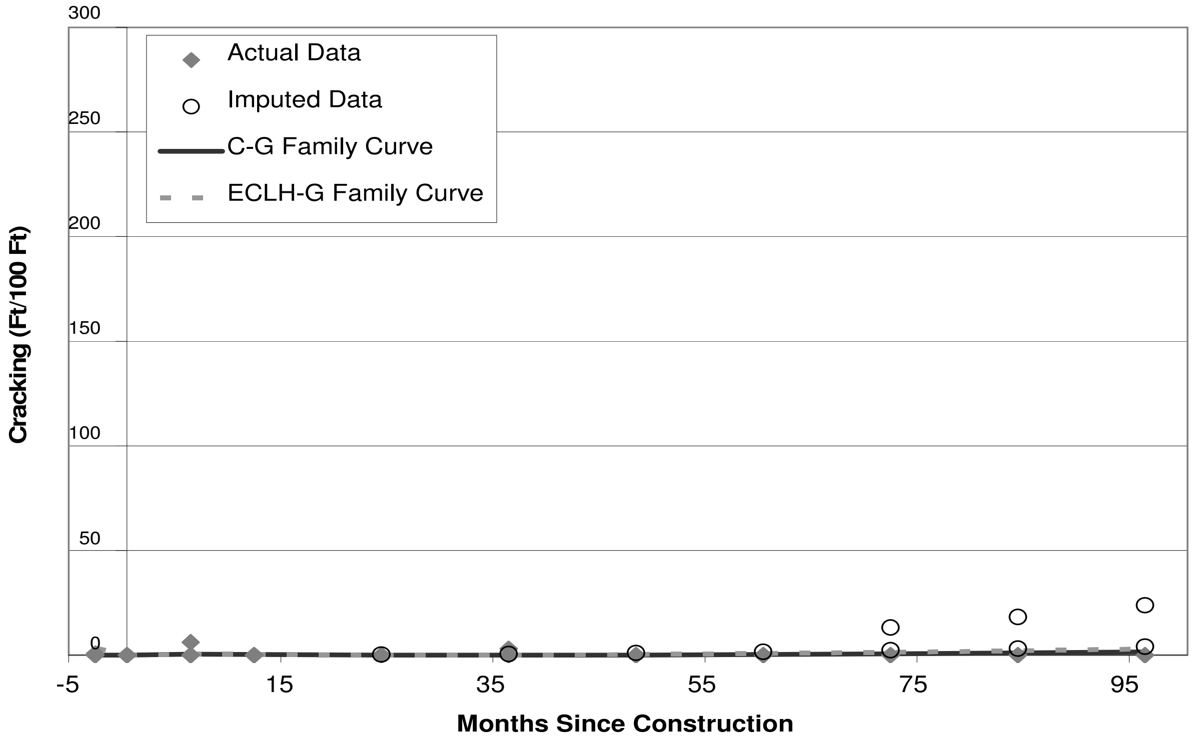

Figure A - 27. Cracking for Unmodified Asphalt Seal Coat, Good Initial Condition (R^2 = 0.194).

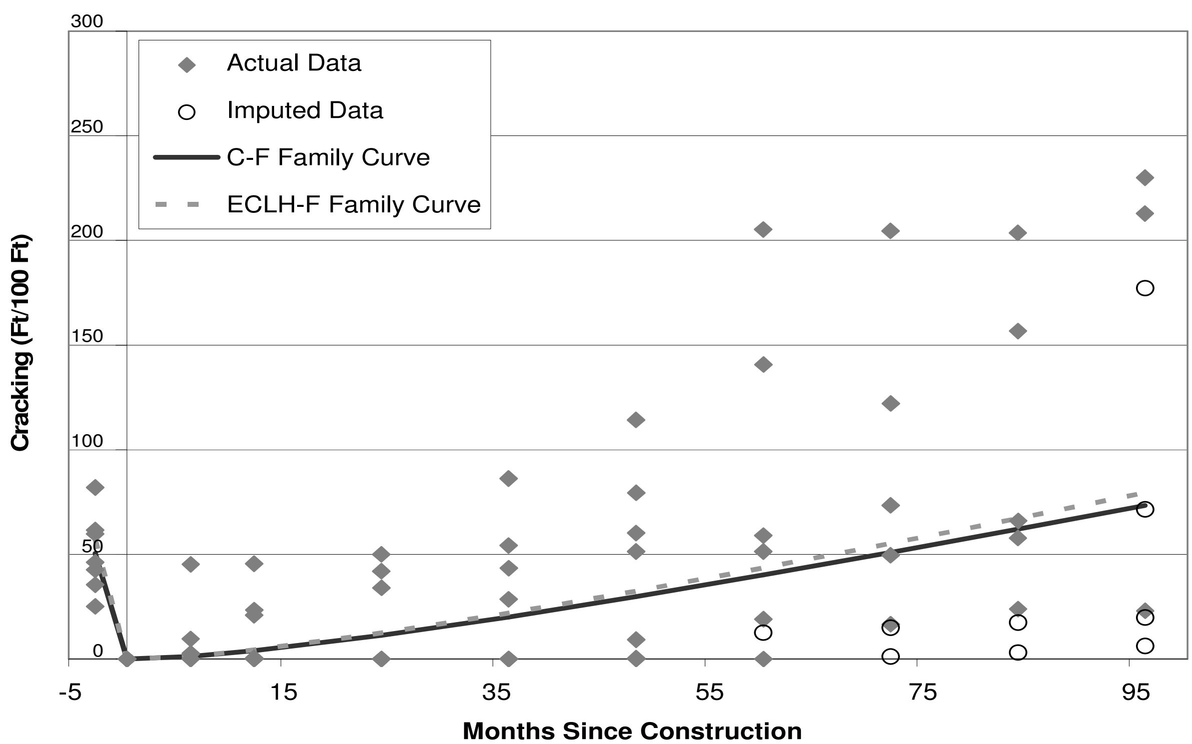

Figure A - 28. Cracking for Unmodified Asphalt Seal Coat, Fair Initial Condition (R^2 = 0.700).

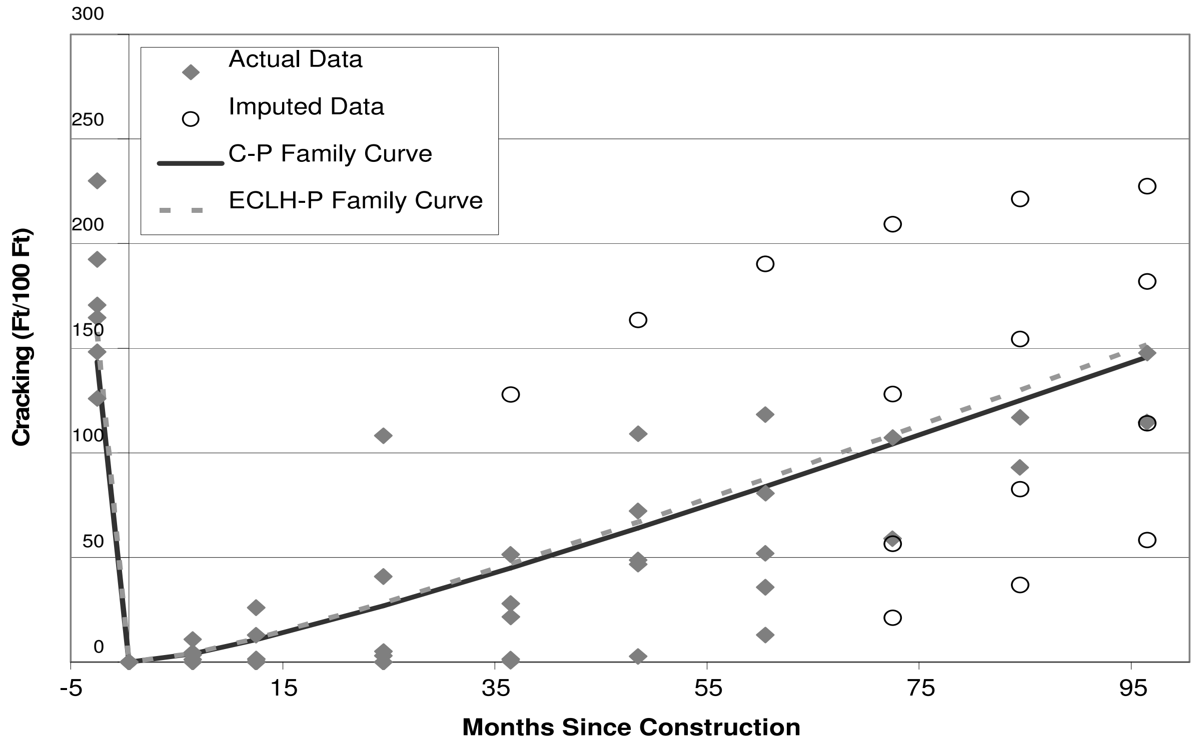

Figure A - 29. Cracking for Unmodified Asphalt Seal Coat, Poor Initial Condition (R^2 = 0.858).

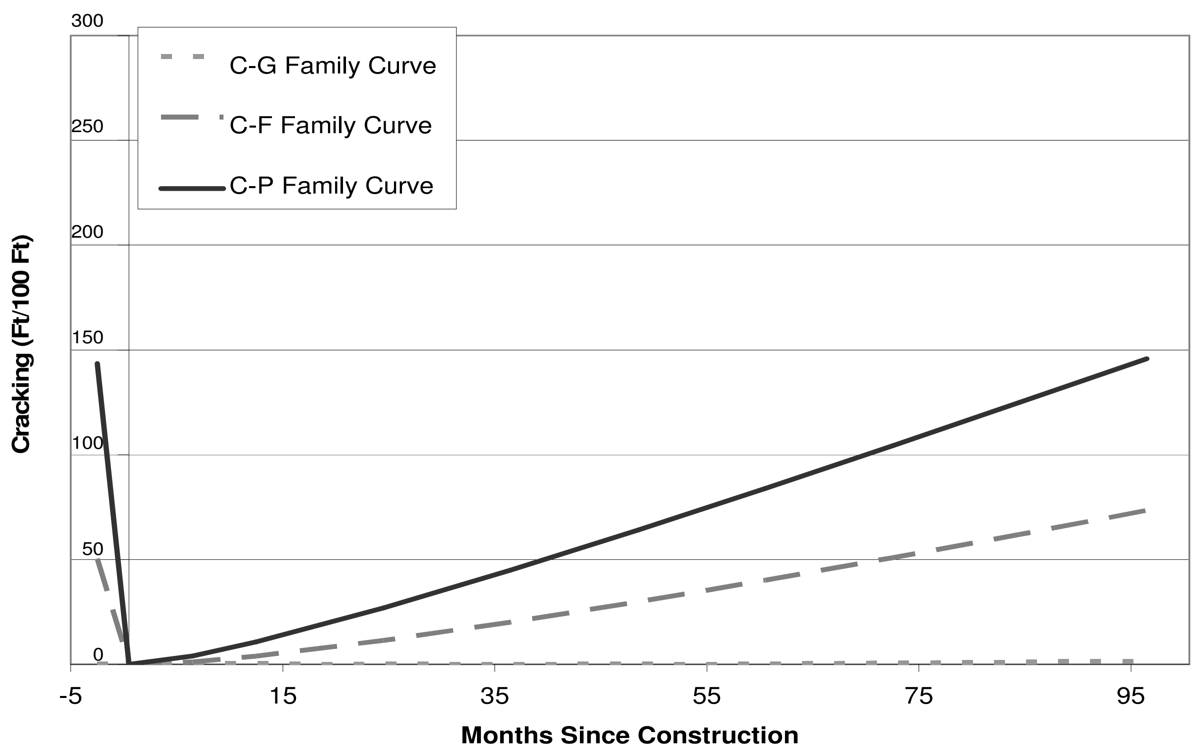

Figure A - 30. Cracking for Unmodified Asphalt Seal Coat, All Initial Conditions.

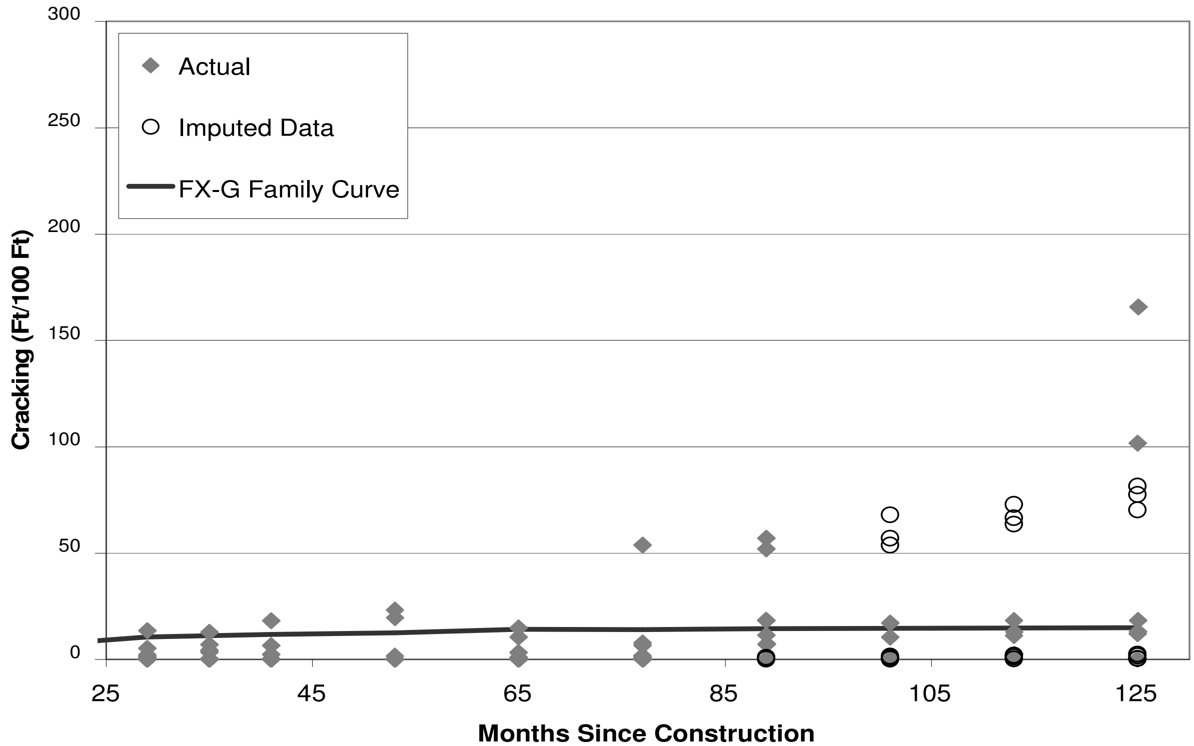

Figure A - 31. Cracking for Fog and Control Sections, Good Initial Condition (R^2 = 0.432).

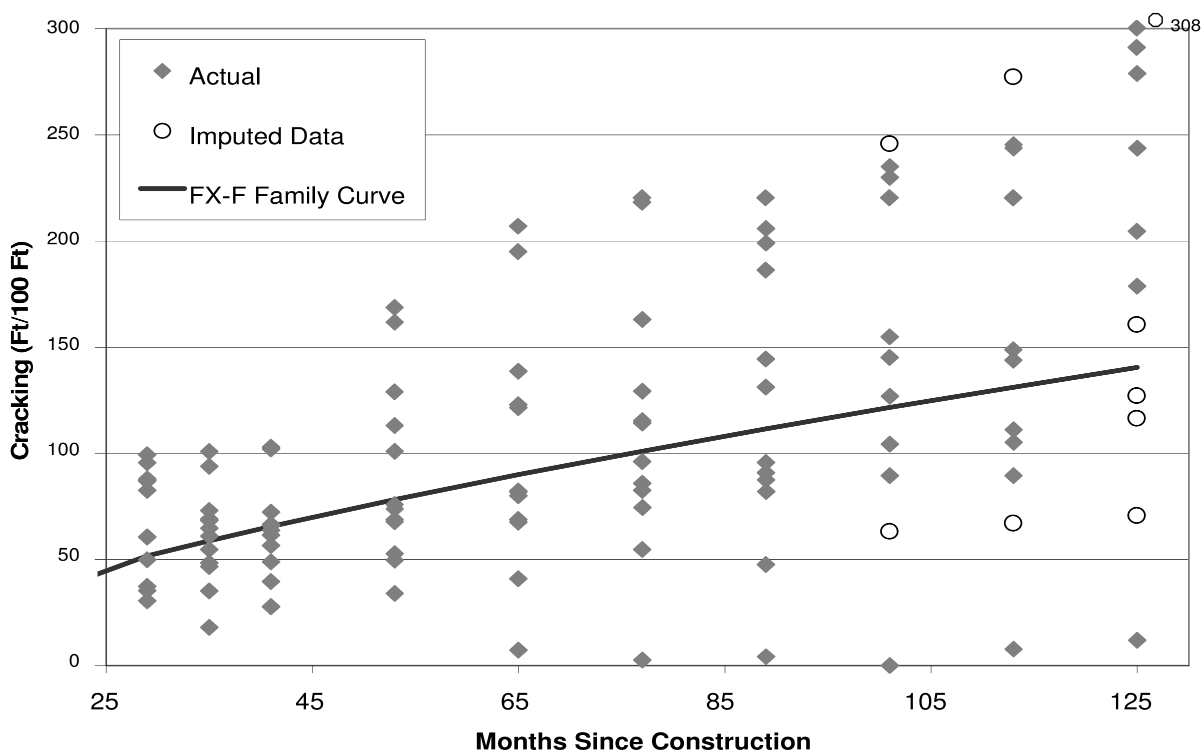

Figure A - 32. Cracking for Fog and Control Sections, Fair Initial Condition (R^2 = 0.906).

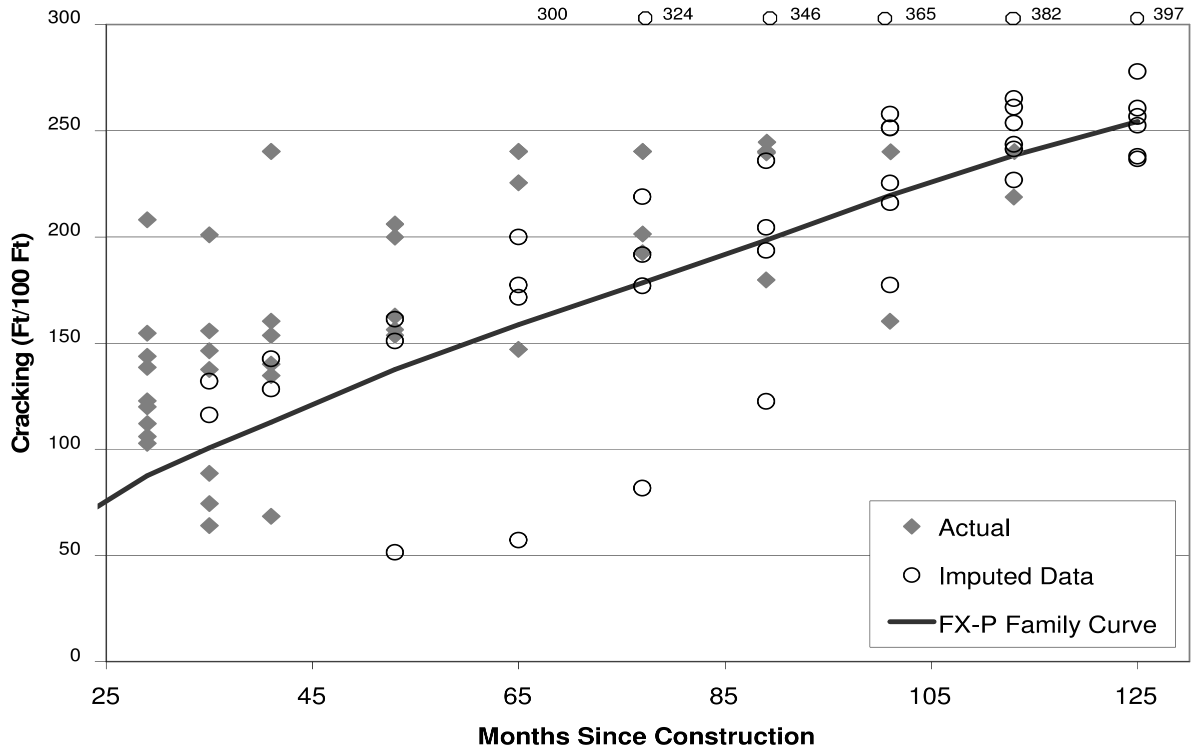

Figure A - 33. Cracking for Fog and Control Sections, Poor Initial Condition (R^2 = 0.979).

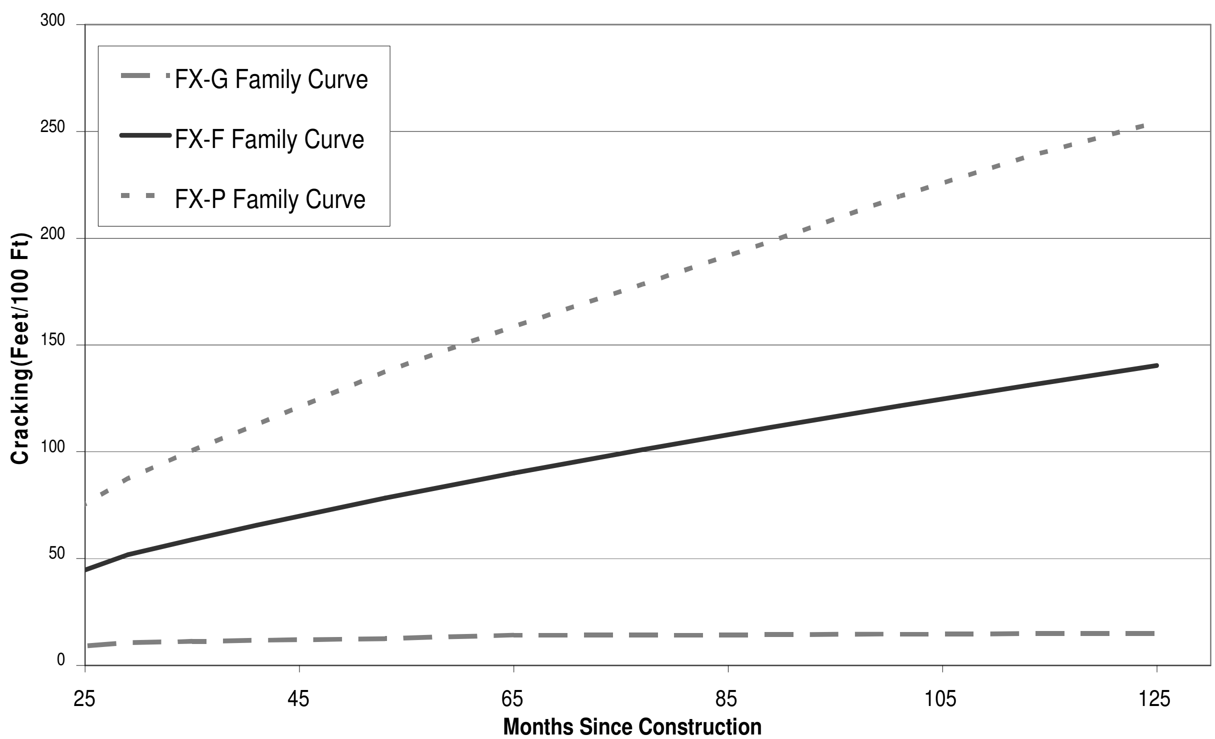

Figure A - 34. Cracking for Fog and Control Sections, All Initial Conditions.

APPENDIX B

BLEEDING PERFORMANCE CURVES

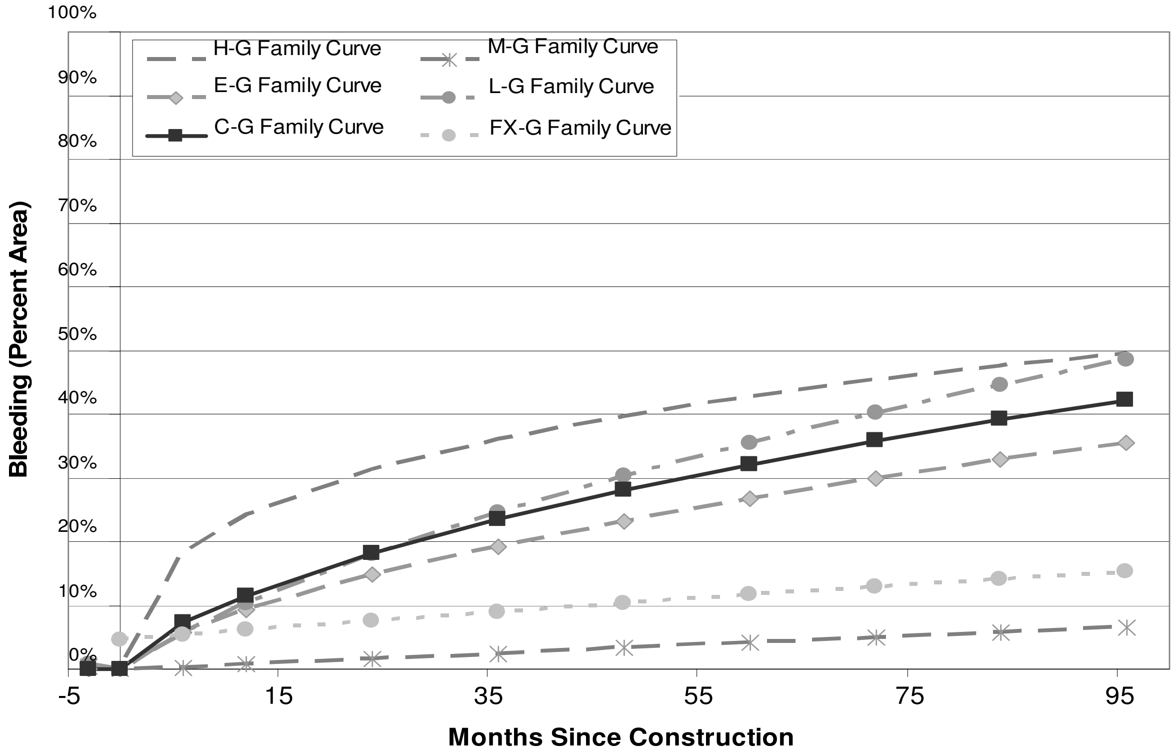

Figure B - 1. Bleeding for All Treatments, Good Initial Condition.

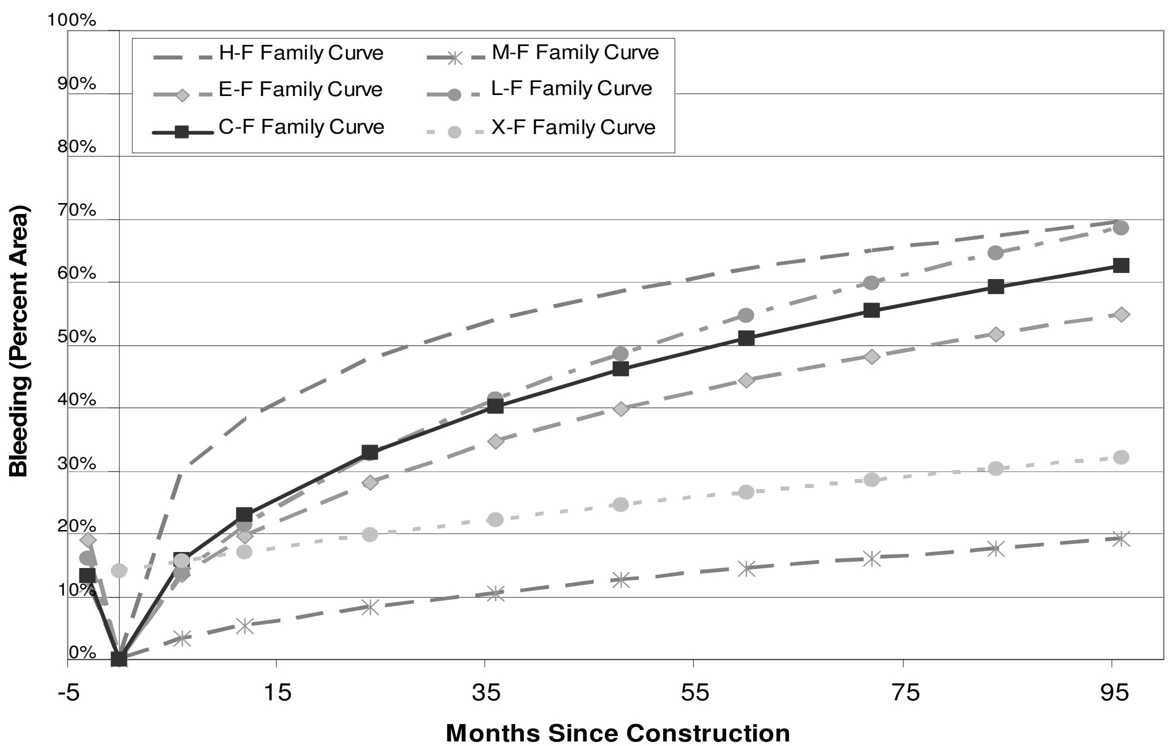

Figure B - 2. Bleeding for All Treatments, Fair Initial Condition.

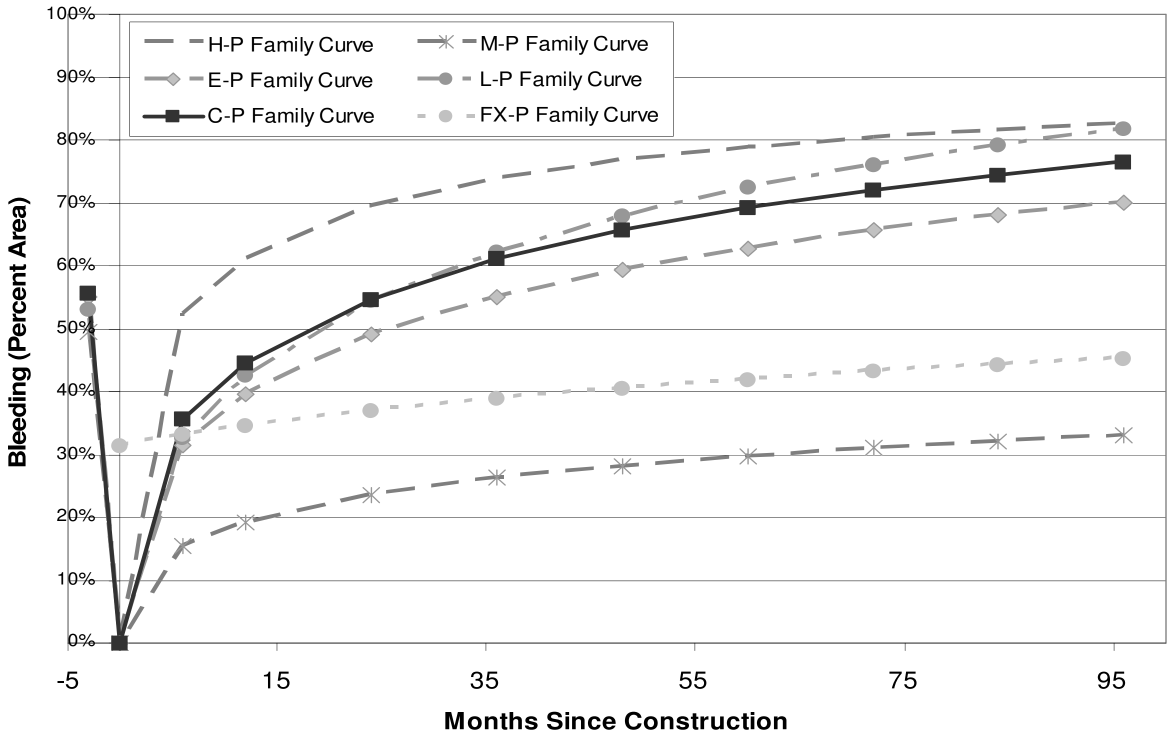

Figure B - 3. Bleeding for All Treatments, Poor Initial Condition.

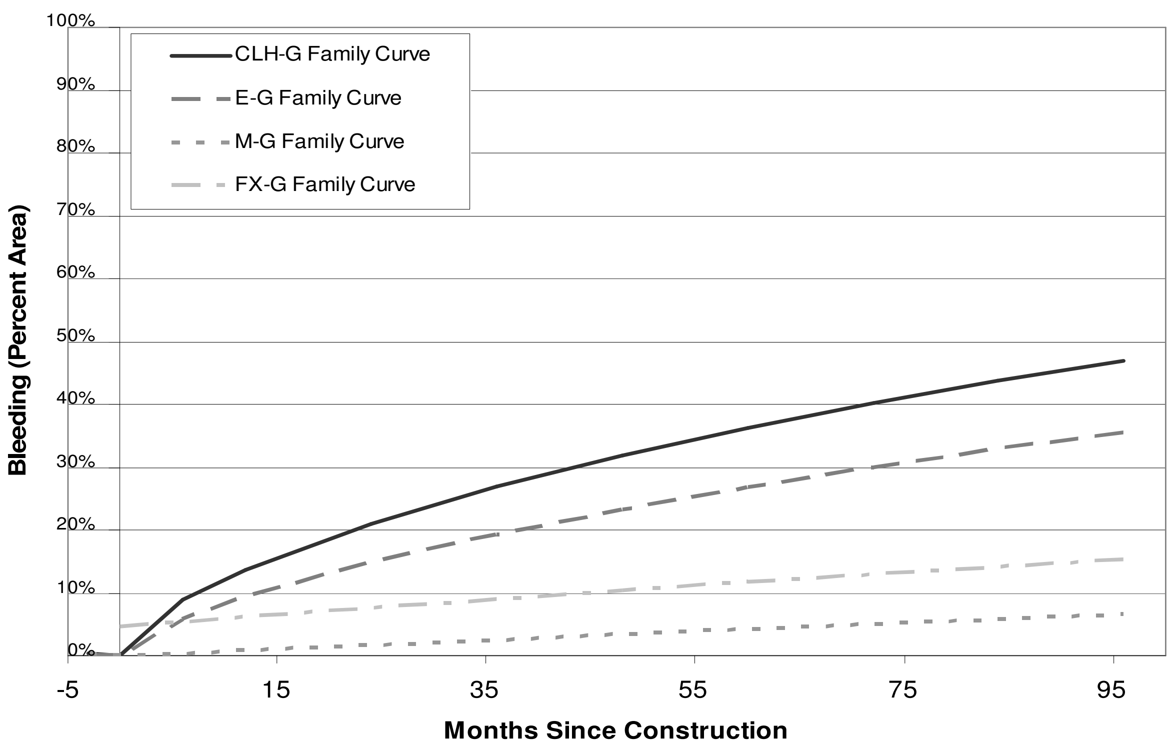

Figure B - 4. Bleeding for All Families, Good Initial Condition.

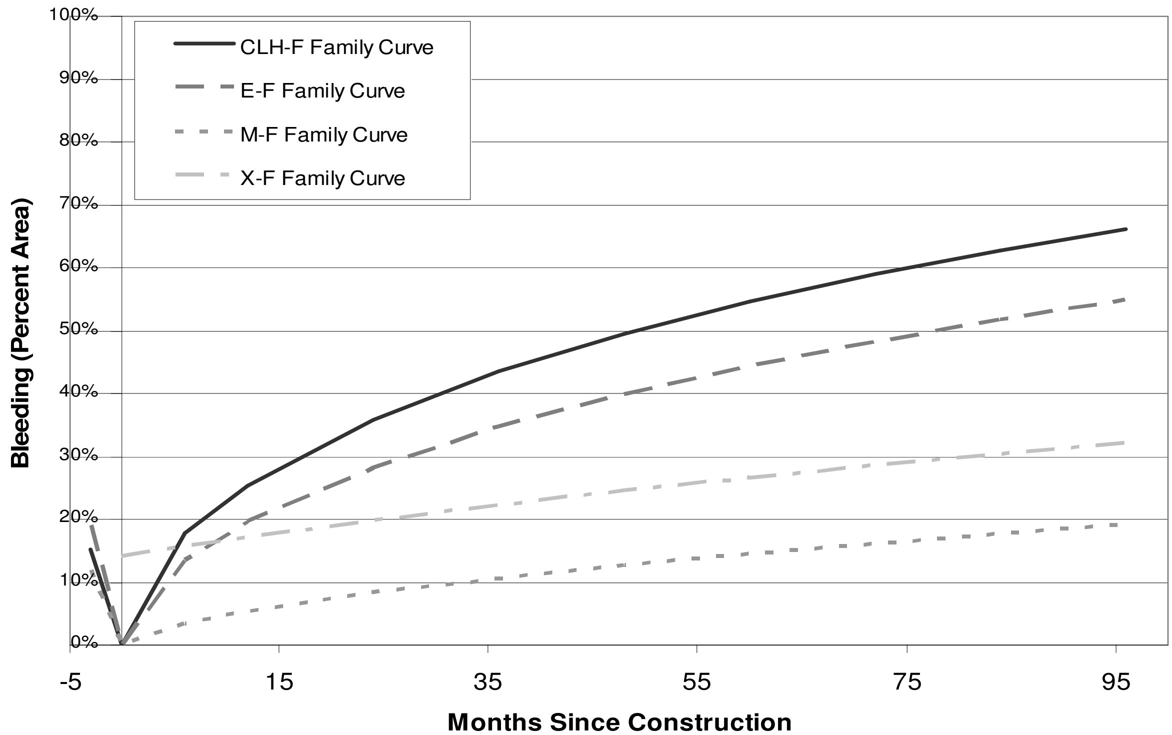

Figure B - 5. Bleeding for All Families, Fair Initial Condition.

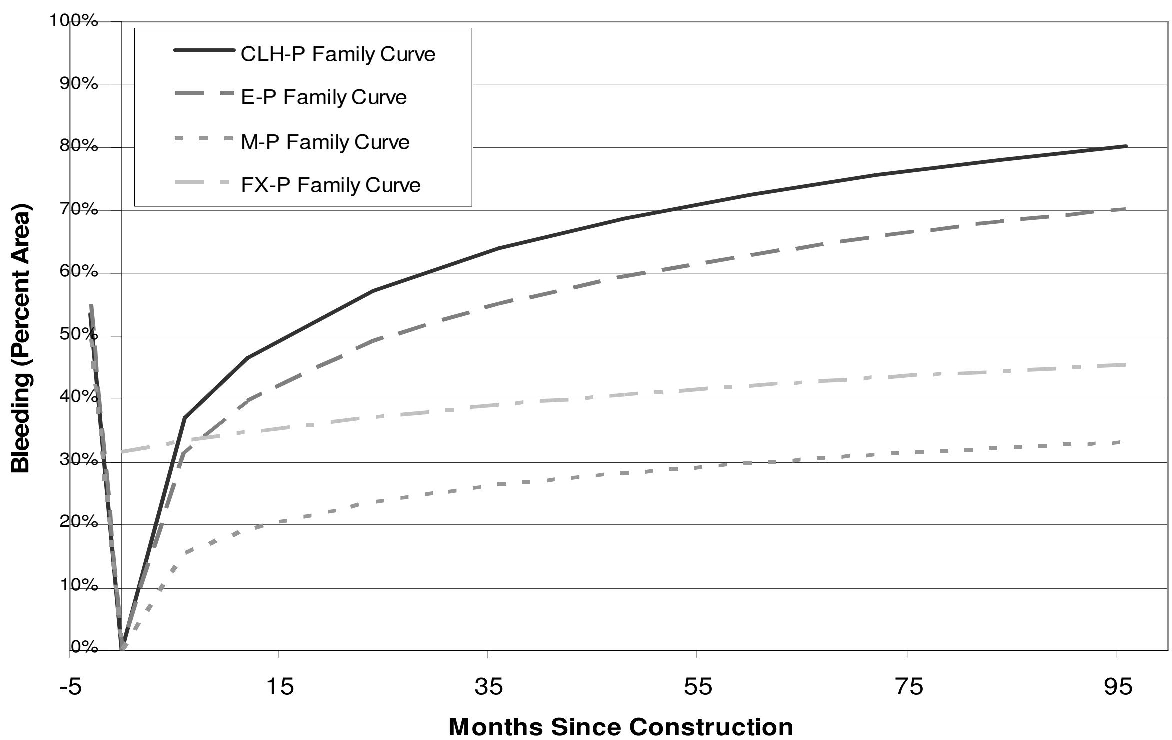

Figure B - 6. Bleeding for All Families, Poor Initial Condition.

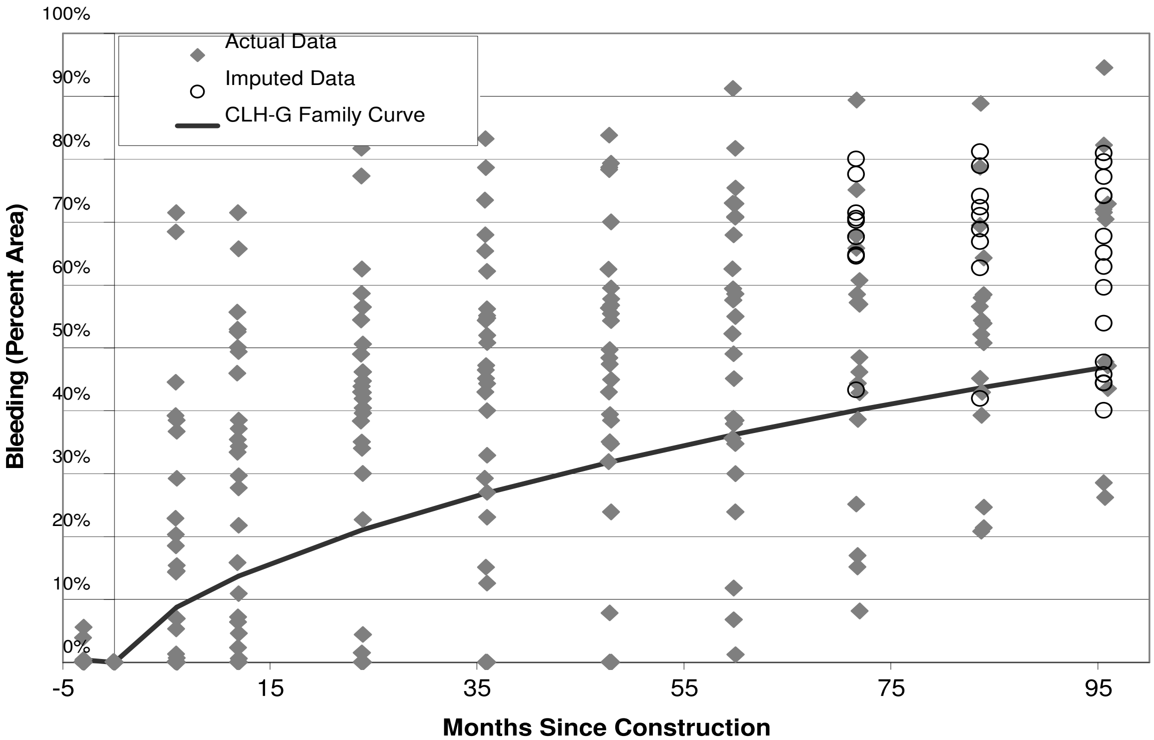

Figure B - 7. Bleeding for CLH Family, Good Initial Condition ($R^2 = 0.880$).

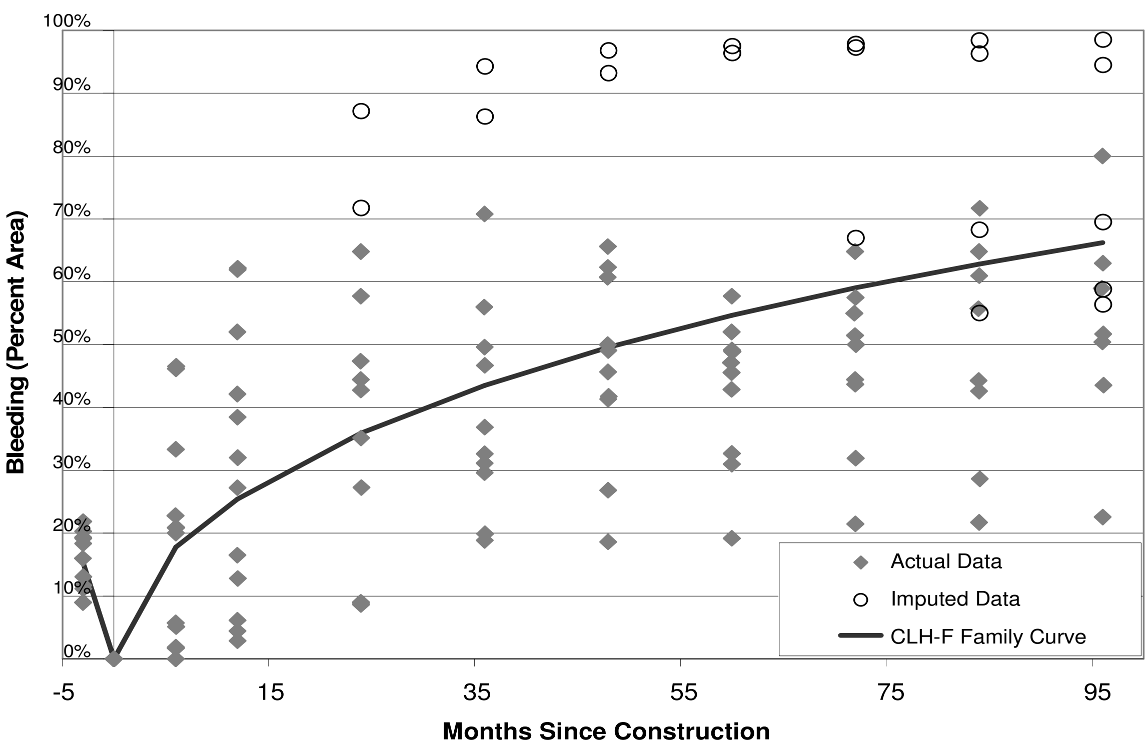

Figure B - 8. Bleeding for CLH Family, Fair Initial Condition ($R^2 = 0.892$).

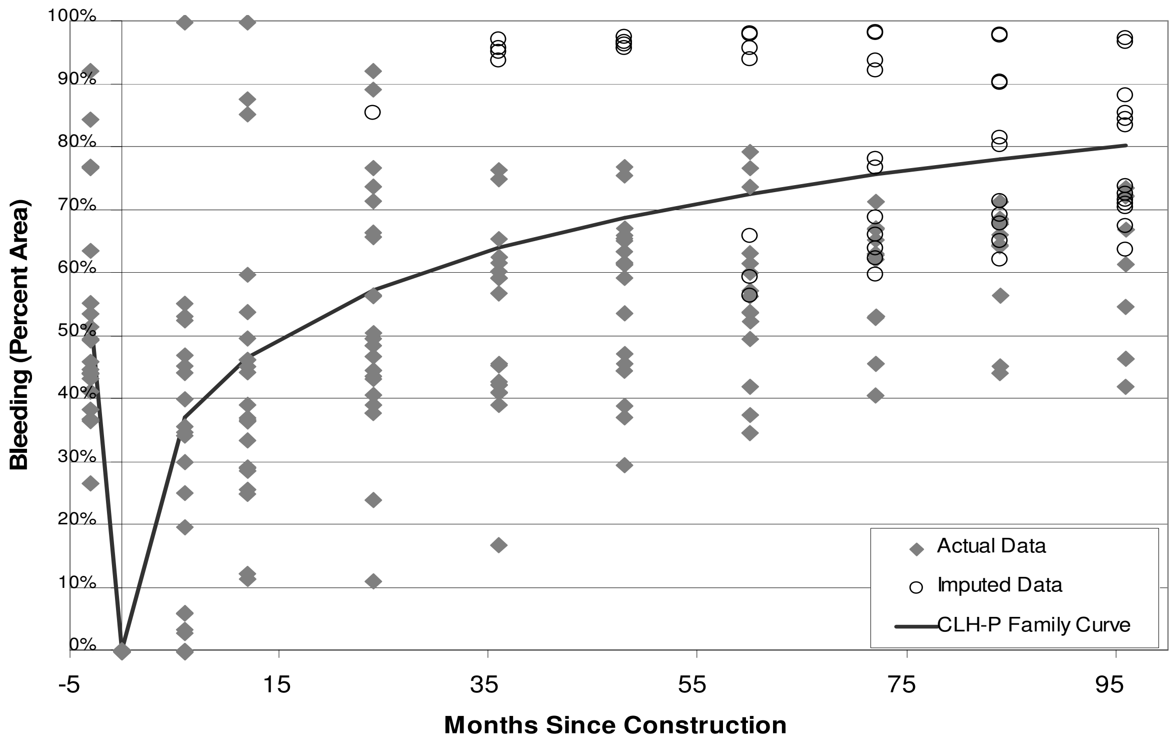

Figure B - 9. Bleeding for CLH Family, Poor Initial Condition (R^2 = 0.925).

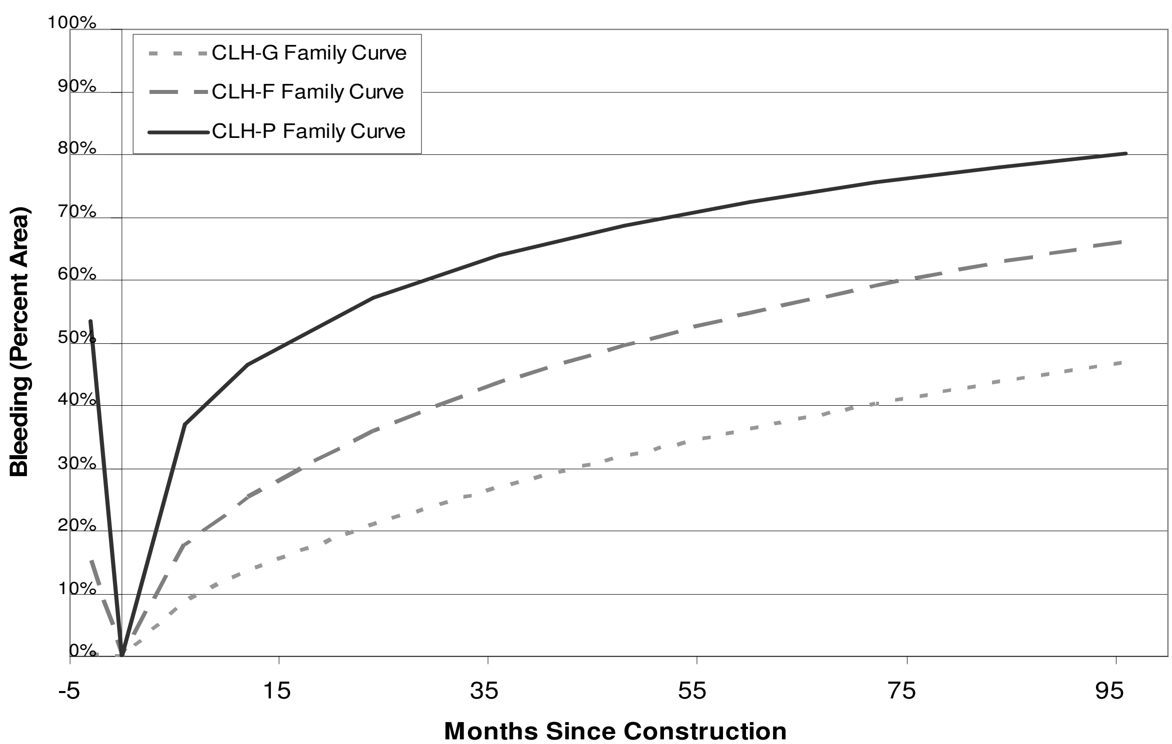

Figure B - 10. Bleeding for CLH Family, All Initial Conditions.

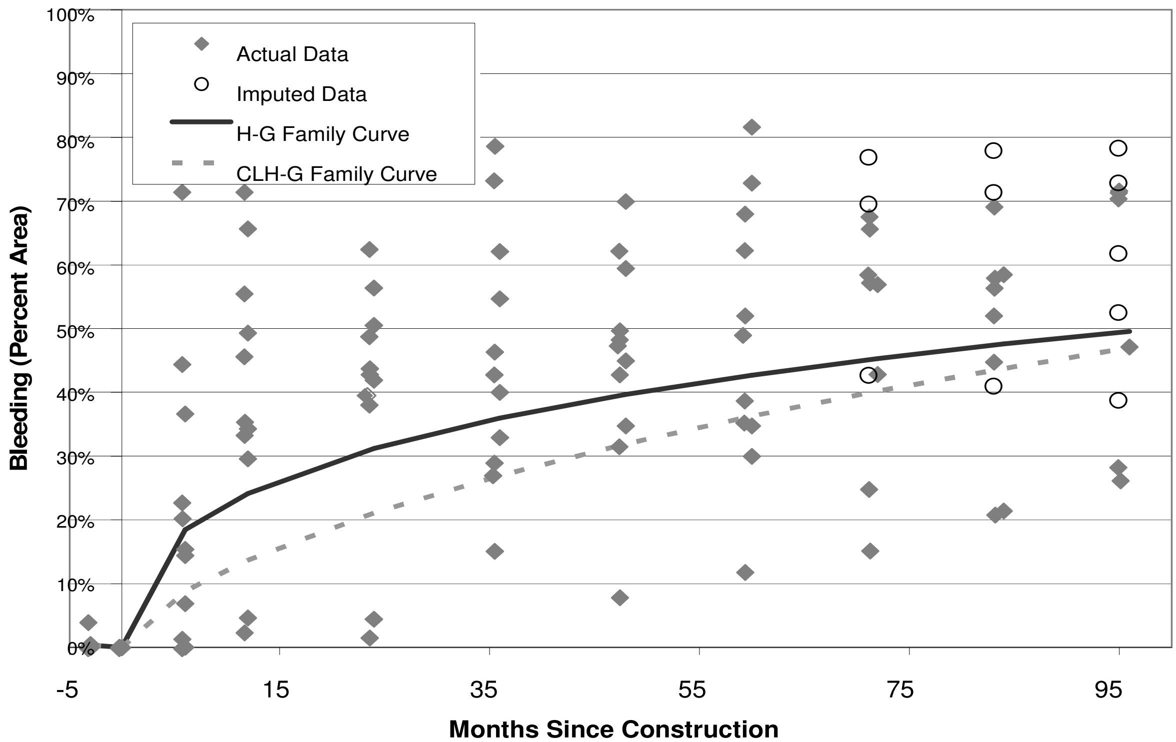

Figure B - 11. Bleeding for Asphalt Rubber Seal Coat, Good Initial Condition (R^2 = 0.911).

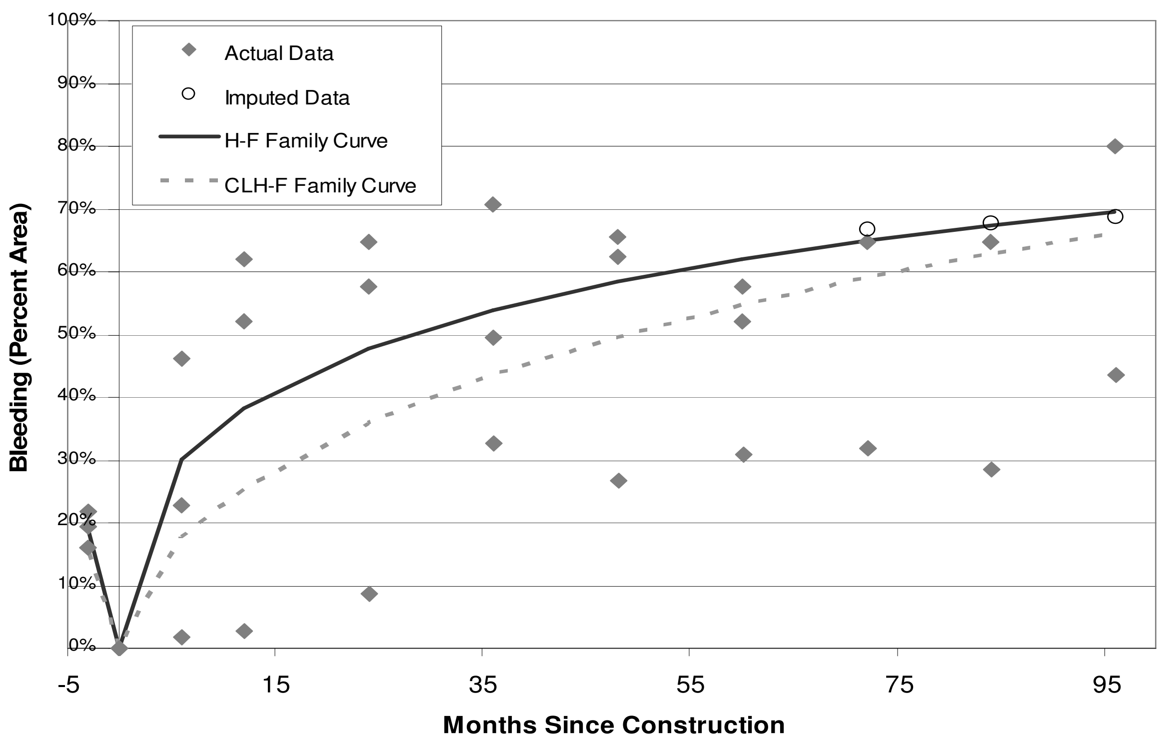

Figure B - 12. Bleeding for Asphalt Rubber Seal Coat, Fair Initial Condition (R^2 = 0.924).

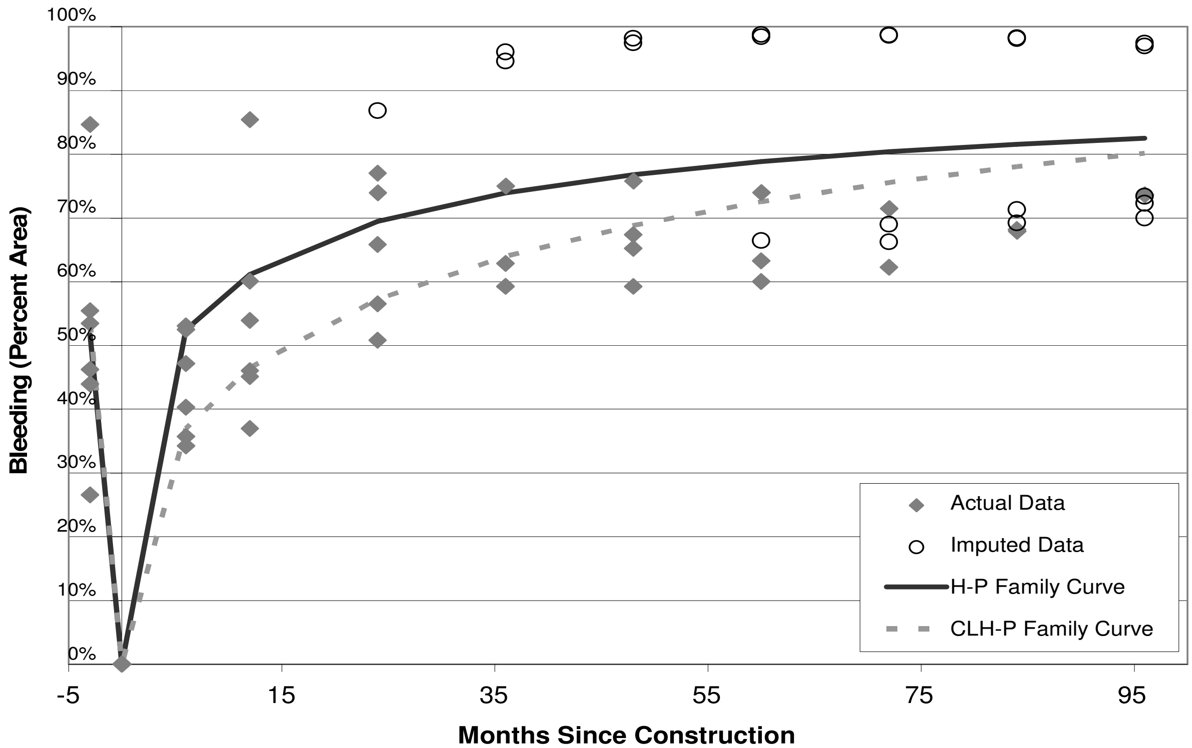

Figure B - 13. Bleeding for Asphalt Rubber Seal Coat, Poor Initial Condition (R^2 = 0.963).

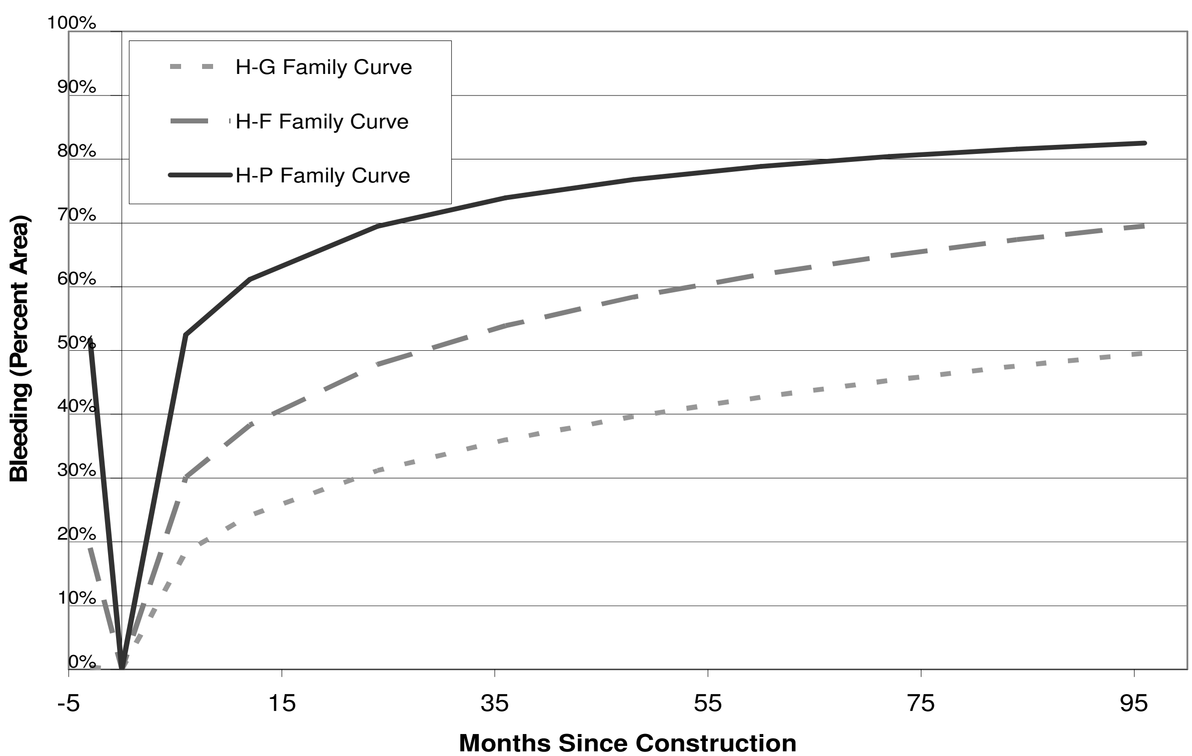

Figure B - 14. Bleeding for Asphalt Rubber Seal Coat, All Initial Conditions.

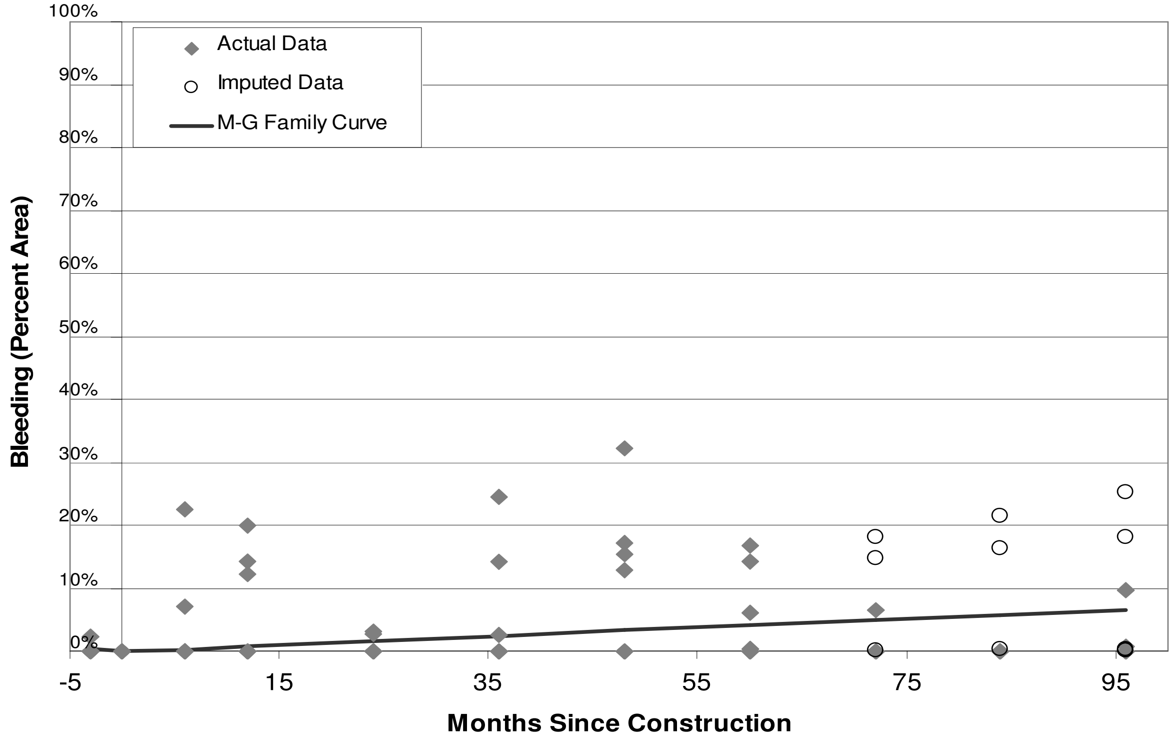

Figure B - 15. Bleeding for Microsurfacing, Good Initial Condition (R^2 = 0.311).

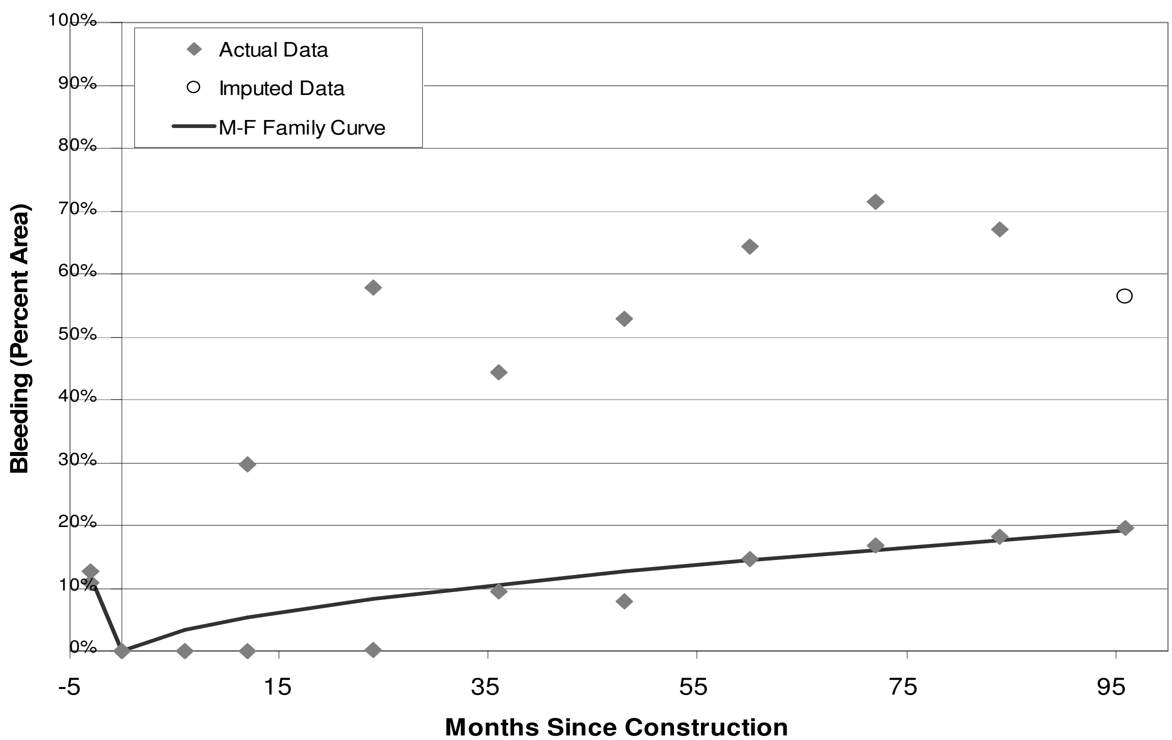

Figure B - 16. Bleeding for Microsurfacing, Fair Initial Condition (R^2 = 0.796).

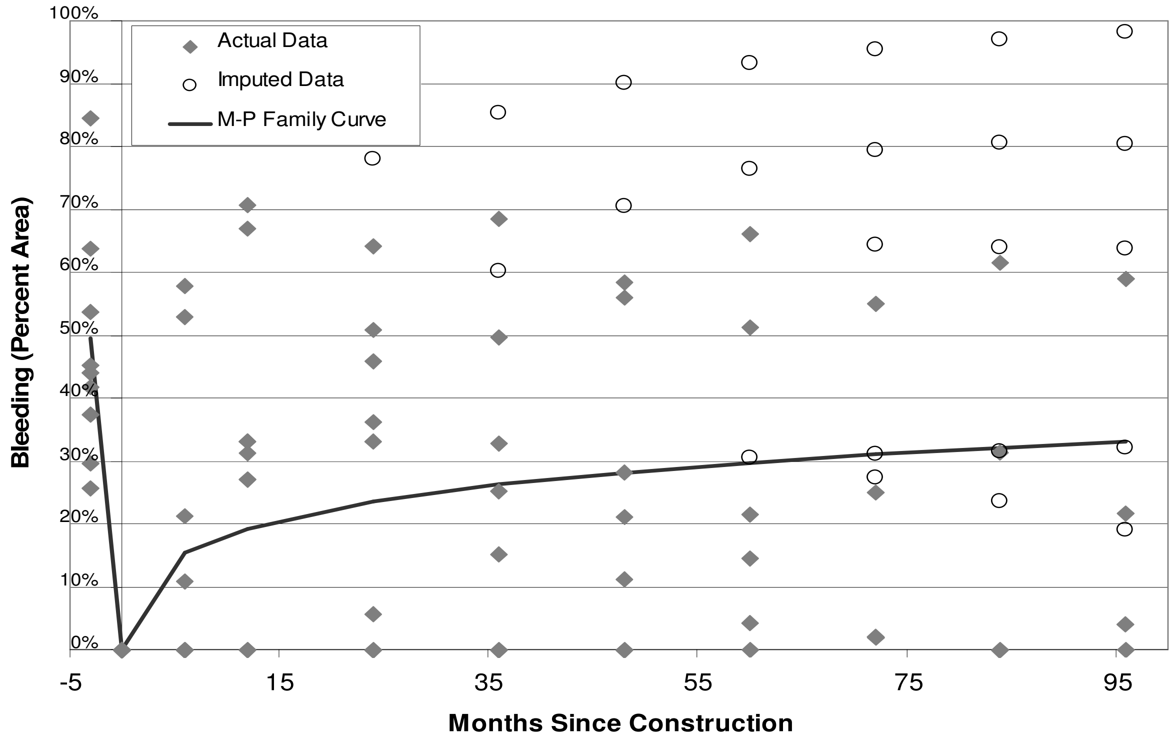

Figure B - 17. Bleeding for Microsurfacing, Poor Initial Condition (R^2 = 0.691).

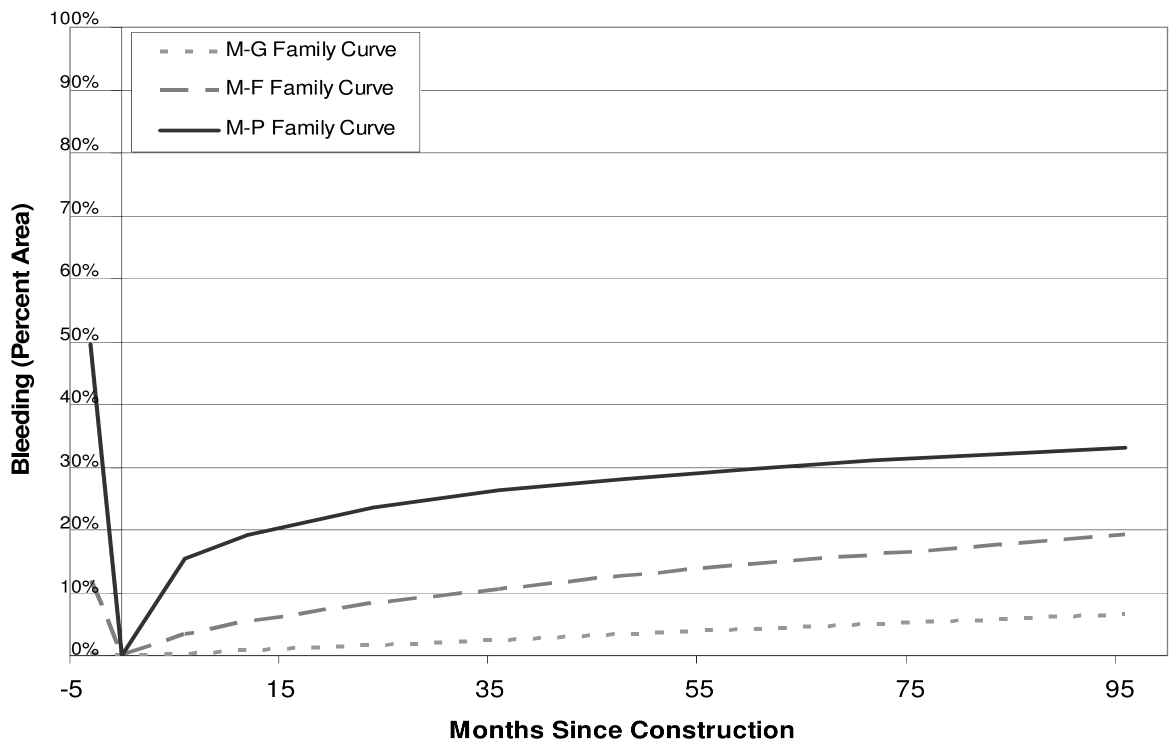

Figure B - 18. Bleeding for Microsurfacing, All Initial Conditions.

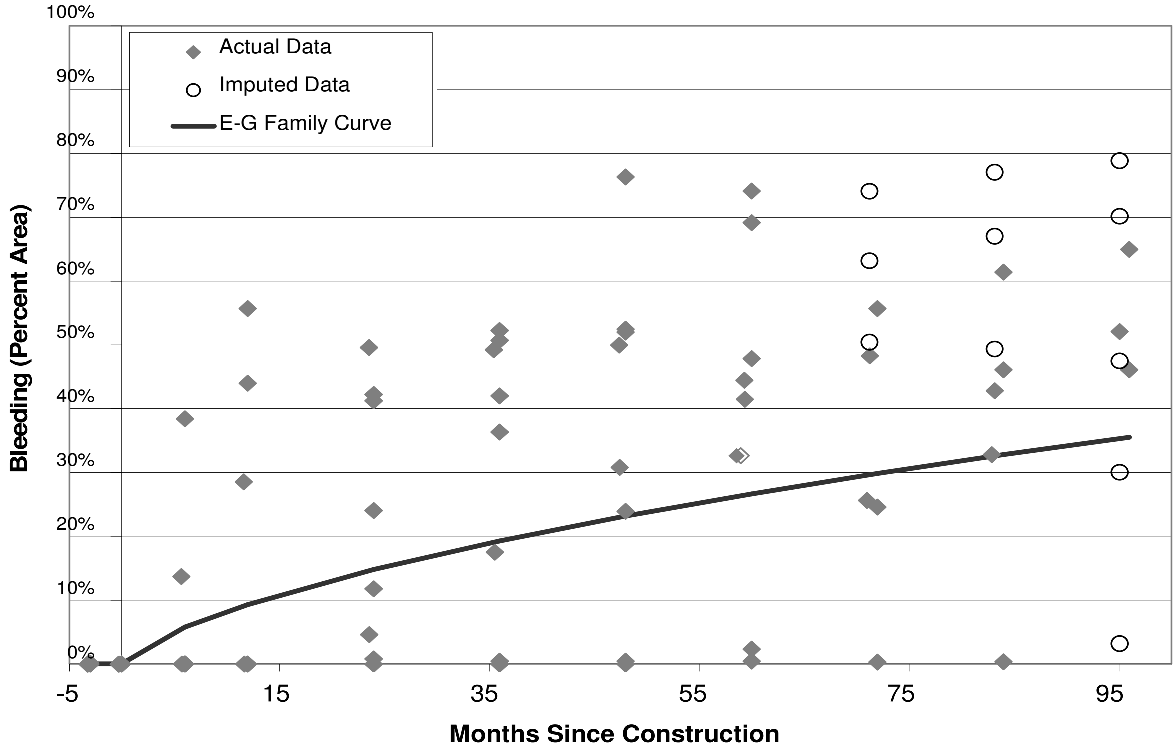

Figure B - 19. Bleeding for Polymer Modified Emulsion Seal Coat, Good Initial Condition (R^2 = 0.776).

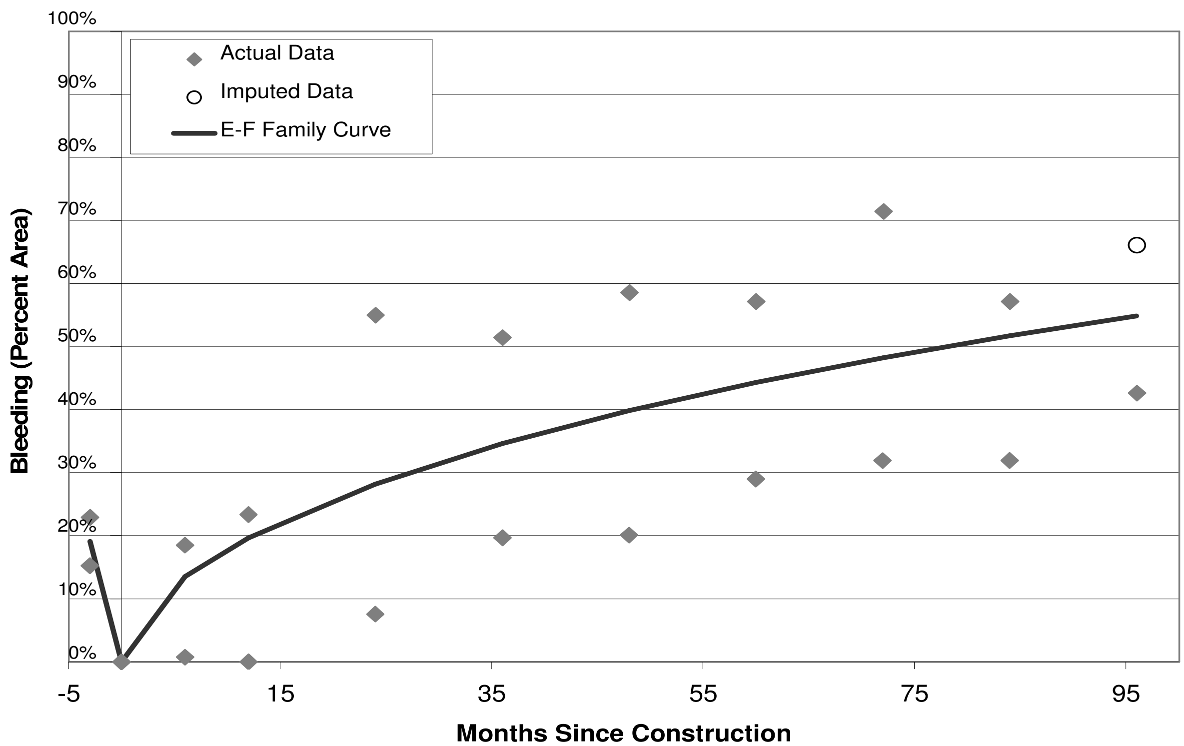

Figure B - 20. Bleeding for Polymer Modified Emulsion Seal Coat, Fair Initial Condition (R^2 = 0.908).

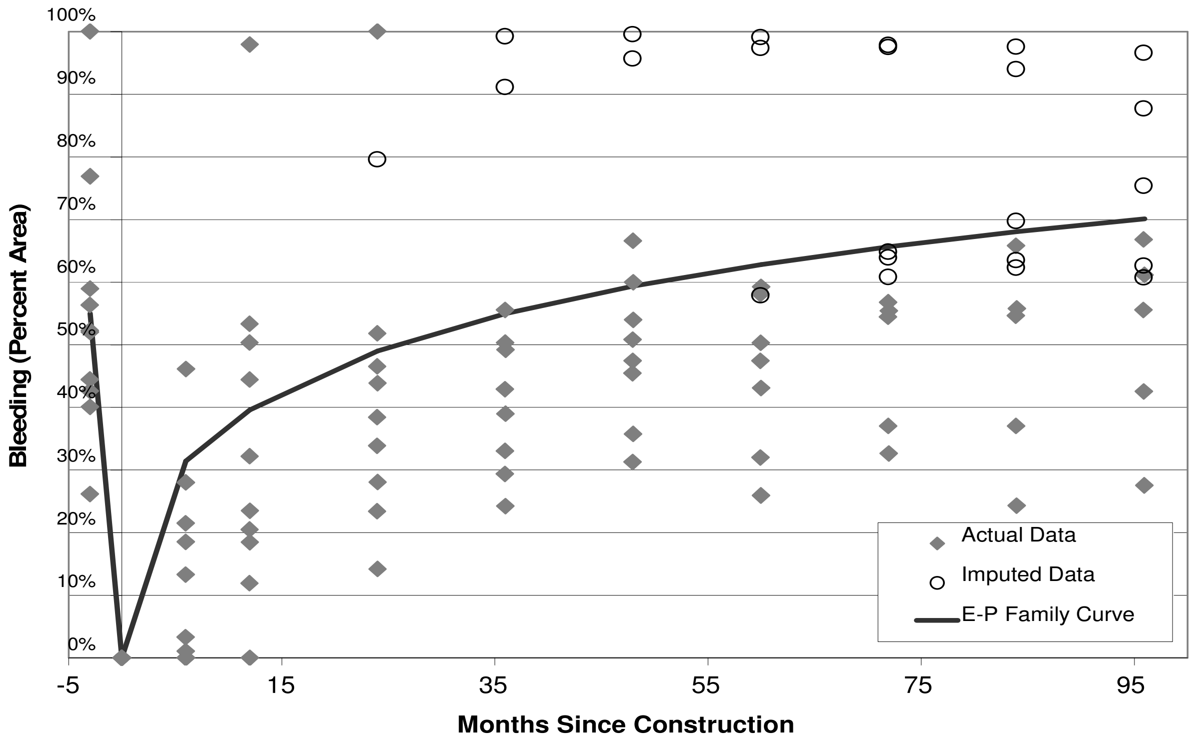

Figure B - 21. Bleeding for Polymer Modified Emulsion Seal Coat, Poor Initial Condition (R^2 = 0.882).

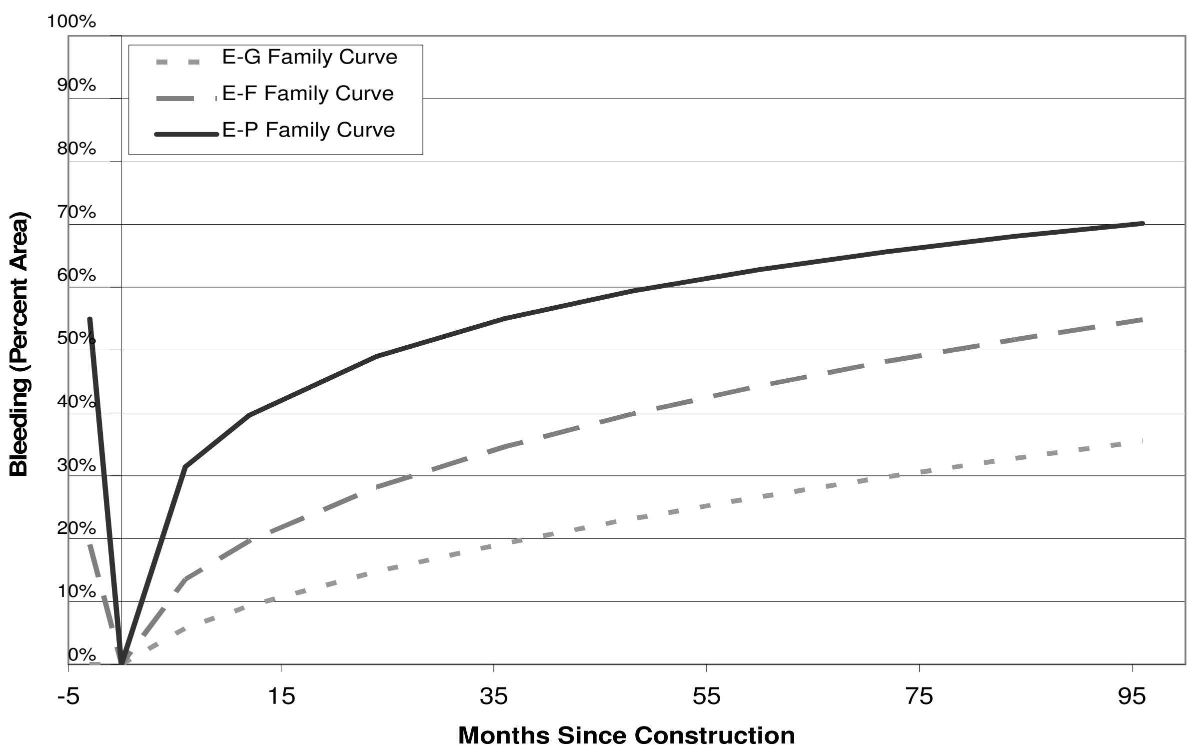

Figure B - 22. Bleeding for Polymer Modified Emulsion Seal Coat, All Initial Conditions.

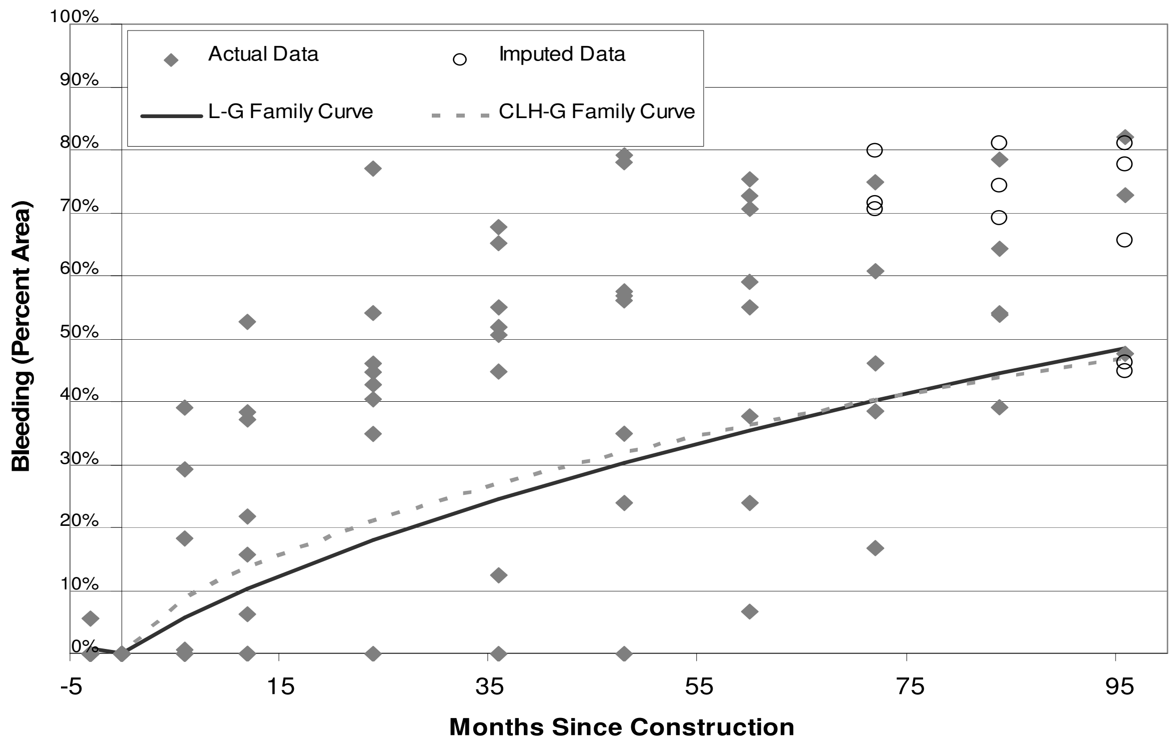

Figure B - 23. Bleeding for Latex Modified Seal Coat, Good Initial Condition ($R^2 = 0.882$).

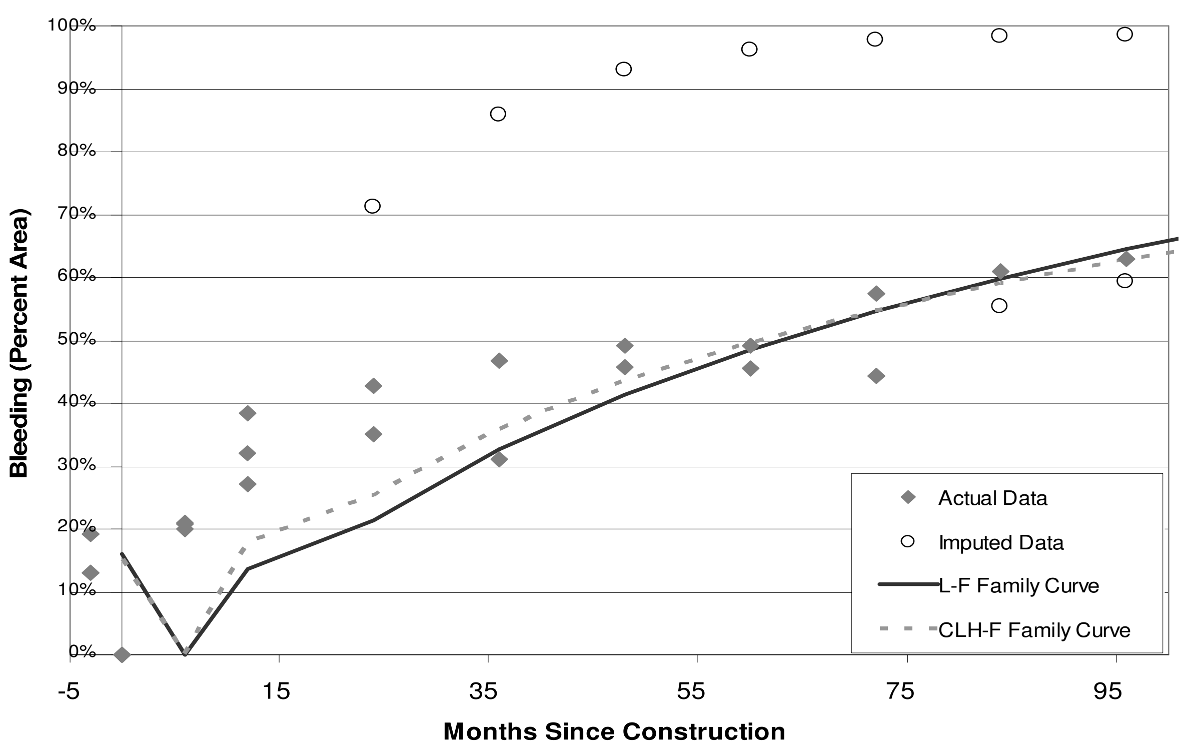

Figure B - 24. Bleeding for Latex Modified Seal Coat, Fair Initial Condition ($R^2 = 0.931$).

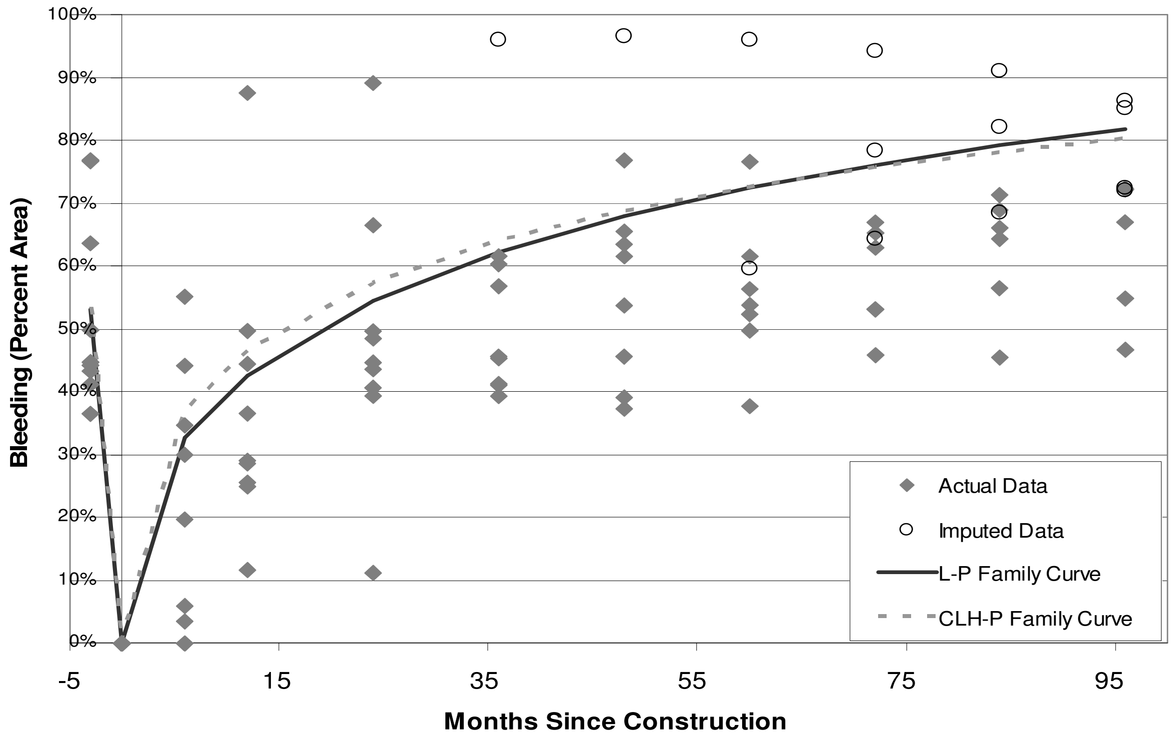

Figure B - 25. Bleeding for Latex Modified Seal Coat, Poor Initial Condition (R^2 = 0.938).

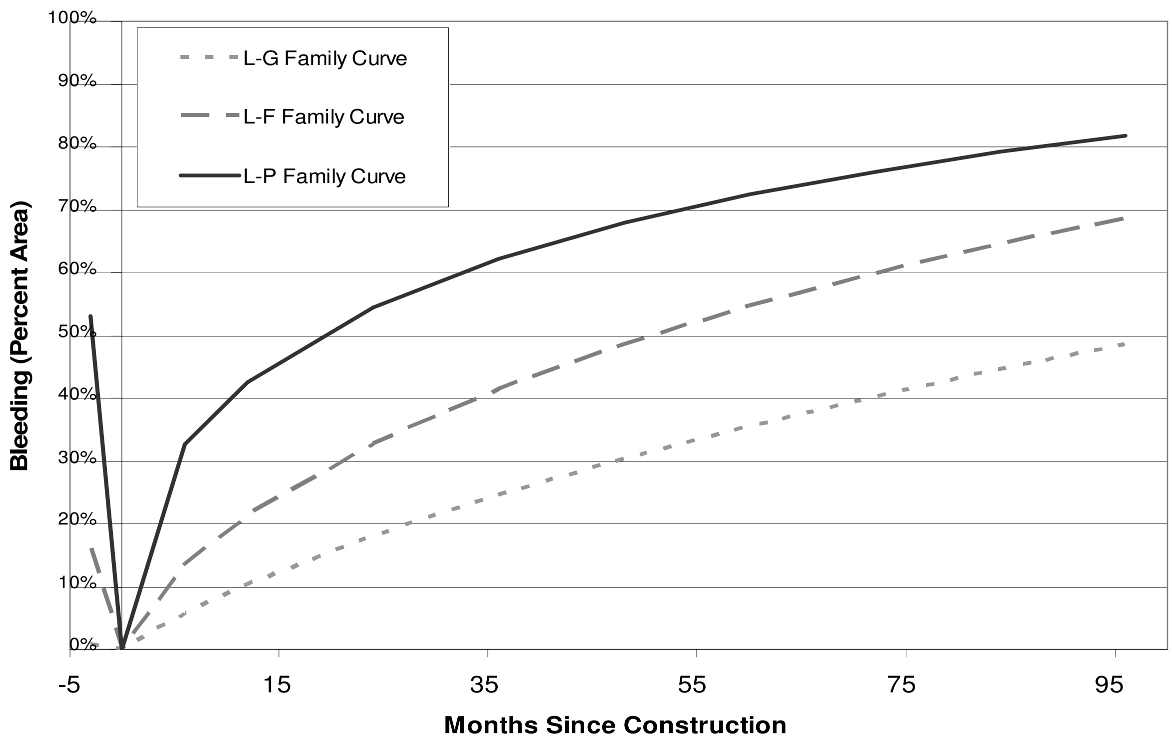

Figure B - 26. Bleeding for Latex Modified Seal Coat, All Initial Conditions.

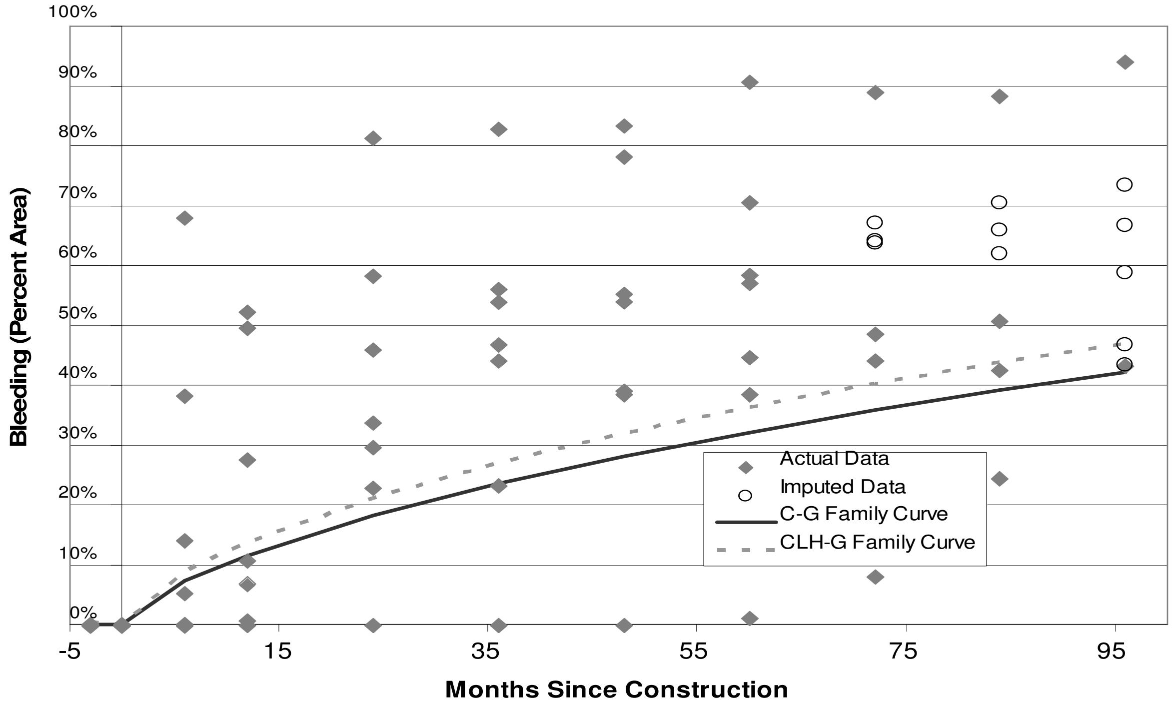

Figure B - 27. Bleeding for Unmodified Asphalt Seal Coat, Good Initial Condition (R^2 = 0.847).

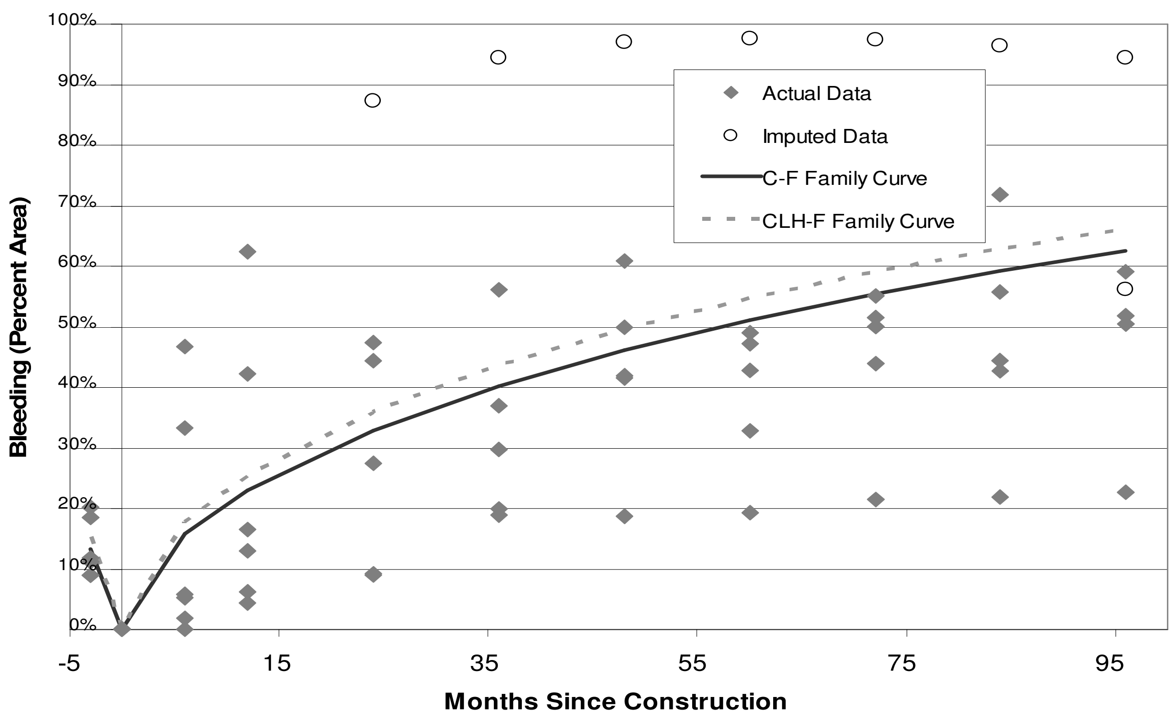

Figure B - 28. Bleeding for Unmodified Asphalt Seal Coat, Fair Initial Condition (R^2 = 0.862).

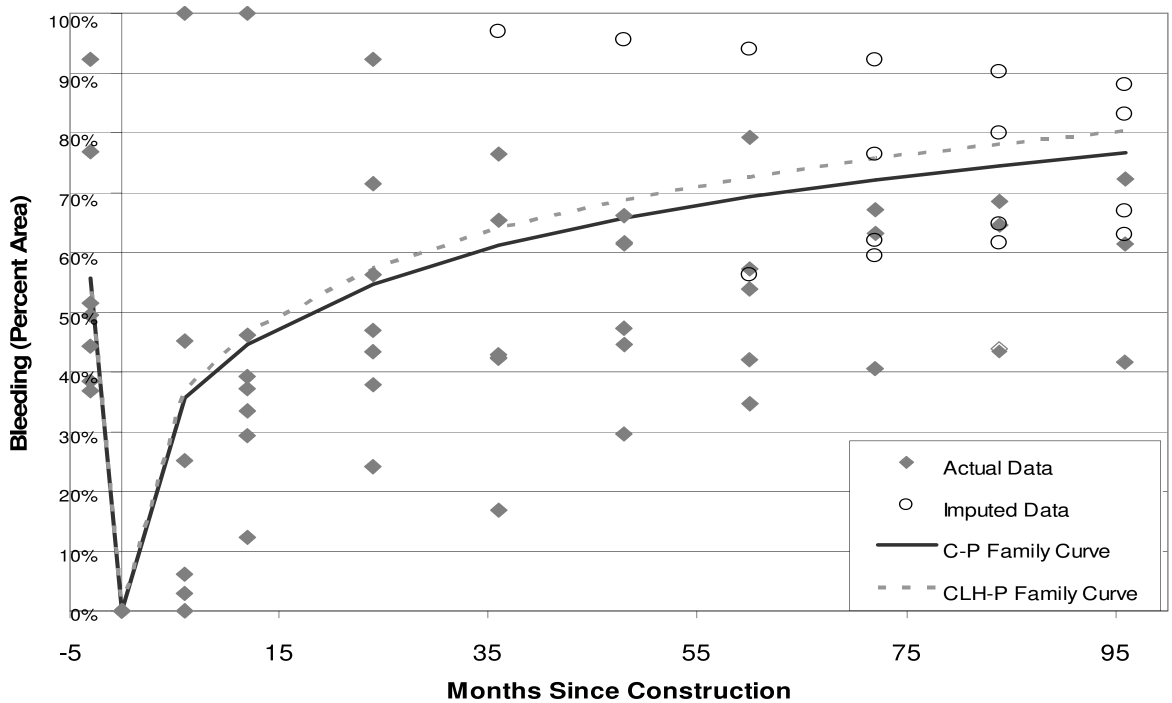

Figure B - 29. Bleeding for Unmodified Asphalt Seal Coat, Poor Initial Condition (R^2 = 0.895).

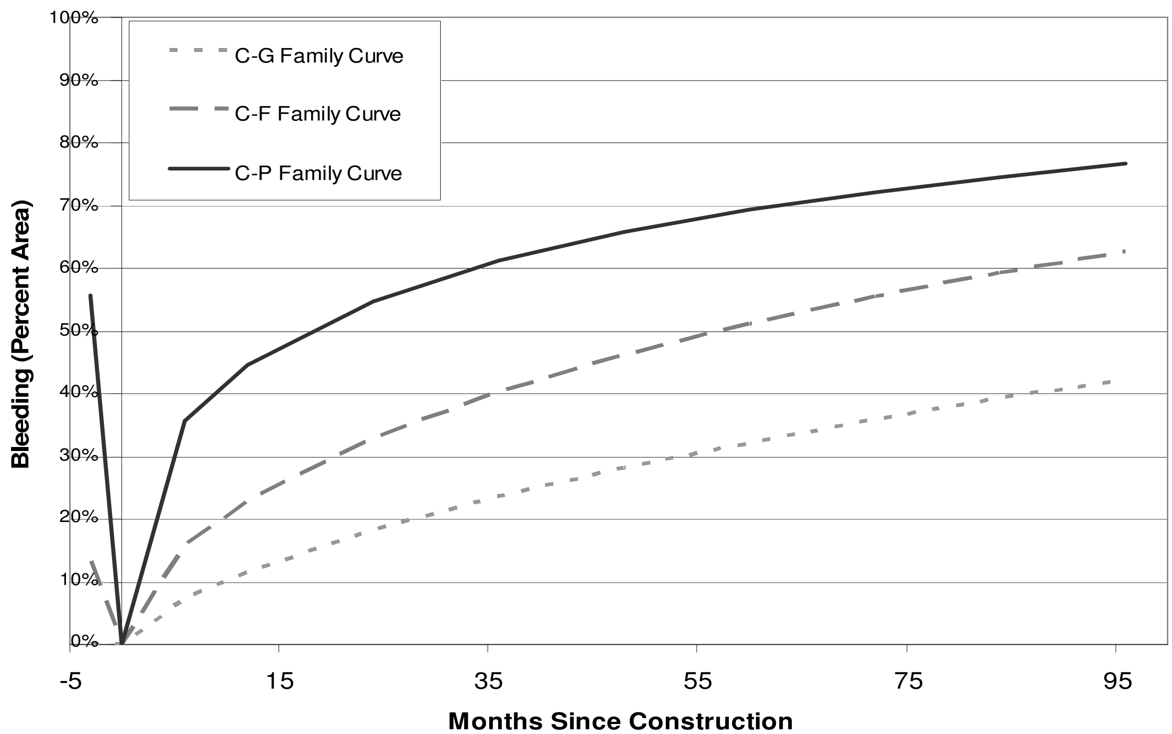

Figure B - 30. Bleeding for Unmodified Asphalt Seal Coat, All Initial Conditions.

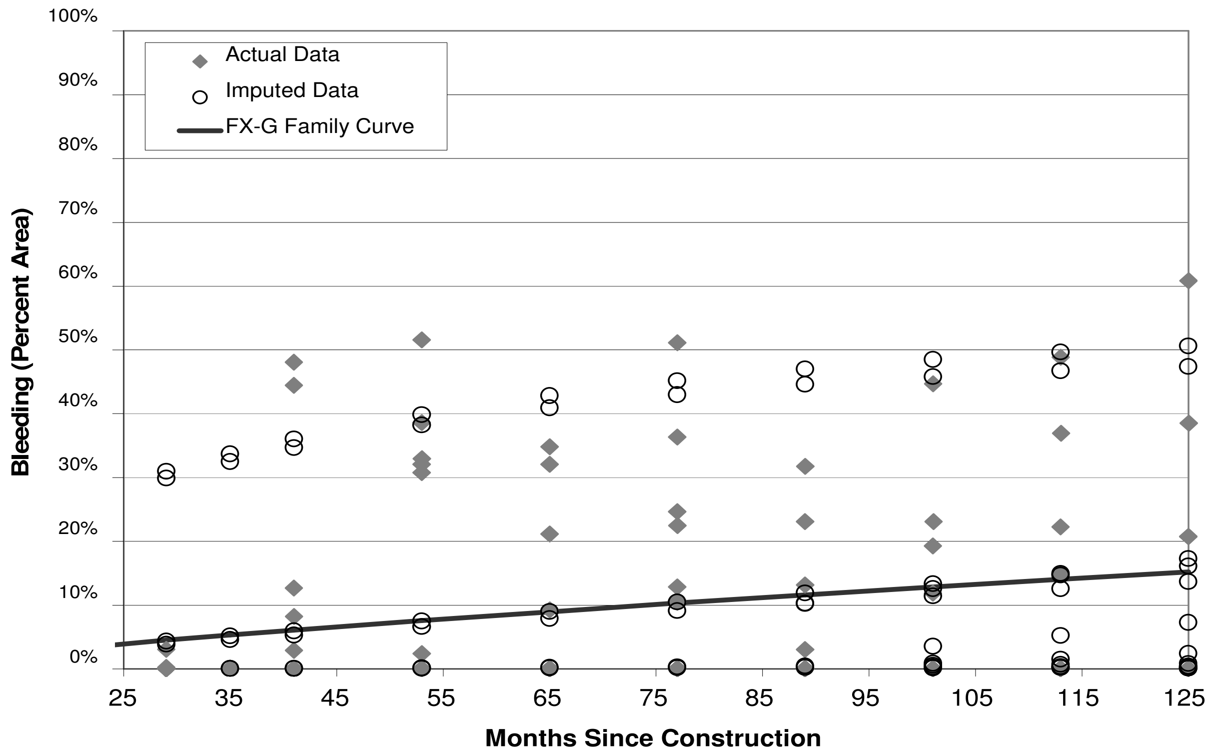

Figure B - 31. Bleeding for Fog and Control Sections, Good Initial Condition (R^2 = 0.383).

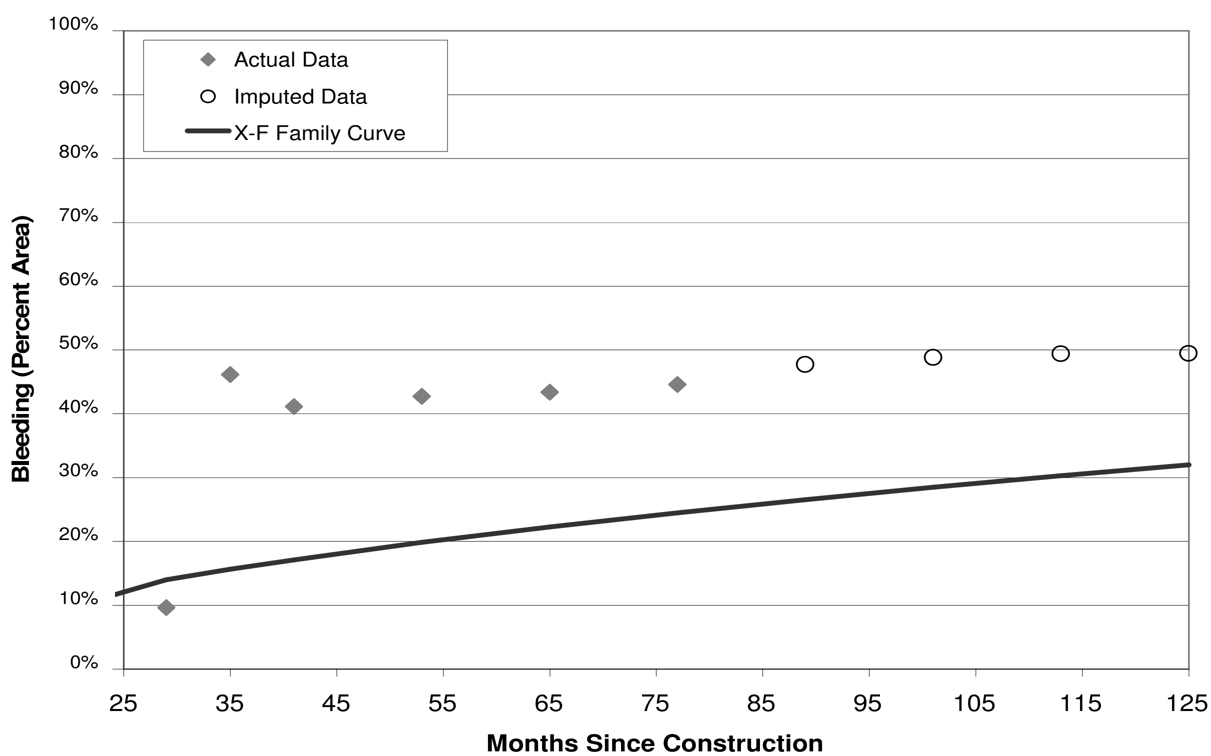

Figure B - 32. Bleeding for Fog and Control Sections, Fair Initial Condition (R^2 = 0.981).

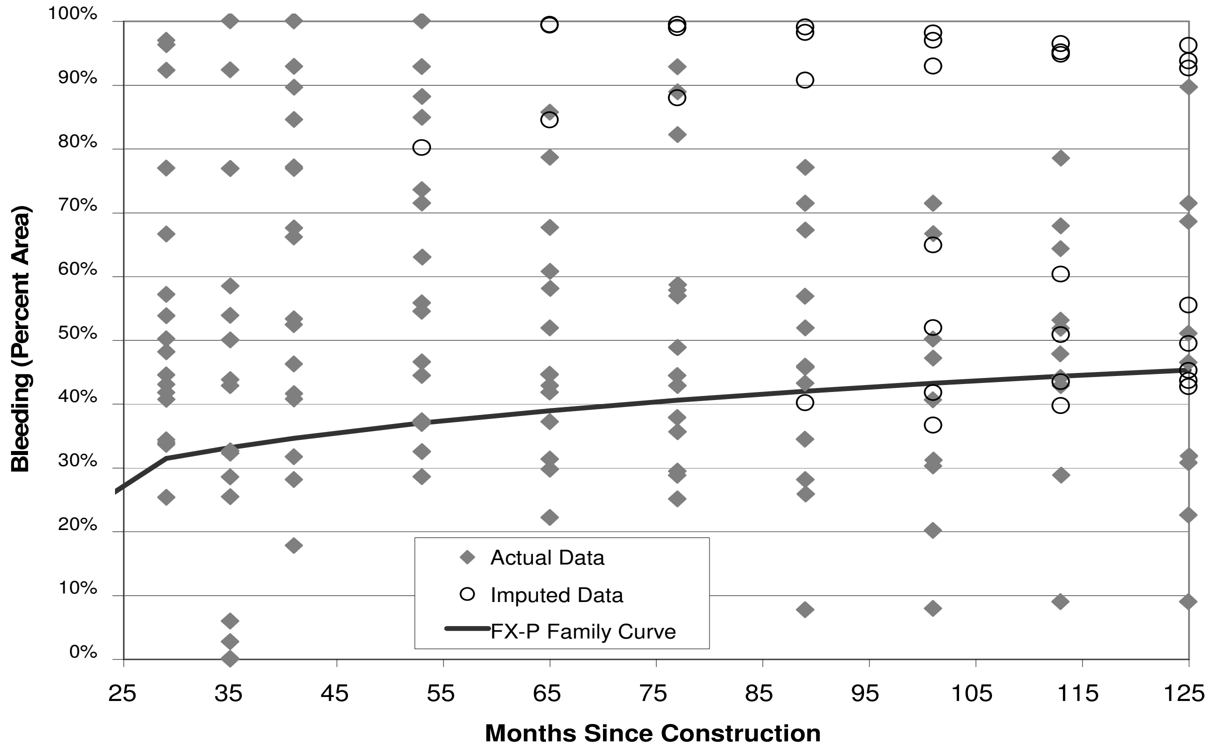

Figure B - 33. Bleeding for Fog and Control Sections, Poor Initial Condition (R^2 = 0.881).

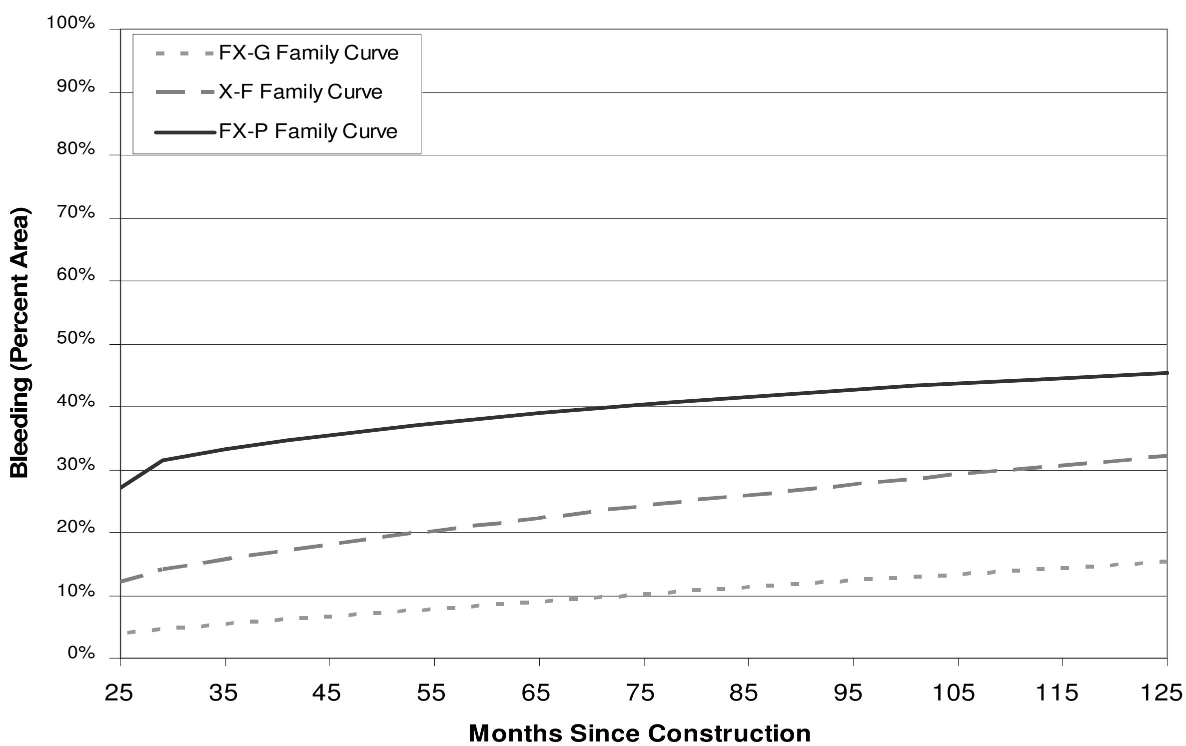

Figure B - 34. Bleeding for Fog and Control Sections, All Initial Conditions.

APPENDIX C

ALLIGATOR CRACKING PLUS PATCHING PERFORMANCE CURVES

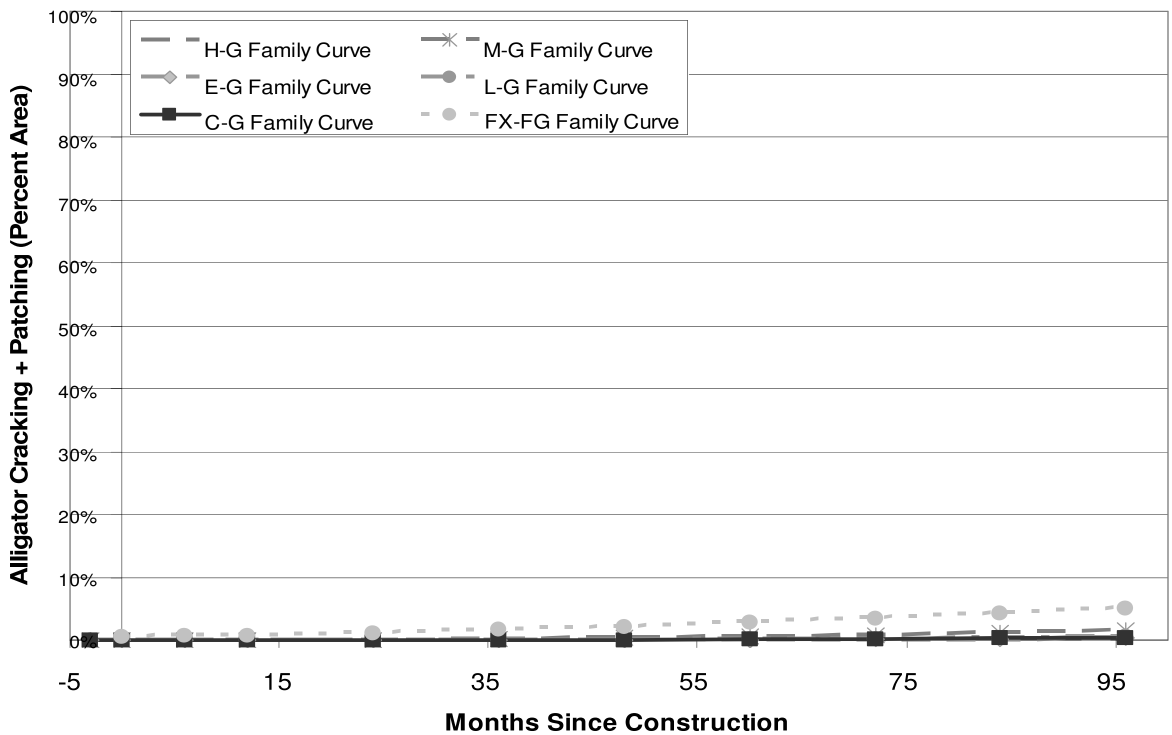

Figure C - 1. Alligator Cracking Plus Patching for All Treatments, Good Initial Condition.

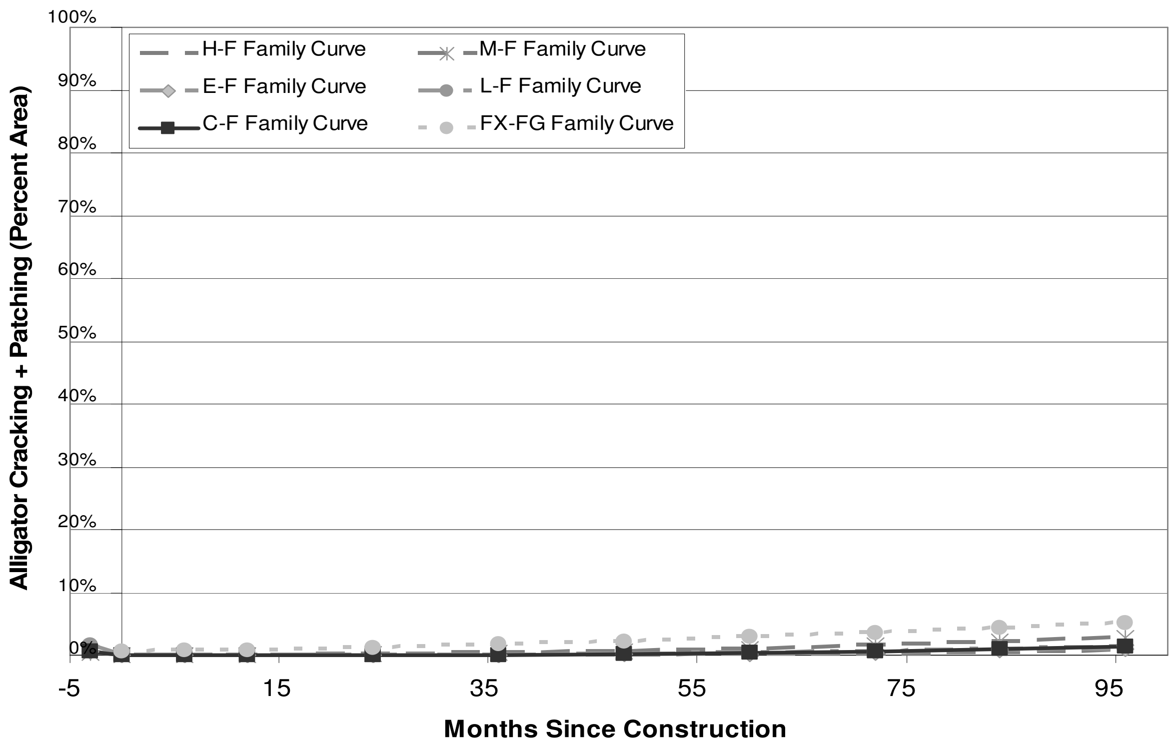

Figure C - 2. Alligator Cracking Plus Patching for All Treatments, Fair Initial Condition.

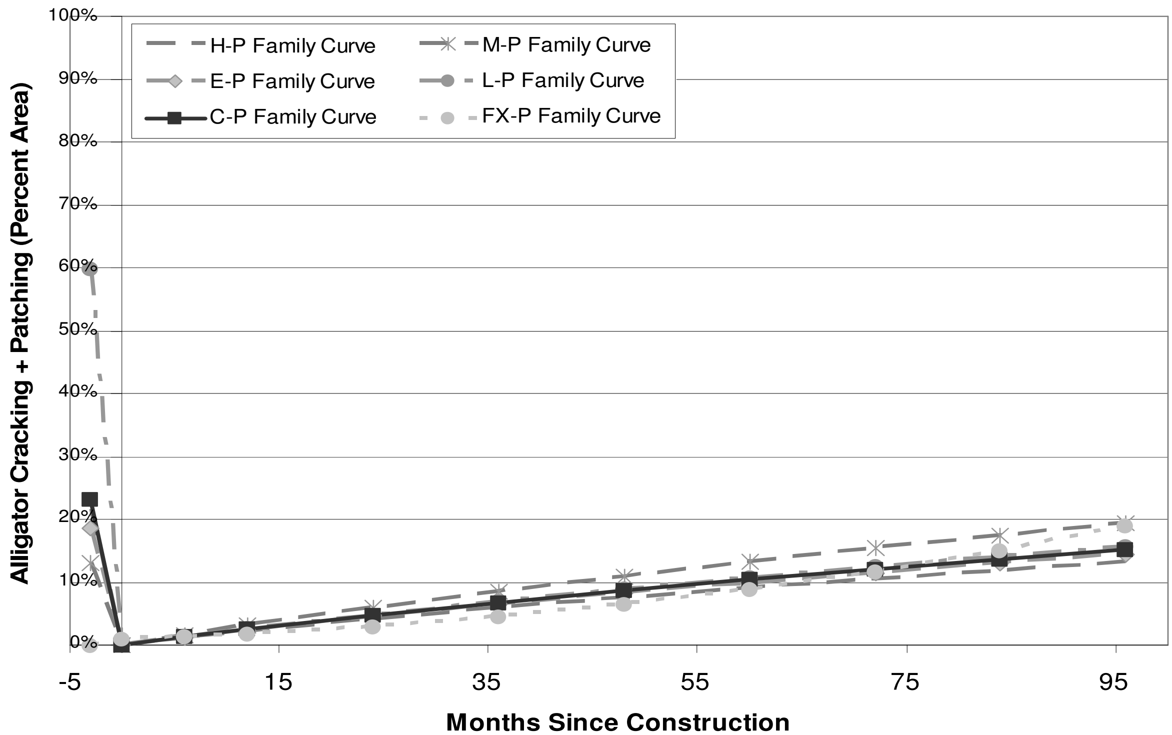

Figure C - 3. Alligator Cracking Plus Patching for All Treatments, Poor Initial Condition.

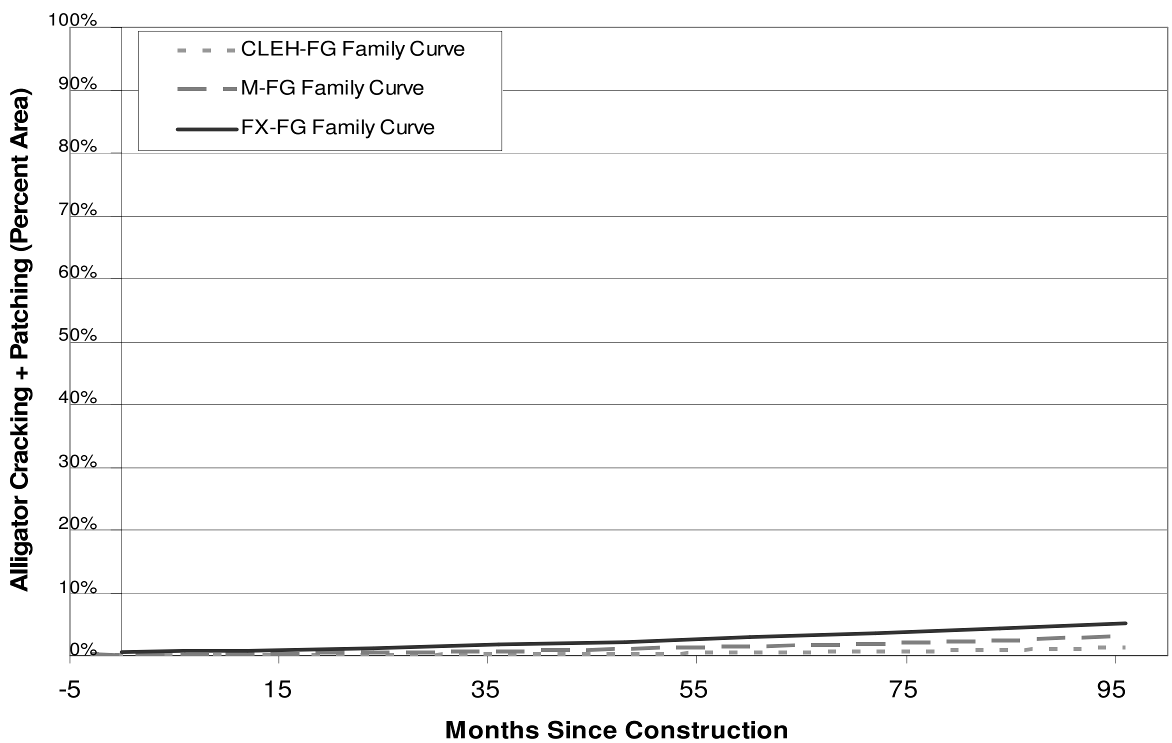

Figure C - 4. Alligator Cracking Plus Patching for All Families, Good and Fair Initial Conditions.

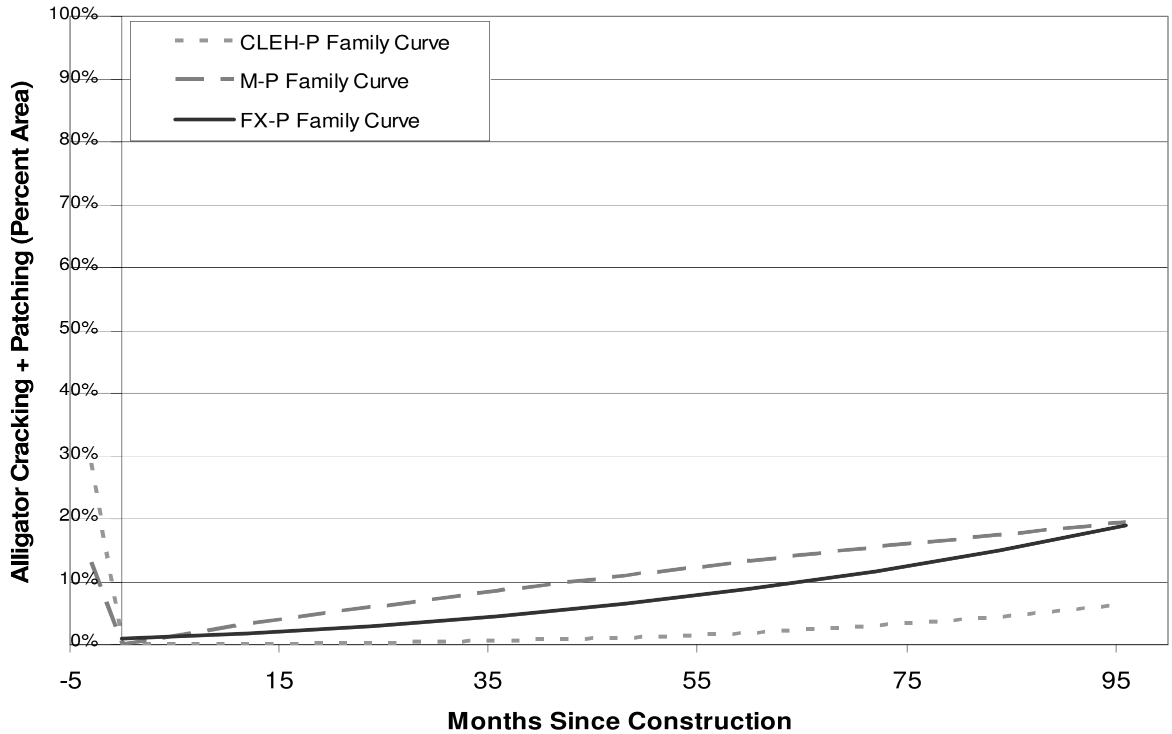

Figure C - 5. Alligator Cracking Plus Patching for All Families, Poor Initial Condition.

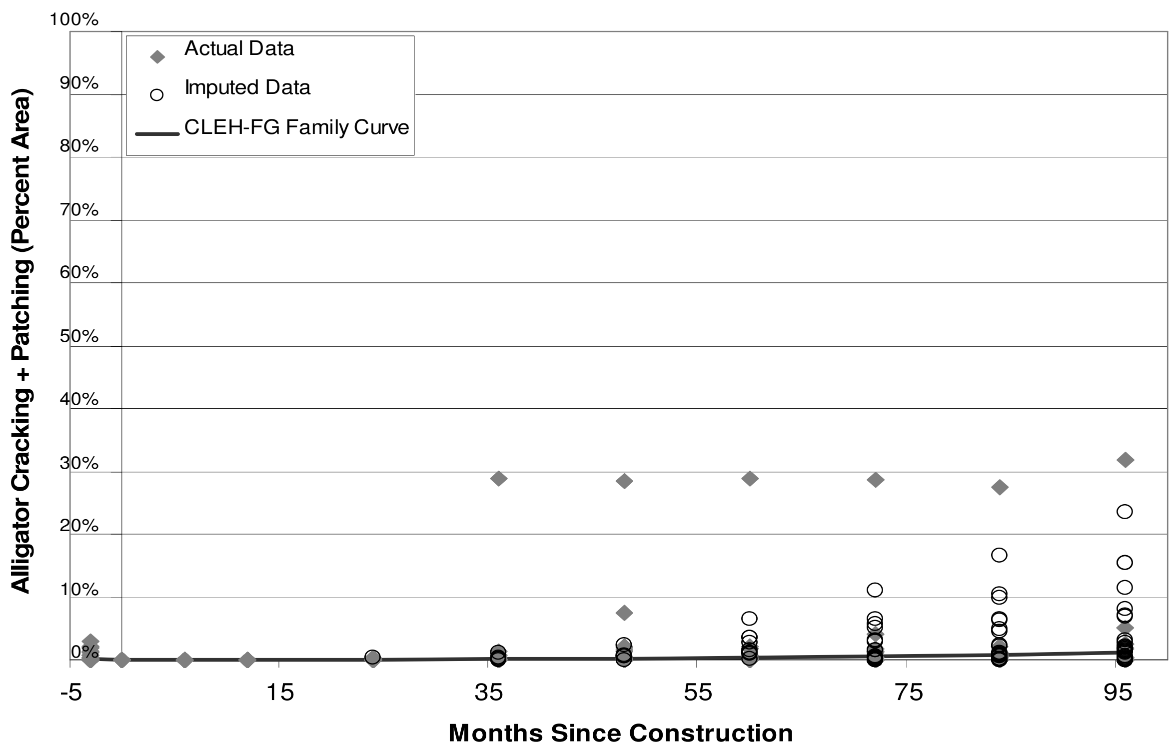

Figure C - 6. Alligator Cracking Plus Patching for ECLH Family, Good and Fair Initial Conditions (R^2 = 0.233).

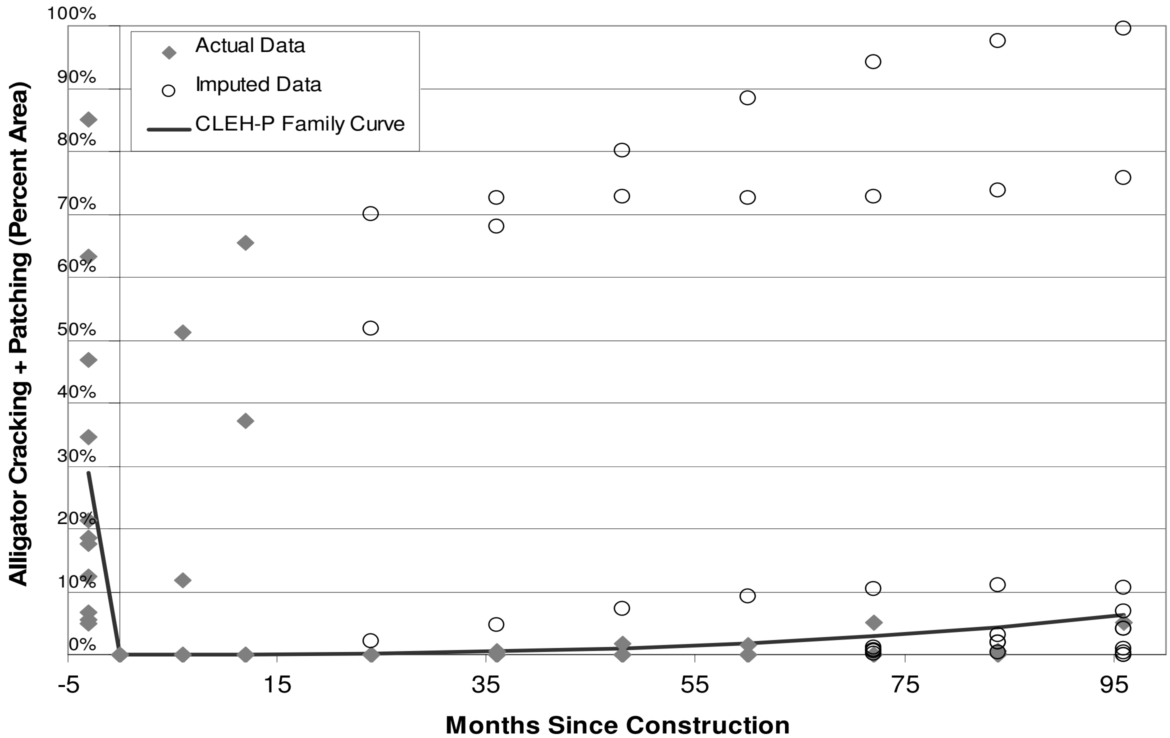

Figure C - 7. Alligator Cracking Plus Patching for ECLH Family, Poor Initial Condition (R^2 = 0.286).

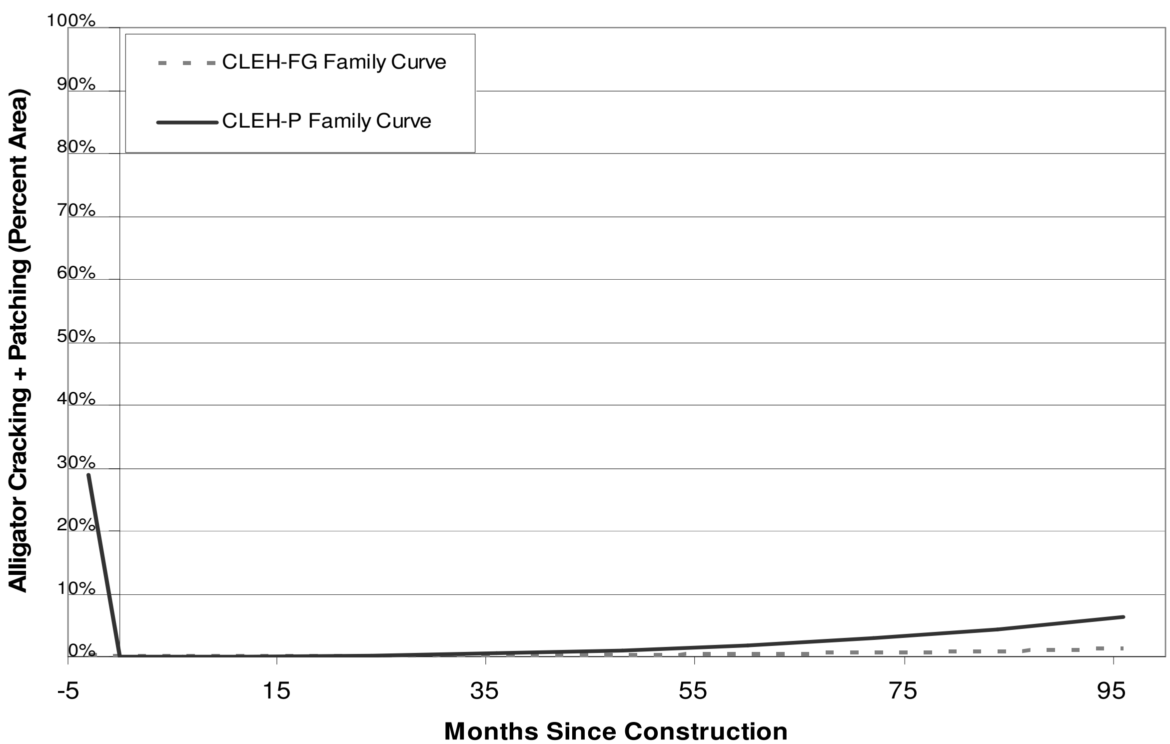

Figure C - 8. Alligator Cracking Plus Patching for ECLH Family, All Initial Conditions.

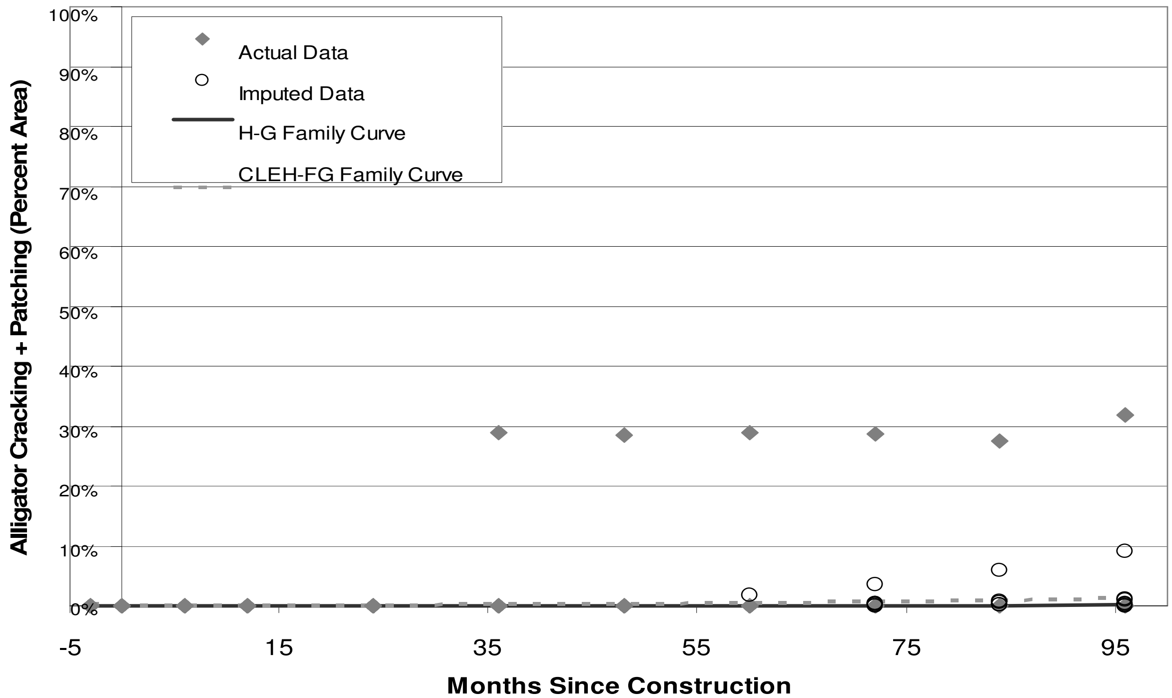

Figure C - 9. Alligator Cracking Plus Patching for Asphalt Rubber Seal Coat, Good Initial Condition (R^2 = 0.184).

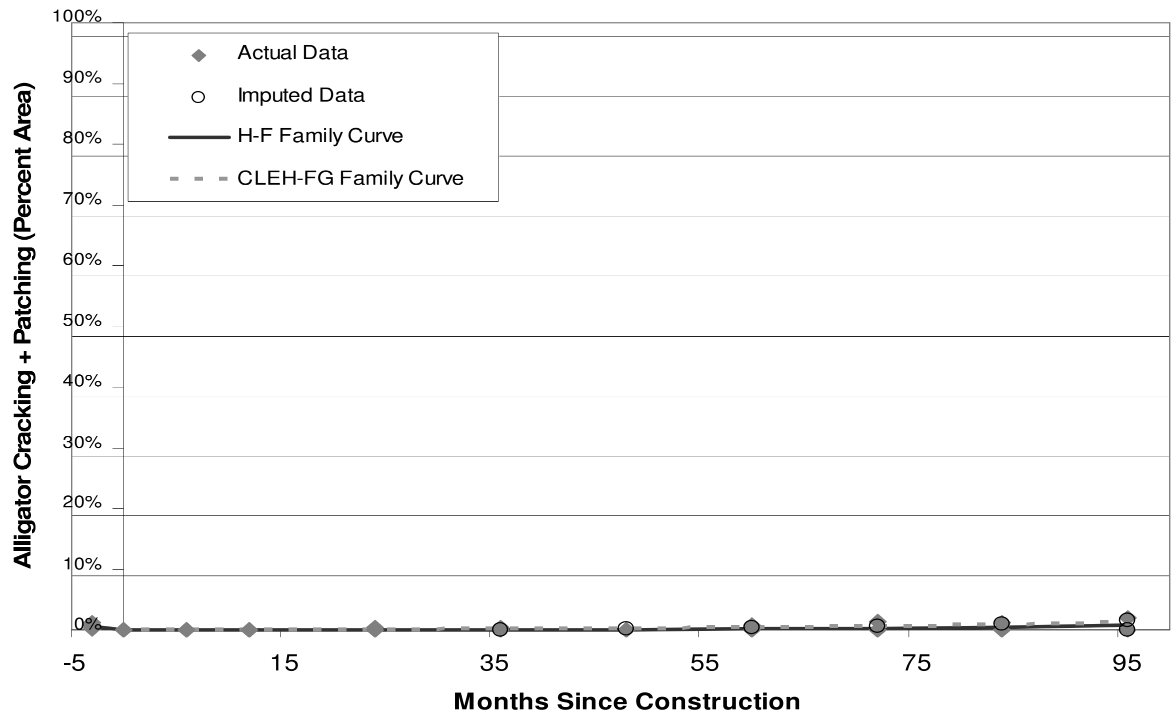

Figure C - 10. Alligator Cracking Plus Patching for Asphalt Rubber Seal Coat, Fair Initial Condition (R^2 = 0.458).

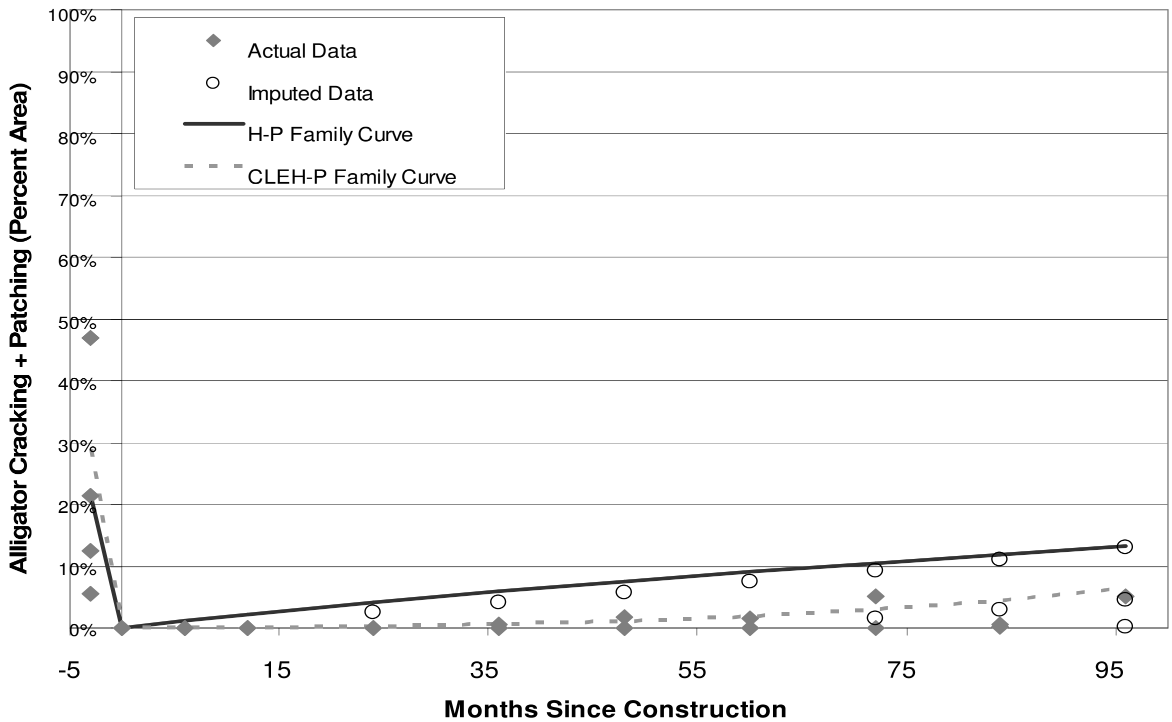

Figure C - 11. Alligator Cracking Plus Patching for Asphalt Rubber Seal Coat, Poor Initial Condition (R^2 = 0.607).

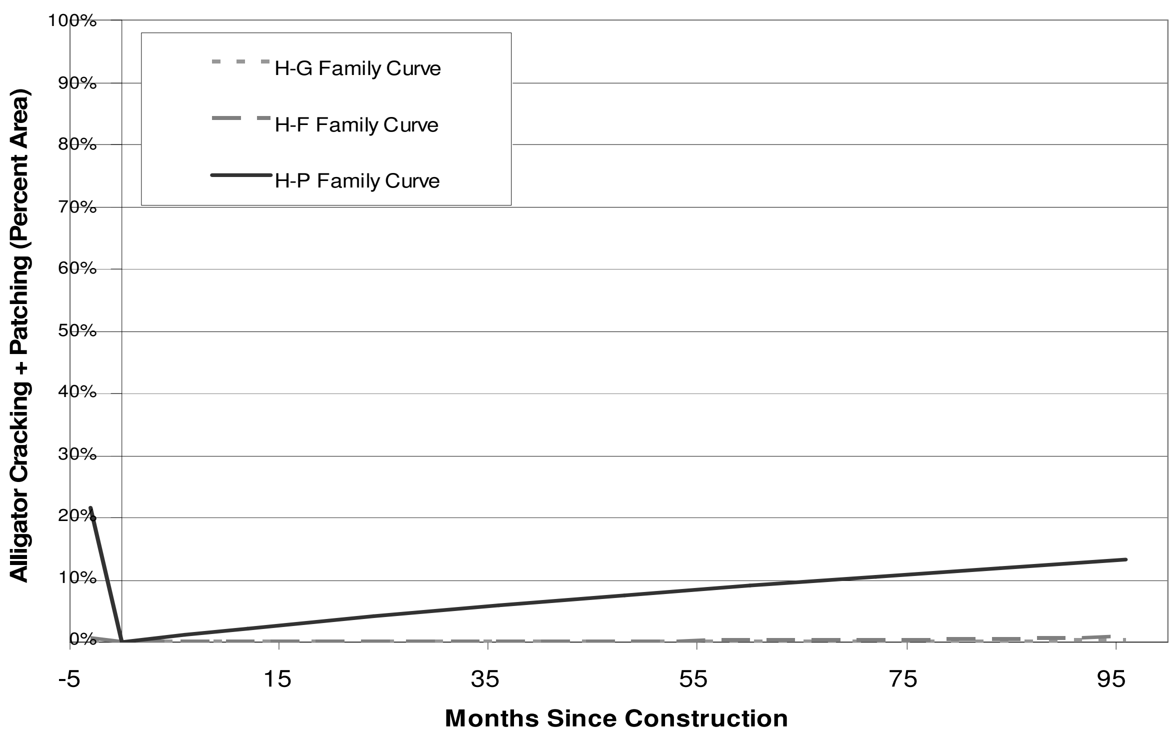

Figure C - 12. Alligator Cracking Plus Patching for Asphalt Rubber Seal Coat, All Initial Conditions.

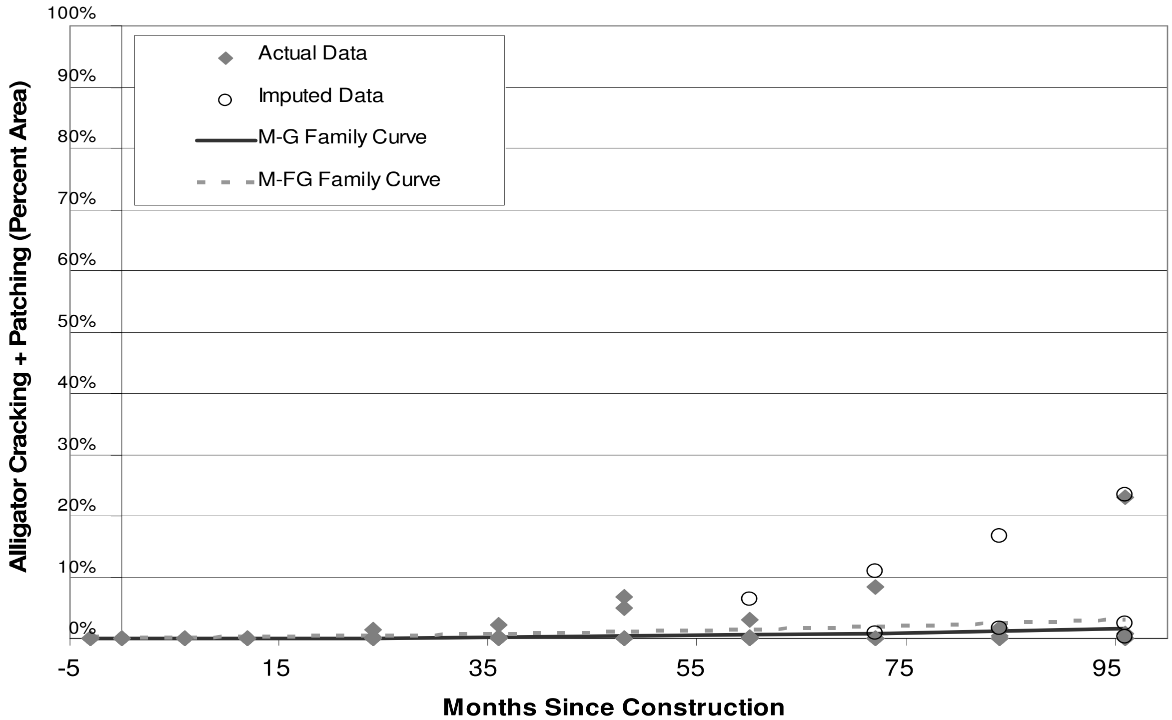

Figure C - 13. Alligator Cracking Plus Patching for Microsurfacing, Good Initial Condition ($R^2 = 0.252$).

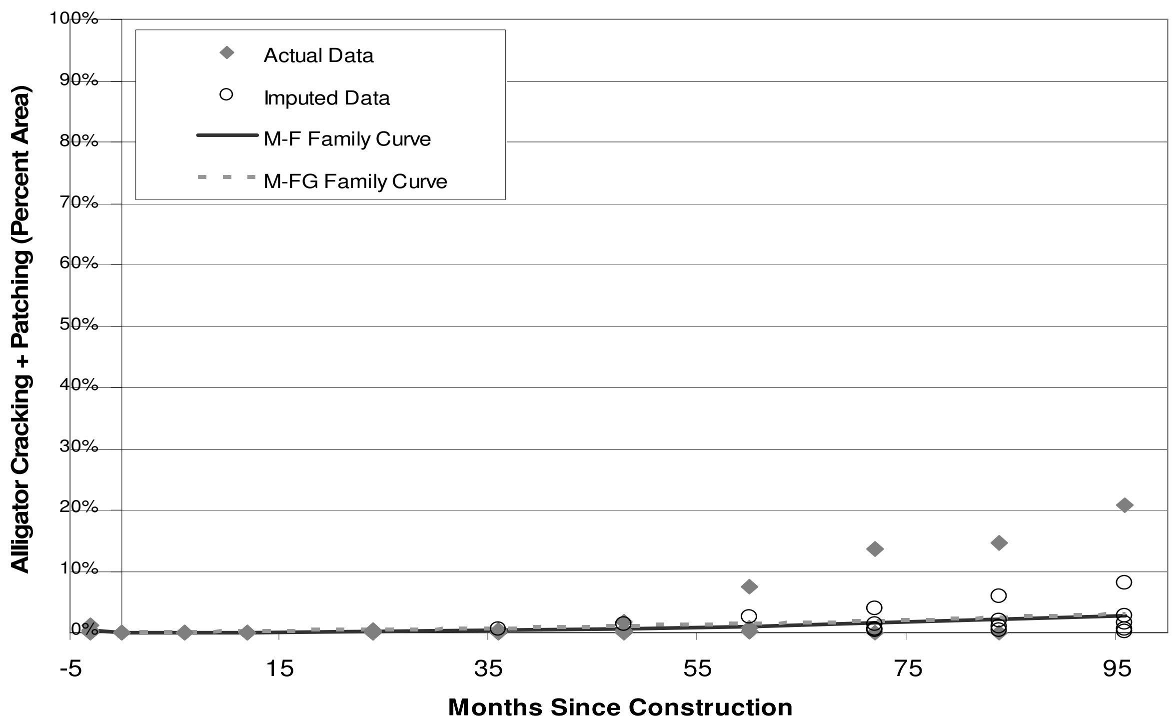

Figure C - 14. Alligator Cracking Plus Patching for Microsurfacing, Fair Initial Condition ($R^2 = 0.603$).

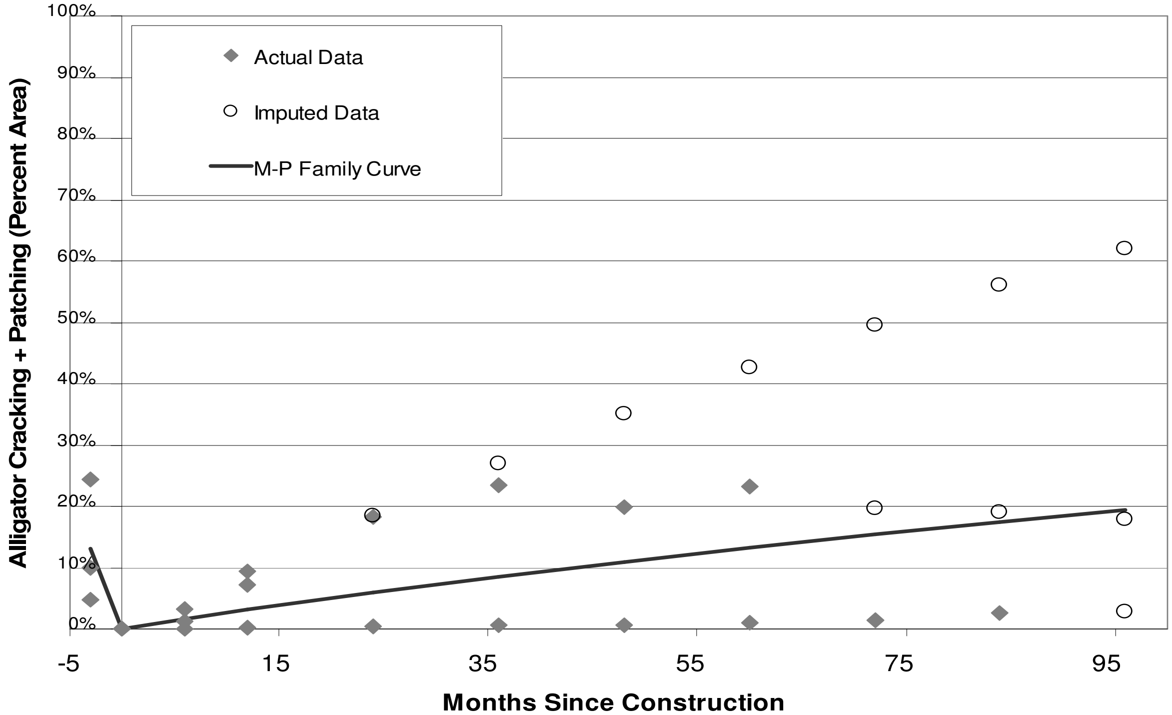

Figure C - 15. Alligator Cracking Plus Patching for Microsurfacing, Poor Initial Condition ($R^2 = 0.733$).

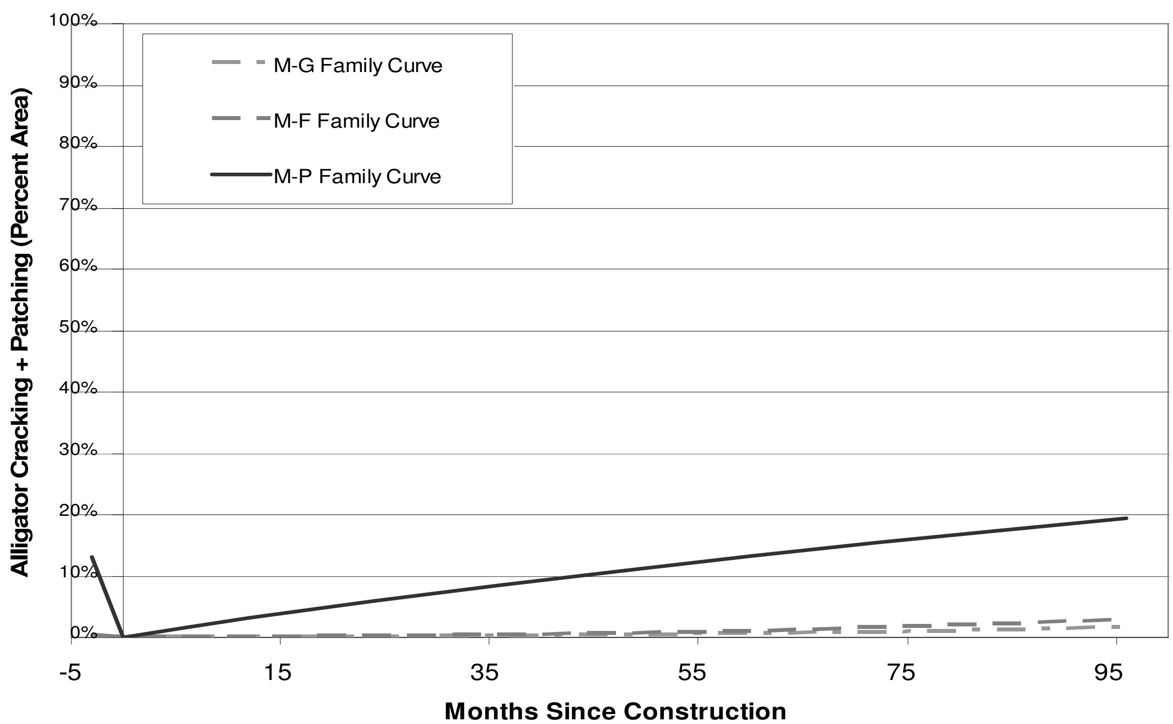

Figure C - 16. Alligator Cracking Plus Patching for Microsurfacing, All Initial Conditions.

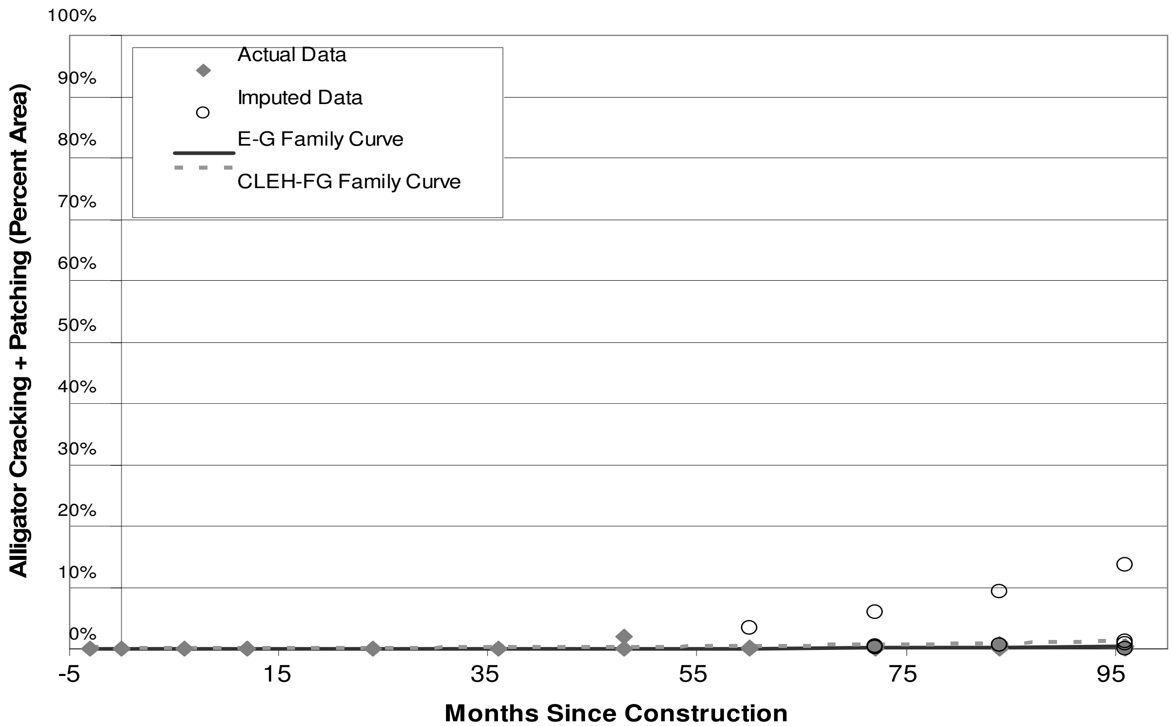

Figure C - 17. Alligator Cracking Plus Patching for Polymer Modified Emulsion Seal Coat, Good Initial Condition ($R^2 = 0.279$).

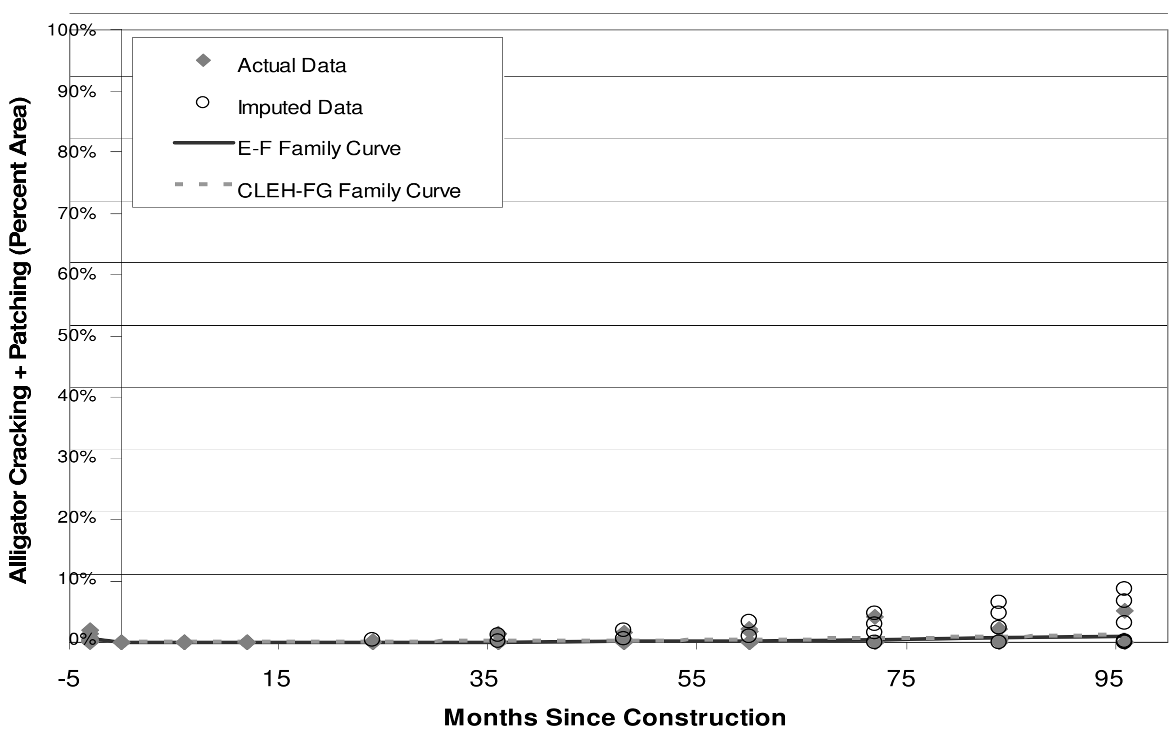

Figure C - 18. Alligator Cracking Plus Patching for Polymer Modified Emulsion Seal Coat, Fair Initial Condition ($R^2 = 0.474$).

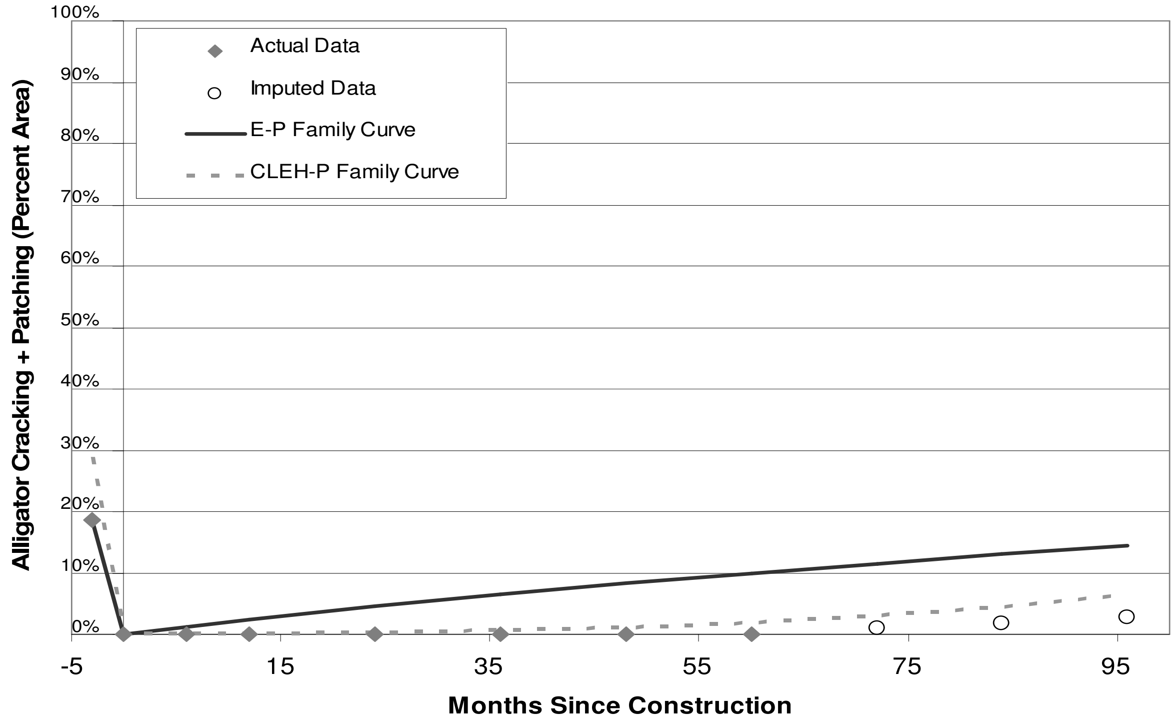

Figure C - 19. Alligator Cracking Plus Patching for Polymer Modified Emulsion Seal Coat, Poor Initial Condition (R^2 = 0.855).

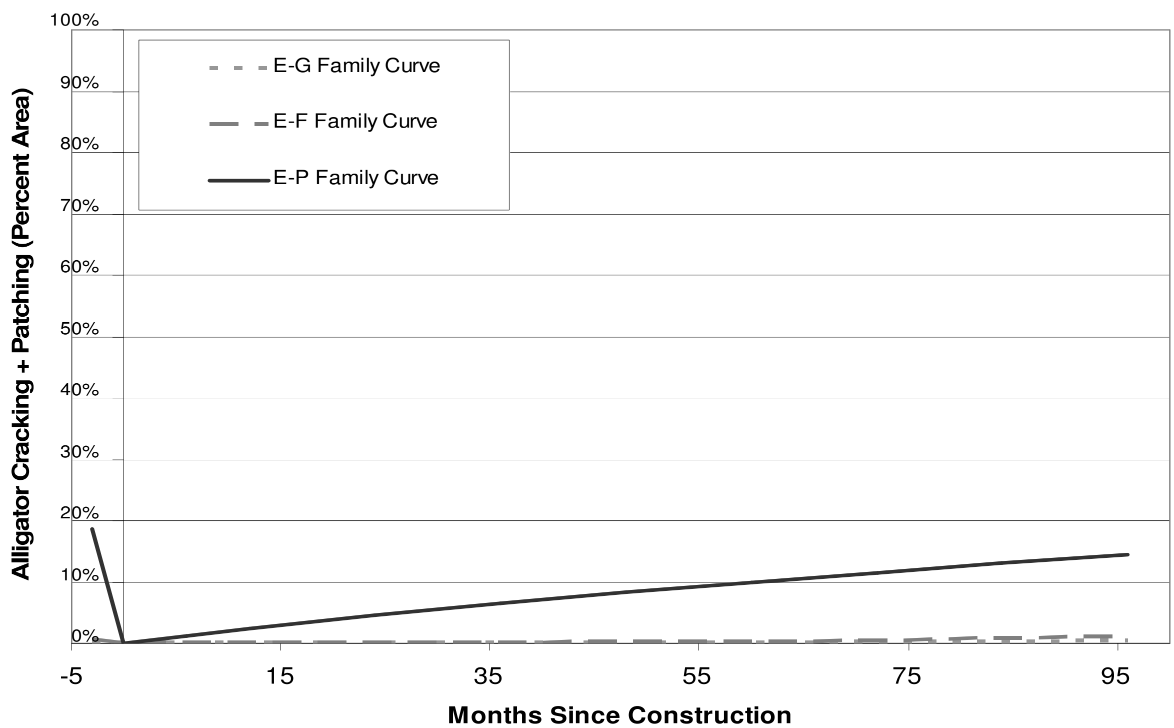

Figure C - 20. Alligator Cracking Plus Patching for Polymer Modified Emulsion Seal Coat, All Initial Conditions.

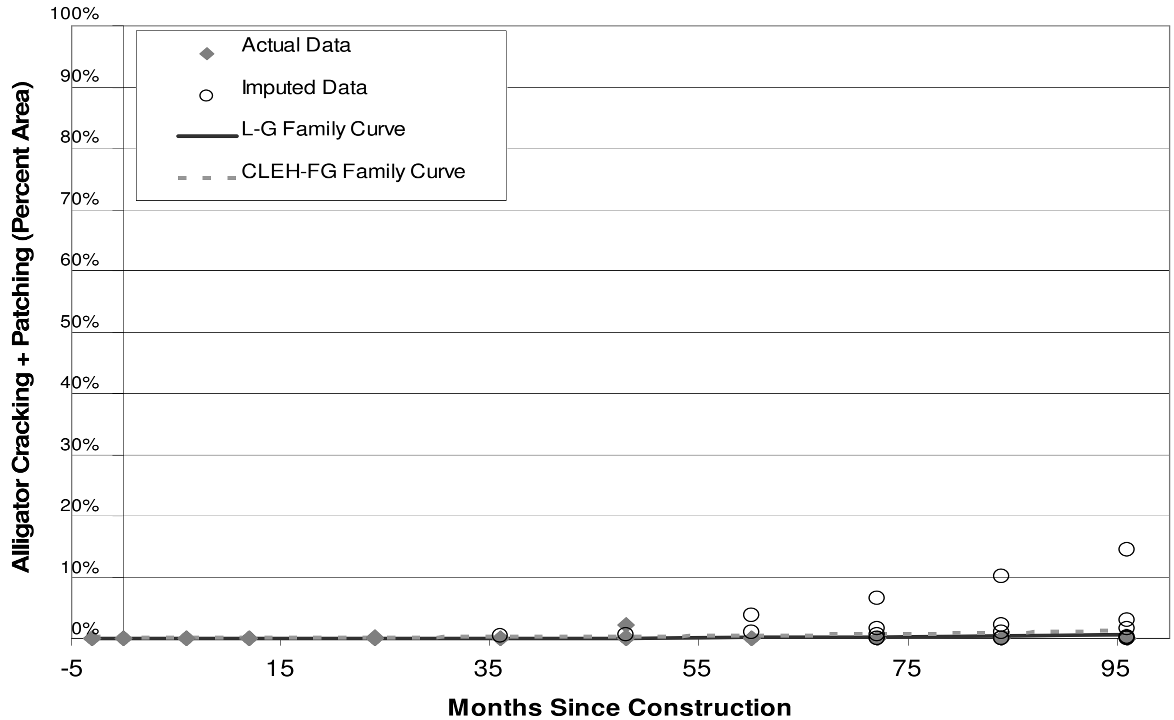

Figure C - 21. Alligator Cracking Plus Patching for Latex Modified Seal Coat, Good Initial Condition ($R^2 = 0.197$).

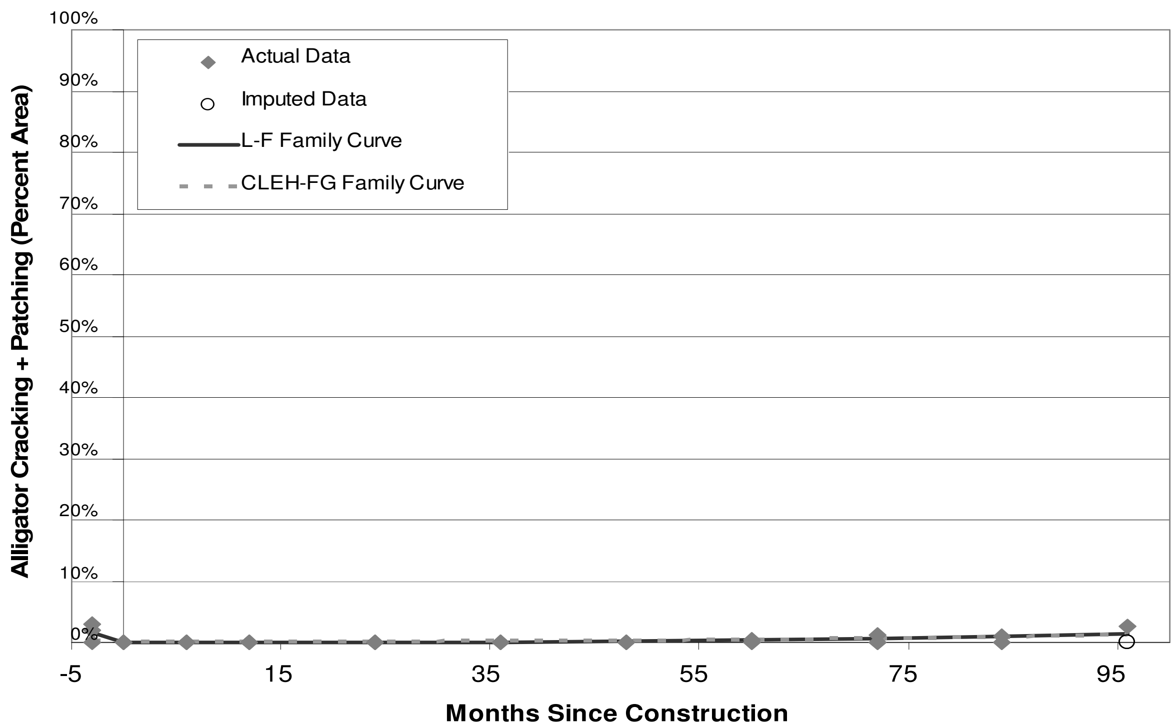

Figure C - 22. Alligator Cracking Plus Patching for Latex Modified Seal Coat, Fair Initial Condition ($R^2 = 0.321$).

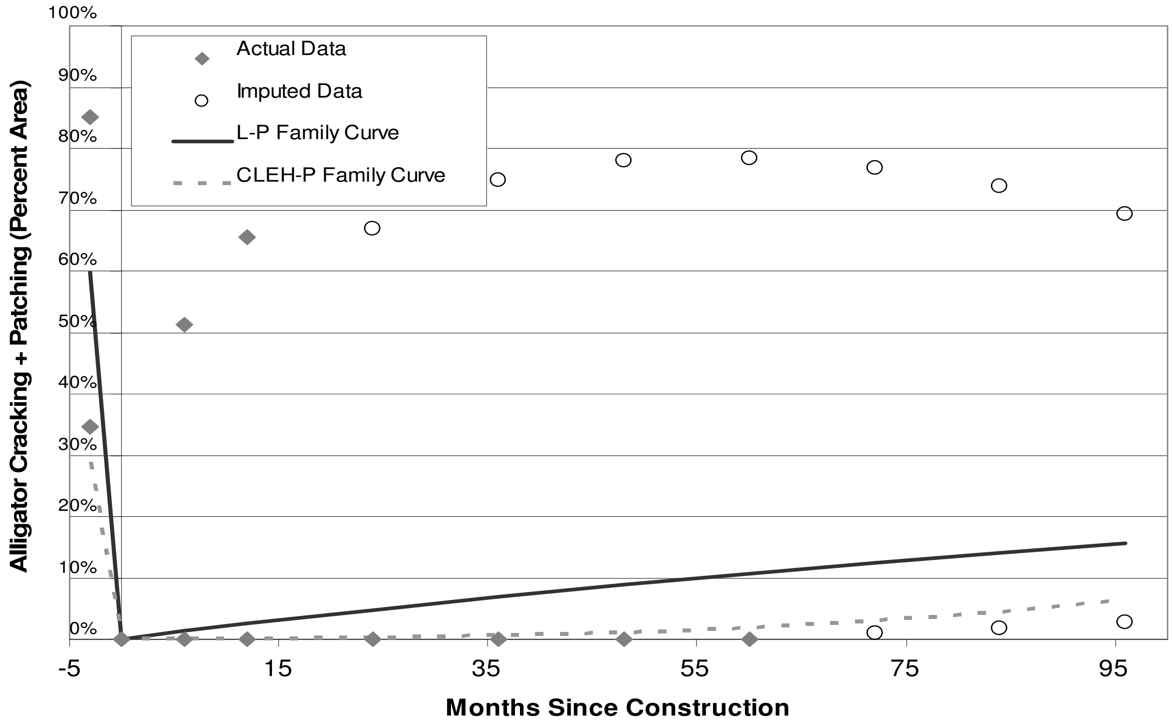

Figure C - 23. Alligator Cracking Plus Patching for Latex Modified Seal Coat, Poor Initial Condition ($R^2 = 0.549$).

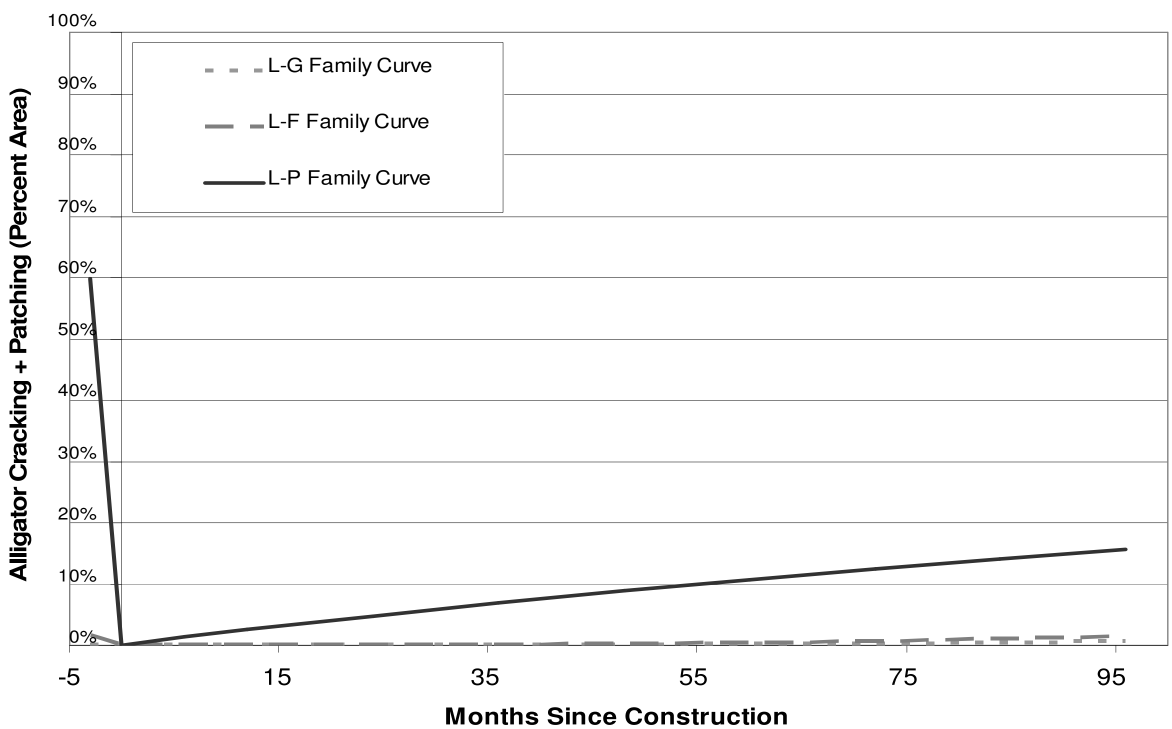

Figure C - 24. Alligator Cracking Plus Patching for Latex Modified Seal Coat, All Initial Conditions.

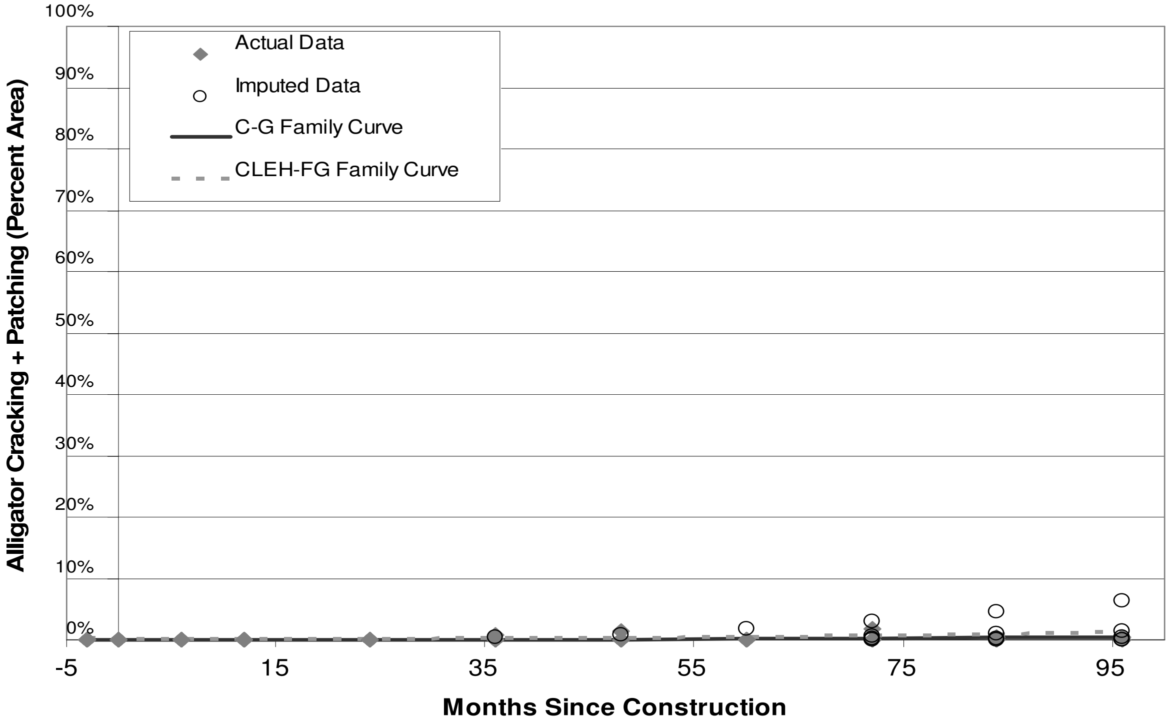

Figure C - 25. Alligator Cracking Plus Patching for Unmodified Asphalt Seal Coat, Good Initial Condition ($R^2 = 0.242$).

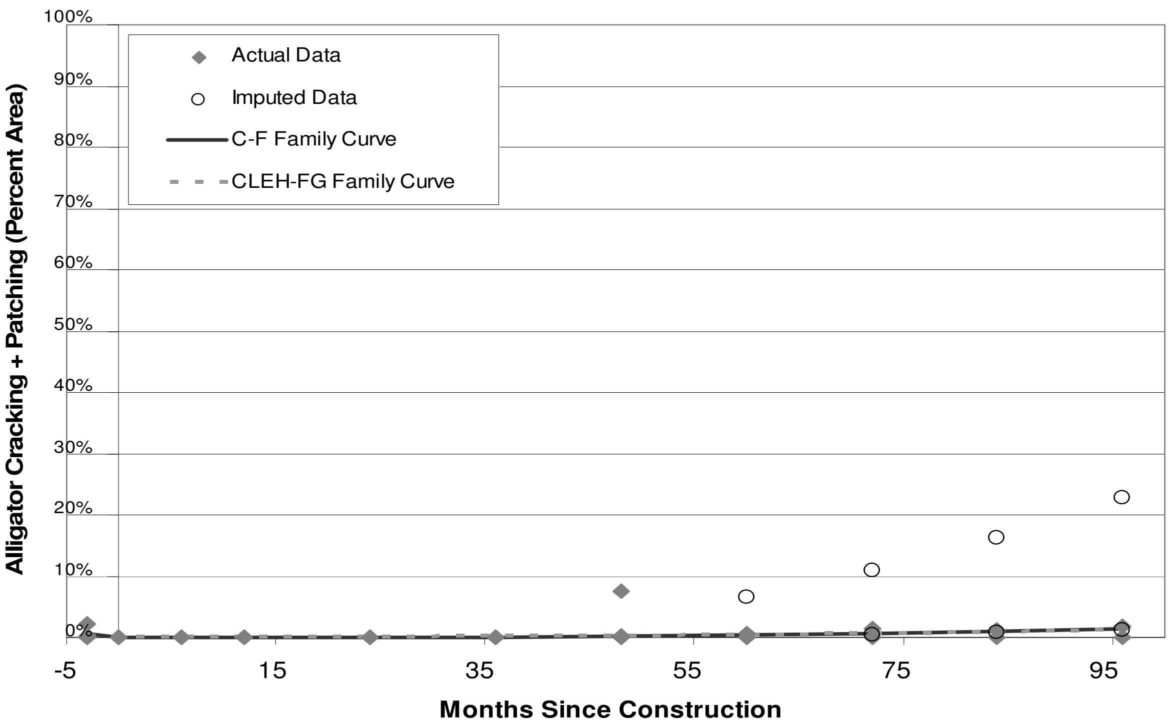

Figure C - 26. Alligator Cracking Plus Patching for Unmodified Asphalt Seal Coat, Fair Initial Condition ($R^2 = 0.470$).

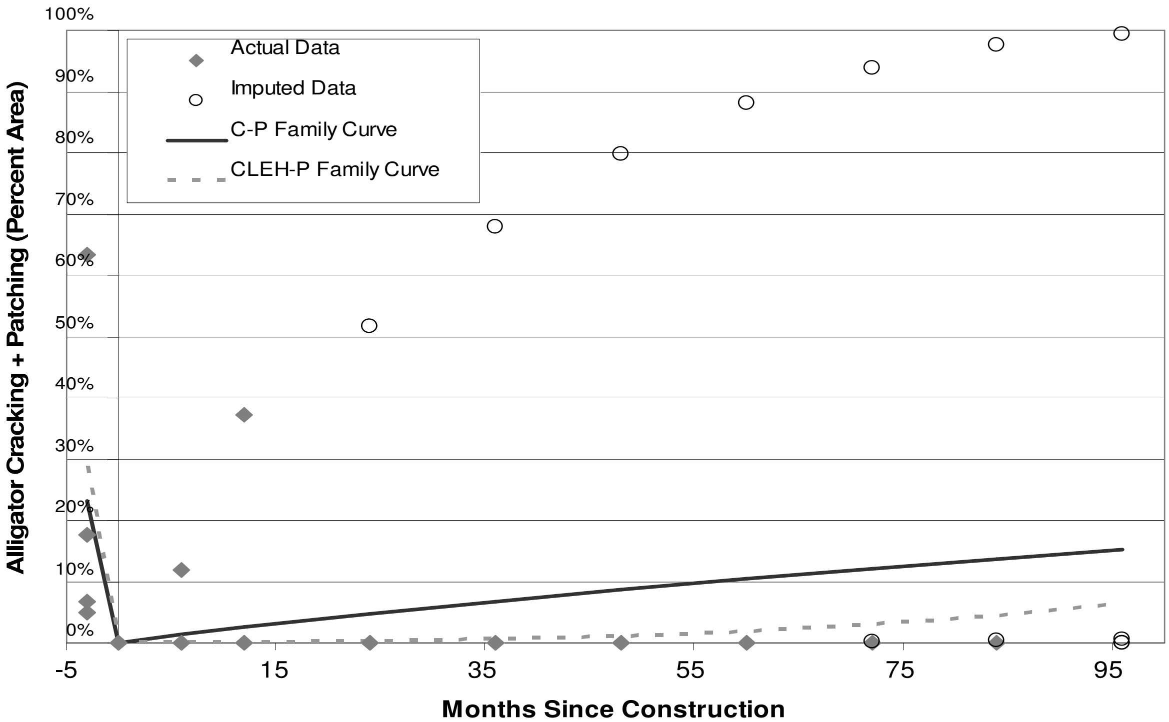

Figure C - 27. Alligator Cracking Plus Patching for Unmodified Asphalt Seal Coat, Poor Initial Condition ($R^2 = 0.265$).

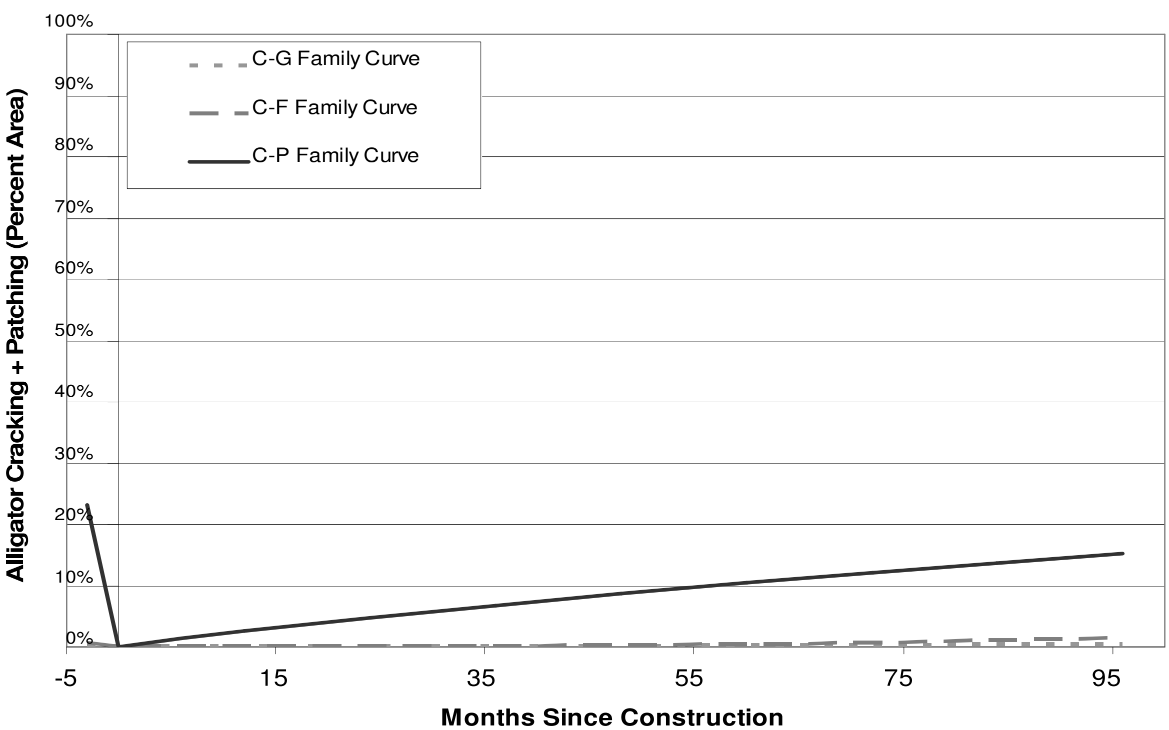

Figure C - 28. Alligator Cracking Plus Patching for Unmodified Asphalt Seal Coat, All Initial Conditions.

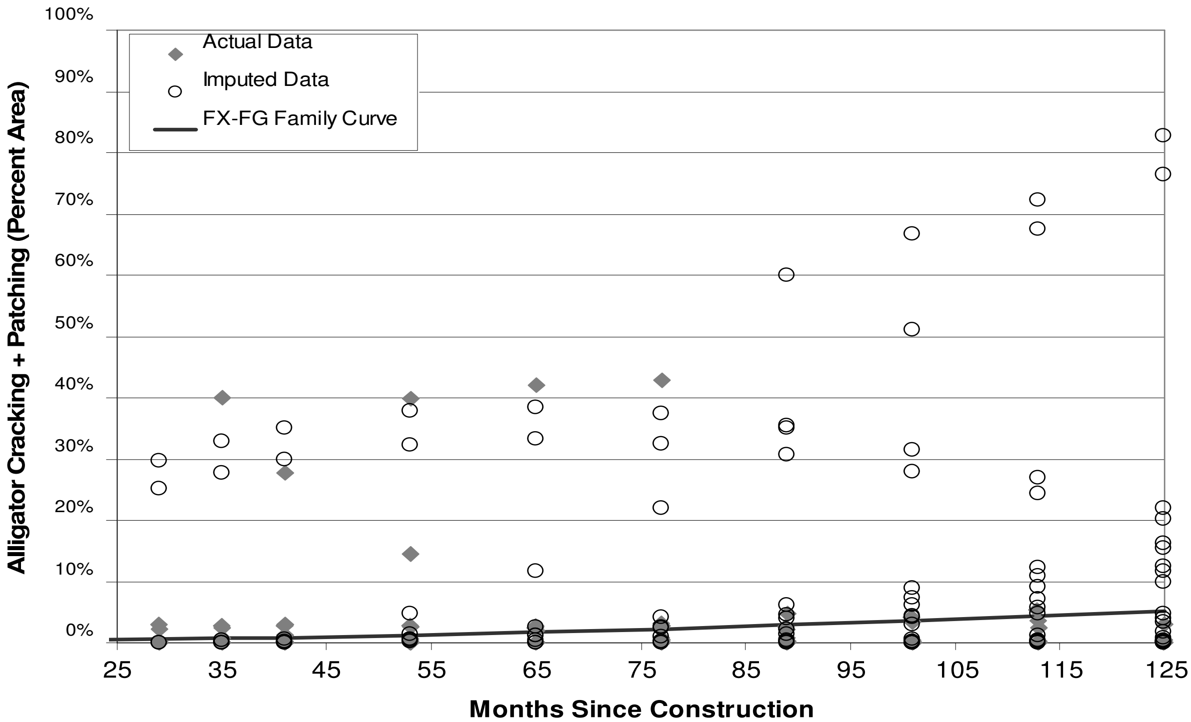

Figure C - 29. Alligator Cracking Plus Patching for Fog and Control Sections, Good and Fair Initial Conditions ($R^2 = 0.243$).

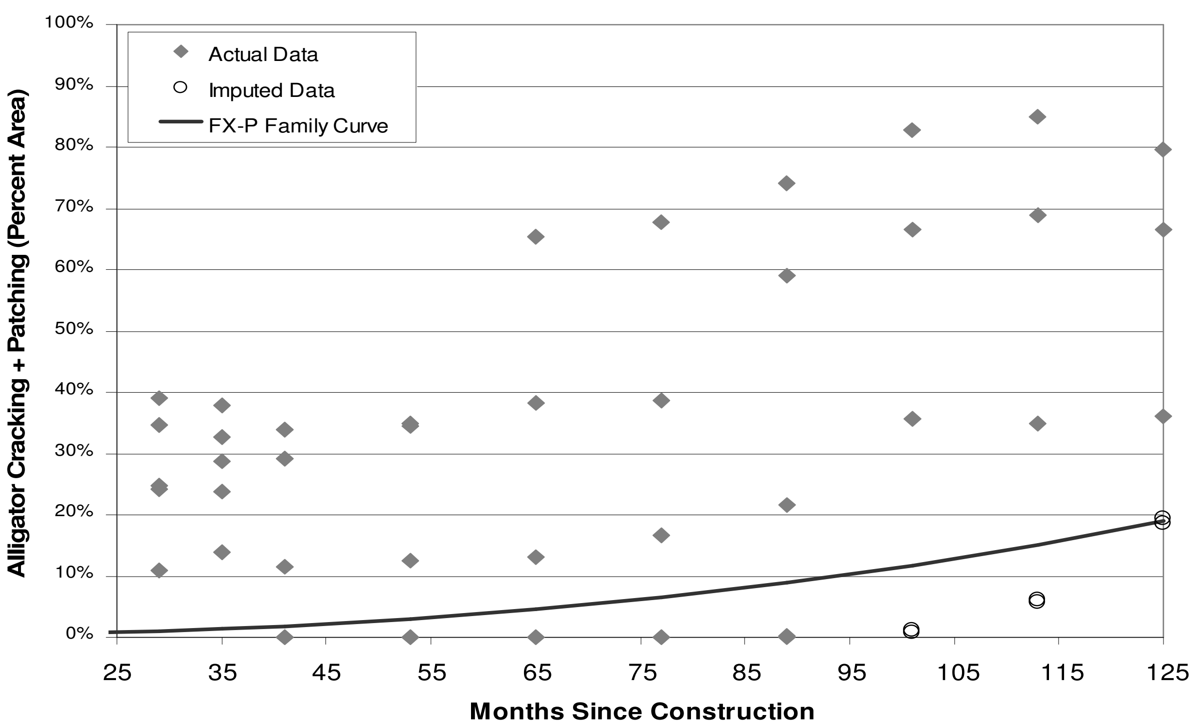

Figure C - 30. Alligator Cracking Plus Patching for Fog and Control Sections, Poor Initial Condition ($R^2 = 0.691$).

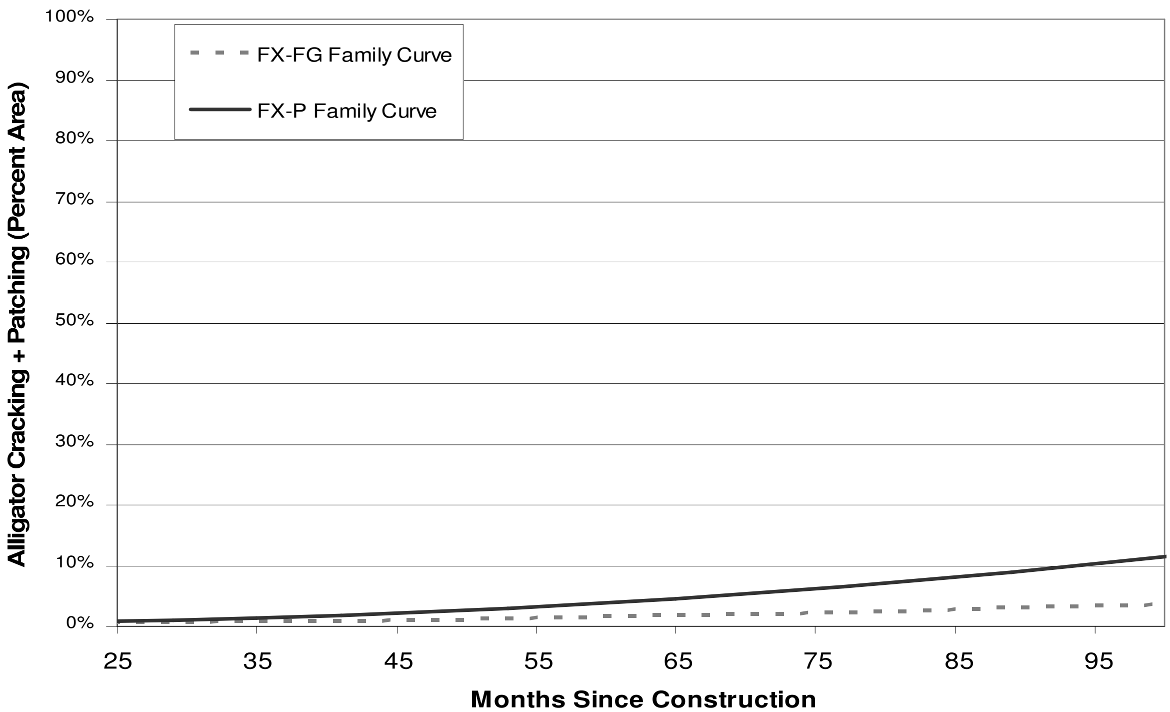

Figure C - 31. Alligator Cracking Plus Patching for Fog and Control Sections, All Initial Conditions (R^2 = 0.372).

APPENDIX D

PAVEMENT CONDITION INDEX PERFORMANCE CURVES

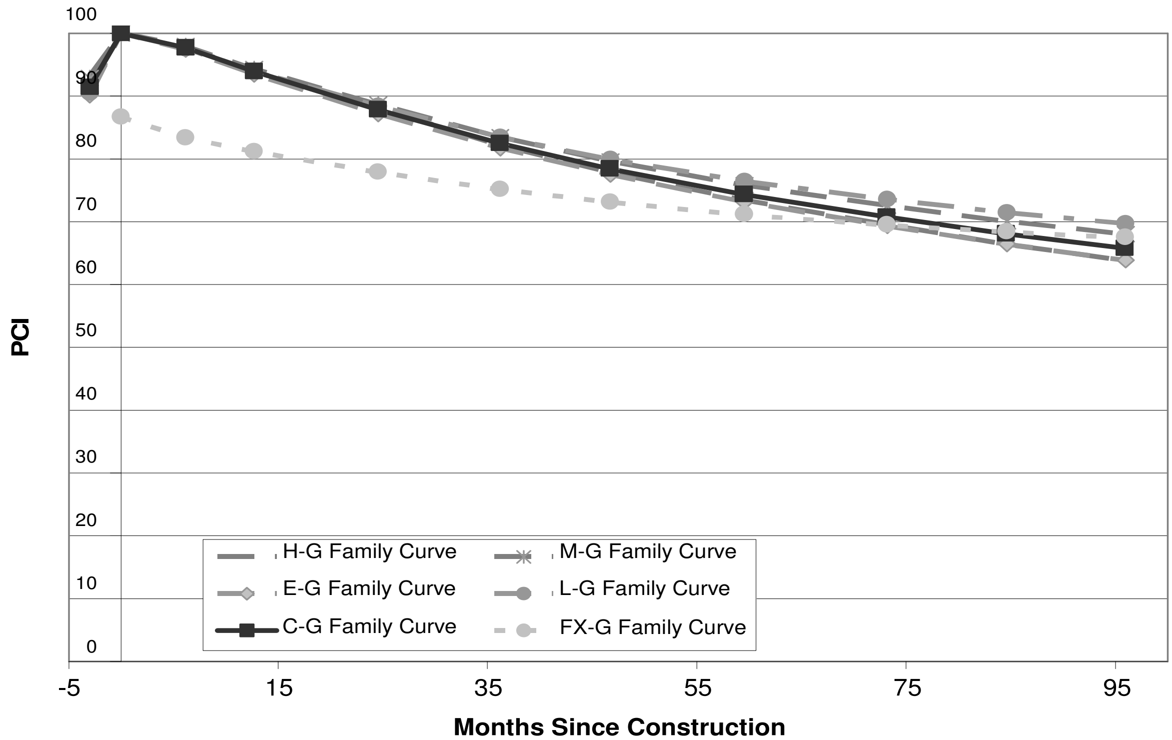

Figure D - 1. PCI for All Treatments, Good Initial Condition.

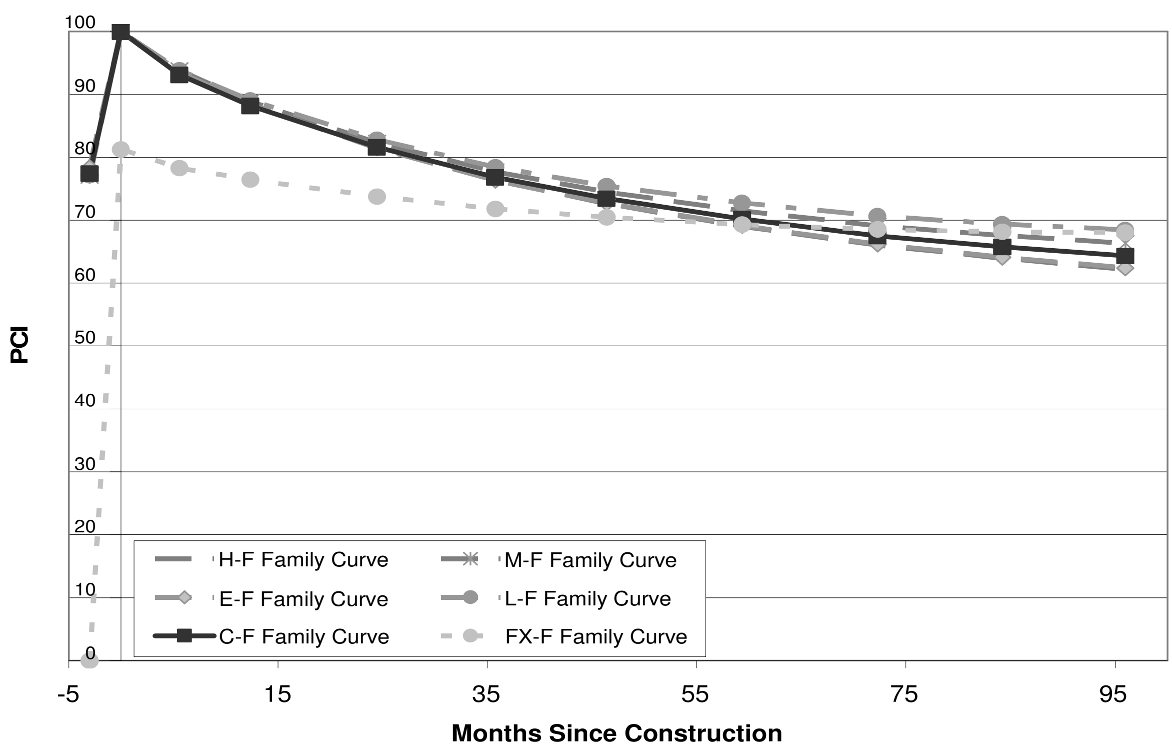

Figure D - 2. PCI for All Treatments, Fair Initial Condition.

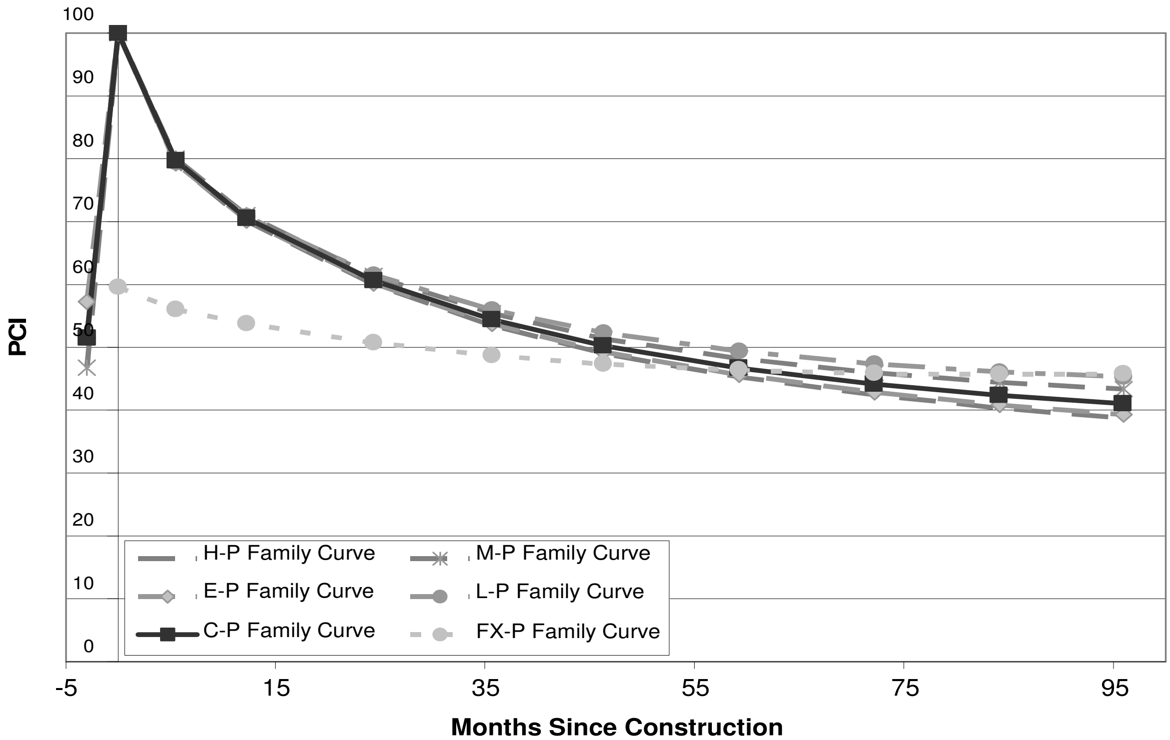

Figure D - 3. PCI for All Treatments, Poor Initial Condition.

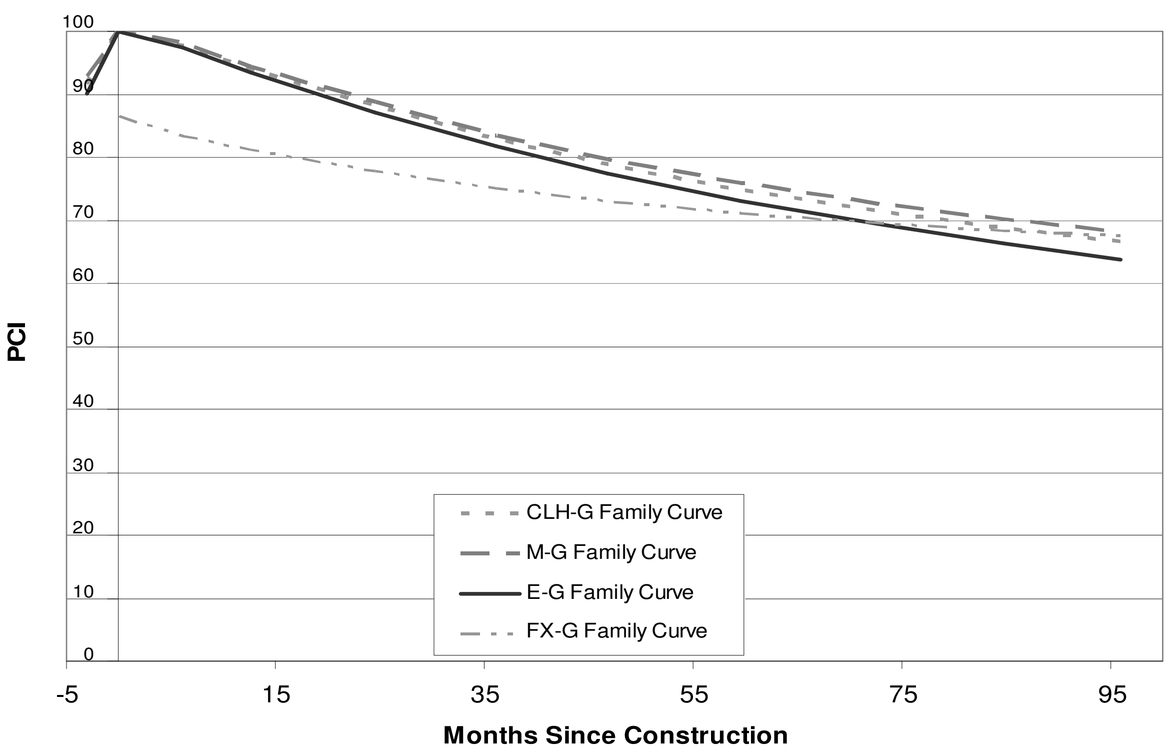

Figure D - 4. PCI for All Families, Good Initial Condition.

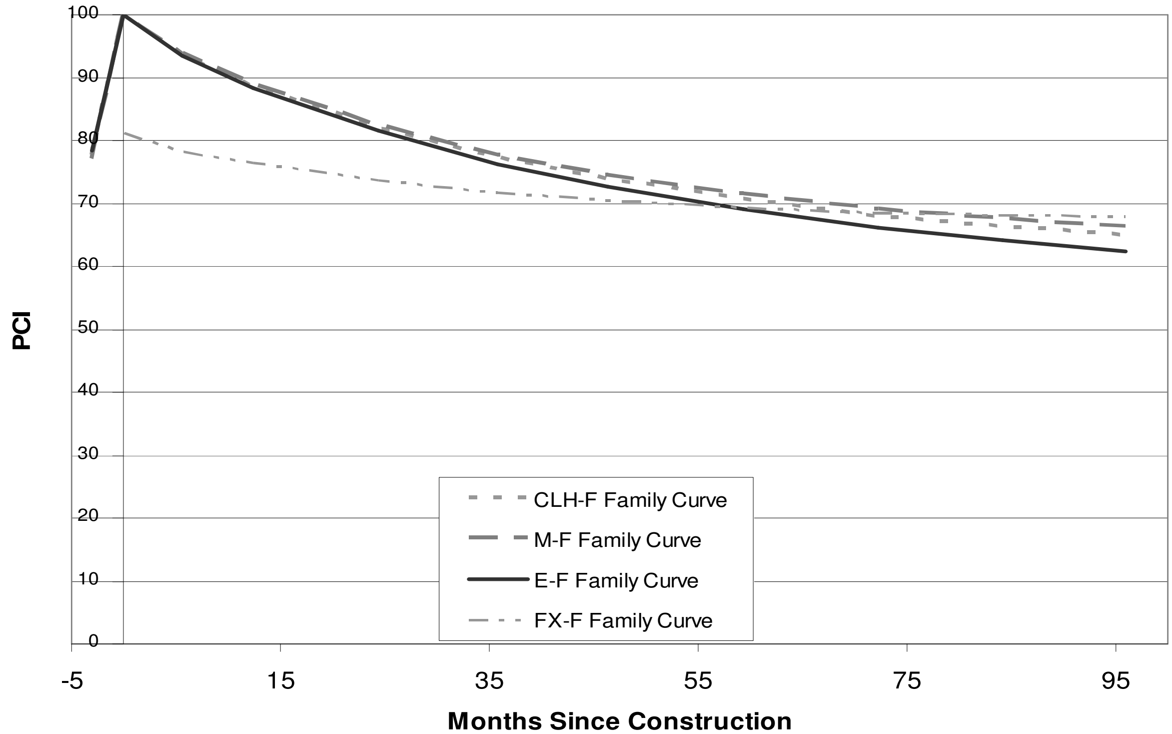

Figure D - 5. PCI for All Families, Fair Initial Condition.

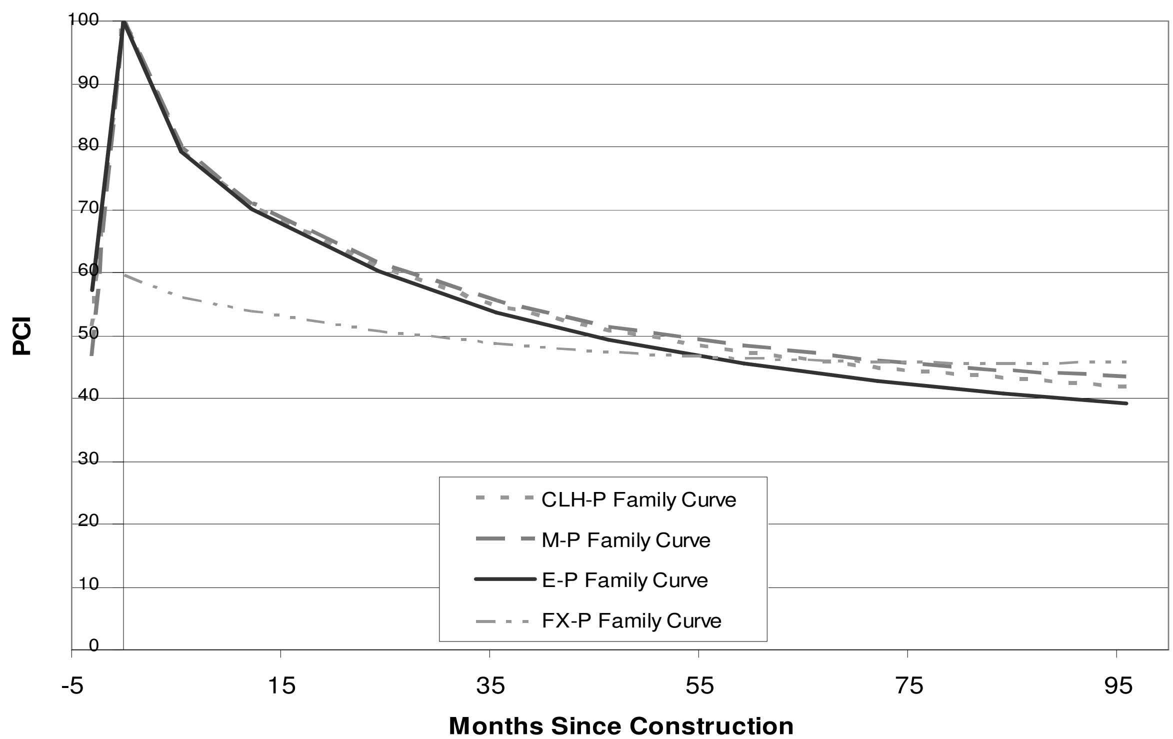

Figure D - 6. PCI for All Families, Poor Initial Condition.

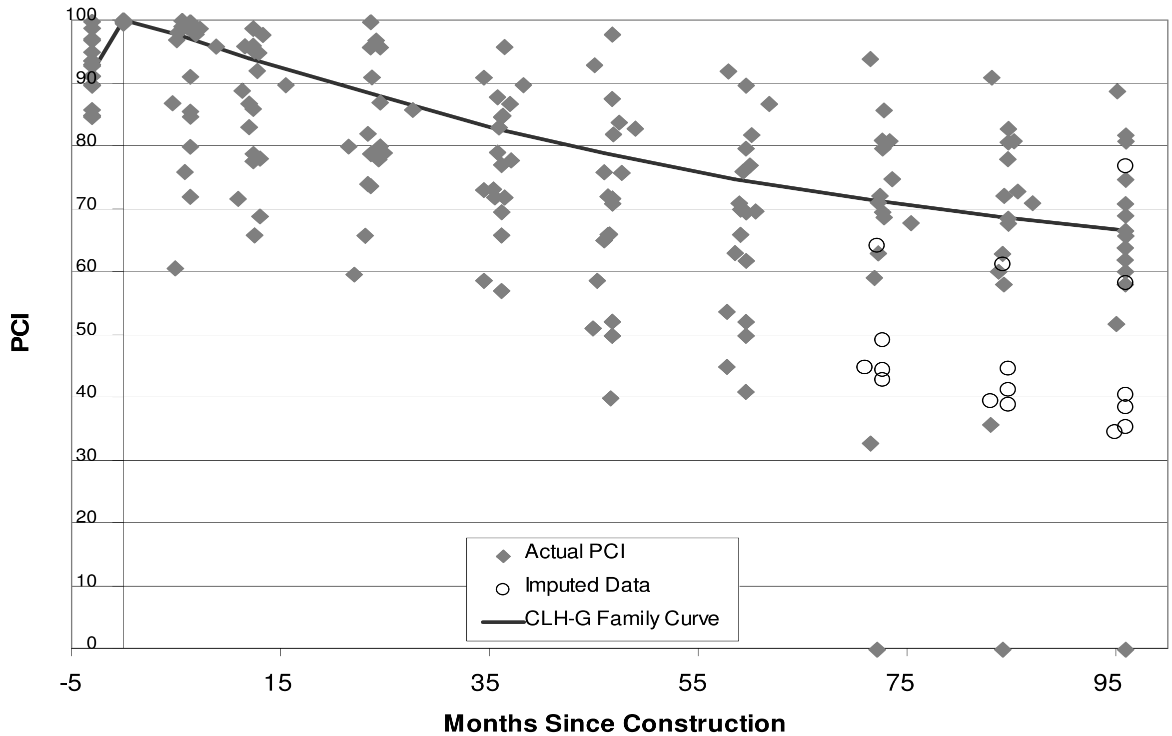

Figure D - 7. PCI for CLH Family, Good Initial Condition (R^2 = 0.902).

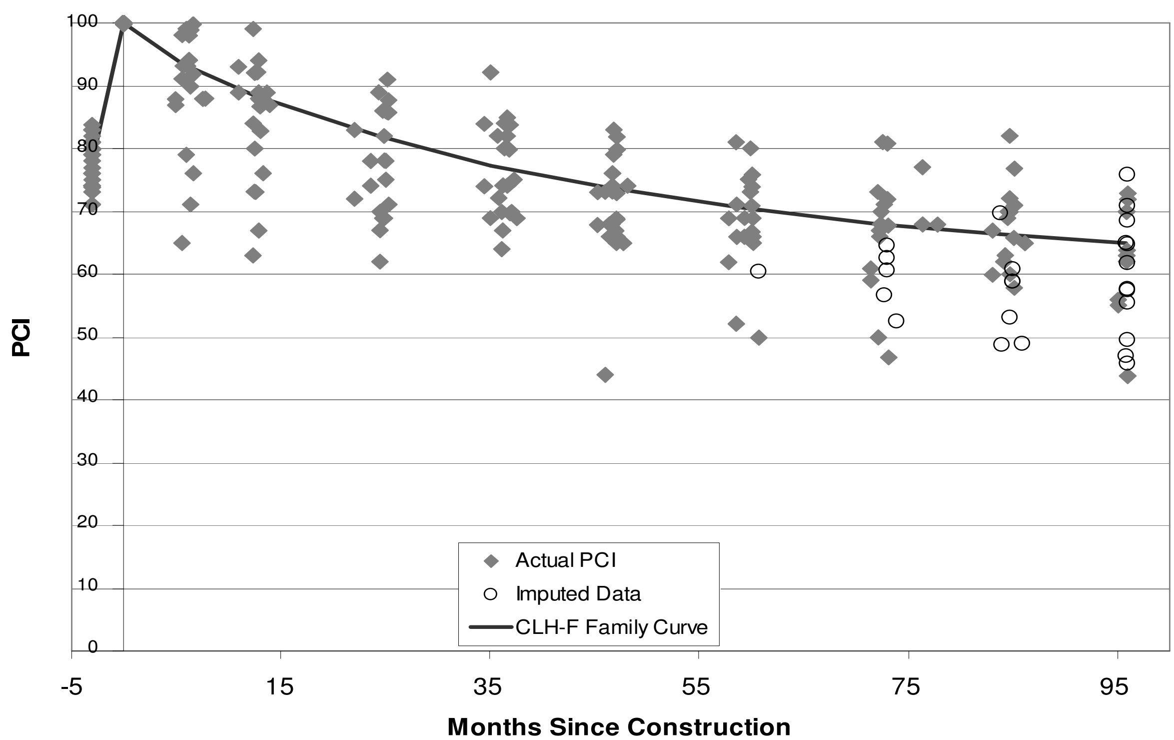

Figure D - 8. PCI for CLH Family, Fair Initial Condition (R^2 = 0.964).

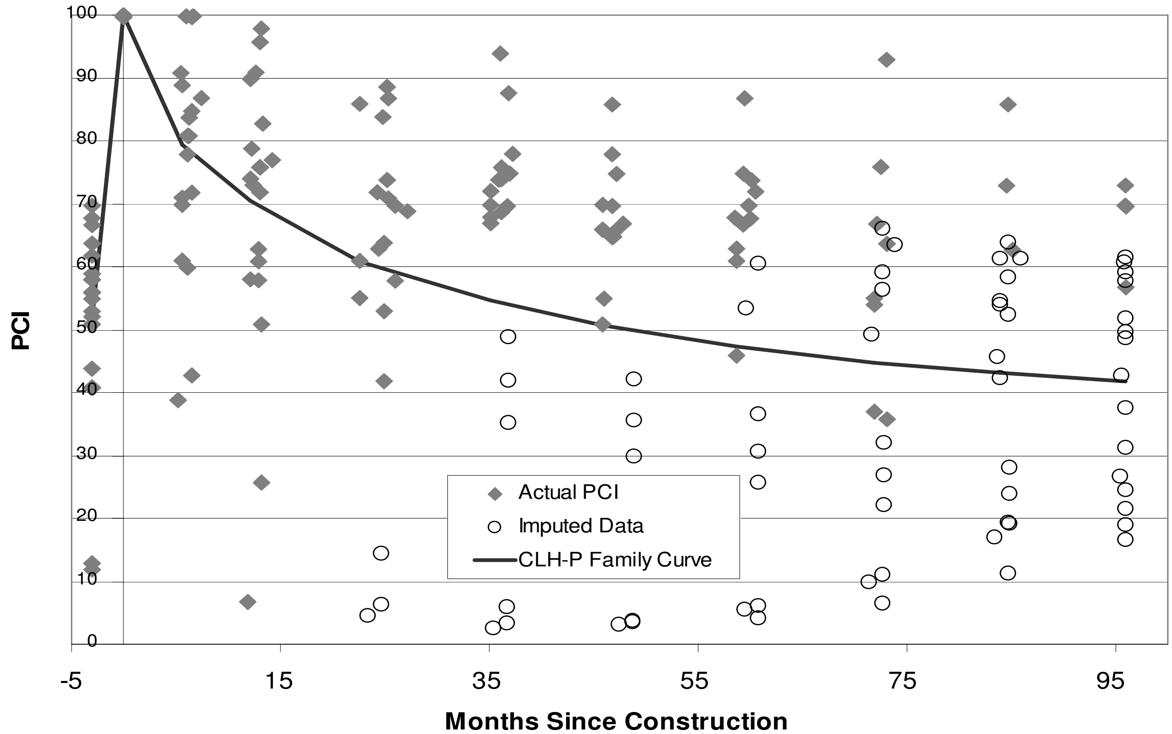

Figure D - 9. PCI for CLH Family, Poor Initial Condition ($R^2 = 0.875$).

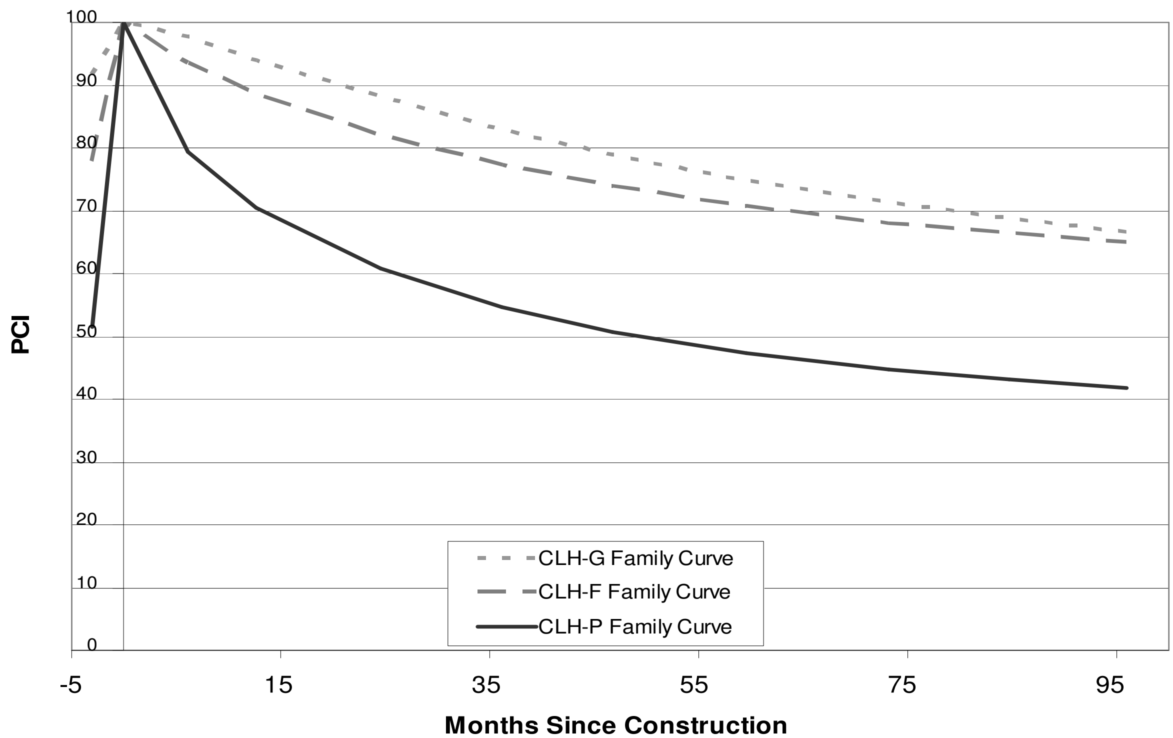

Figure D - 10. PCI for CLH Family, All Initial Conditions.

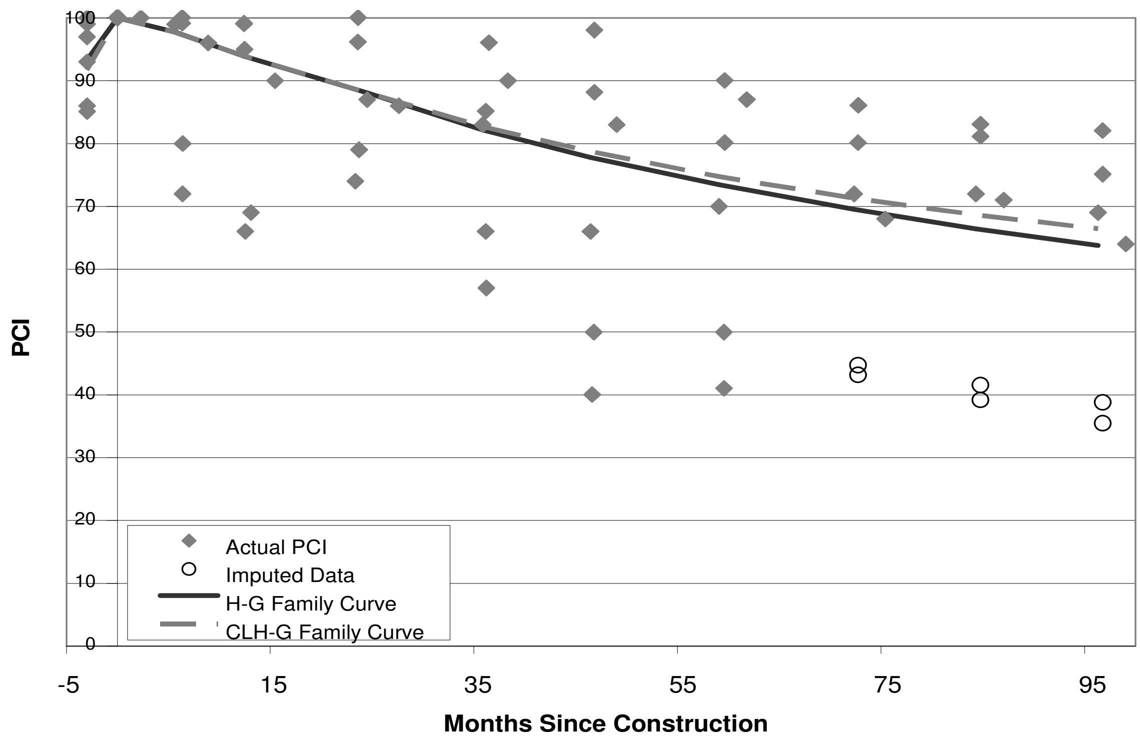

Figure D - 11. PCI for Asphalt Rubber Seal Coat, Good Initial Condition (R^2 = 0.862).

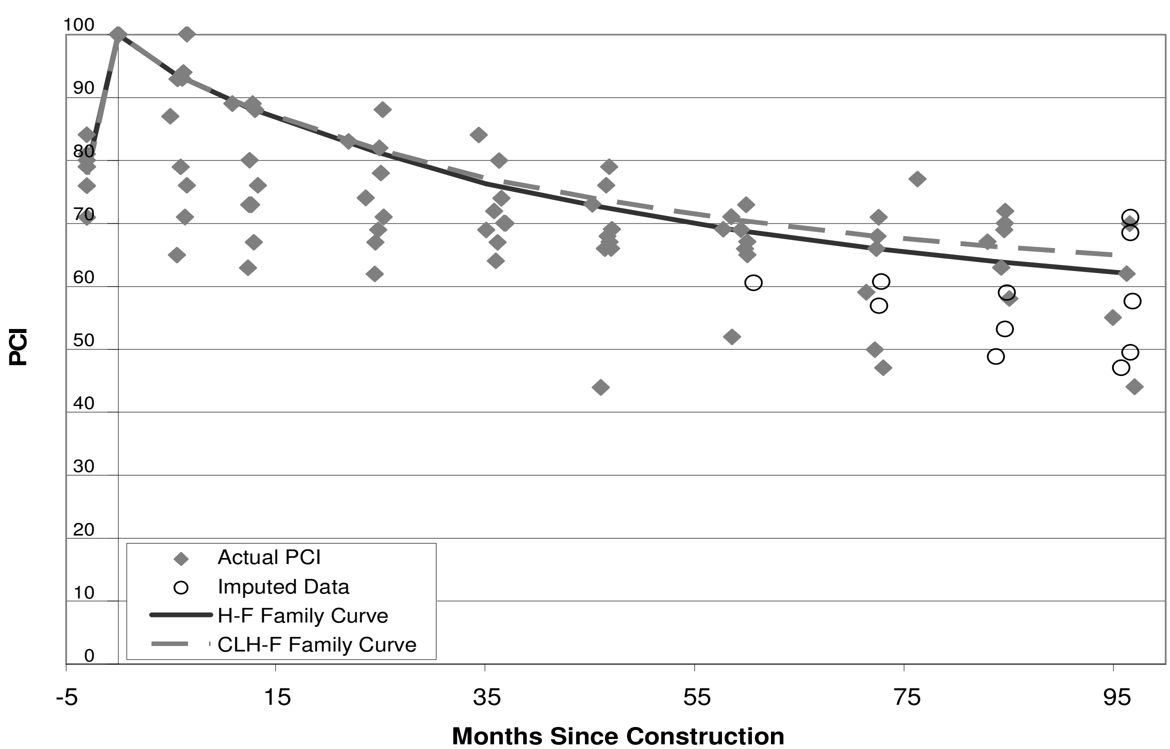

Figure D - 12. PCI for Asphalt Rubber Seal Coat, Fair Initial Condition (R^2 = 0.968).

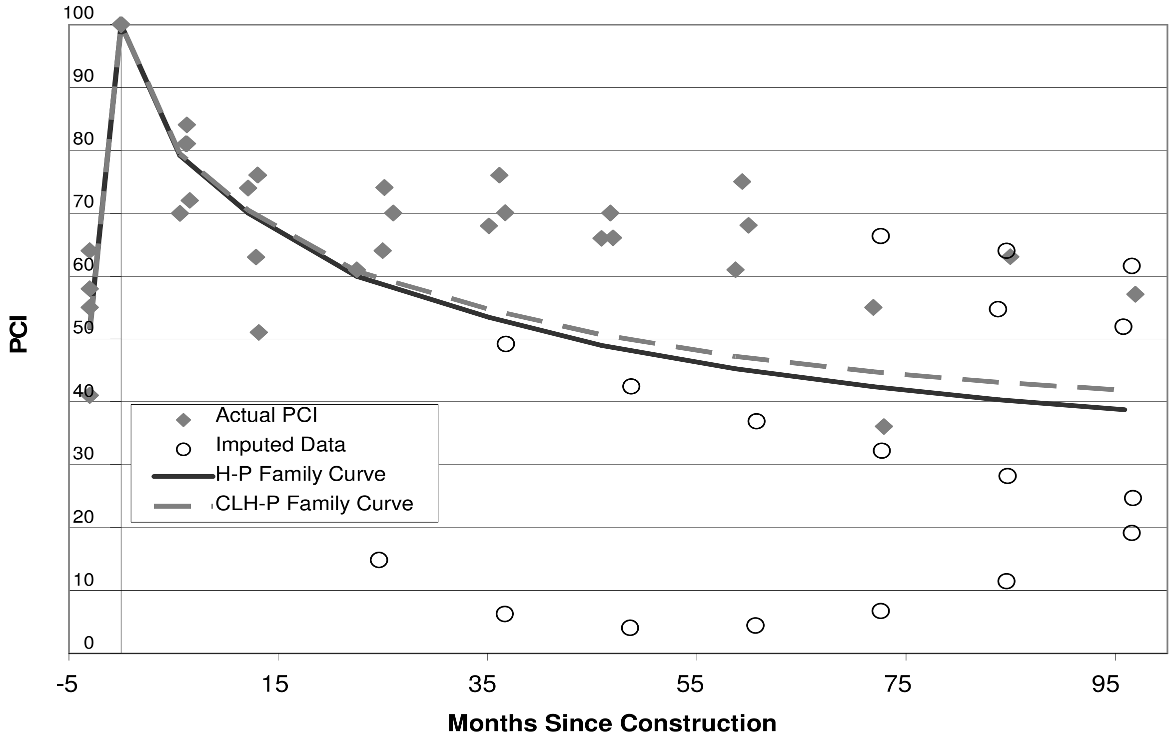

Figure D - 13. PCI for Asphalt Rubber Seal Coat, Poor Initial Condition ($R^2 = 0.911$).

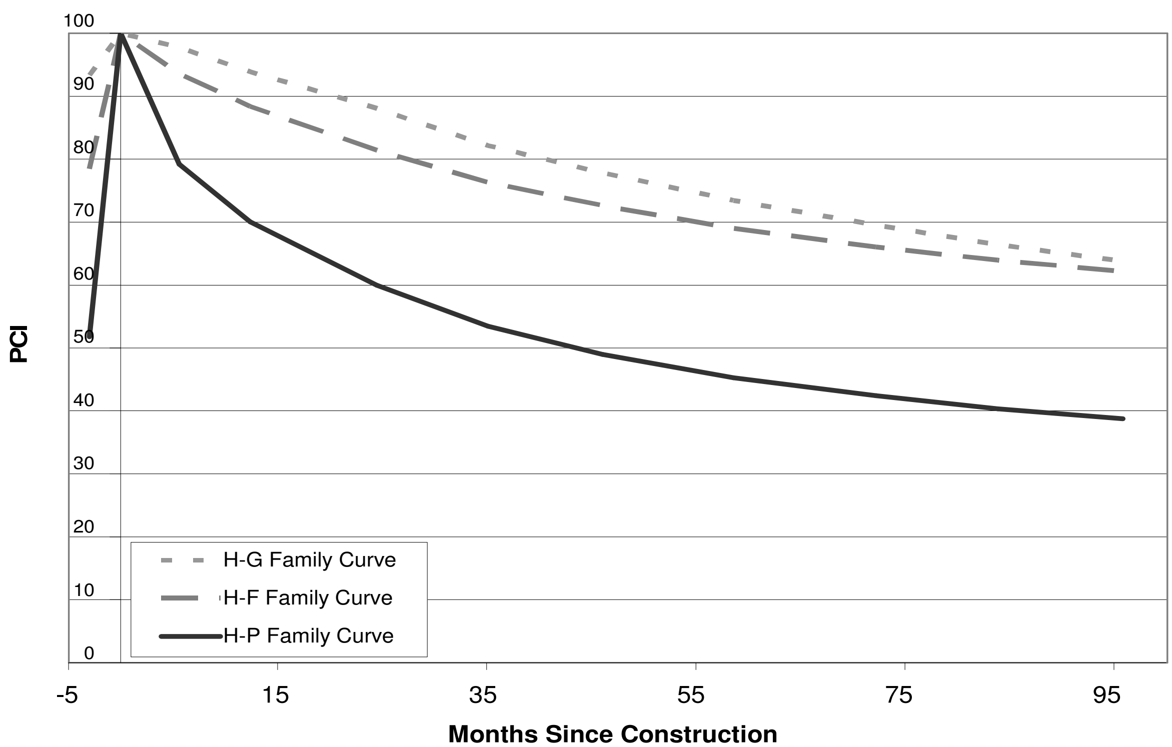

Figure D - 14. PCI for Asphalt Rubber Seal Coat, All Initial Conditions.

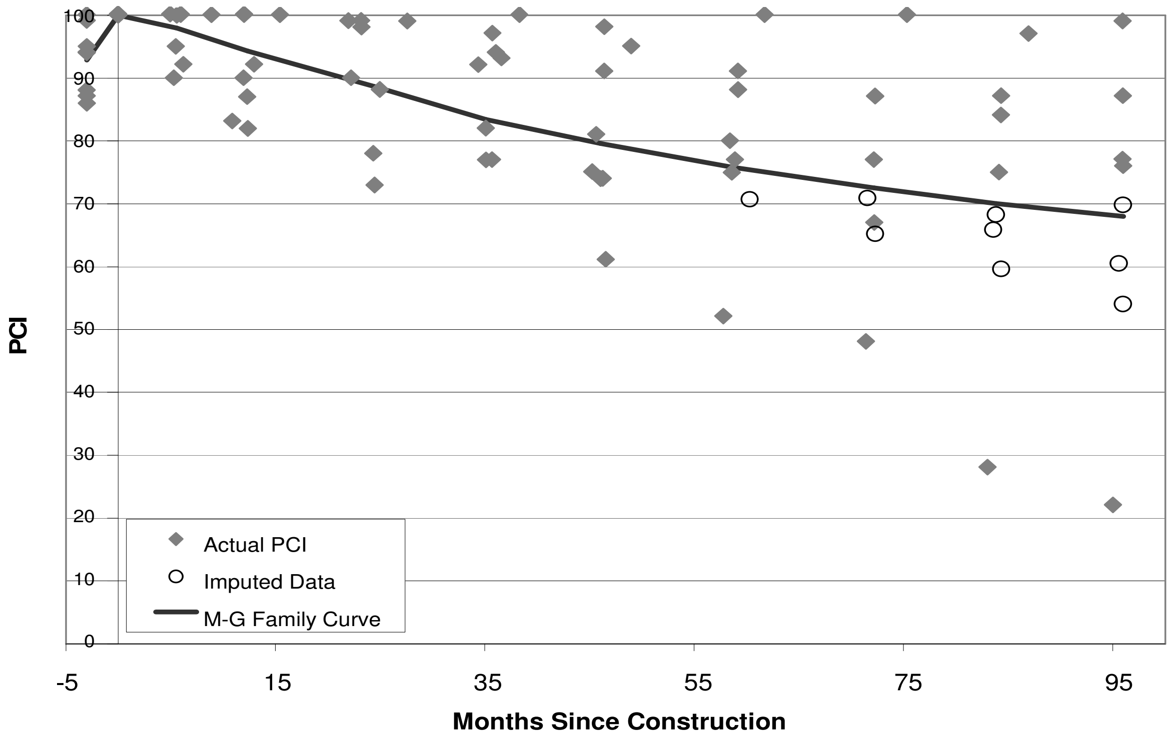

Figure D - 15. PCI for Microsurfacing, Good Initial Condition ($R^2 = 0.794$).

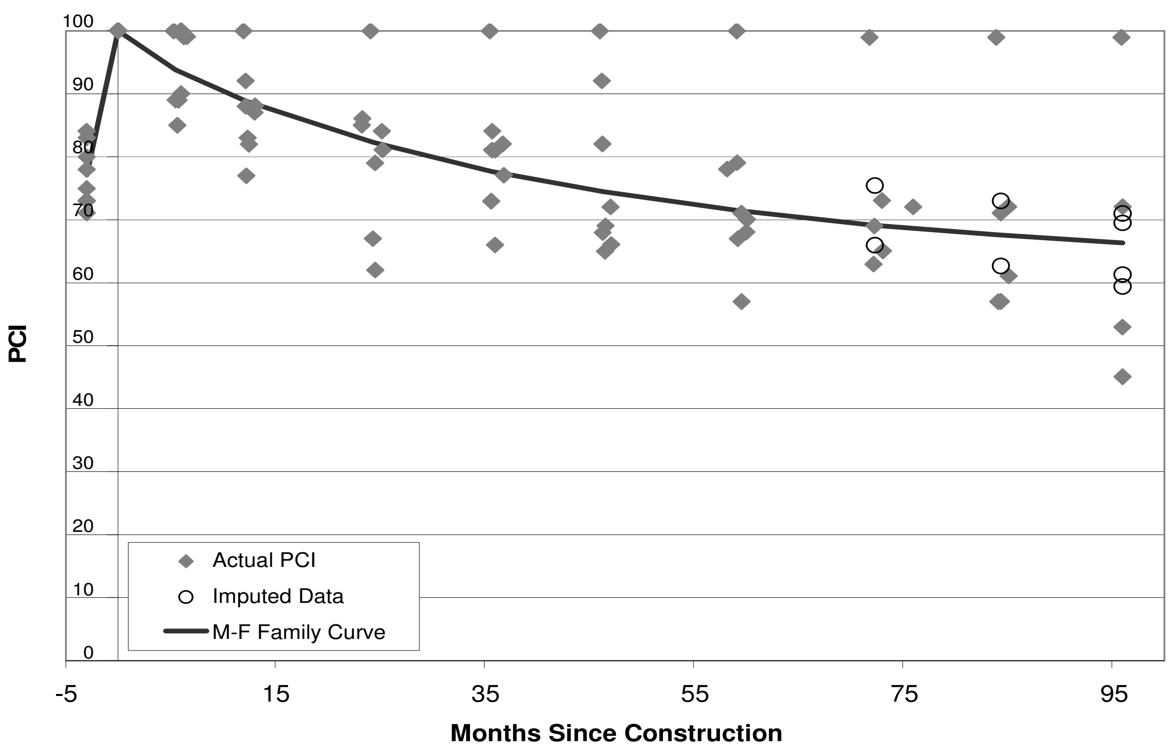

Figure D - 16. PCI for Microsurfacing, Fair Initial Condition ($R^2 = 0.865$).

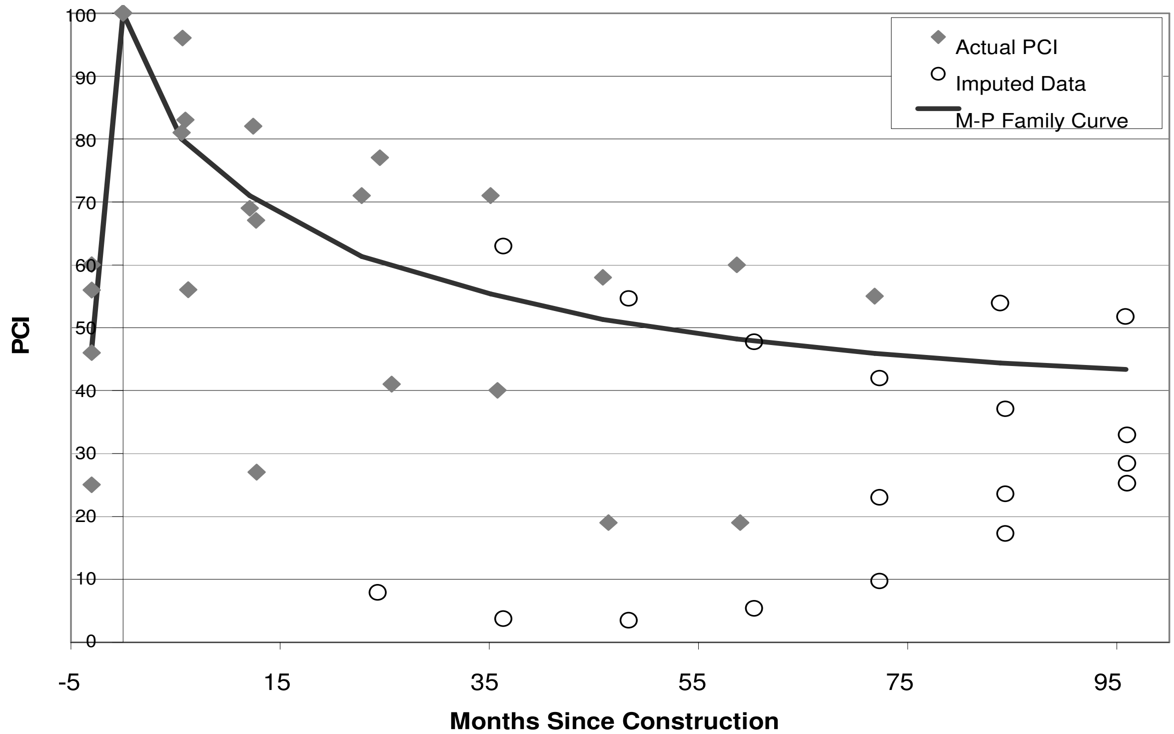

Figure D - 17. PCI for Microsurfacing, Poor Initial Condition (R^2 = 0.929).

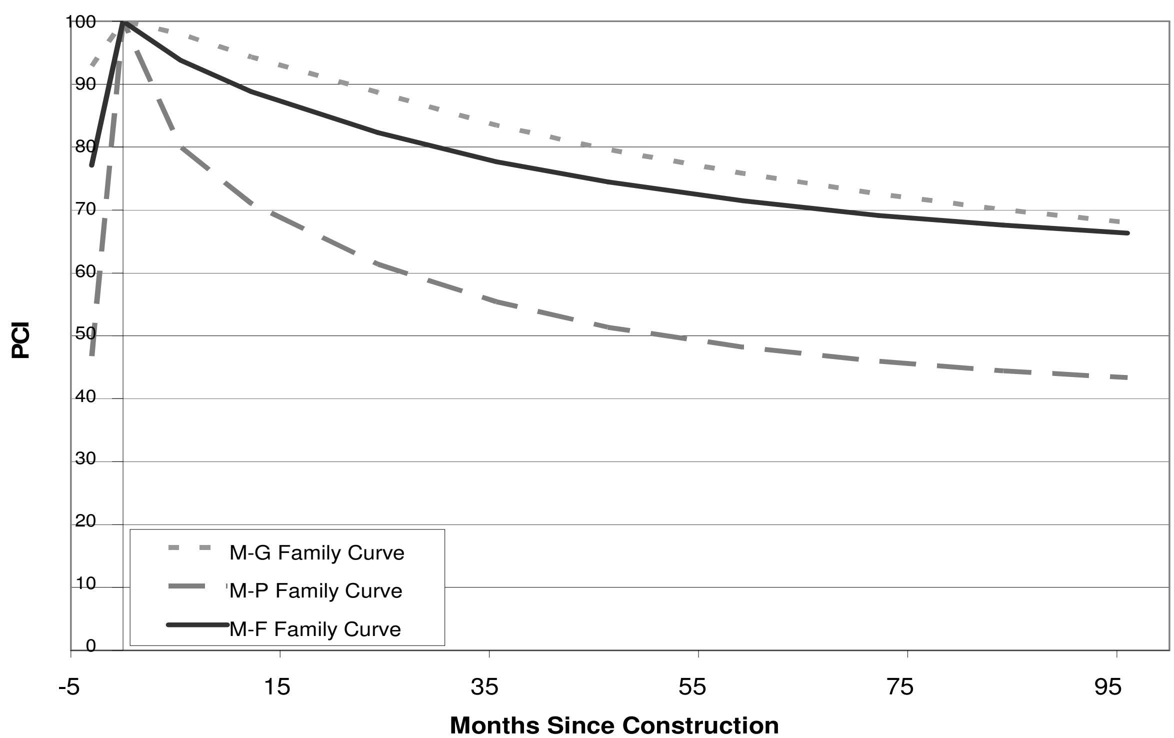

Figure D - 18. PCI for Microsurfacing, All Initial Conditions.

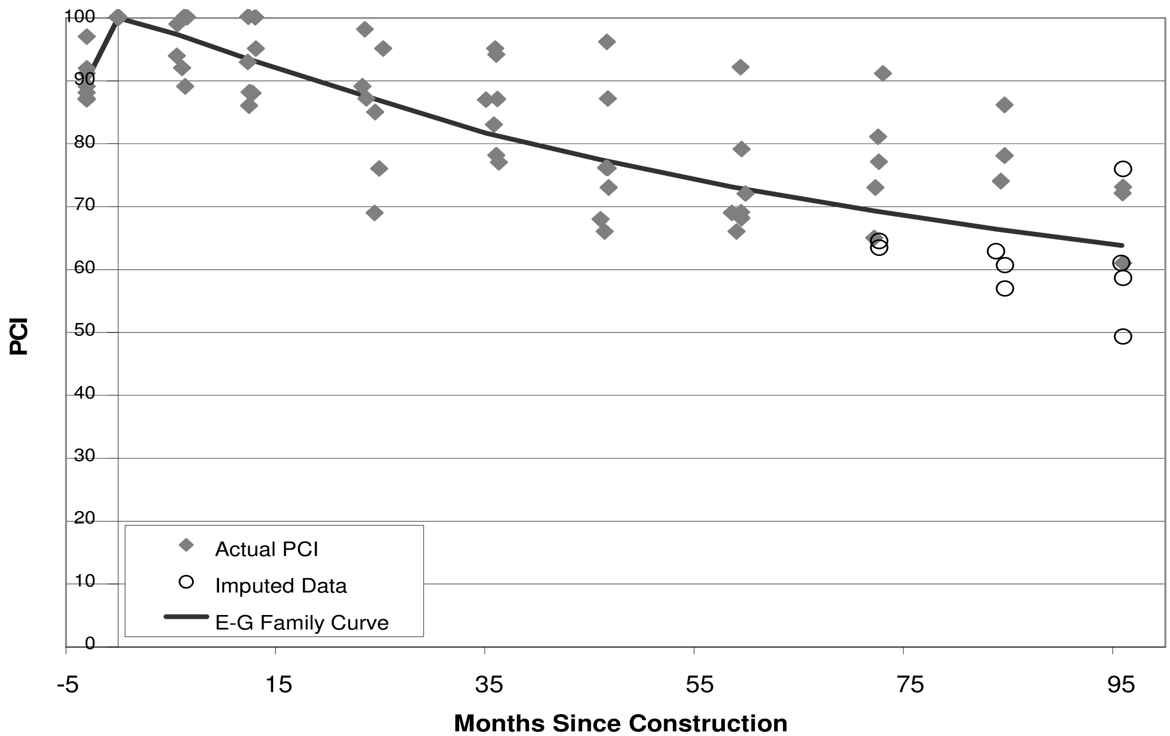

Figure D - 19. PCI for Polymer Modified Emulsion Seal Coat, Good Initial Condition ($R^2 = 0.929$).

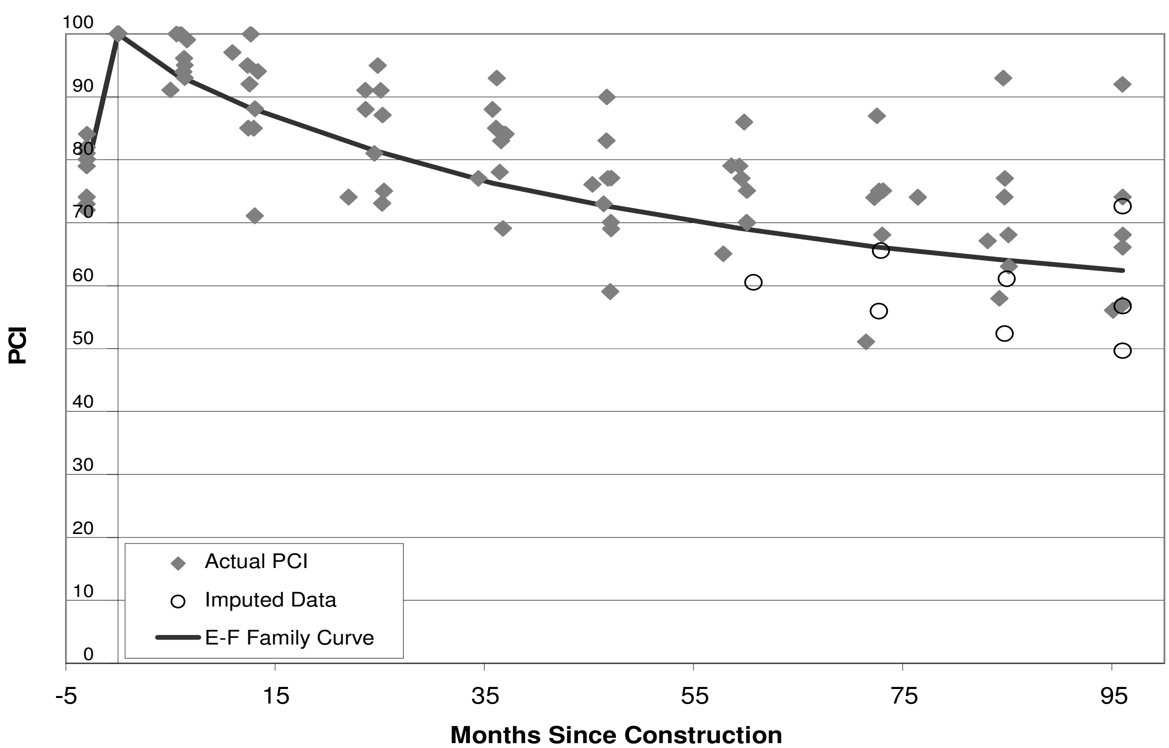

Figure D - 20. PCI for Polymer Modified Emulsion Seal Coat, Fair Initial Condition ($R^2 = 0.943$).

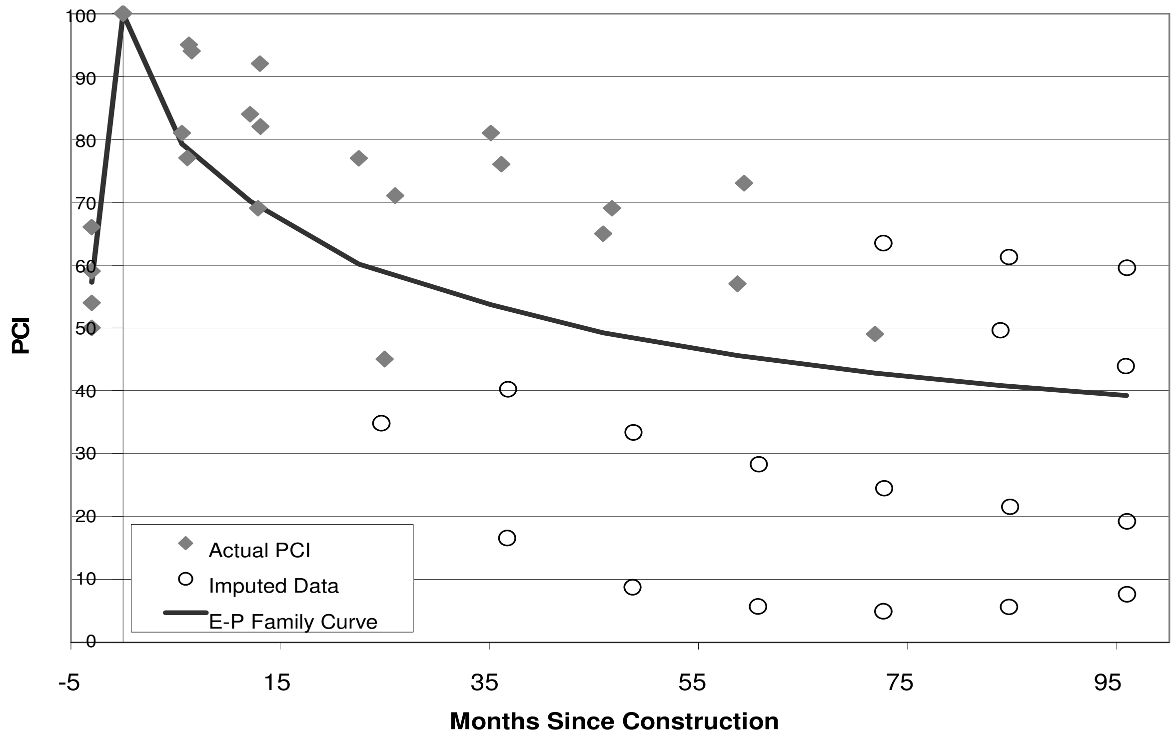

Figure D - 21. PCI for Polymer Modified Emulsion Seal Coat, Poor Initial Condition ($R^2 = 0.913$).

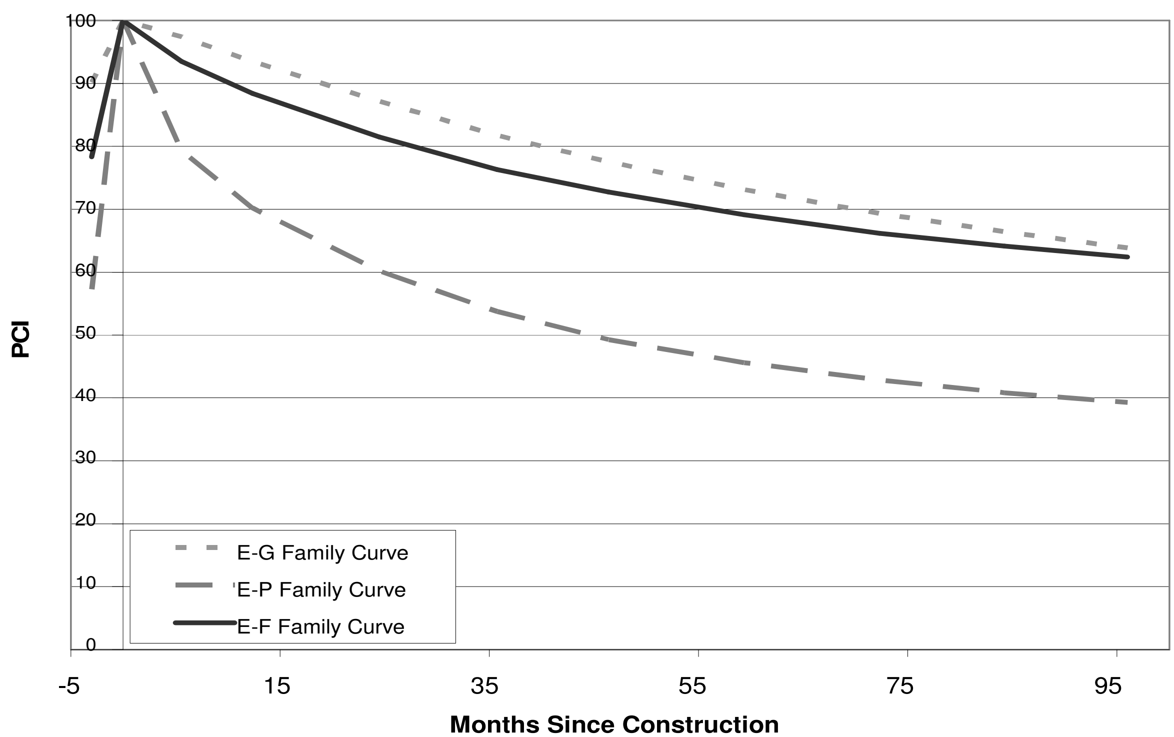

Figure D - 22. PCI for Polymer Modified Emulsion Seal Coat, All Initial Conditions.

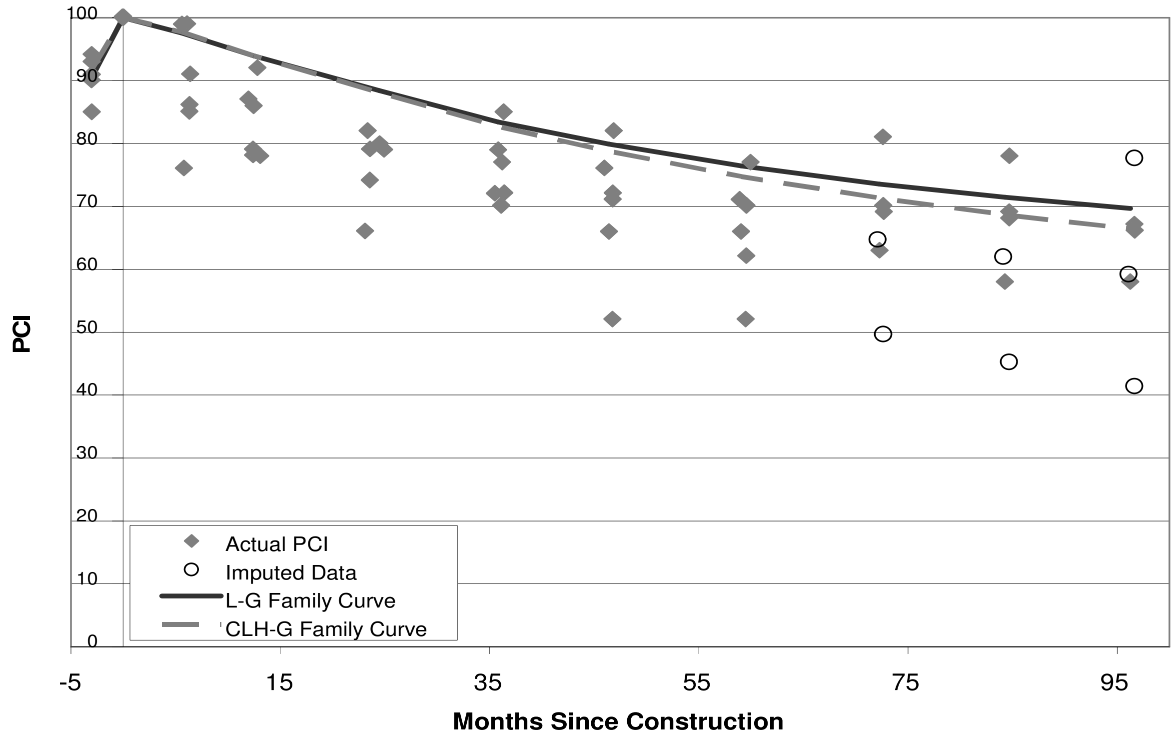

Figure D - 23. PCI for Latex Modified Seal Coat, Good Initial Condition ($R^2 = 0.968$).

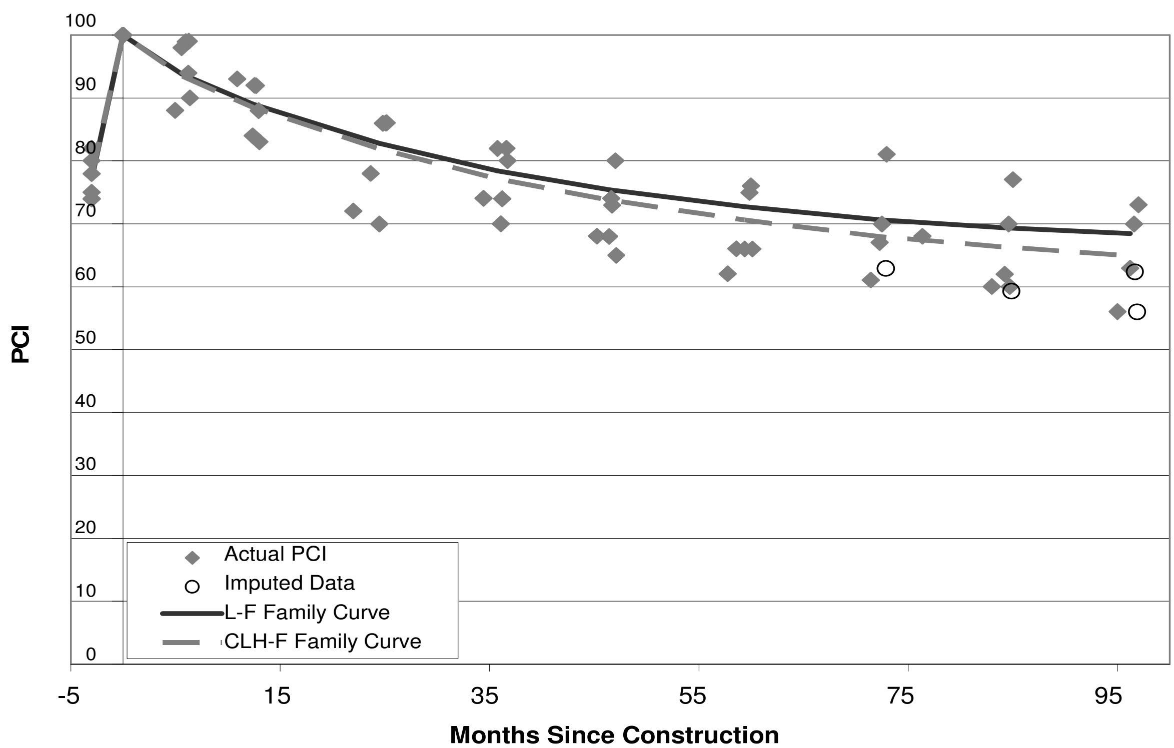

Figure D - 24. PCI for Latex Modified Seal Coat, Fair Initial Condition ($R^2 = 0.981$).

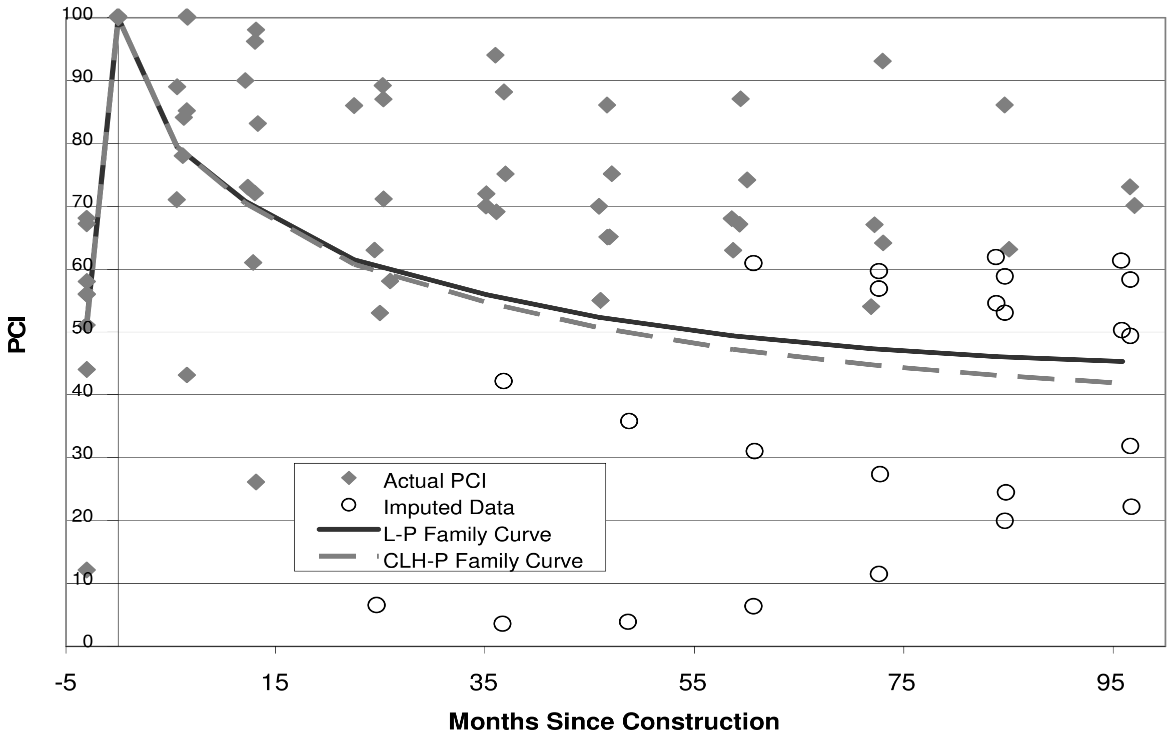

Figure D - 25. PCI for Latex Modified Seal Coat, Poor Initial Condition ($R^2 = 0.854$).

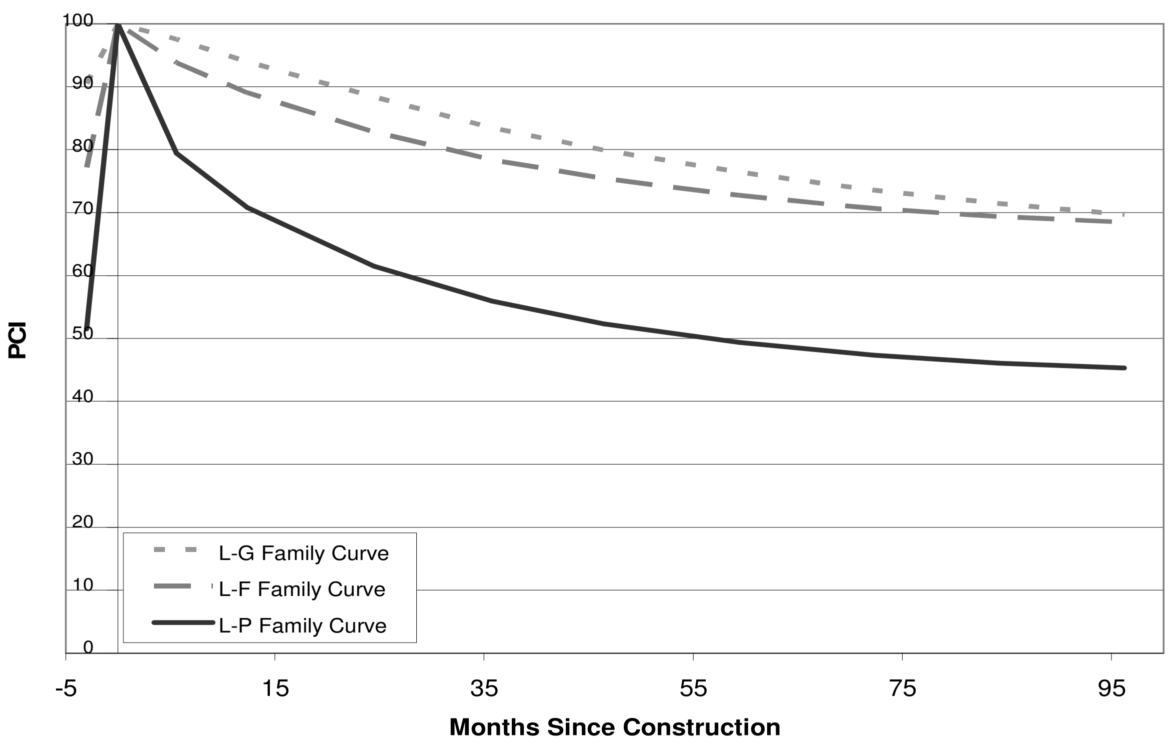

Figure D - 26. PCI for Latex Modified Seal Coat, All Initial Conditions.

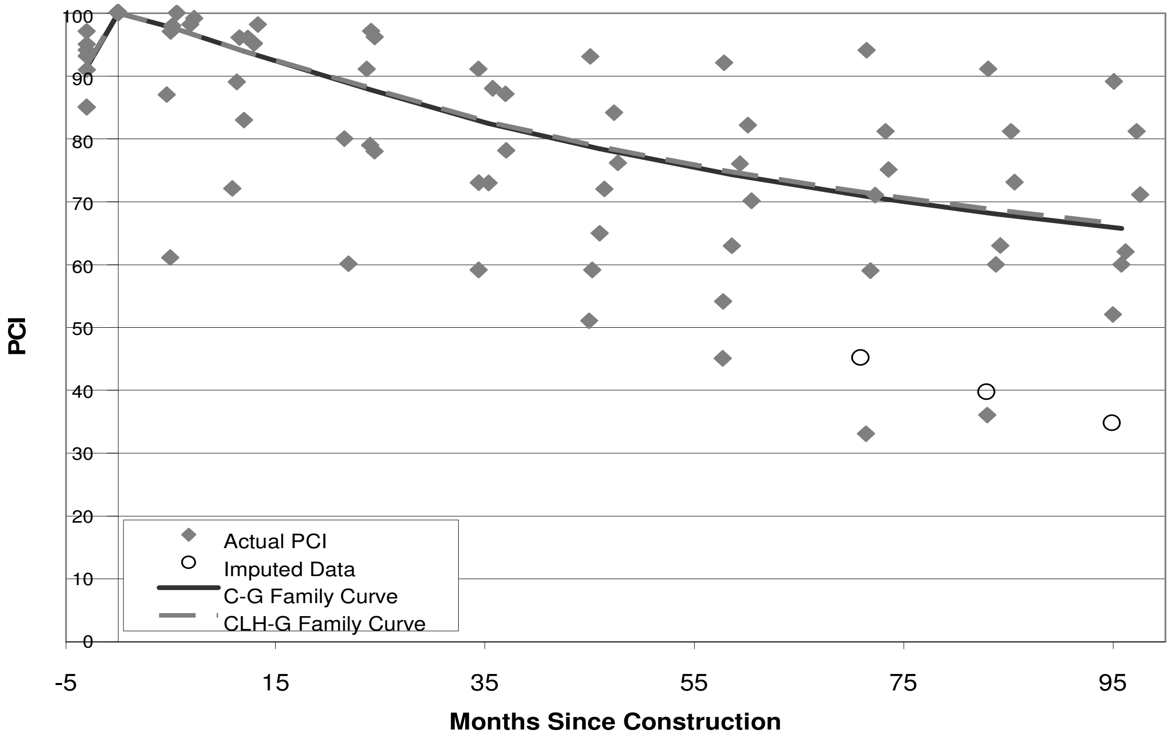

Figure D - 27. PCI for Unmodified Asphalt Seal Coat, Good Initial Condition (R^2 = 0.885).

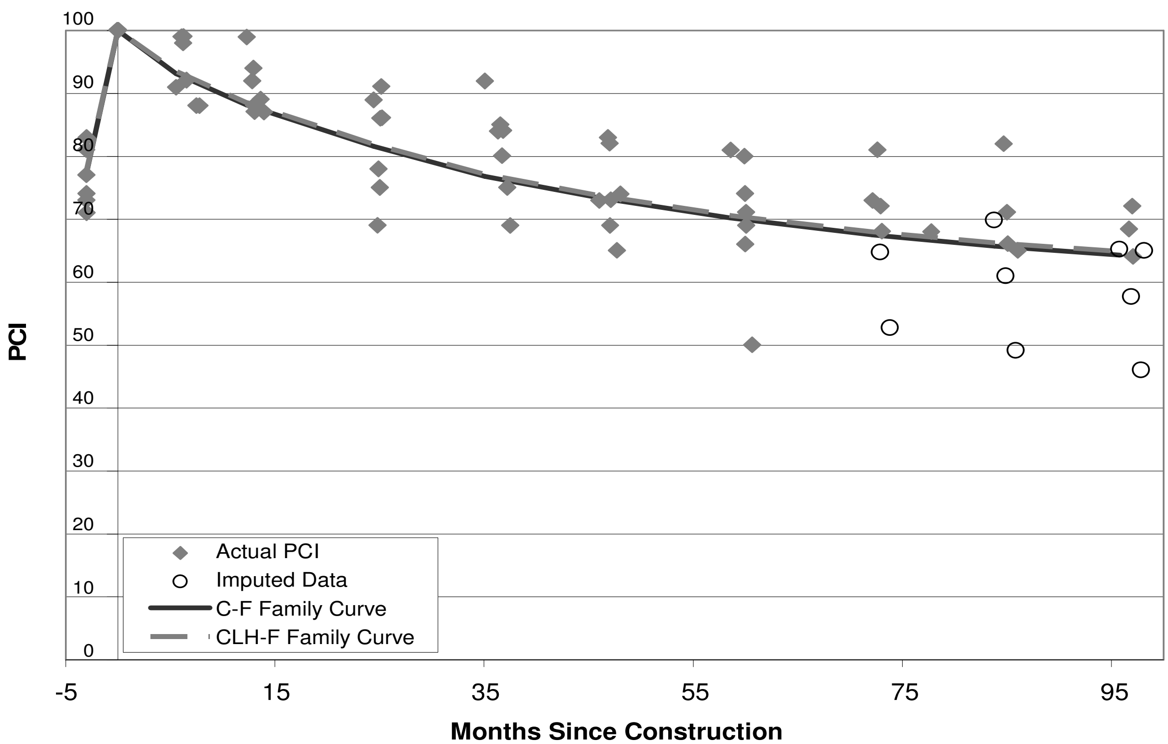

Figure D - 28. PCI for Unmodified Asphalt Seal Coat, Fair Initial Condition (R^2 = 0.968).

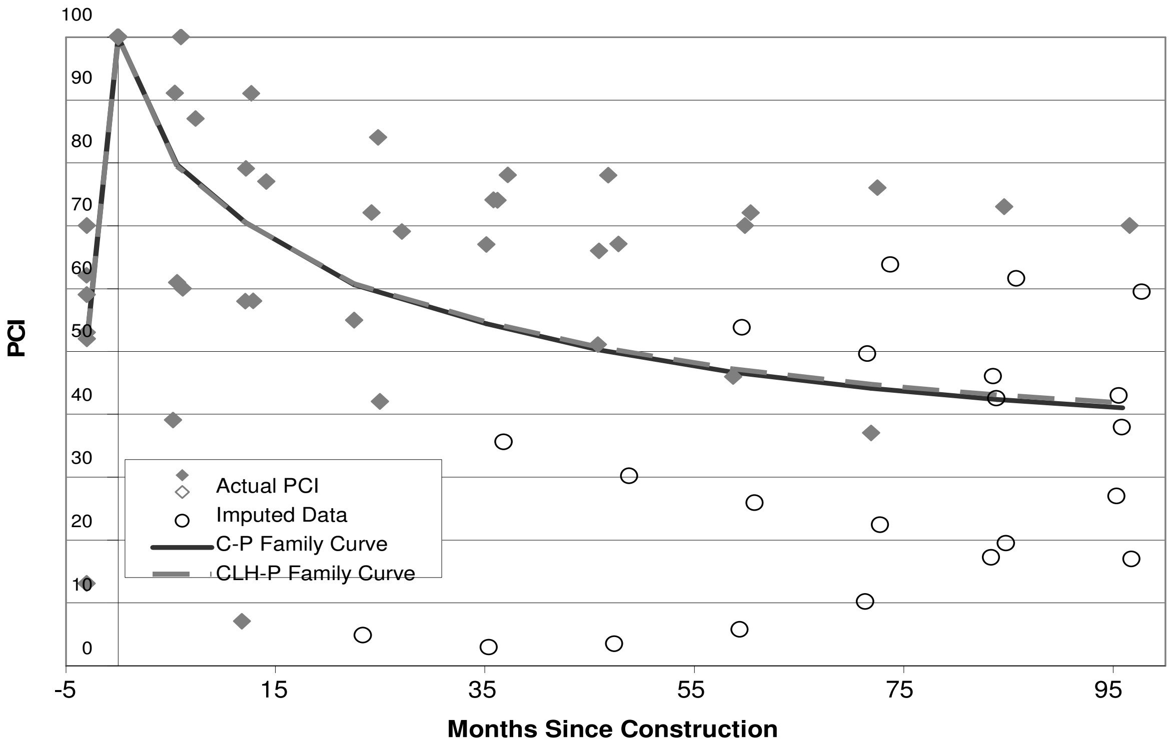

Figure D - 29. PCI for Unmodified Asphalt Seal Coat, Poor Initial Condition (R^2 = 0.883).

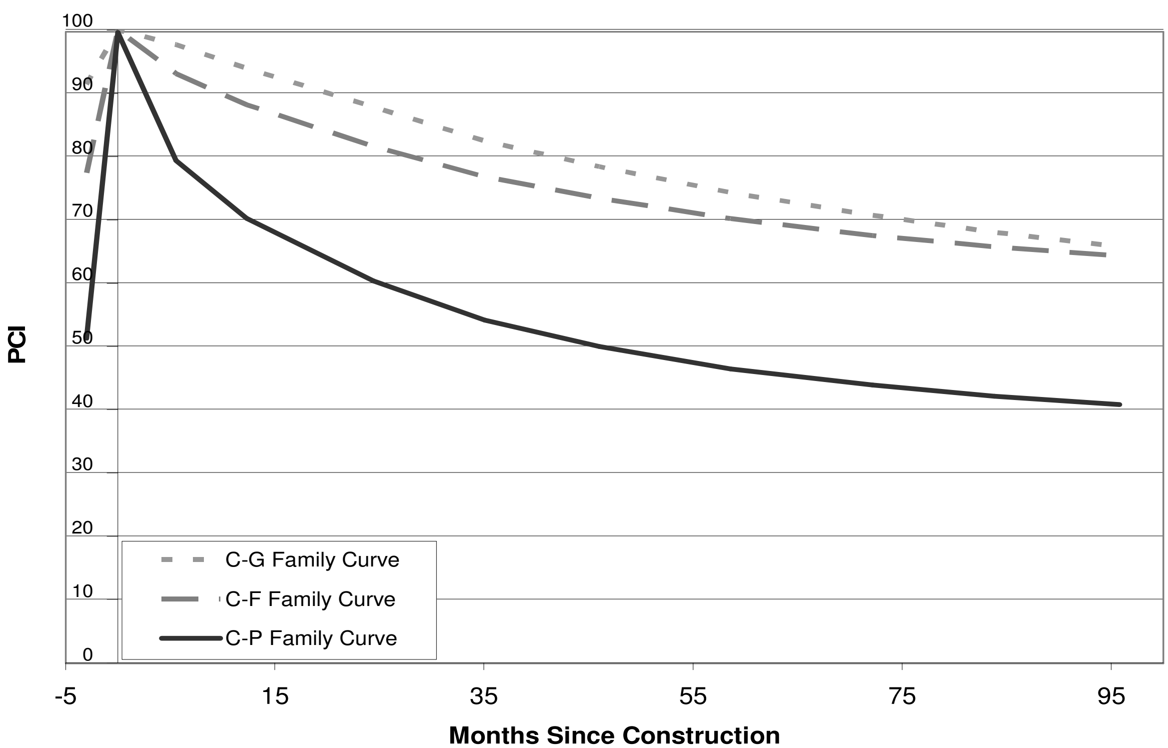

Figure D - 30. PCI for Unmodified Asphalt Seal Coat, All Initial Conditions.

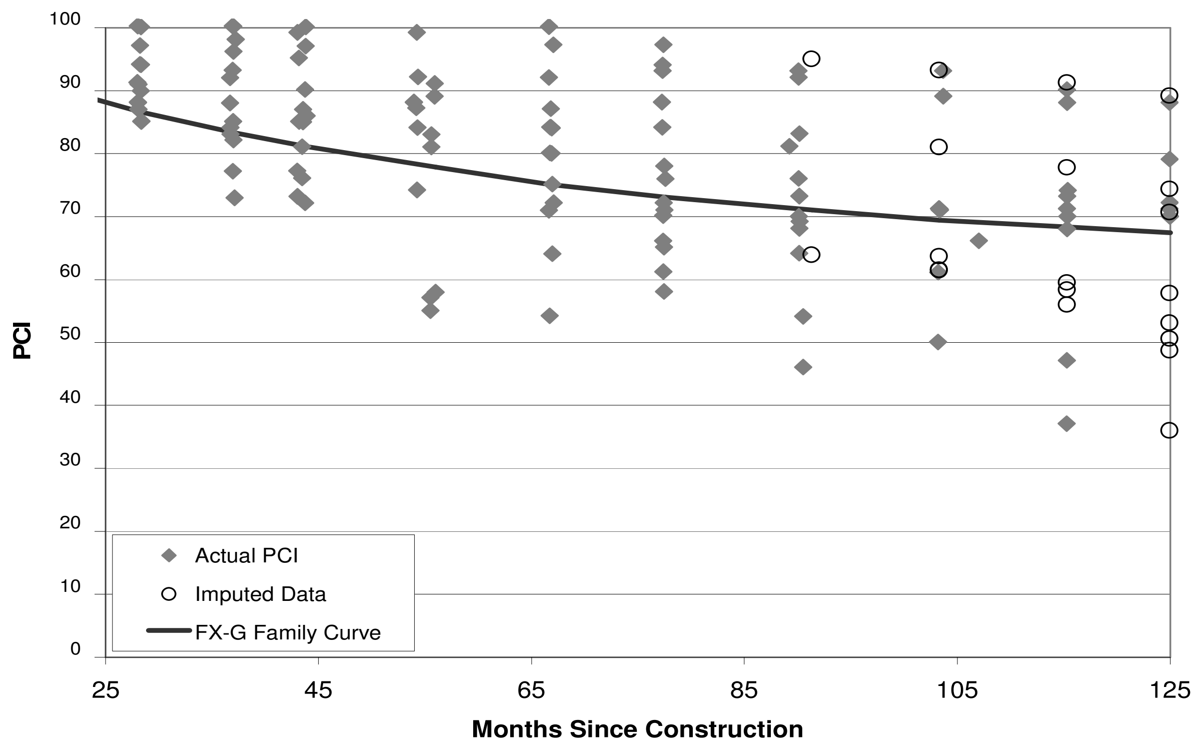

Figure D - 31. PCI for Fog and Control Sections, Good Initial Condition ($R^2 = 0.888$).

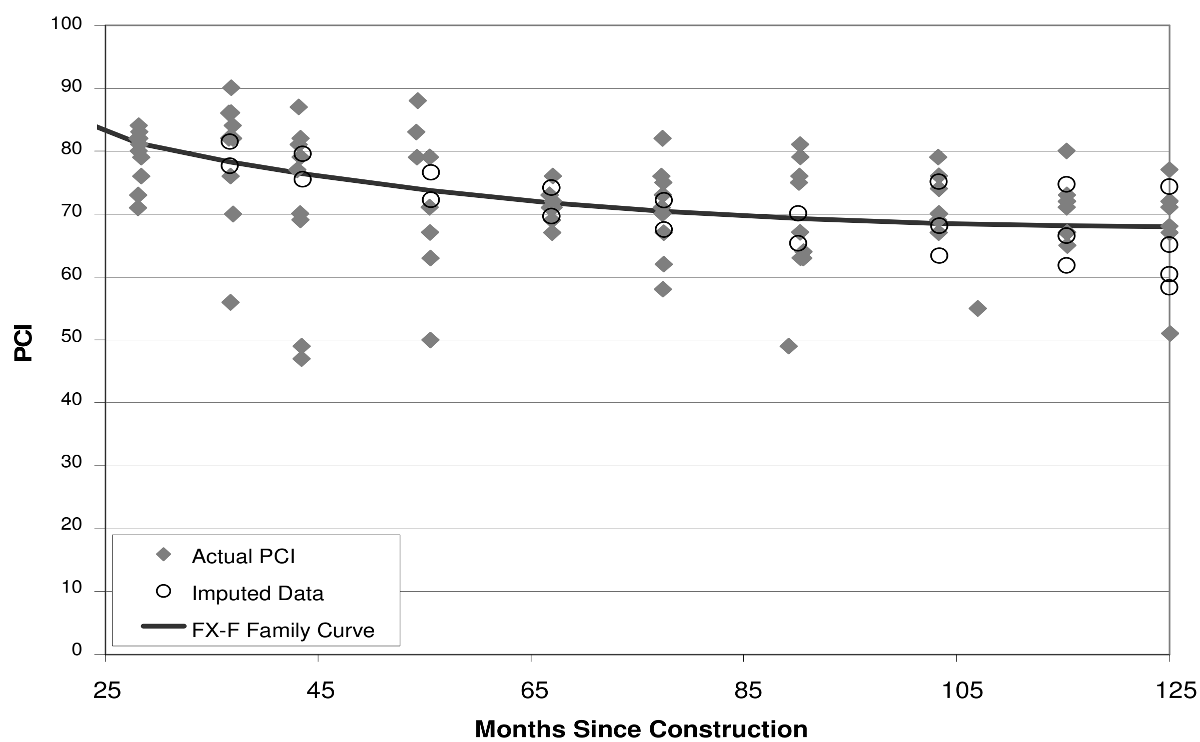

Figure D - 32. PCI for Fog and Control Sections, Fair Initial Condition ($R^2 = 0.976$).

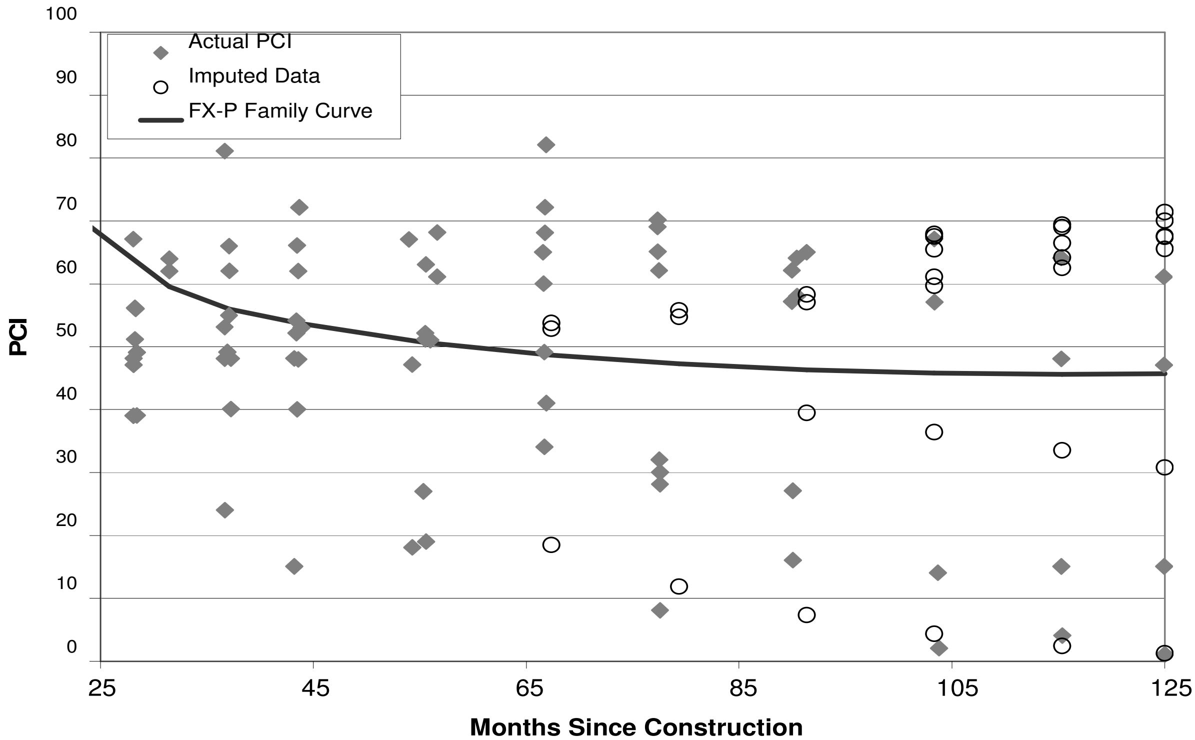

Figure D - 33. PCI for Fog and Control Sections, Poor Initial Condition ($R^2 = 0.921$).

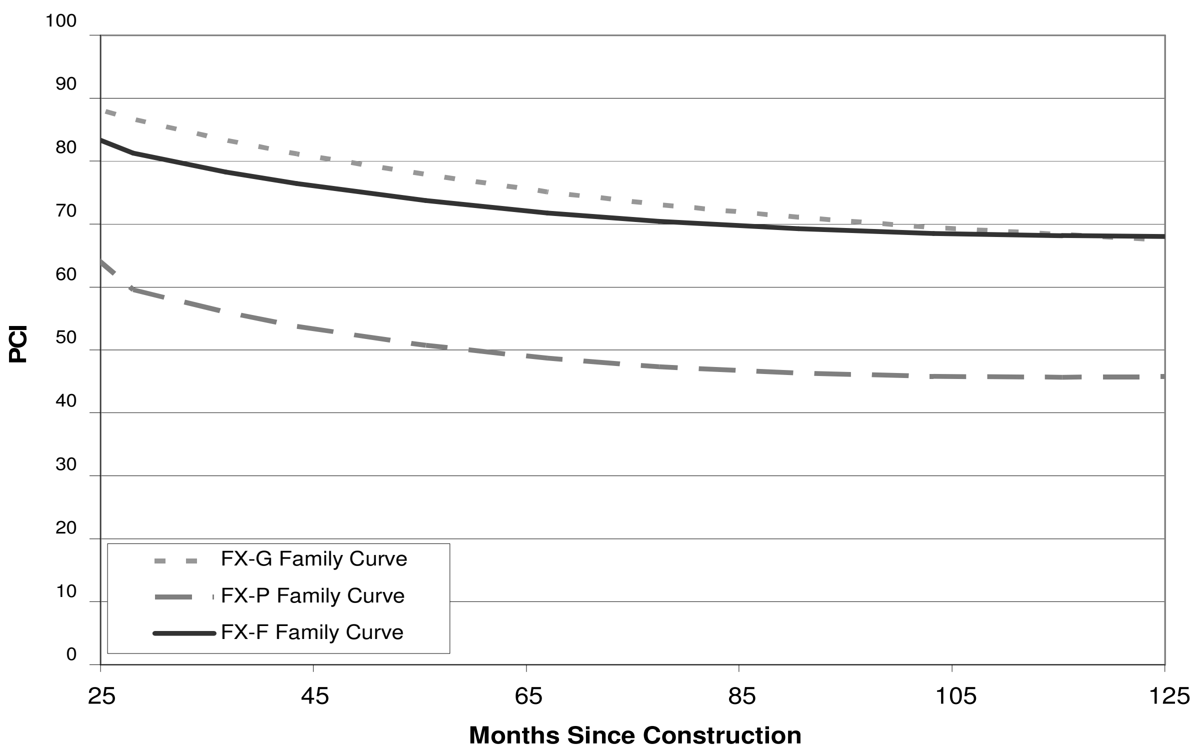

Figure D - 34. PCI for Fog and Control Sections, All Initial Conditions.

APPENDIX E

APPLICATION RATE DATA

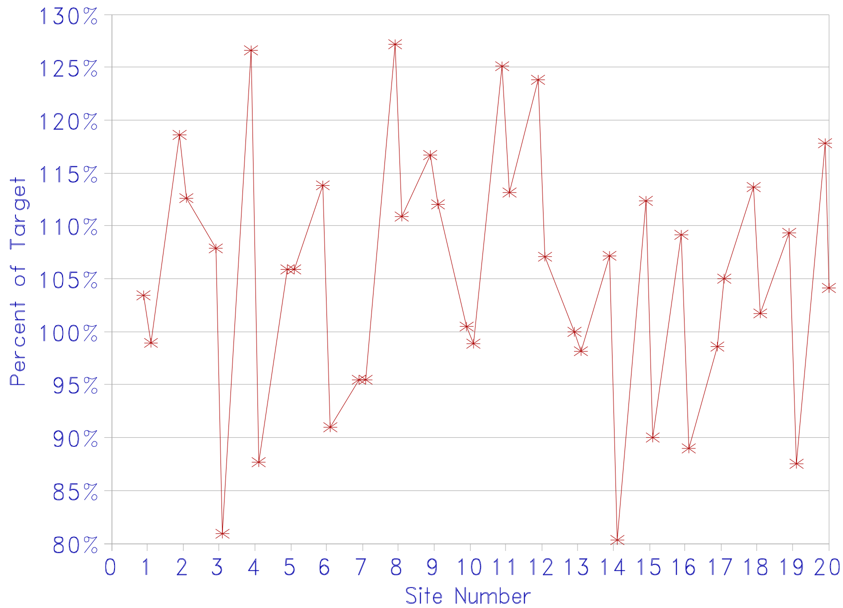

Figure E-1. Asphalt Application Rate - Asphalt Rubber Seal Coat.

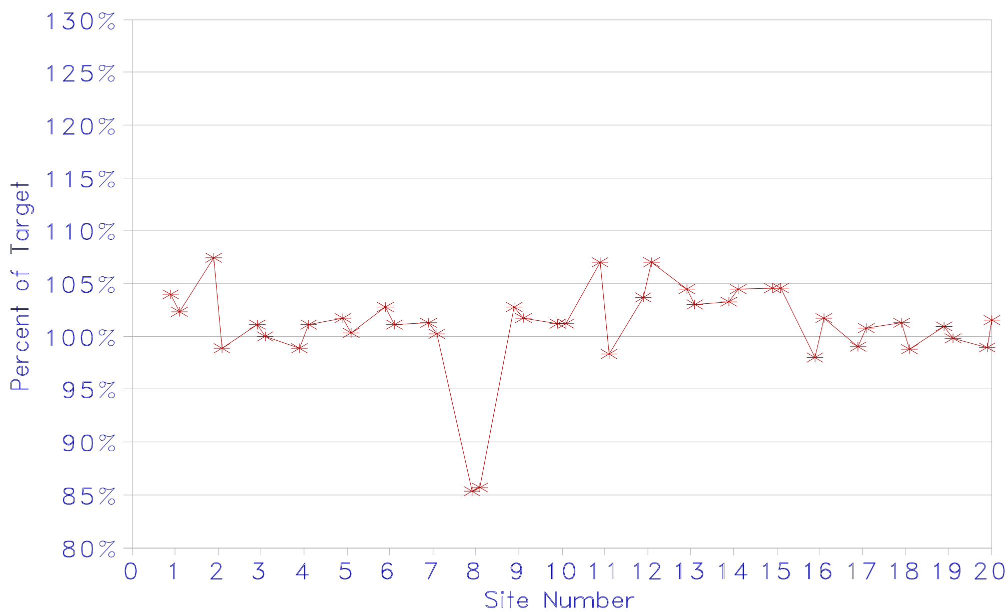

Figure E-2. Asphalt Application Rate - Polymer Modified Emulsion Seal Coat.

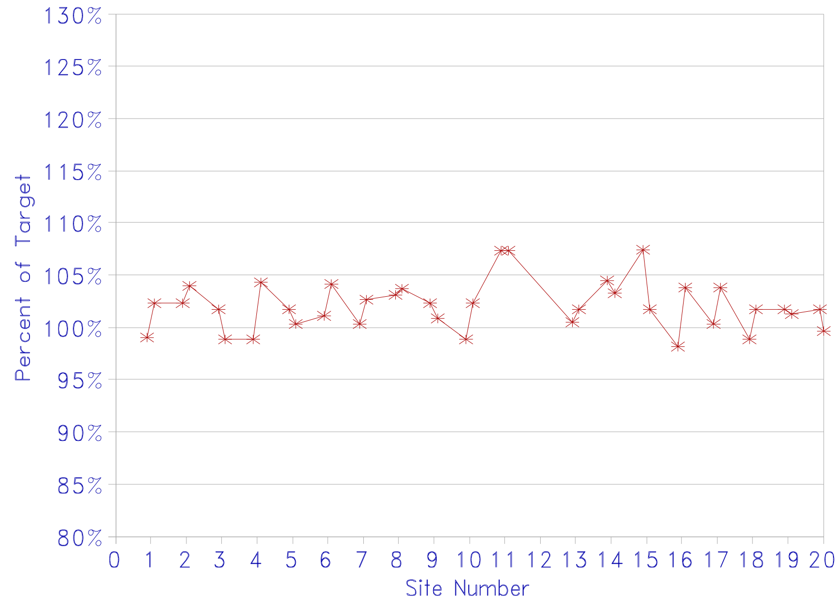

Figure E-3. Asphalt Application Rate - Latex Modified Asphalt Cement Seal Coat.

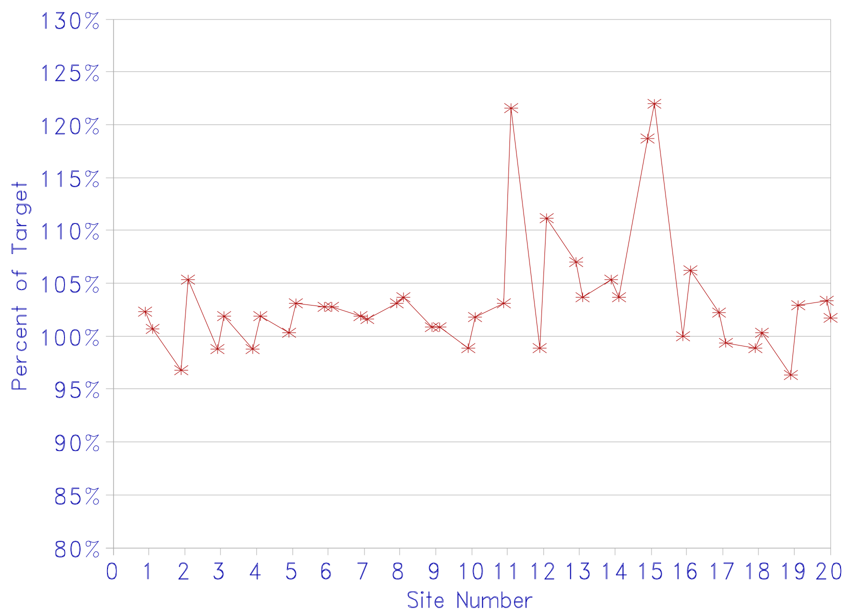

Figure E-4. Asphalt Application Rate - Unmodified Asphalt Cement Seal Coat.

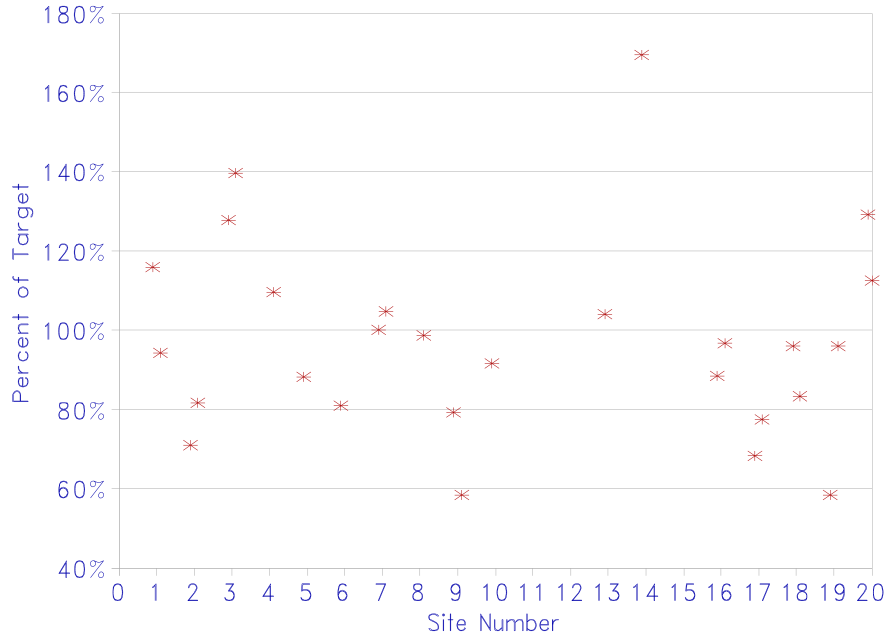

Figure E-5. Aggregate Application Rate in Wheelpath - Asphalt Rubber Seal Coat.

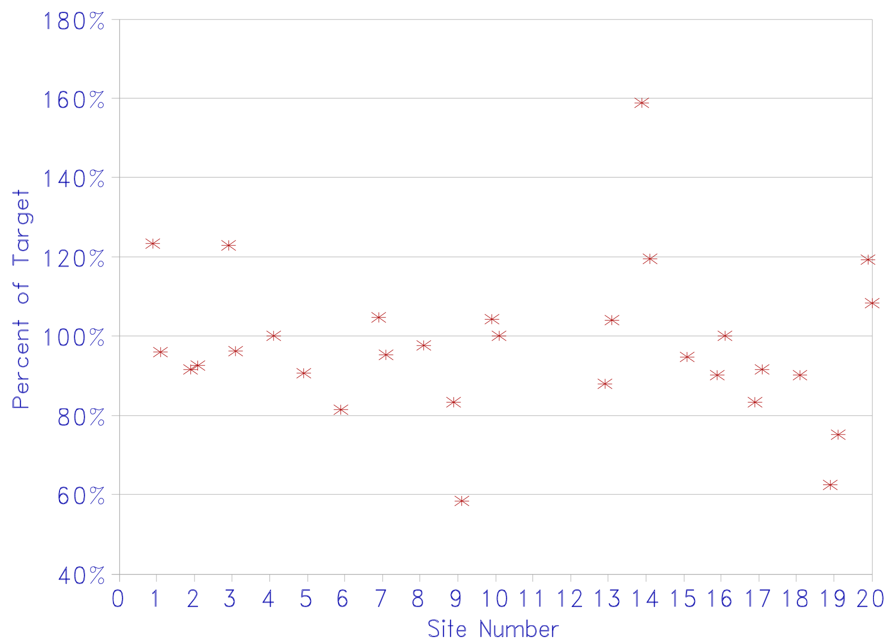

Figure E-6. Aggregate Application Rate between Wheelpaths - Asphalt Rubber Seal Coat.

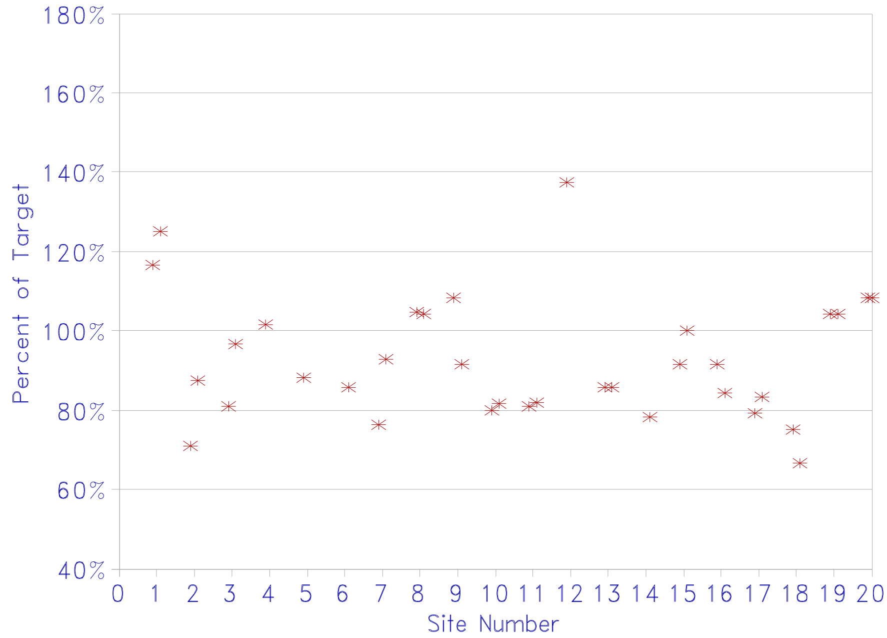

Figure E-7. Aggregate Application Rate in Wheelpath - Polymer Modified Emulsion Seal Coat.

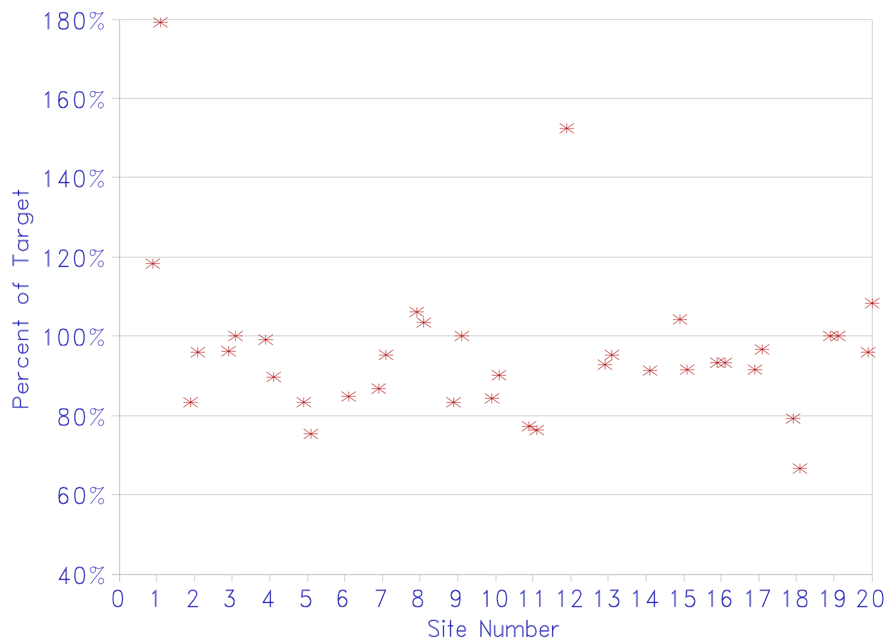

Figure E-8. Aggregate Application Rate between Wheelpaths - Polymer Modified Emulsion Seal Coat.

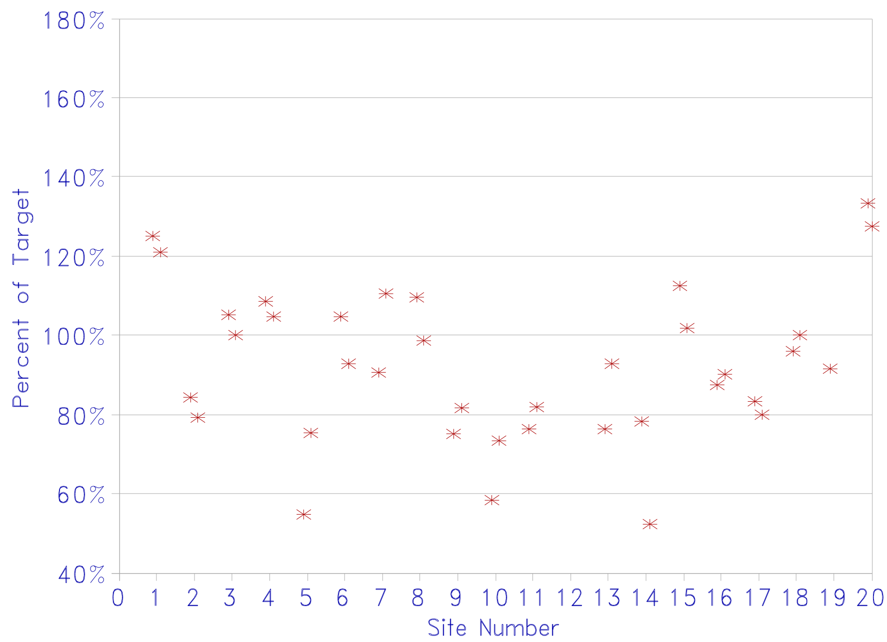

Figure E-9. Aggregate Application Rate in Wheelpath - Latex Modified Seal Coat.

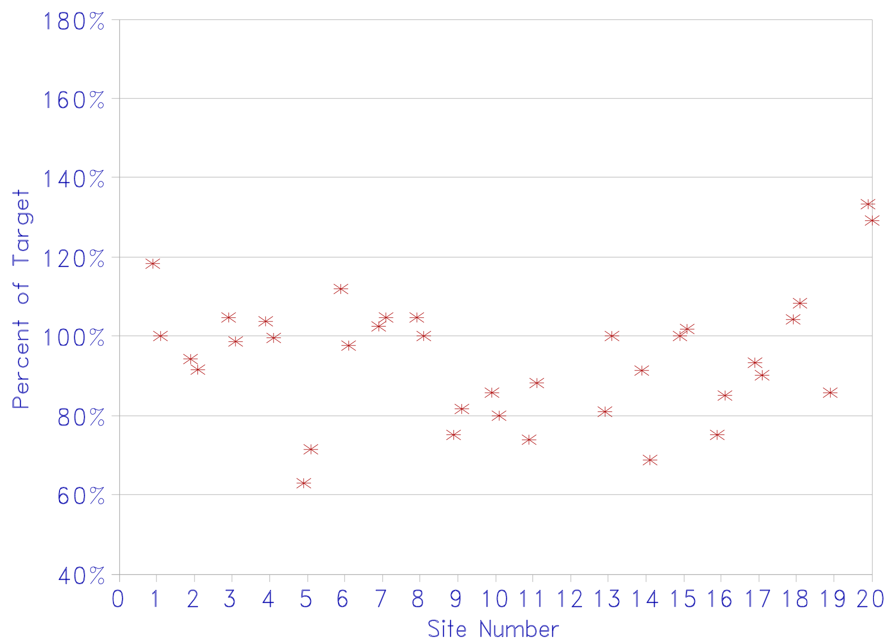

Figure E-10. Aggregate Application Rate between Wheelpaths - Latex Modified Seal Coat.

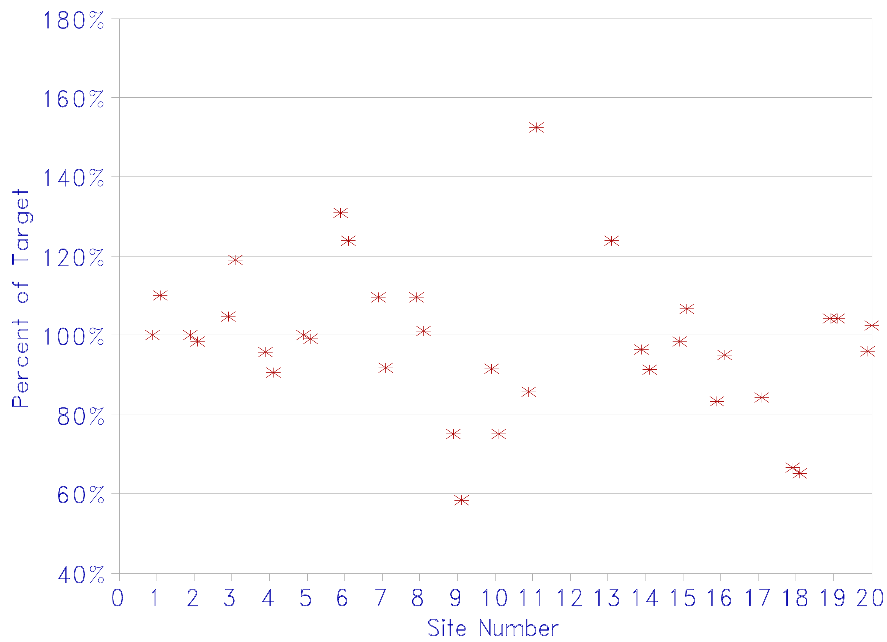

Figure E-11. Aggregate Application Rate in Wheelpath - Unmodified AC Seal Coat.

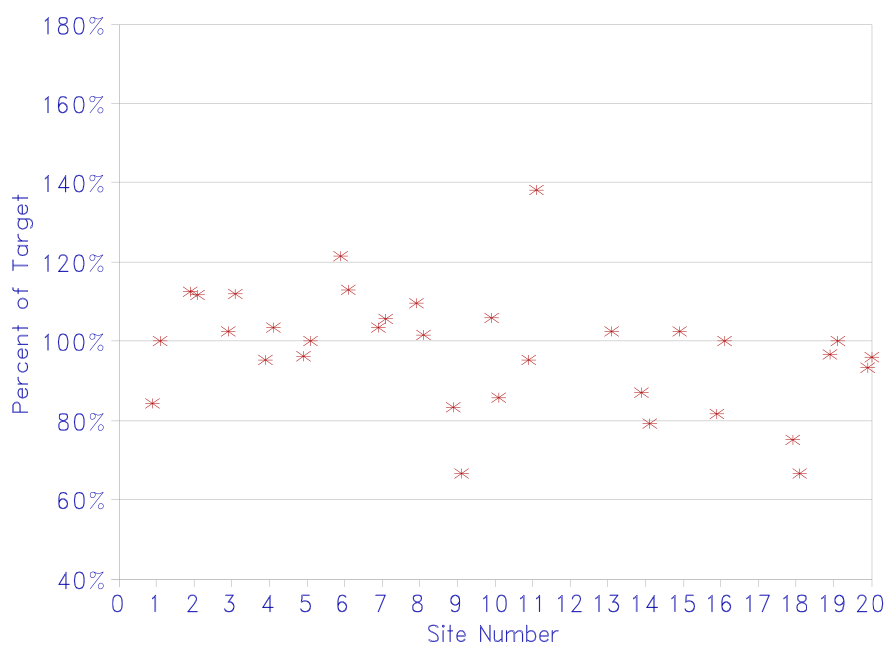

Figure E-12. Aggregate Application Rate between Wheelpaths - Unmodified AC Seal Coat.

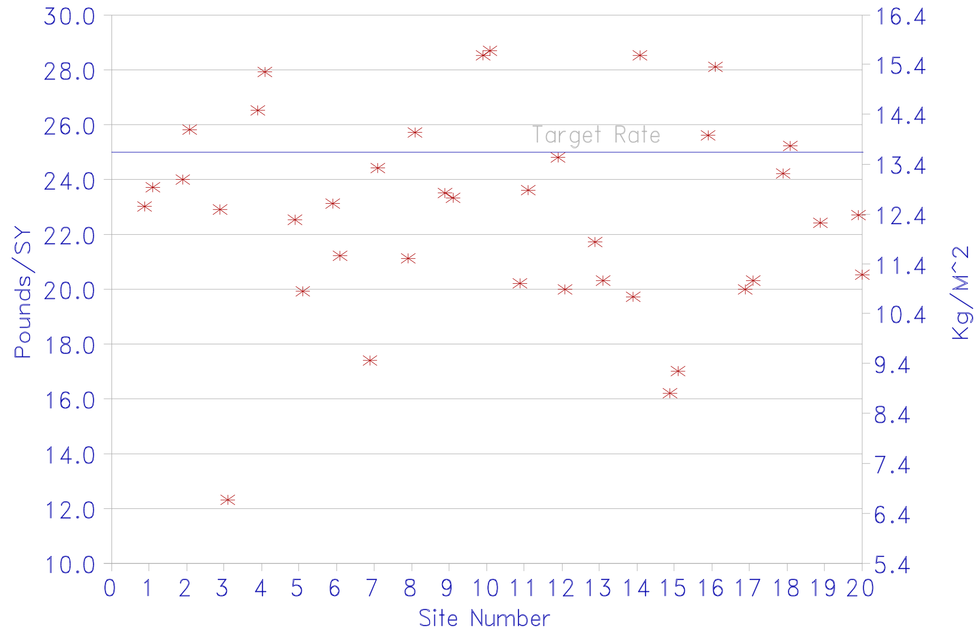

Figure E-13. Application Rate - Micro-Surfacing Section.