SETTING APPROPRIATE BENEFIT/CONDITION JUMPS FOR PAVEMENT TREATMENTS

by

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ABSTRACT

SALMAN KHAN. Setting appropriate benefit/condition jumps for pavement treatments. (Under the direction of DR. DON CHEN)

This research was conducted to determine pavement performance jumps after treatment, which are defined as the difference between pre-treatment and post-treatment Pavement Condition Rating (PCR) values. the North Carolina Department of Transportation (NCDOT) resets the PCR of roadway sections to its highest value of 100 after a treatment is applied. However, the condition of a pavement after treatment depends on the treatment applied, indicating that the PCR after treatment can be less than 100. This research dealt with this issue by determining PCR values after treatment. The data for this research was collected using windshield surveys, and it was divided into treatment families which were based on the most common treatments applied by the NCDOT on their asphalt and concrete pavements. Pre-treatment and post-treatment values were calculated to determine the performance jumps, and after-treatment performance curves were developed. These jumps along with the performance curves can enable better prediction of the pavement condition over its life after a treatment is applied, and eventually allow agencies to make informed pavement management decisions.

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CHAPTER 1: INTRODUCTION

1.1 Introduction and Background

This research was conducted to determine pavement performance jumps after treatment for the North Carolina Department of Transportation (NCDOT). In this study, the performance jump is defined as the difference between pre-treatment PCR values and the post-treatment PCR value.

The NCDOT Pavement Management System (PMS) measures the performance of a pavement section in terms of Performance Condition Rating (PCR), whose value ranges from 0 to 100. A PCR of 100 denotes that the pavement is free of any distresses, and the NCDOT resets the value of PCR to 100 after a treatment is performed, effectively inducing an improvement of performance. This practice is not invalid since it has been observed in other PMS as engineering judgment plays a significant role in such systems (Khattak and Baladi 2015). However, research has shown that this improvement, or performance jump, depends on a number of factors including the type of treatment applied (Dean and Baladi 2013). This indicates that the PCR value after treatment, or the post-treatment PCR value, might be less than 100.

1.2 Research Goals and Objectives

The goal of this research was to determine the performance jumps of the most common types of treatment utilized by the NCDOT. To achieve this goal, the sections with performance jumps were identified and their age reset to zero, and a sigmoidal model form was used to calculate the PCR value after treatment at age zero. Additionally, after-treatment performance curves were developed from estimates obtained during the calculation of after-treatment PCR values. To visually evaluate the effectiveness of pavement treatments, these curves were compared with performance curves before treatment. The data being analyzed included treatment history and pavement condition records based on the windshield survey collection method for asphalt and concrete pavements. Windshield data was preferred over automated data since the amount of automated records were not enough to calculate the jumps.

1.3 Significance of this Study

Setting a different value for the post-treatment PCR other than 100 will help maintenance managers make effective decisions, as the pavement condition can drop to the treatment threshold quicker. For example, a drop from 92 to 60 is smaller than a drop from 100 to 60. Keeping this in mind, the decision makers can recommend the best pavement preservation strategy based on the treatments being applied and the benefit they provide in terms of performance jump. It will also enable them to predict the performance of pavements more accurately using the after-treatment performance curves developed during this study. This is because the deterioration of a section changes once it is treated.

1.4 Organization of the Thesis

Chapter 1 provides the background of the study and lays down the research goals and objectives. Chapter 2 is a comprehensive review of the literature available on performance jumps and other relevant topics. The methodology of this research has been shown in detail within chapter 3, and the results have been presented and discussed in chapter 4. Finally, chapter 5 concludes the research and provides the limitations to this study, as well as recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 Pavement Management System

Pavement Management System (PMS) is a set of tools used to assist decision-makers in making better choices when it comes to pavement management (AASHTO 2001). It is a systematic approach to manage pavements, which enables the agencies to evaluate the consequences associated with various investment decisions, and to determine the most cost-effective use of their funds for maintaining their roads and highways (AASHTO 2012). The NCDOT uses its PMS to maintain a system of 79,000 miles of roadways (Corley-Lay and Mastin 2009).

Pavement management systems were conceived in the late 1960s and early 1970s from the need of state highway agencies to preserve their huge investments in pavements (Kulkarni and Miller 2003). These systems evolved over years, and allowed relevant authorities to make pavement preservation decisions based on their needs and requirements. A recent study shows that some form of PMS is employed by the states at varying levels of maturity based on the degree of sophistication of the tool and the extent to which the data are integrated into the agency's decision processes (Zimmerman 2017). The two basic elements of a PMS are (Paterson 1987):

1. An information system, comprising a database of pavement sections, current and historical pavement condition, traffic volume and loadings, maintenance works, and regular monitoring of the network to update the data; and

2. A decision-support system, which analyses the data and identifies current and future needs based on the prescribed criteria (screening process) or by the ranking of alternatives (prioritization).

Pavement management system can be classified into two administration levels: project level and network level. Project level systems are confined to individual pavement sections and attempt to evaluate project priorities based on the current conditions of these sections, whereas the network level systems address planning issues such as the impact of limited budgets and analysis of preventive versus deferred maintenance (Kulkarni and Miller 2003). The NCDOT PMS is capable of performing analyses at both levels.

2.2 Pavement Performance

Pavement performance is a measure of how pavements change their condition or serve their intended function with accumulating use (Lytton 1987). Pavement performance measurements are the basis of pavement performance models. Highway agencies all over the country have different methods to measure the condition of their pavements and model the performance. International Roughness Index (IRI) and rut depth (RUT) are among the performance indicators collected regularly by the agencies (Irfan et al. 2009).

In addition to IRI and RUT, a well-documented method of measuring pavement performance is the Pavement Condition Index (PCI). PCI is a composite index which is based on the information about distress type, severity, and extent of the distresses of pavement sections visually surveyed (AASHTO 2012). There are two methods by which pavement sections are surveyed (Findley et al. 2011):

1. The traditional manual method which involves trained personnel making observations by slowly walking or driving on the road
2. Automated data collection process which utilizes vehicles mounted with cameras and other observational equipment

2.2.1 Performance Condition Rating

NCDOT relies on a composite index called Pavement Condition Rating (PCR) to measure the condition of its pavements. It is a point based deduction matrix system that removes points depending on the amount of distresses on the roadway (Dye 2014). The matrix starts with a value of 100 for a perfect roadway, and deductions are made based on the severity levels observed in the field. These deduction values have been derived by the NCDOT engineers based on their years of experience (Chen et al. 2014). Not all distresses are treated the same, some distresses may have a greater impact than others (Dye 2014).

An index like the PCR must be designed to transfer real distress data to a scalar that can be used to express the health of the network (Baladi et al. 2011). In this regards, the NCDOT publishes a manual for the surveys which outlines the method to measure the type of the distress, as well as the severity in categories of low, medium, or high (NCDOT 2011). Deduct values are assigned based on the categories of severity. NCDOT collects pavement performance data using windshield surveys as well as automated surveys adopted recently According to Corley-Lay et al. (2010), North Carolina surveys 100% of its flexible pavements and a 20% sample of each rigid pavement on a 2-year cycle. This study focuses on the data collected using the manual method, also referred to as the windshield survey method.

2.3 Pavement Performance Modelling

A PMS serves as a means for collecting and analyzing pavement condition data and recommend feasible action to mitigate anticipated deterioration of roads, and this requires the use of pavement performance models (Mills et al. 2012). Therefore, pavement performance models are an important feature of PMS. They may serve the following purposes (AASHTO 2012):

- Estimate future pavement conditions and identify the appropriate time and cost-effective strategies for pavement maintenance.
- Estimate state wide needs required to address agency goals, objectives, and constraints, as well as demonstrate consequences of different investment strategies.
- Establish performance criteria for performance specifications and warranty contracts.

Essentially, pavement models are equations in which pavement conditions overtime are represented (AASHTO 2012). Deterministic models and probabilistic models are the two types of models commonly used in PMS (Li et al. 1997). The NCDOT uses deterministic models because of their simplicities.

Several studies are available on pavement performance models. Rajagopal and George (1990) explored the influence of timing and intensity of maintenance activities on pavement condition. They developed mechanistic empirical models based on time series pavement performance data, which were used to predict the immediate jump in pavement condition. The US Army Corps of Engineers developed the family curve technique as a method to predict pavement conditions accurately and determine the consequences of different maintenance strategies at the section level (Shahin et al. 1994). The family curve relies on the concept that pavements with similar characteristics and subject to the same environmental conditions deteriorate at very similar rates. Dawson et al. (2011) have argued that pavement performance models can be used for cost-benefit analysis and optimization of the selection of the type and timing of pavement treatments.

More recently, Chen et al. (2014) have presented and validated a method to develop piecewise linear models for pavement condition based on the data provided by NCDOT. A data cleaning method was developed by the authors for their research which has been used for this study. Most importantly, Chen et al. (2014) developed the sigmoidal performance models and derived the model expression that was utilized to calculate the post-treatment PCR in this research.

2.3.1 Pavement Families

Some agencies use a family modeling approach in order to simplify pavement performance modelling, in which condition data for pavement sections with similar characteristics are grouped together. This determines a representative model to signify the typical deterioration pattern for a data set, and reduces the variables used directly in the model (AASHTO 2012). Such grouping is particularly useful because certain treatments might not be applied to certain families e.g. chip seal is typically not applied on Interstate routes (Lamptey et al. 2008). The NCDOT uses pavement families based on the pavement type, e.g. asphalt pavement or concrete pavement, functional classification (Interstate/U.S./state highways, and local roads), and Average Annual Daily Traffic (AADT) (Chen et al. 2014).

2.4 Treatment Effectiveness and Performance Jumps

Whenever the condition of a pavement section falls below a predefined threshold, a treatment is applied to rehabilitate the section. These treatments can be categorized as preventive maintenance or corrective maintenance (Haas et al. 1994). Preventive maintenance is performed to maintain a section's performance above the threshold whereas corrective maintenance is aimed at sections which have fallen below acceptable condition.

The treatment is assumed to repair or restore the pavement condition, or performance, to a level substantially higher than the pre-treatment level (Rajagopal and George 1990). One method of determining treatment effectiveness is determining the area under the pavement condition versus time curve, where a large area indicates greater effectiveness (Mamlouk and Zaniewski 1998). The improvement in the remaining service life of a pavement section after a treatment is applied is another measure of treatment effectiveness (Amador-Jiménez and Afghari 2015; Baladi et al. 2011).

Labi and Sinha (2003) have termed performance jumps as another measure of treatment effectiveness in the short term for individual treatments, as opposed to long term effectiveness which can be determined by evaluating multiple treatments applied over a pavement life cycle. Nevertheless, short term effectiveness has long term implications, as it enables the relevant authorities make pavement management decisions, as a pavement with high short term effectiveness may render the pavement eligible for treatment quicker than other treatments. In another study, Labi and Sinha (2003) have stated that performance jump is simply the vertical, or instantaneous elevation in the performance or condition of a pavement due to maintenance. As an indicator of treatment effectiveness, performance jumps can be used to select an optimal treatment for pavement distresses from the available alternatives as well as optimum timing to apply these treatments (Haider and Dwaikat 2011; Wang et al. 2011). It can also be used to measure the cost effectiveness of treatments applied (Irfan et al. 2009). In this study, performance jump is the difference between the PCR before and after treatment. Figure 1 shows a typical performance curve with PCR values plotted against age, whereas Figure 2 shows the performance jump at age 'n' due to treatment.

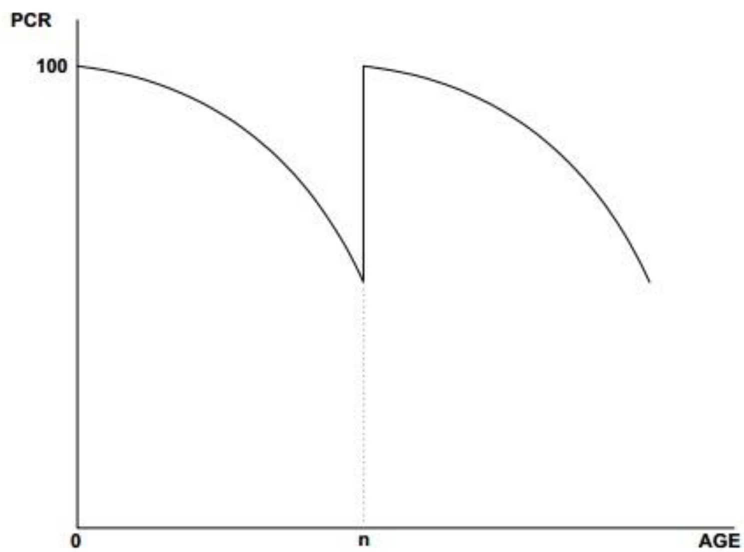


Figure 1: Typical pavement performance curve with treatment at age 'n'

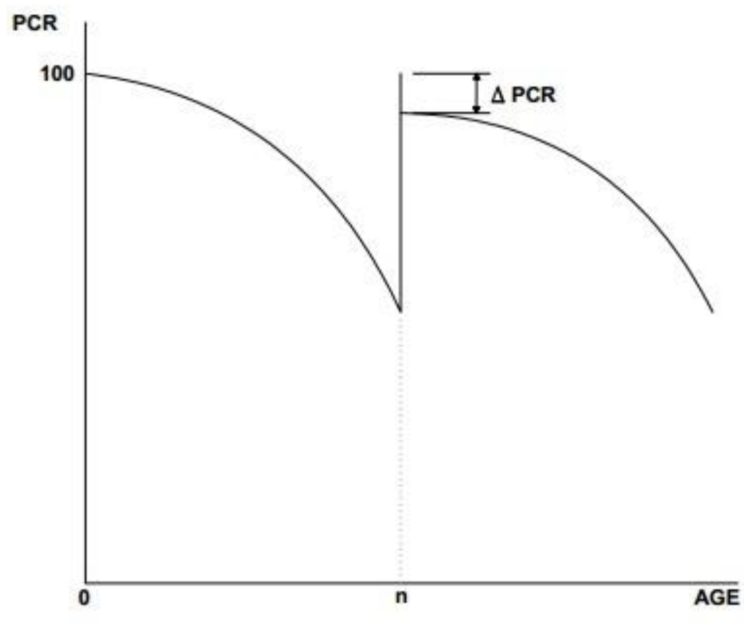


Figure 2: Pavement performance curve with a difference in PCR after treatment

2.5 Previous Studies on Performance Jumps

In their paper, Labi and Sinha (2003) demonstrated that there were limited examples of studies on calculation of performance jumps for different treatments in pavement preservation. In an attempt to study the economic benefits of preventive maintenance treatments, Al-Mansour and Sinha (1994) studied the gain in Pavement Serviceability Index (PSI) as a result of seal coating in Indiana by comparing the pre-treatment and post-treatment PSI within one year of the treatment being applied. The PSI ranges from 1 to 5 with 5 being the highest value. The authors concluded that a pavement should not be allowed to deteriorate beyond a PSI of 3 to achieve the maximum benefits in terms of performance and costs.

Labi and Sinha (2003) on the other hand defined performance jumps as a measure of short term effectiveness of pavement treatments and compared them with two other effectiveness measures: Deterioration Reduction Level (DRL) and Deterioration Rate Reduction (DRR). The authors argued that relative timing between pavement maintenance and performance survey is vital in the computation of short term effectiveness, and they derived expressions based on these relative scenarios as a prelude to the overall process of maintenance effectiveness evaluation.

Building on the previously mentioned study, Labi et al. (2007) used performance jumps in RUT, IRI, and PCR and developed a method to measure the effectiveness of microsurfacing treatements for roadway sections in Indiana. This study showed the immediate benefits of microsurfacing in all three performance measures, with PCR showing an increase of 3-9 units. Similarly, performance jumps of resurfacing treatments were calculated to demonstrate treatment effectiveness and cost effectiveness using pavement data in Tennessee (Qiao et al. 2011). In both studies, performance jumps were considered as an appropriate measure of short term effectiveness of treatments, however the treatments analyzed were surficial in nature.

Bao et al. (2010) calculated the performance jumps for two treatments: minor leveling and in-situ stabilization. These treatments were applied to mitigate pavement rutting (RUT) and roughness (IRI) in New Zealand. The authors concluded that in-situ stabilization was more effective over the long run. Lu and Tolliver (2012) used performance jumps in IRI to calculate the effectiveness of hot mill overlay, crack sealing, aggregate seal, and chip seal treatments using data from the Long Term Pavement Performance (LTPP) program. In a study sponsored by the Louisiana Department of Transportation and Development (DOTD), Khattak and Baladi (2015) determined new ‘reset values’ for overlay, chip seal, micro surfacing, and replacement by plotting IRI of pavement sections against time and using best fit curves. Reset value is another description for pavement condition after treatment because of performance jump. In these examples, the performance jumps were calculated in terms of IRI and RUT instead of a composite index such as PCR.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter introduces the methodology developed for this study. The aim of this research was to calculate PCR values after treatment and quantifying the performance jump after a specific treatment was performed. The NCDOT records its pavement data in two separate datasets: performance data and construction history. The two datasets were merged together, and the unified dataset was divided to obtain pavement and treatment families.

The treatment families were analyzed to identify performance jumps which involves several steps. Firstly, the ages of the sections with the jump were reset to zero and all the sections at age zero were removed, the model parameters were estimated from the data using the sigmoidal model form, and after-treatment PCR values for treatment families were calculated using the estimated parameters at age zero in the sigmoidal model equation. The model parameters were then used to create after-treatment performance curves showing the pavement performance after treatment. These curves were also compared with the performance curves before treatment. The methodology is same for both asphalt and concrete pavements, and is summarized by the flowchart in Figure 3.

3.2 Development of Pavement and Treatment Families

As mentioned earlier, two separate datasets were obtained from the NCDOT for their pavement data. These datasets include:

1. Windshield data for asphalt and concrete pavements
2. Statewide construction history

The windshield data comes under the category of pavement performance data and includes the pavement distress information from the survey, along with the rating number (PCR) and AADT information. It also includes the year when the condition of the section was surveyed, termed as effective year (EFF_YEAR). The records available were from the year 1982 to 2010, and 2014 to 2015. This information was vital for creating pavement family datasets. On the other hand, the construction data has the year in which the section was constructed or reconstructed (completion year or YEAR_COMP), as well as the history of treatments applied on the roadway sections from the year 1920 to 2016. The treatment history was important to subdivide the pavement families into treatment families. The route and county information for the sections is common to both datasets.

For both asphalt and concrete pavements, the performance data was merged with the construction data, matching the route and county information to develop a unified dataset. A number of samples were then removed from the unified dataset whose year of construction was later than the year when it was surveyed. This condition was necessary to eliminate the possibility of negative age being reported, as age of a section is the difference between the year it was completed (YEAR_COMP) and the year it was surveyed (EFF_YEAR).

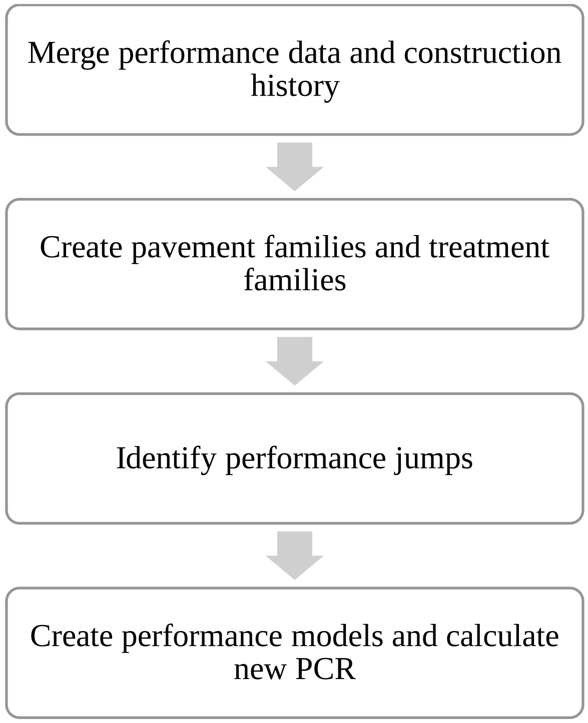
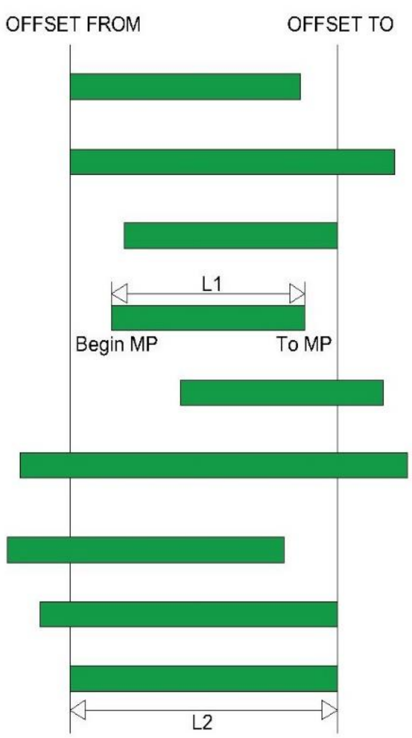


Figure 3: Methodology flowchart

The construction history and performance data record the length of the sections differently. In the construction data, section length is recorded between mileposts (recorded as Begin_MP and To_MP) whereas the performance data records section lengths within offsets (OFFSET_FROM and OFFSET_TO). The length of the section surveyed is often times different than the length of the section that was treated (Chen and Mastin 2015). The merging process matches the sections based on their route and county information which leaves a possibility that the mileposts are either partially or entirely outside of the offset lengths.

The mileposts ending before the beginning of the offset, or beginning after the end of the offset, were removed entirely while the partially overlapping sections were evaluated based on the nine situations that occurred because of the merging process shown in Figure

4. The sections with at least 50% of the distance between their mileposts lying within the offsets were kept and the rest were discarded. A threshold of 50% was selected after conversation with the NCDOT engineers. The threshold captures a large number of sections, while avoiding sections whose overlap is too short as the after-treatment performance ratings of these short sections cannot accurately represent the performance of the remaining section that were not treated. The resulting dataset was then divided by functional classification and AADT, as shown in Table 1.



	Keep the Roadway?
Situation #1	Yes, if L1>=0.5*L2
Situation #2	Yes
Situation #3	Yes, if L1>=0.5*L2
Situation #4	Yes, if L1>=0.5*L2
Situation #5	Yes, if L1>=0.5*L2
Situation #6	Yes
Situation #7	Yes, if L1>=0.5*L2
Situation #8	Yes
Situation #9	Yes

Figure 4: Nine situations arising as a result of the merging process

Table 1: Pavement Families

Functional Classification	AADT	Pavement Family
Interstate	0-50k	Interstate 0-50k
	>50k	Interstate 50k+
US Routes	0-5k	US 0-5k
	5-15k	US 5-15k
	15-30k	US 15-30k
	>30k	US 30k+
North Carolina Routes	0-1k	NC 0-1k
	1-5k	NC 1-5k
	5-15k	NC 5-15k
	>15k	NC 15k+
Secondary Routes	0-1k	SR 0-1k PR
	1-5k	SR 1-5k PR
	5-15k	SR 5-15k PR
	>15k	SR 15k+ PR
Concrete Pavements	All	JCP

Prior to the creation of the pavement families, the construction history was analyzed to extract the treatments recorded, which have been presented in Table 2. These 17 treatment types are common to both asphalt and concrete pavements, however not all of them are applied with the same frequency. Therefore, for this study, the treatments that had the most number of sections (Table 3 and Figure 5) were considered for analysis. Of these 17 treatment types, the sections for 'Resurface' and 'Resurface + Widen' were combined due to the similar nature of these two treatments.

Table 3 shows the sample sizes of the different treatment types in the pavement families for asphalt pavements, while Figure 5 displays the samples sizes in a bar chart. Five treatment types, AC construction/reconstruction, chip seal, JCP construction/reconstruction, mill and resurface, and resurfacing with widening have the most number of sections within them. JCP construction/reconstruction was not considered for analysis for asphalt pavements since it is not a treatment typical to asphalt pavements and its presence could be attributed to erroneous record keeping. Ultimately, the sections from the following four treatment types were selected for analysis:

1. AC Construction/Reconstruction
2. Chip Seal
3. Mill + Resurface
4. Resurface and Resurface + Widen

Similarly, Table 4 and Figure 6 show the number of sections for concrete pavements. Treatments such as asphalt and CRC construction/reconstruction, resurface and resurface + widen, mill and resurface were not considered for analysis due to their nature as treatments for asphalt pavements. Conversation with the NCDOT engineers revealed that some of the concrete pavements could have been converted into composite pavements and treated as asphalt pavements. This explains the presence of these roadway sections within the concrete pavement section. The most frequent treatments for concrete pavements include:

1. JCP Construction/Reconstruction
2. JCP Minor Rehab
3. Unbonded Concrete Overlay (UBC)

Each of the 14 asphalt pavement families, shown in Table 1, were subdivided into treatment families. For the asphalt pavements, chip seal treatment family for Interstate 0-50k and Interstate 50k plus were not considered since chip seal is not typically applied on Interstate highways. Therefore, a total of 56 asphalt treatment families were created. The 1 concrete pavement family was also subdivided into 3 concrete pavement treatment families.

Table 2: Treatment types used by NCDOT

Treatment Types
AC Construction/Recon
Chip Seal
Crack Seal
CRC Construction/Recon
JCP Construction/Recon
JCP Minor Rehab
Mill + Resurface
Mill + Resurface + Shoulder
Mill + Resurface + Widen
Patching
Rehab
Resurface
Resurface + Shoulder Work
Resurface + Widen
Shoulder Work
Unbonded Concrete Overlay (UBC)
Widen

Table 3: Number of roadway sections for asphalt pavement and treatment families

Treatment Type	Pavement Family				TOTAL	% of each treatment
	Interstate	US	NC	SR		
AC Construction/Recon	9,849	69,071	98,325	24,520	201,765	11.03%
Chip Seal	493	8,805	16,702	313,111	339,111	18.54%
Crack Seal	14	269	522	2,741	3,546	0.19%
CRC Construction/Recon	1,257	47	0	0	1,304	0.07%
JCP Construction/Recon	5,879	29,546	12,586	799	48,810	2.67%
JCP Minor Rehab	11	0	0	0	11	0.00%
Mill + Resurface	8,302	14,433	8,004	6,226	36,965	2.02%
Mill + Resurface + Shoulder	448	10	8	6	472	0.03%
Mill + Resurface + Widen	576	1,736	1,713	369	4,394	0.24%
Patching	137	149	176	556	1,018	0.06%
Rehab	507	58	53	23	641	0.04%
Resurface and Resurface + Widen	20,803	303,987	331,584	516,557	1,172,931	64.11%
Resurface + Shoulder	1,176	954	66	45	2,241	0.12%
Shoulder Work	3,409	221	130	32	3,792	0.21%
UBC	5	0	0	0	5	0.00%
Widen	841	6,516	3,732	1,380	12,469	0.68%

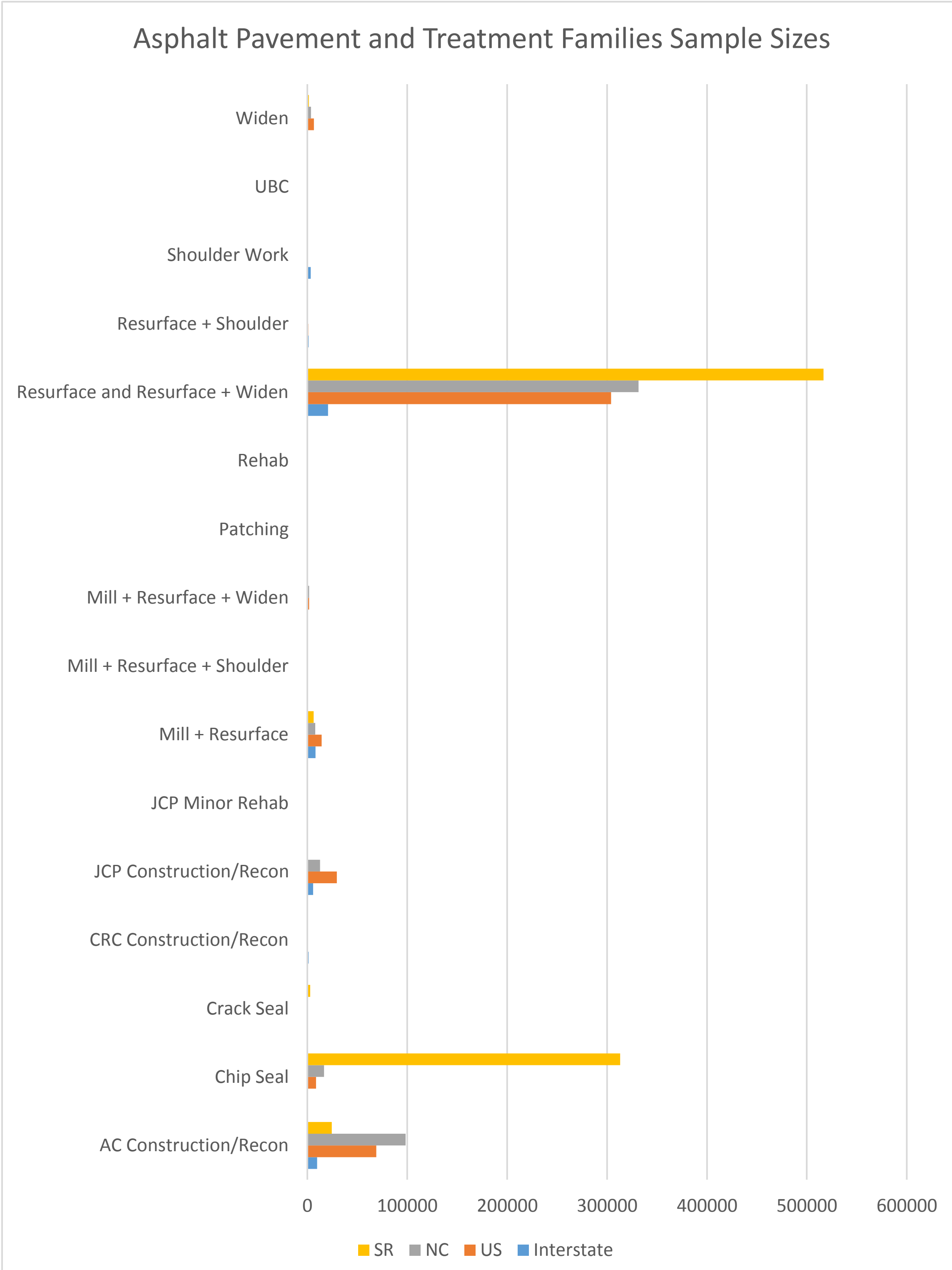


Figure 5: Number of roadway sections for asphalt pavement and treatment families

Table 4: Number of roadway sections for concrete treatment families

Treatment Type	JCP Family	% of each treatment
AC Construction/Recon	506	3.00%
Chip Seal	108	0.64%
Crack Seal	0	0.00%
CRC Construction/Recon	863	5.12%
JCP Construction/Recon	11,006	65.36%
JCP Minor Rehab	558	3.31%
Mill + Resurface	351	2.08%
Mill + Resurface + Shoulder	0	0.00%
Mill + Resurface + Widen	20	0.12%
Patching	0	0.00%
Rehab	20	0.12%
Resurface and Resurface + Widen	2,011	11.94%
Resurface + Shoulder	105	0.62%
Shoulder Work	921	5.47%
UBC	343	2.04%
Widen	28	0.17%

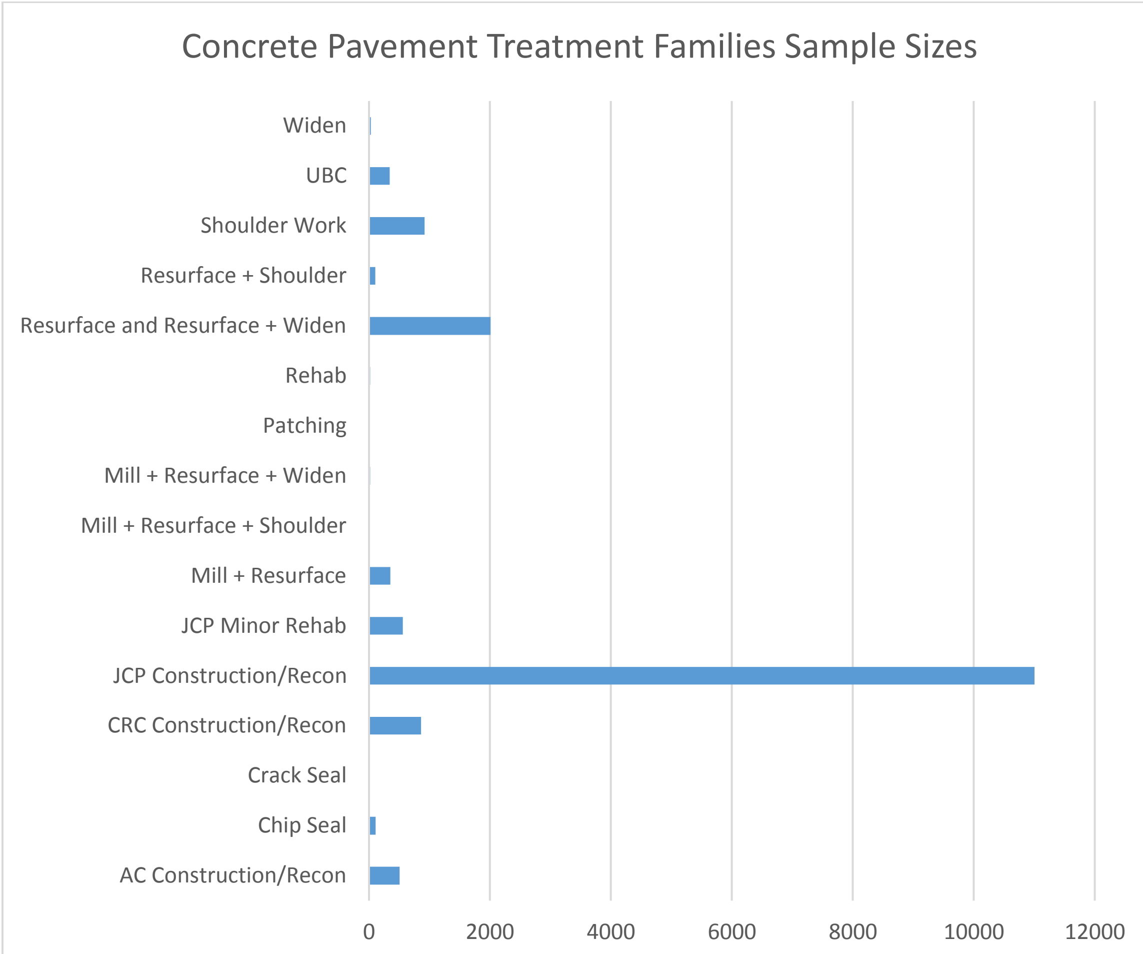


Figure 6: Number of roadway sections for concrete pavement treatment families

3.3 Identification of Roadway Sections Required for Analysis

As mentioned earlier, a performance jump occurs after a treatment is applied on a section. It was imperative for this research to identify these sections and calculate their post-treatment PCR values. The data points right before the sections identified with having a jump were also flagged to calculate pre-treatment PCR values. The pre-treatment PCR values was later used to calculate the performance jump as the difference between the pre and post-treatment PCR values.

3.3.1 Identifying Sections with Performance Jumps

It was essential to identify the roadway sections where treatment was applied, flag these observed jumps, and reset their age so their influence can be appropriately considered during the development of performance models for treatment families. The resetting of age ensures that when a jump is identified, the age at which it occurred is set to be zero, and the ages of subsequent data points be adjusted accordingly.

In order to identify these jumps, the data from the same roadway section was grouped together in ‘age groups’. The sections were grouped according to their route, their offset point (OFFSET_FROM), and the year they were completed which ensured that each age group contains the treatment history of one section over the years. These age groups enable the comparison of these sections using ‘Three-point method’. This method allows for the comparison of the PCR values of three consecutive sections to each other. Points are identified as either being erroneous and marked for deletion, or a jump and marked for their age to be reset. A graphical representation of this process is shown in Figure 7. A jump is identified when the difference between the PCR values of two points is greater than the threshold of 20. This threshold was identified in consultation with NCDOT engineers. Smaller jumps can be attributed to the subjective opinion of pavement raters (Chen et al. 2014), therefore a threshold smaller than 20 is not viable.

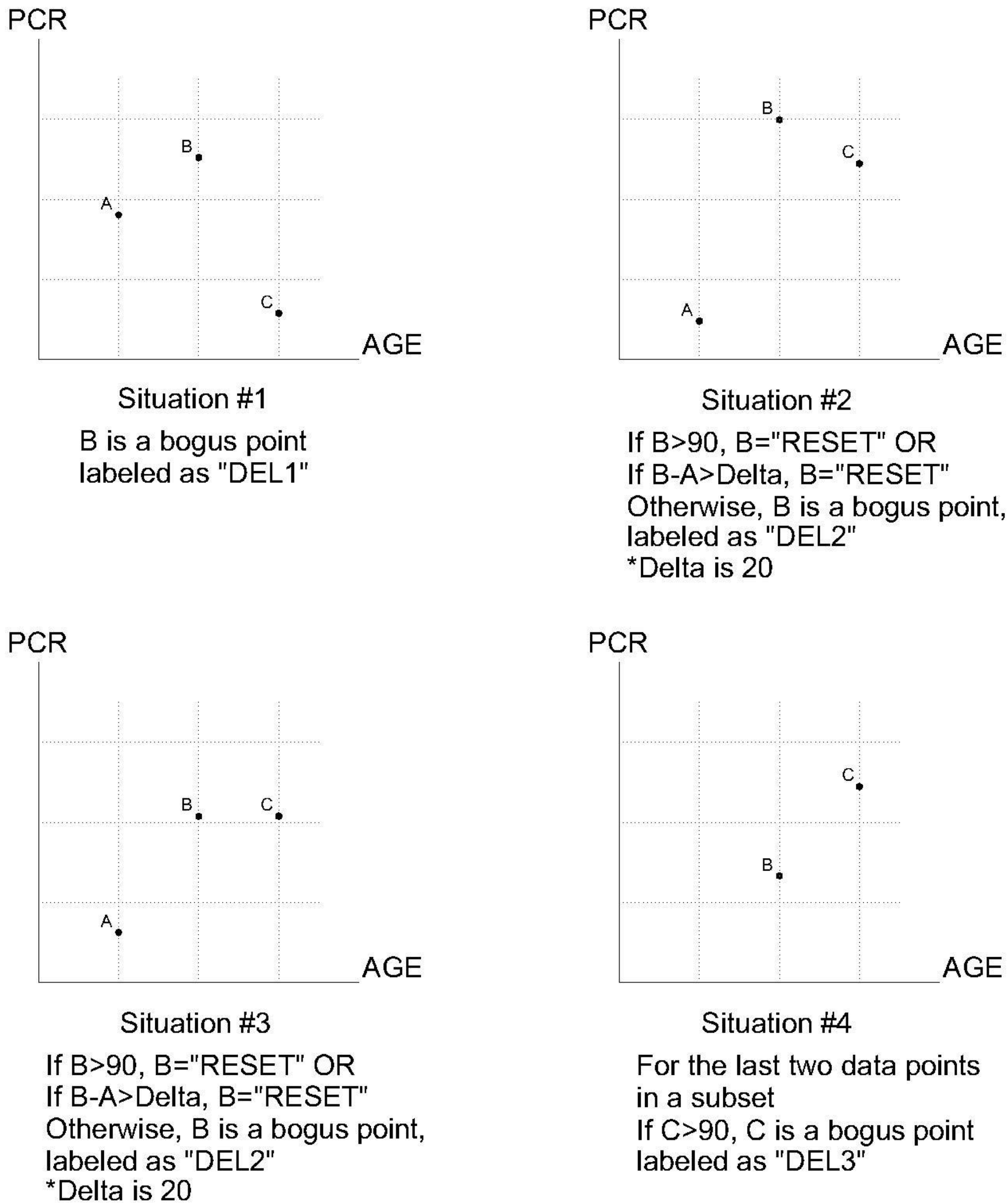


Figure 7: Comparing PCR of consecutive data points using Three-point method

3.3.2 Pre-Treatment PCR of Sections

After the identification of performance jumps, the age groups were further examined to identify the PCR values of roadway sections right before the treatment was applied. Not all age groups would have these data points, and the challenge was to make sure that a data point identified to be prior to an activity belonged within the same age group. Sections with age of 0 and PCR 100 were flagged, and the PCR values right before them were analyzed. If these data points were within the same age group as the flagged sections, they were marked as having an age of -1, meaning the year before a roadway section was treated, or 'reborn'. The pre-treatment PCR value was used to determine the calculated jump, as opposed to the observed jump of the pavement sections identified using the three point method. The calculated jump is the difference between the pre-treatment and post-treatment PCR values.

The PCR values of these sections were statistically analyzed to to obtain a pre-treatment PCR value for that pavement family. The first step in the analysis was to determine if the PCR values were normally distributed or not using SAS. If the data was not normally distributed, the next step was to transform the data into a normal distribution, calculate the mean, and retransform to the original distribution to determine the mean of the data. The transformation was carried out using Box-Cox power transformation, which is a common type of power transformation. The Box-Cox transformation is described as (Box and Cox 1964):

$$f(x) = \left\{ \begin{matrix} \dfrac{x^{\lambda} - 1}{\lambda} & \lambda \neq 0 \\ \ln(x) & \lambda = 0 \end{matrix} \right\}$$

Where:

x: PCR rating

λ: transformation parameter

The values of the transformation parameter (λ) are unique to each dataset, and were determined using SAS as described by Dimakos (1997).

3.4 Calculating Post-treatment PCR Values

Once the jumps were identified in the treatment families using the Three-point method, they were used to calculate the post-treatment PCR values. These values were calculated by substituting the estimated values of model parameters 'a', 'b', and 'c' in the sigmoidal model equation at age zero. The sigmoidal model form was used because it fits the performance data well (Chen et al. 2014).

The expression for the sigmoidal model is:

$$y = \frac{a}{1 + e^{-\frac{x-b}{c}}}$$

Where:

y: PCR rating

x: pavement age

a, b, c: model parameters

In order to improve the accuracy of these estimates, the first 20 years of data was selected and the outliers were removed using a method based on Interquartile ranges, which is a standard outlier removal method (Shoemaker 2008). For the first 10 years, PCR values below the first quartile (Q1) were deleted, whereas for the next 10 years PCR values above the third quartile (Q3) were removed. Additionally, all the data points at age zero were removed in order to estimate the after-treatment PCR value at age zero.

To develop nonlinear sigmoidal performance models, initial estimates of model parameters ‘a’, ‘b’, and ‘c’ were calculated and were then used to calculate final estimates of these parameters. These estimates were determined using SAS by a two-step process:

1. Linear regression of the sigmoidal model form to calculate the initial estimates, and
2. Non-linear regression of the sigmoidal model form to calculate the final estimates.

The initial estimate of parameter ‘a’ was chosen to be 100 since parameter ‘a’ determines the beginning of the curve and the curve would pass through the (0,100) point in before-treatment curves. On the other hand, parameters ‘b’ and ‘c’ determine the horizontal shift and slope of the curve respectively. The initial parameters were substituted in the sigmoidal equation to calculate the final values of these parameters. SAS allows the parameters to be either fixed as the provided value, or varying wherein the best estimate is calculated based on the data. In this case, parameter ‘c’ was kept fixed to its initial value, while parameters ‘a’ and ‘b’ were allowed to change to achieve the best fit. Tables 5a and 5b show the final values of the model parameters for asphalt pavements while Table 6 shows the values for concrete pavements. Once the final estimates of the model parameters were determined, these estimates were substituted into the equation and PCR for age zero was calculated. This new PCR value at age zero is the post-treatment PCR for treatment families.

Table 5a: Values of model parameters for asphalt treatment families

Final Estimates of Model Parameters		AC Construction/Recon			Chip Seal		
		a	b	c	a	b	c
Road Families	Interstate 0-50k	97.88	26.63	-4.55			
	Interstate 50k plus	93.83	28.80	-4.22			
	US 0-5k	93.07	19.51	-3.31	93.03	17.03	-3.40
	US 5-15k	93.44	22.27	-3.66	93.46	20.75	-4.59
	US 15-30k	94.77	27.02	-5.80	93.91	27.25	-6.49
	US 30k plus	98.13	42.62	-13.56	99.09	7.78	-1.52
	NC 0-1k	92.87	19.84	-3.52	93.85	19.77	-4.02
	NC 1-5k	92.65	18.58	-3.66	93.84	18.41	-3.67
	NC 5-15k	92.94	22.60	-4.17	92.38	22.92	-4.40
	NC 15k plus	93.66	25.03	-4.69	92.77	34.40	-5.84
	SR 0-1k	96.01	20.68	-3.09	93.49	17.28	-3.10
	SR 1-5k	95.41	19.74	-3.47	91.87	21.39	-4.08
	SR 5-15k	98.06	16.52	-2.61	92.75	28.67	-6.17
	SR 15k plus	94.51	20.96	-3.11	97.00	30.62	-9.00

Table 5b: Values of model parameters for asphalt treatment families (cont.)

Final Estimates of Model Parameters		Mill + Resurface			Resurface and Resurface + Widen		
		a	b	c	a	b	c
Road Families	Interstate 0-50k	94.99	23.99	-3.45	95.26	24.18	-4.03
	Interstate 50k plus	94.02	23.30	-3.18	94.42	28.30	-4.27
	US 0-5k	93.50	22.77	-3.81	92.82	18.61	-3.52
	US 5-15k	92.16	21.99	-3.36	91.62	18.99	-3.24
	US 15-30k	90.52	21.89	-3.72	91.81	19.54	-3.23
	US 30k plus	92.47	26.09	-4.86	94.27	22.11	-4.55
	NC 0-1k	92.99	25.97	-4.42	93.33	19.36	-3.03
	NC 1-5k	92.07	22.21	-2.95	92.29	18.67	-3.07
	NC 5-15k	90.56	19.49	-3.18	91.36	19.82	-3.36
	NC 15k plus	89.55	20.49	-3.56	92.29	20.44	-3.85
	SR 0-1k	95.37	19.42	-2.35	94.64	18.99	-2.74
	SR 1-5k	93.43	19.00	-2.74	93.00	17.98	-2.70
	SR 5-15k	92.37	20.88	-3.63	91.52	18.81	-3.01
	SR 15k plus	94.10	19.08	-3.48	91.16	20.12	-3.49

Table 6: Values of model parameters for concrete treatment families

Final Estimates of Model Parameters	JCP Construction/Recon			JCP Minor Rehab			UBC		
	a	b	c	a	b	c	a	b	c
JCP	100	20.00	-7.40	100	9.70	-2.24	97.34	255.8	-84.6

3.5 After-treatment Performance Curves

The final estimates of model parameters presented in Table 5a, 5b, and 6 were used to create after-treatment performance curves for the treatment families. These performance curves exhibit the pavement performance of a section after treatment. Figure 8 shows an example of an after-treatment performance curve, created using Maple, based on the final model parameters, with the post-treatment PCR value which is lower than 100. The rest of the curves are presented in Appendix A.

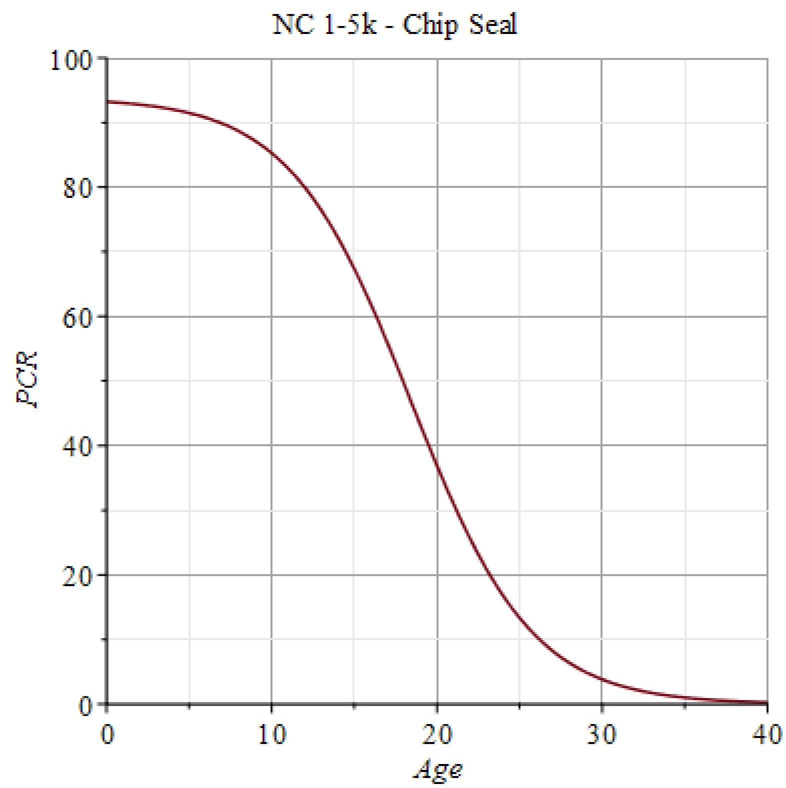


Figure 8: After-treatment performance curve

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results of the calculations for pre-treatment and post-treatment PCR values. The results for asphalt pavement are presented first, followed by the results for concrete pavements. No pre-treatment PCR values were calculated for concrete pavements due to their small number of roadway sections.

4.2 Results for Asphalt Pavements

4.2.1 Post-treatment PCR Values for Asphalt Pavements

Table 7 presents the post-treatment PCR values for asphalt pavements. No values were recorded for chip seal in Interstate pavements since chip seal treatment is not typically applied to interstate highways.

4.2.2 Pre-treatment PCR Values for Asphalt Pavements

Pre-treatment PCR values were determined to calculate the performance jump after post-treatment PCR values were obtained. The PCR values of the sections identified as having and age of '-1' i.e. PCR values before a treatment was applied, were analyzed to determine if they were normally distributed or not. The analysis revealed that these values were not normally distributed, and a transformation was necessary to determine an appropriate pre-treatment PCR value. Each treatment family was analyzed separately to determine its transformation parameter (λ), which was then used in the Box-Cox transformation to normally distribute the data and the mean was recorded for that distribution. This mean was then retransformed to the original distribution to determine the mean of the treatment family. The pre-treatment PCR values for asphalt pavements are shown in Table 8.

Table 7: Post-treatment PCR values for asphalt pavements

PCR Values for Asphalt Pavements		Treatment Types			
		AC Construction/ Recon	Chip Seal	Mill + Resurface	Resurface and Resurface + Widen
Pavement Families	Interstate 0-50k	97.60		94.90	95.03
	Interstate 50k plus	93.73		93.96	94.30
	US 0-5k	92.82	92.41	93.27	92.35
	US 5-15k	93.22	92.45	92.03	91.36
	US 15-30k	93.88	92.52	90.26	91.59
	US 30k plus	94.07	98.51	92.05	93.54
	NC 0-1k	92.54	93.17	92.73	93.18
	NC 1-5k	92.07	93.23	92.02	92.07
	NC 5-15k	92.53	91.88	90.36	91.11
	NC 15k plus	93.21	92.51	89.26	91.84
	SR 0-1k	95.90	93.14	95.35	94.54
	SR 1-5k	95.09	91.39	93.34	92.89
	SR 5-15k	97.89	91.86	92.08	91.34
	SR 15k plus	94.40	93.88	93.71	90.88

Table 8: Mean of pre-treatment PCR values for asphalt pavements

Mean of Pre-treatment PCR values		Asp Con/Recon	Chip Seal	Mill + Resurface	Resurface/Resurf + Widen
Road Families	Interstate 0-50k	78.03		72.00	76.88
	Interstate 50k plus				
	US 0-5k	60.51	62.67	61.39	64.25
	US 5-15k	66.53	61.82	63.64	66.17
	US 15-30k	71.15		68.18	72.95
	US 30k plus	65.14		69.46	65.59
	NC 0-1k	62.68	70.14		70.85
	NC 1-5k	64.49	61.98	62.46	65.80
	NC 5-15k	63.67	58.89	61.42	65.95
	NC 15k plus	65.13		58.14	65.30
	SR 0-1k	82.86	70.86		73.85
	SR 1-5k	60.82	59.54		67.97
	SR 5-15k	66.74	60.88	63.67	66.84
	SR 15k plus				72.74

There are some omissions in Table 8. These values were omitted because of their small sample sizes, as the pre-treatment PCR value of treatment families with less than 30 sections was not calculated.

4.2.3 Calculated Jumps

The difference between the pre-treatment and post-treatment values is the calculated jump and it shows the condition improvement after a treatment is applied. Tables 9a and 9b provide the pre-treatment and post-treatment PCR values for asphalt treatment families, as well as the difference between the two values. Tables 9a and 9b also provide the averages of the pre-treatment and post-treatment values, and the average of the performance jumps.

The post-treatment PCR values of treatment families was omitted for the treatment families whose pre-treatment PCR was not determined.

Table 9a: Pre and Post-treatment PCR values with jumps for asphalt pavements

Pre and Post Treatment Values		AC Construction/Recon			Chip Seal		
		Pre	Post	Jump	Pre	Post	Jump
Road Families	Interstate 0-50k	78.03	97.60	19.57			
	Interstate 50k plus						
	US 0-5k	60.51	92.82	32.31	62.67	92.41	29.74
	US 5-15k	66.53	93.22	26.69	61.82	92.45	30.63
	US 15-30k	71.15	93.88	22.73			
	US 30k plus	65.14	94.07	28.93			
	NC 0-1k	62.68	92.54	29.86	70.14	93.17	23.03
	NC 1-5k	64.49	92.07	27.58	61.98	93.23	31.25
	NC 5-15k	63.67	92.53	28.86	58.89	91.88	32.99
	NC 15k plus	65.13	93.21	28.08			
	SR 0-1k	82.86	95.90	13.04	70.86	93.14	22.28
	SR 1-5k	60.82	95.09	34.28	59.54	91.39	31.85
	SR 5-15k	66.74	97.89	31.15	60.88	91.86	30.98
	SR 15k plus						
Average		67.31	94.24	26.92	63.35	92.44	29.09

Table 9b: Pre and Post-treatment PCR values with jumps for asphalt pavements (cont.)

Pre and Post Treatment Values		Mill + Resurface			Resurface and Resurface + Widen		
		Pre	Post	Jump	Pre	Post	Jump
Road Families	Interstate 0-50k	72.00	94.90	22.90	76.88	95.03	18.15
	Interstate 50k plus						
	US 0-5k	61.39	93.27	31.88	64.25	92.35	28.10
	US 5-15k	63.64	92.03	28.39	66.17	91.36	25.19
	US 15-30k	68.18	90.26	22.08	72.95	91.59	18.64
	US 30k plus	69.46	92.05	22.59	65.59	93.54	27.95
	NC 0-1k				70.85	93.18	22.33
	NC 1-5k	62.46	92.02	29.56	65.80	92.07	26.27
	NC 5-15k	61.42	90.36	28.94	65.95	91.11	25.16
	NC 15k plus	58.14	89.26	31.12	65.30	91.84	26.54
	SR 0-1k				73.85	94.54	20.70
	SR 1-5k				67.97	92.89	24.91
	SR 5-15k	63.67	92.08	28.41	66.84	91.34	24.50
	SR 15k plus				72.74	90.88	18.14
Average		64.48	91.80	27.32	68.86	92.44	23.58

The results indicate that, on average, the pavements are being treated when the PCR is in the range of 63 to 67, with pavements section in resurface/resurface and widen families are treated earlier than other families. Resurfacing treatments are usually less intensive which is evident from the fact the treatment shows the lowest average calculated jump and the second lowest PCR value after treatment. Asphalt construction and reconstruction shows the highest posttreatment PCR value since it is a very intense treatment and it would mitigate a large number of distresses in the pavements. Chip seal exhibits the highest average calculated jump despite it being a less intensive treatment and mostly used on low volume roads. Conversation with NCDOT engineers revealed that the practices of the agency while applying chip seal treatments were instrumental in providing a high-quality pavement, thus explaining the higher calculated jump.

Tables 9a and 9b show that Interstate routes are not allowed to deteriorate too much and are treated at a higher threshold than other pavements. For example, the pre-treatment PCR values for Interstate 0-50k families are either close to 70 or above. The sections that are allowed to deteriorate to low PCR values show a high jump, however their post-treatment PCR values are relatively lower. For example, NC 15k plus family had a pre-treatment PCR of 58.14 when mill and resurface was applied, and although the calculated jump of 31.12 was above the average of 27.32 for mill and resurfacing, the post-treatment PCR was below 90. From Tables 9a and 9b, most likely an early treatment can ensure a better pavement condition after maintenance.

4.3 Results for Concrete Pavements

4.3.1 Post-treatment PCR Values for Concrete Pavements

Post-treatment PCR values for concrete pavements were calculated in a similar manner to the jumps of asphalt pavement, but concrete treatment families had a smaller sample size. Table 10 shows the new PCR values for concrete pavements.

Table 10: Post-treatment PCR values for concrete pavements

PCR Values for Concrete Pavements	Treatment Types		
	JCP Construction/Recon	JCP Minor Rehab	UBC
JCP	95.22	99.96	92.83

JCP minor rehab showed the highest post-treatment PCR, followed by JCP construction and reconstruction. It was expected that construction and reconstruction would exhibit a higher post-treatment PCR value, but minor rehab having a smaller sample size could explain its highest PCR value. Unbonded concrete overlay had a smaller post-treatment PCR value than JCP construction and reconstruction, which is reasonable because JCP construction and reconstruction is a more intense treatment.

4.4 Comparison of Before and After-Treatment Performance Curves

Performance curves after treatment were created using the model parameters estimated during the calculation of after-treatment PCR values. These curves document the performance of the pavement after a treatment is applied. The after-treatment performance curves were compared with the performance curves before treatment, which were developed by Chen et al. (2014) for the NCDOT. Although the authors did not develop treatment families in their study, the before treatment curves developed for the roadway families represent the performance of that roadway family for all treatments. These curves can be compared to after-treatment performance curves for treatment families developed within this study.

The comparison of the performance curves shows that after a treatment is applied, the pavement deterioration can either be similar or different to the deterioration before treatment. Figure 9 shows the performance curves of NC 1-5k where the before and after treatment are relatively parallel to each other in the first 20 years. This means that the deterioration of NC 1-5k after asphalt construction and reconstruction treatment is applied is similar to the deterioration it experiences over the years before any treatment is applied.

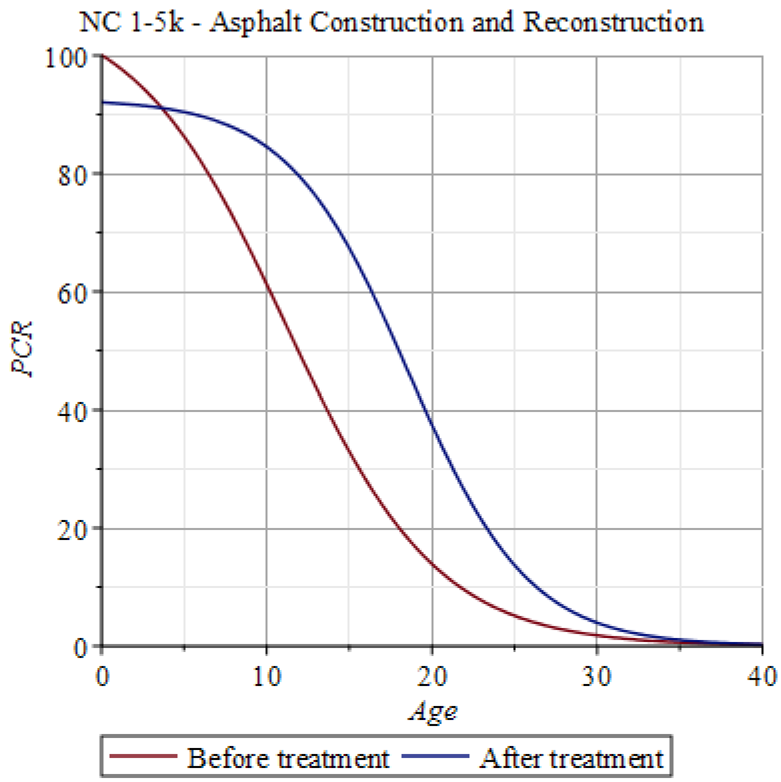


Figure 9: Parallel performance curves

When it comes to the performance curves having different deterioration, the after treatment performance curve could either move away or come close to the performance curve before treatment. If the after-treatment curve moves away then the treatment is providing greater benefits, as the condition of that pavement will reach its service life later than it would. Figure 10 shows the performance curves for US 15-30k, where the after-treatment curve is moving away from the before treatment curve. For US 15-30k family, asphalt construction and reconstruction is a good choice based strictly on the improvement in performance it provides.

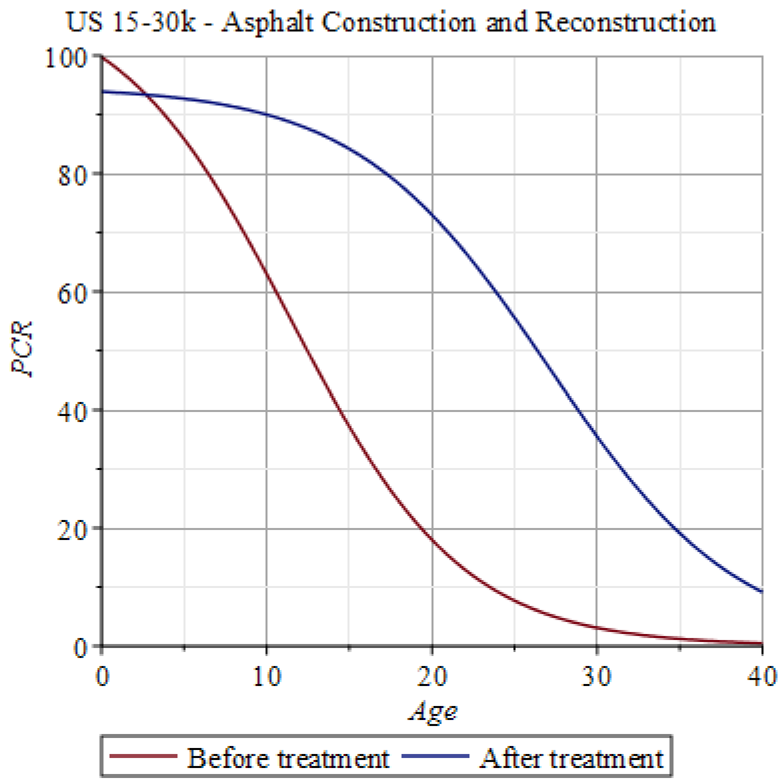


Figure 10: After-treatment performance curve moving away from the before-treatment curve

If the after-treatment curve is close to the curve before treatment, then the treatment being applied is not appropriate, and a different treatment should be utilized. Figure 11 shows the performance curves for SR 0-1k, where the after-treatment curve is moving closer to the before treatment curve and meeting it. This shows that for SR 0-1k, chip seal might not be a good treatment option when it comes to its performance, and a different treatment should be considered. The comparisons for the rest of the treatment families have been provided in Appendix B.

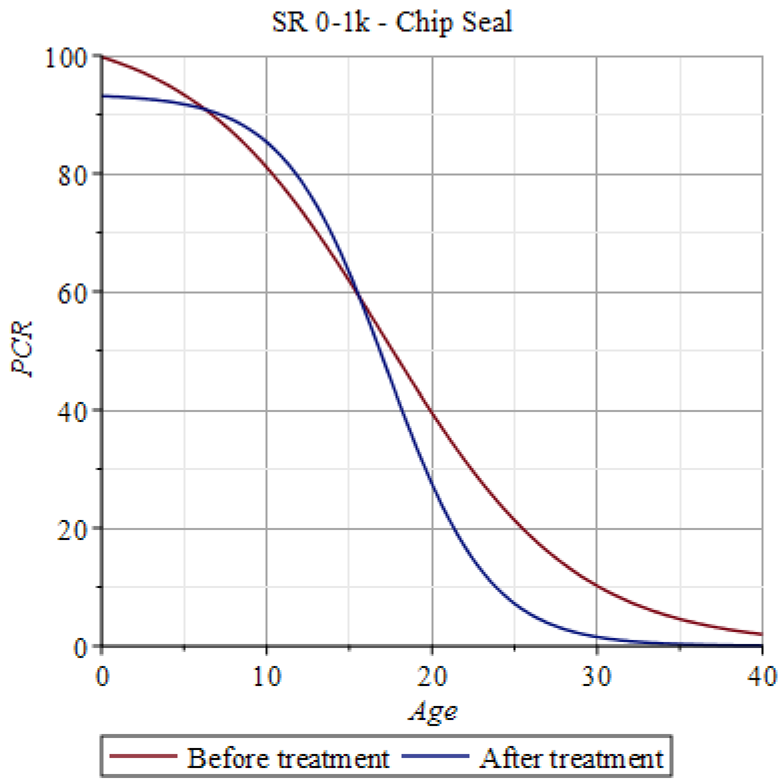


Figure 11: After-treatment performance curve coming closer to before-treatment curve

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

The aim of this research was to determine performance jumps after a treatment is applied. This was achieved by analyzing the data provided by NCDOT of the most common treatments for both asphalt and concrete pavements, and identifying the performance jumps within the family datasets. The sigmoidal model form was used to estimate model parameters and calculate the post-treatment PCR at age zero. These model parameters were then used to create after-treatment performance curves to exhibit the pavement performance after treatment.

Providing appropriate PCR values after treatment makes the benefits achieved from the treatments more realistic in terms of the type of treatment applied. These values, along with the after-treatment performance curves developed in this study, can help NCDOT engineers make better predictions about the state of their pavements. This will ultimately help them make informative investment decisions for the different stages in a pavements service life. The after-treatment performance curves can enable the selection of the treatment that provides the most benefits and slower deterioration, ensuring that treatment would be required at a later stage in a pavements life and thus providing financial benefits.

5.1 Summary of Results

The average post-treatment PCR values for asphalt pavement treatments are 94.24 for asphalt construction and reconstruction, 92.44 for chip seal, 91.80 for mill and resurfacing, and 92.44 for resurfacing/resurfacing and widening. The average pre-treatment PCR values for the four asphalt pavement treatment families are 67.31, 63.35, 64.48, and 68.86 for asphalt construction and reconstruction, chip seal, mill and resurfacing, and resurfacing/resurfacing and widening respectively. Chip seal had the highest calculated jump of 29.09, followed by asphalt construction and reconstruction with 26.92 and mill and resurfacing with 27.32. Resurface/resurface and widening had the lowest calculated jump with 23.58.

When it comes to concrete pavement families, the post-treatment values are 95.22 for JCP construction and reconstruction, 99.96 for JCP minor rehab, and 92.83 for unbonded concrete overlay. No pre-treatment PCR values were recorded for concrete pavements as they were flagged as outliers and removed.

5.2 Conclusions

Some treatments had a higher average post-treatment PCR value due to their intense nature, such as asphalt construction and reconstruction which had the highest PCR value after treatment. Resurfacing and resurfacing had the lowest calculated jump, however the pre-treatment PCR values of the sections being resurfaced were the highest indicating that those sections were treated earlier. High volume roads were also being treated earlier as evident from their high pre-treatment PCR values. Although the results indicate that some treatments are more effective than others, the results should be considered along with the performance curves developed in this study, as the sections would behave differently over time and may require treatment at different stages of their life. Sections with lower pre-treatment PCR values than average exhibited a higher jump but their posttreatment PCR values were lower than average. This indicates that the performance of a pavement section should not only be evaluated by its post-treatment PCR value, but also over its entire service life.

5.3 Recommendations for Future Research

Following are the recommendations for future studies. It is recommended that pavement condition data from automated survey should be used to calculate the performance jumps. Although the NCDOT uses both manual and automated survey methods to collect data, this study used data from manual survey since the records were extensive. However, the manual data exhibits variations due to the subjective opinion of human raters (Chen and Mastin 2015). Data collected through automated techniques can provide more accurate results.

It is recommended that influence of pre-treatment conditions should be considered in the calculations for performance jumps. Pavement condition before treatment has a significant impact on the pavement performance after treatment (Dean and Baladi 2013). A more accurate analysis can be performed by considering the effect of the pavement condition before treatment.

It is recommended that the influence of factors associated with treatments be considered. This study focused on the dominant types of treatments applied, but future studies may focus on the materials used in these treatments, the thicknesses of overlays, and the effects of treatment combinations.

It is recommended that the impact of early treatment be studied. In this study, some roadway sections treated by resurfacing and resurfacing were treated earlier and had the lowest performance jump. Deferring resurfacing these roadway sections might ease budget constraints and incur greater benefits.

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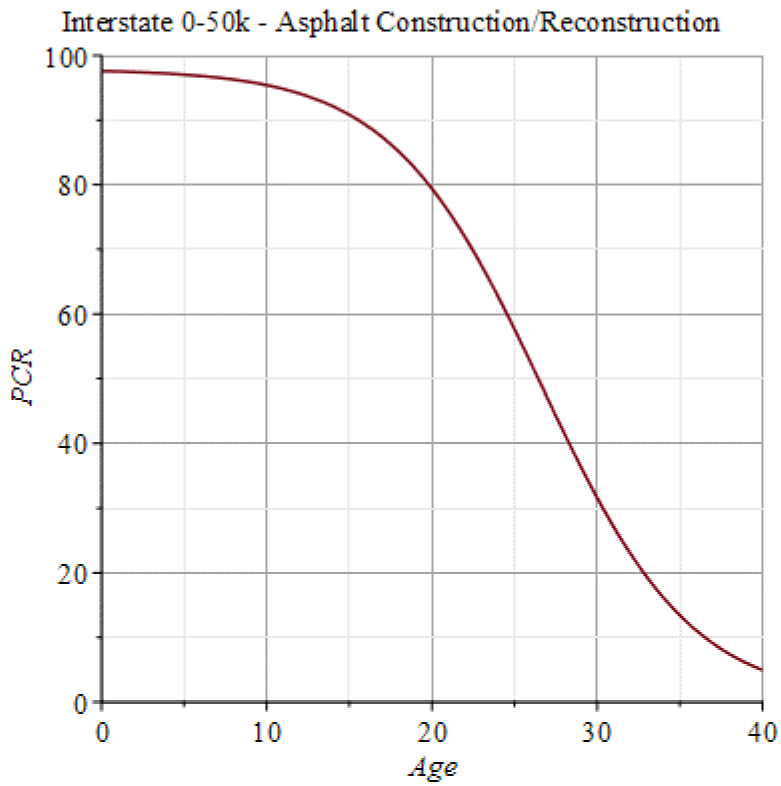
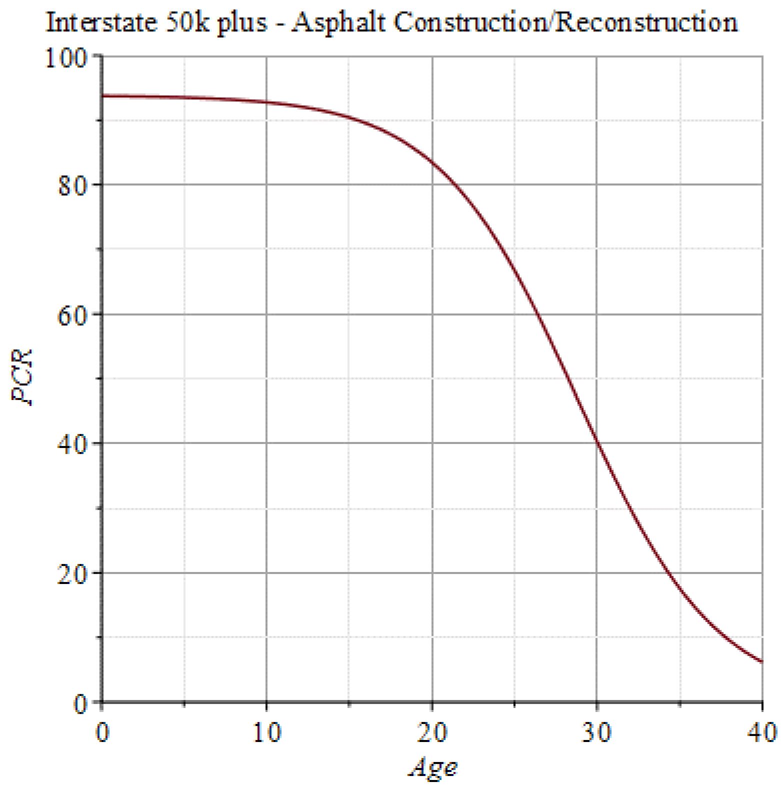
APPENDIX A: AFTER-TREATMENT PERFORMANCE CURVES

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PCR
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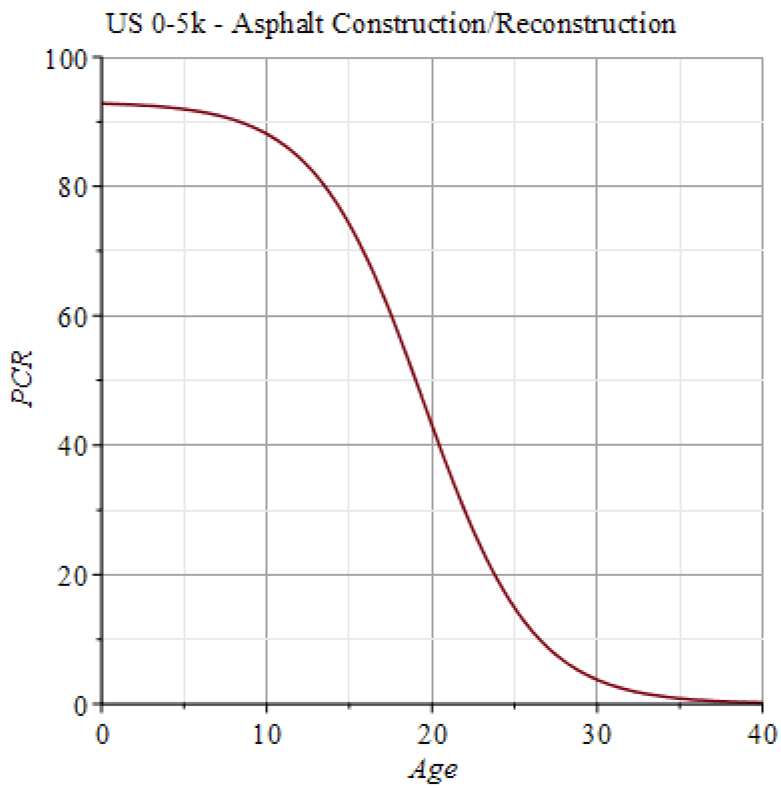
Age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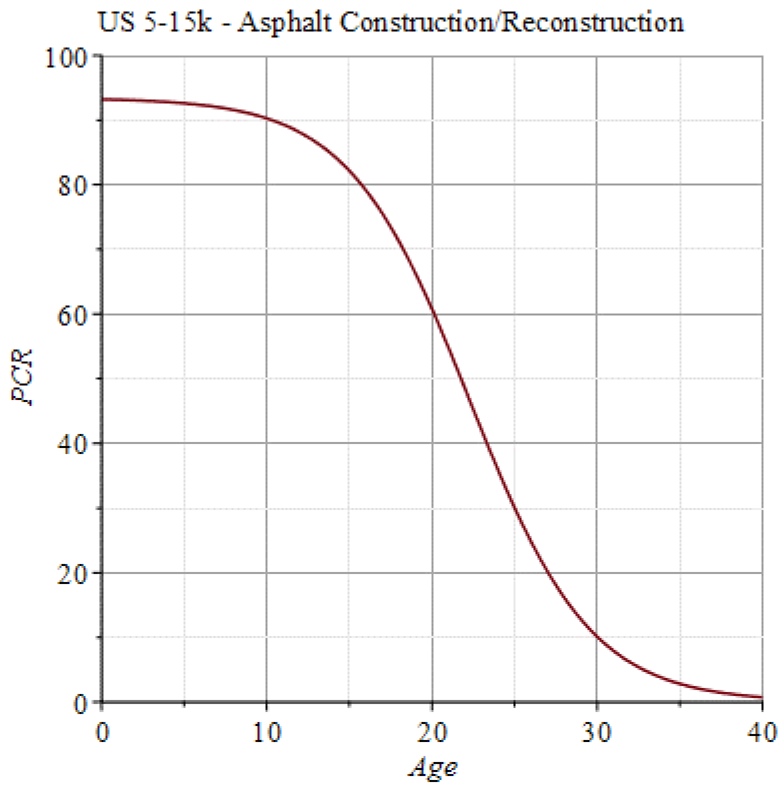
Age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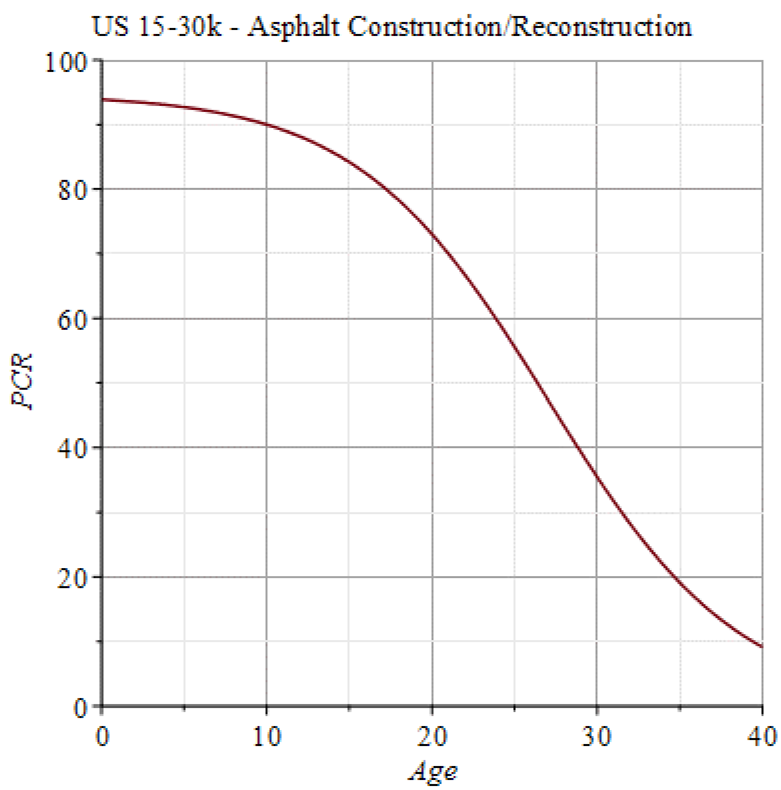
Age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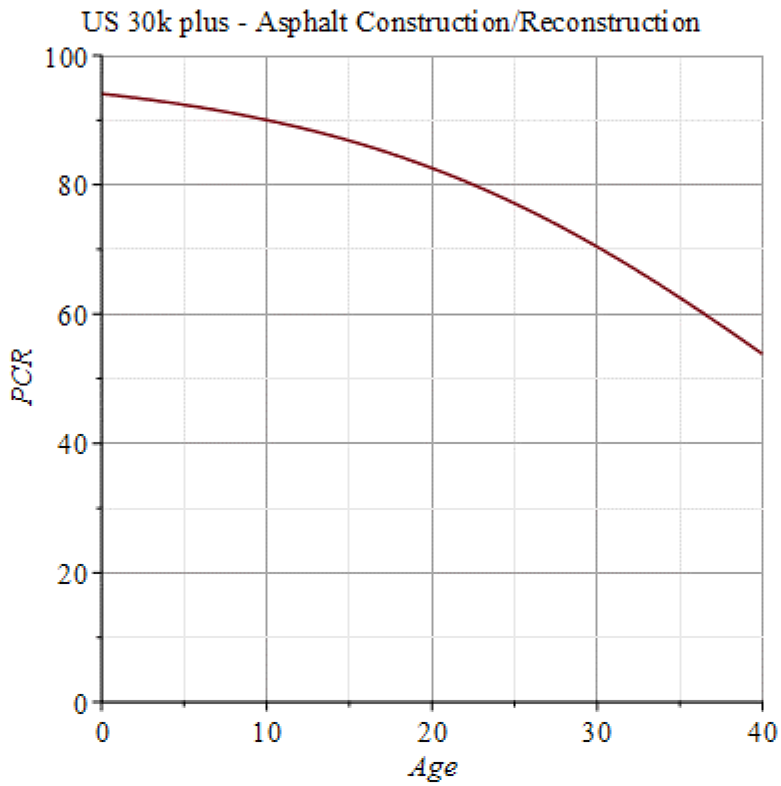
Age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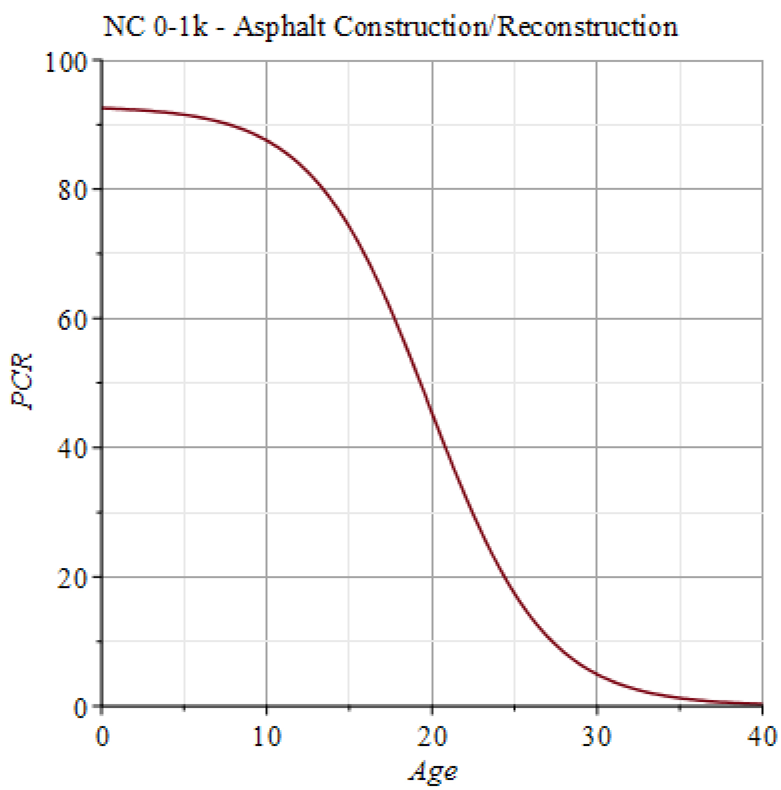
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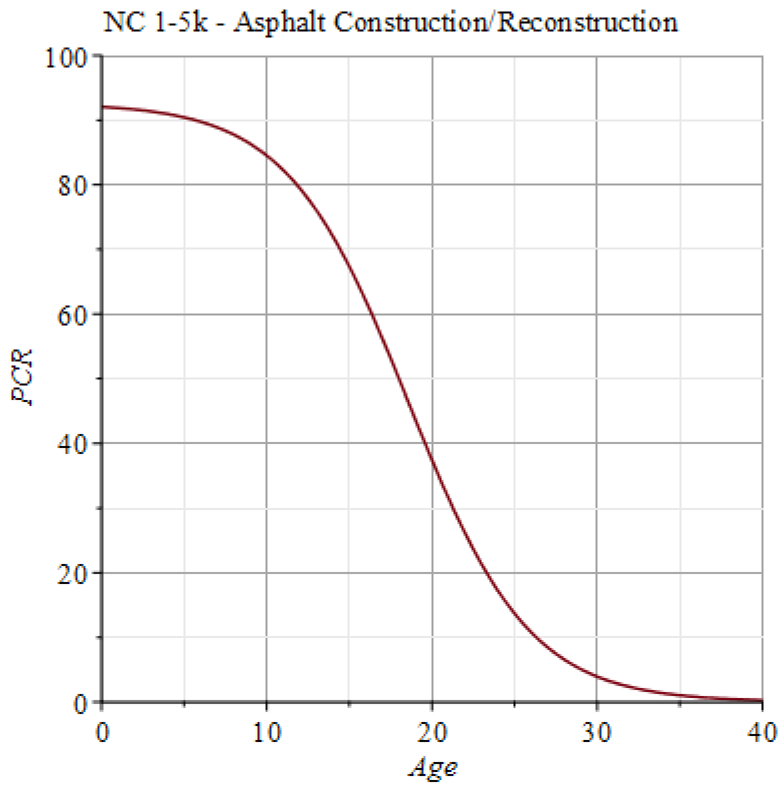
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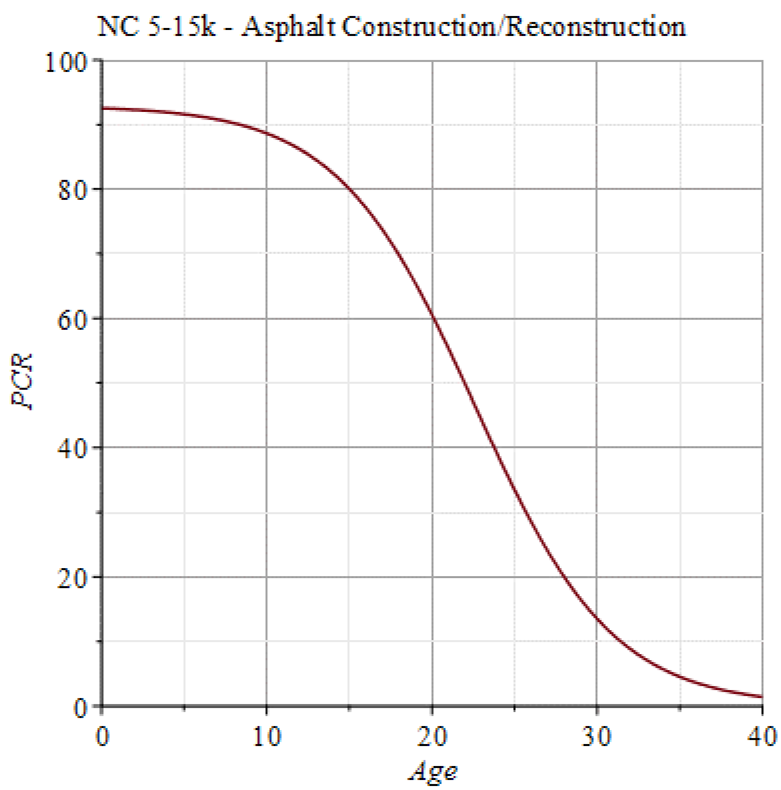
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Age

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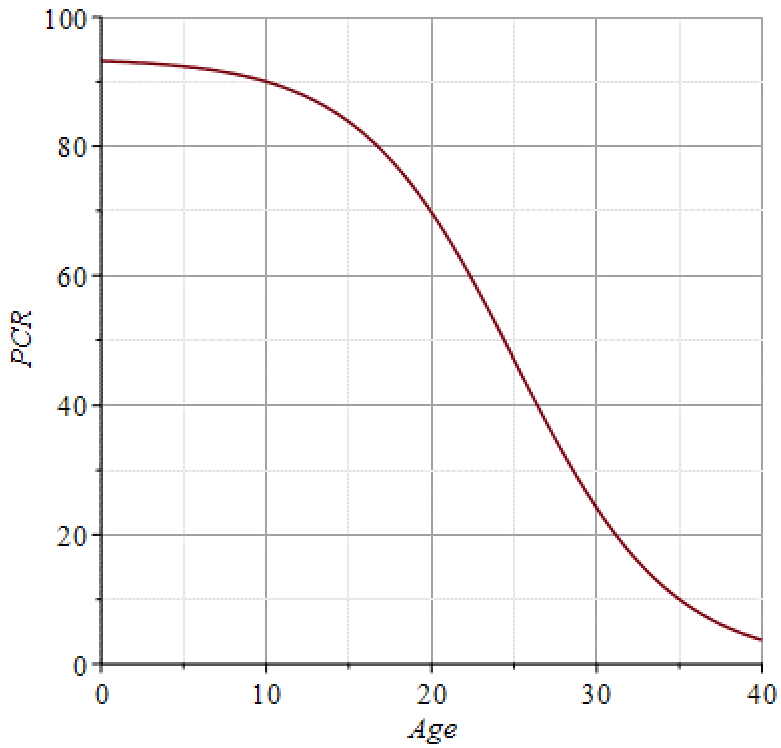

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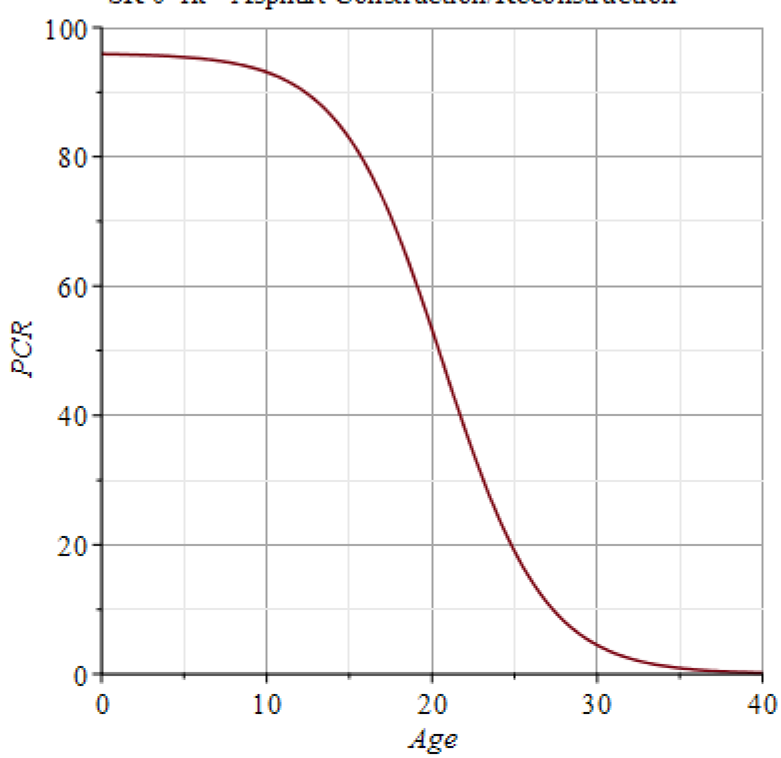

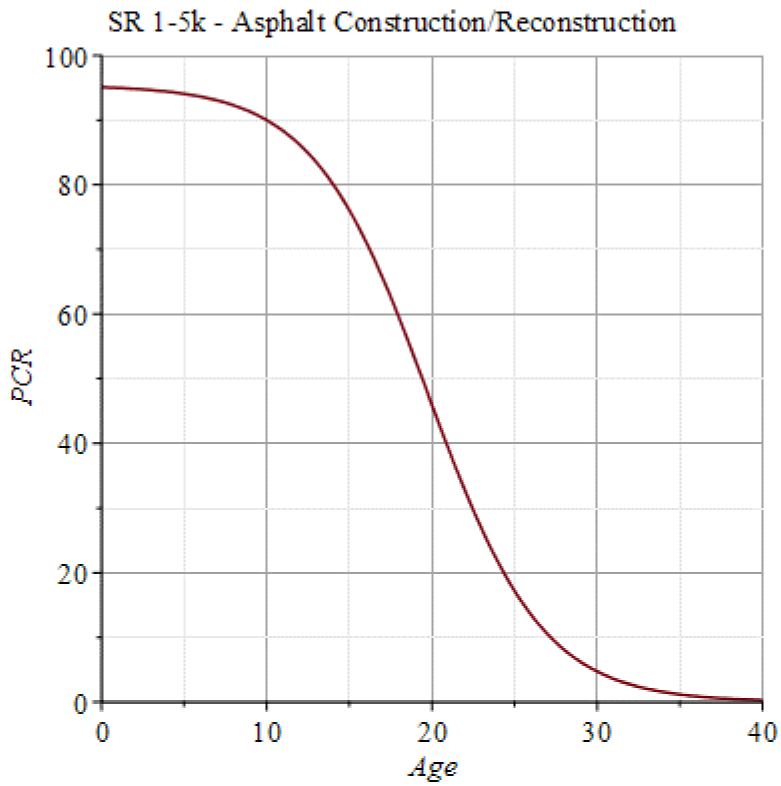
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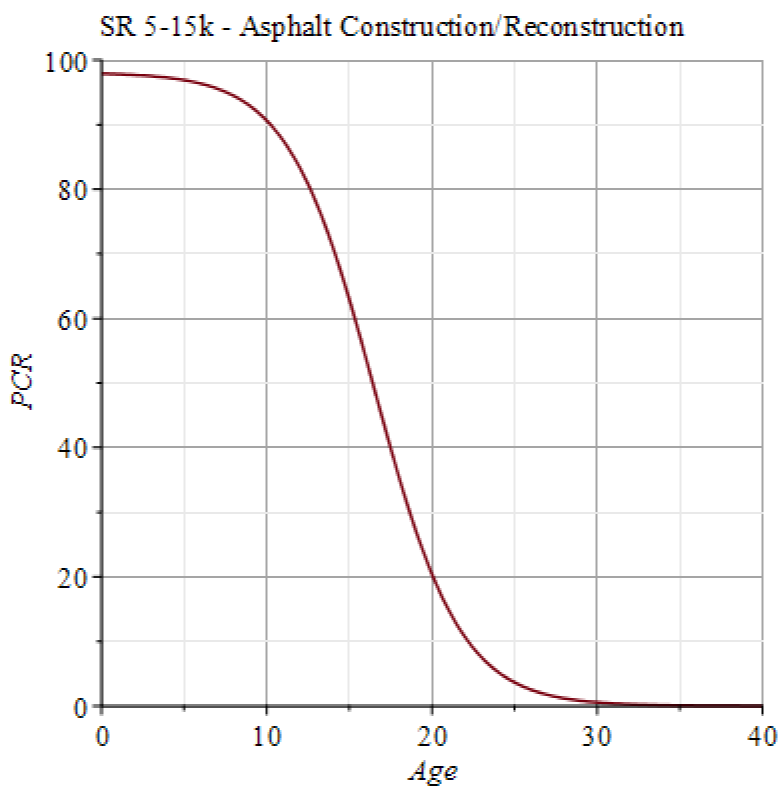
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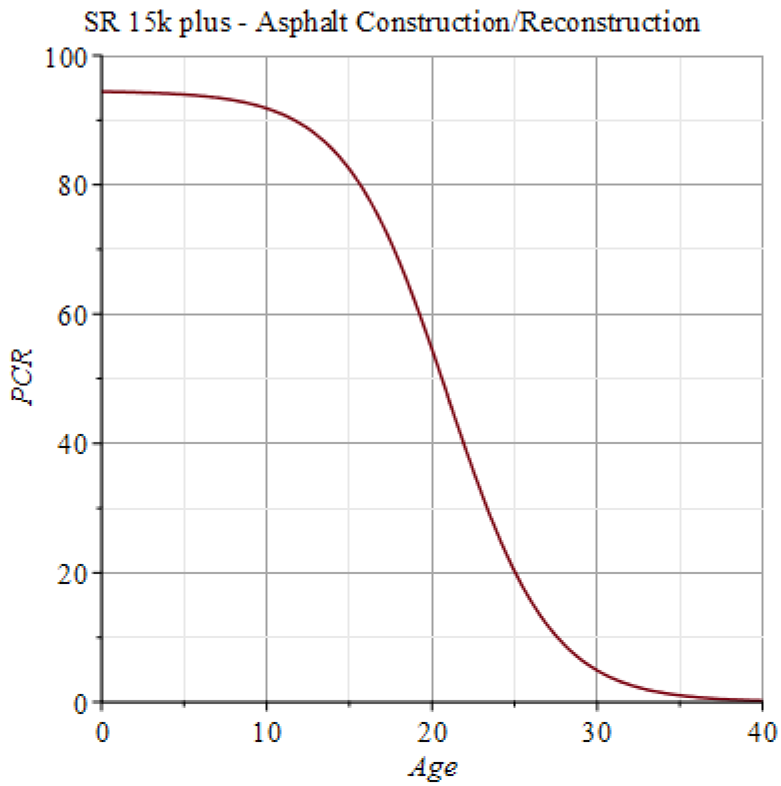
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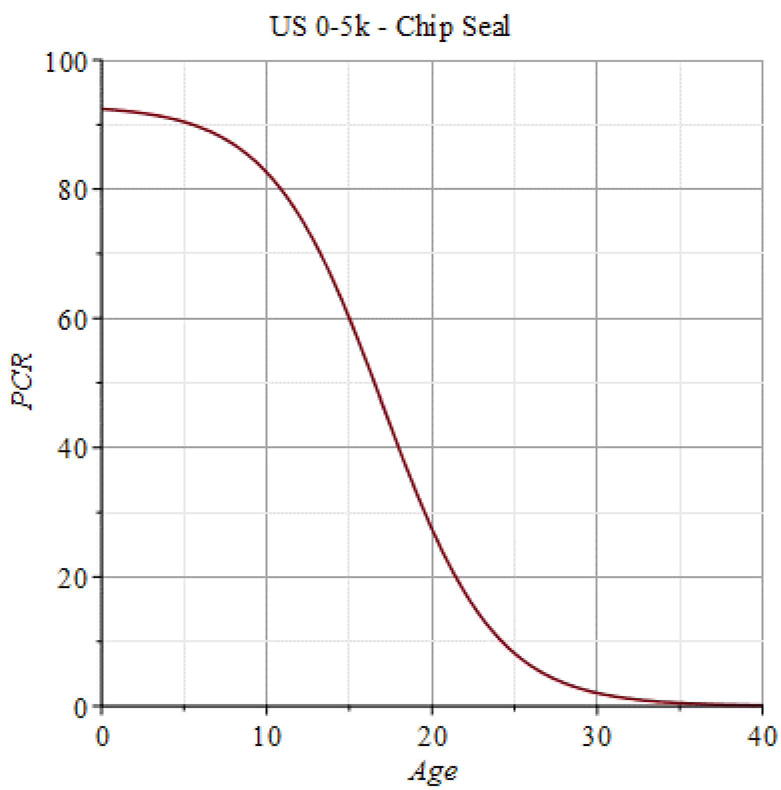
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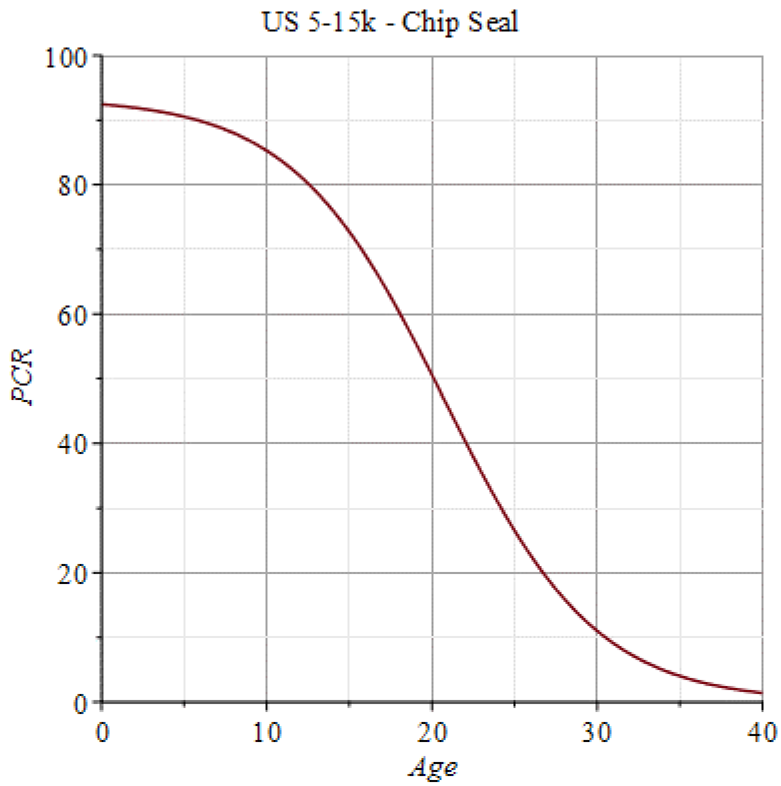
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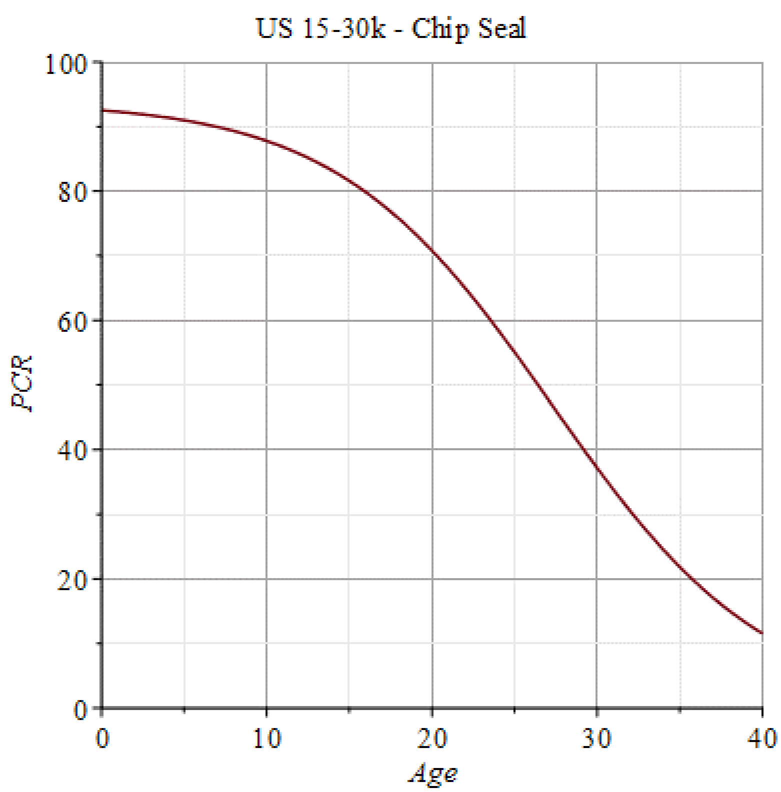
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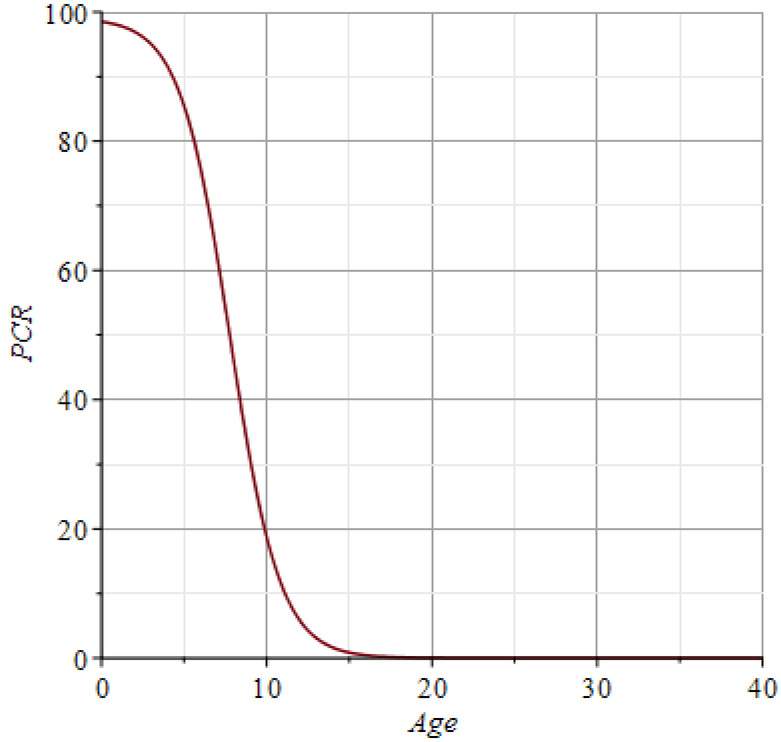
US 30k plus - Chip Seal



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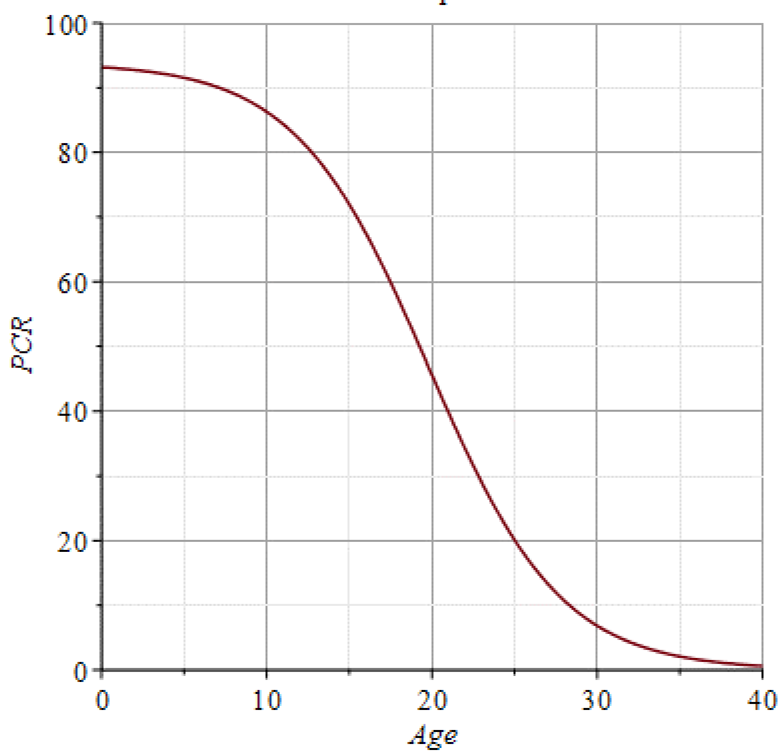

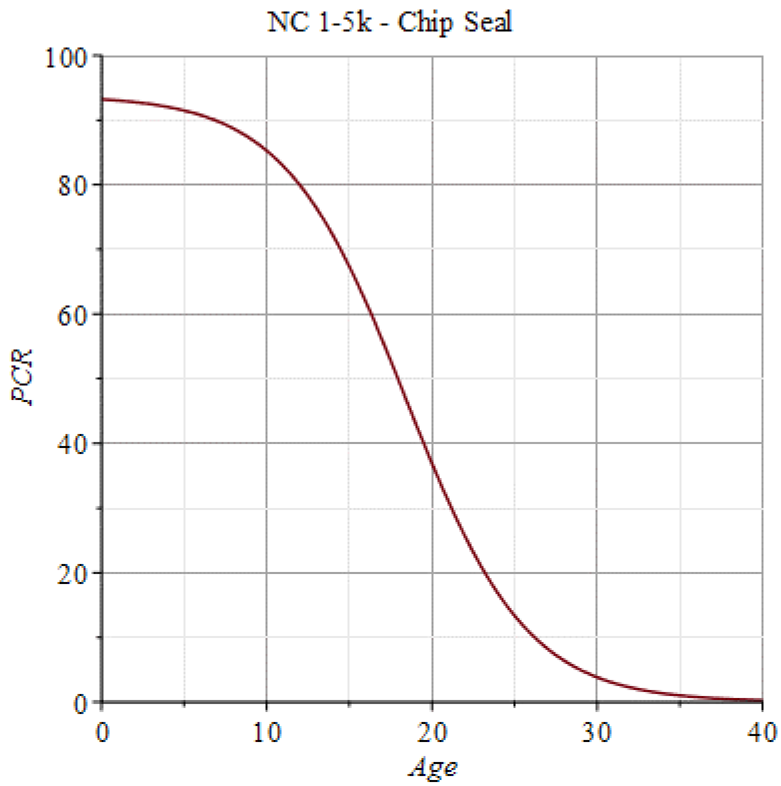
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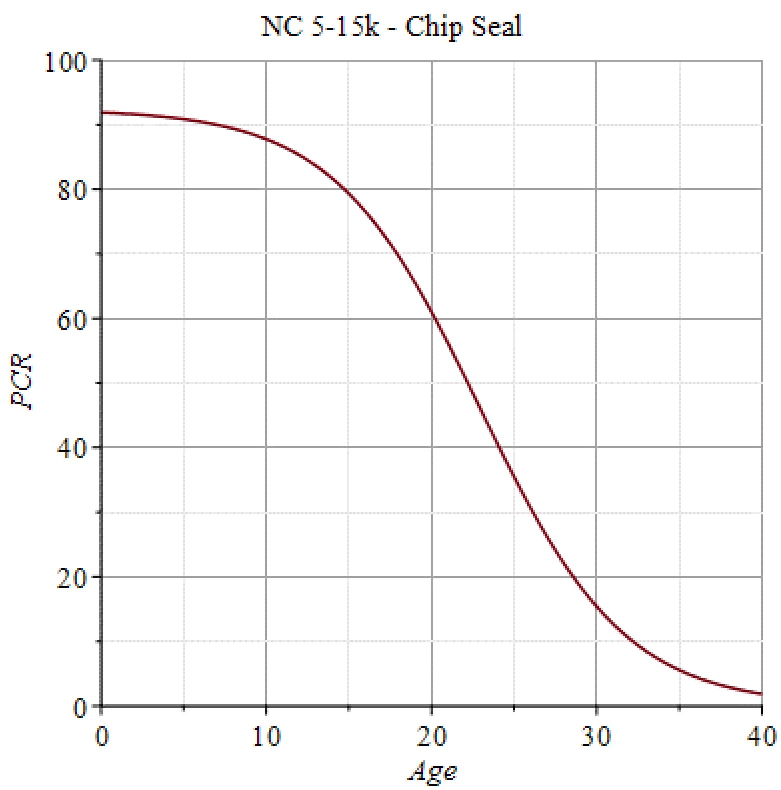
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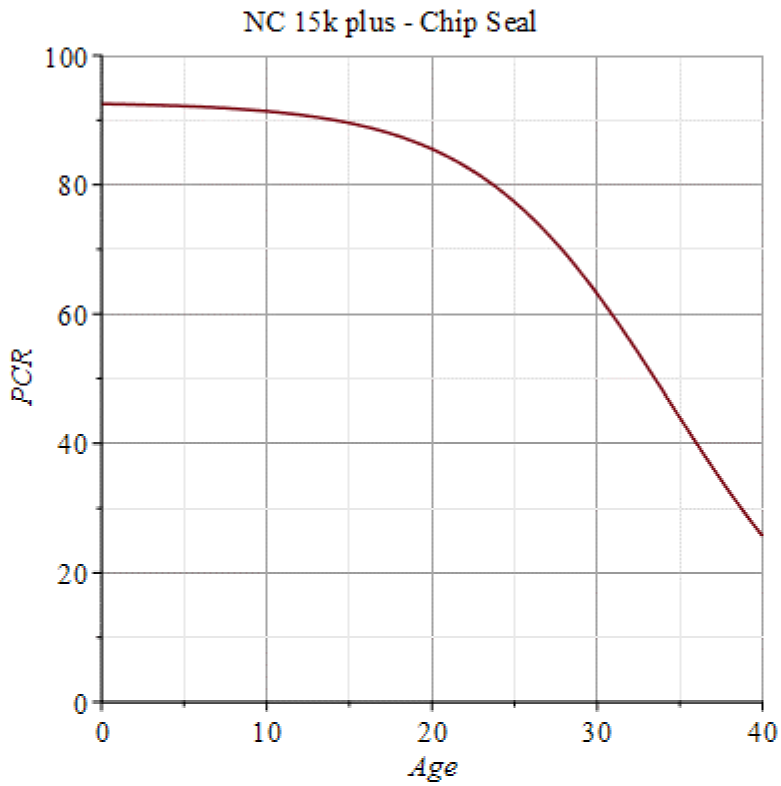
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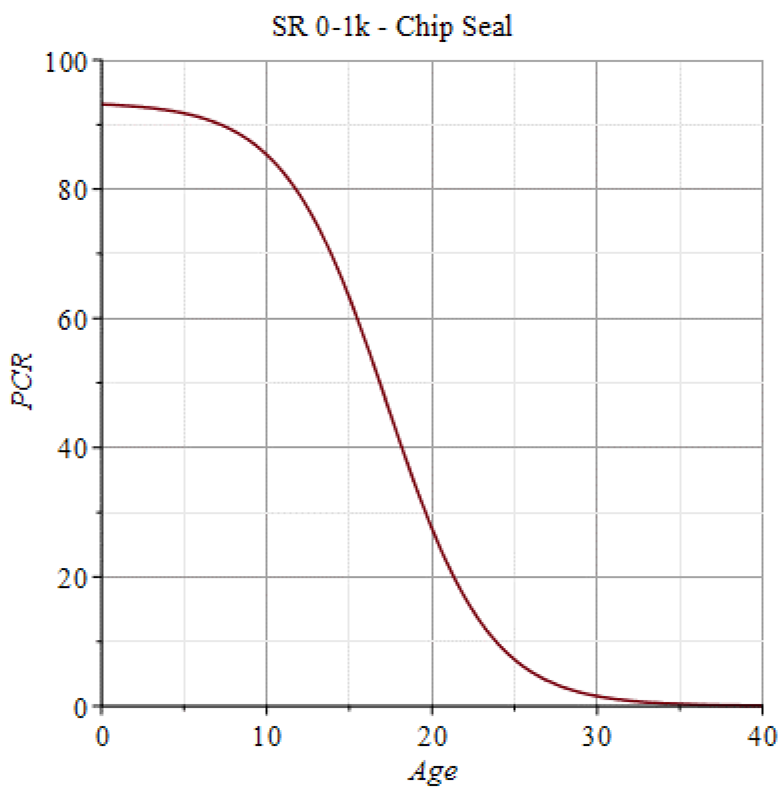
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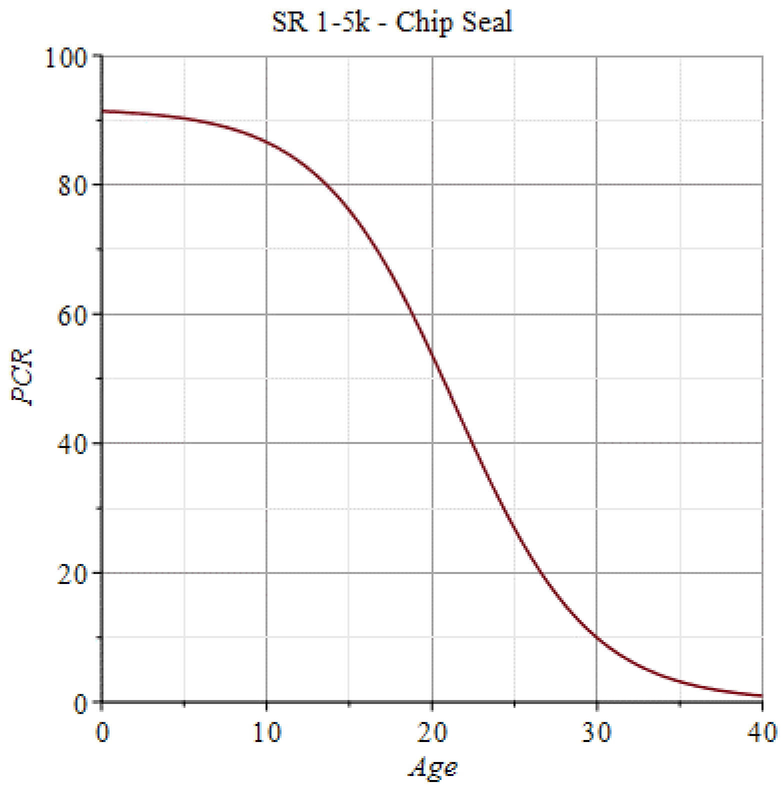
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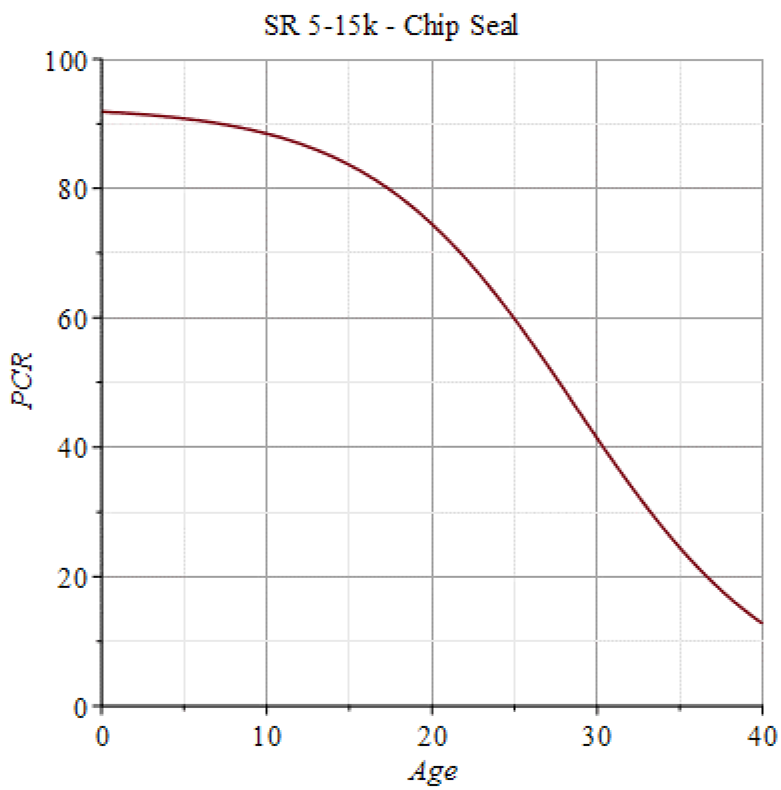
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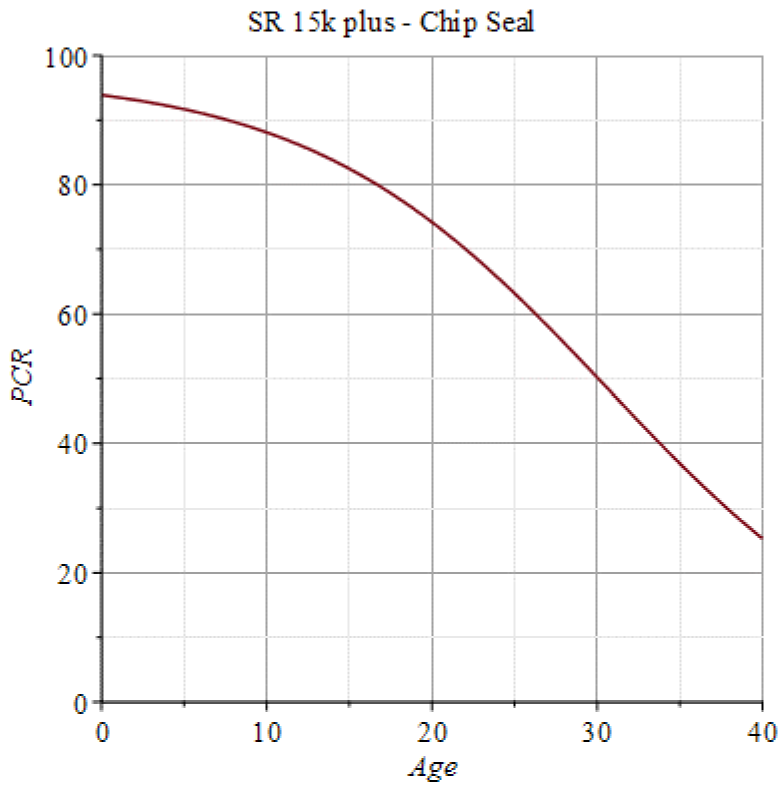
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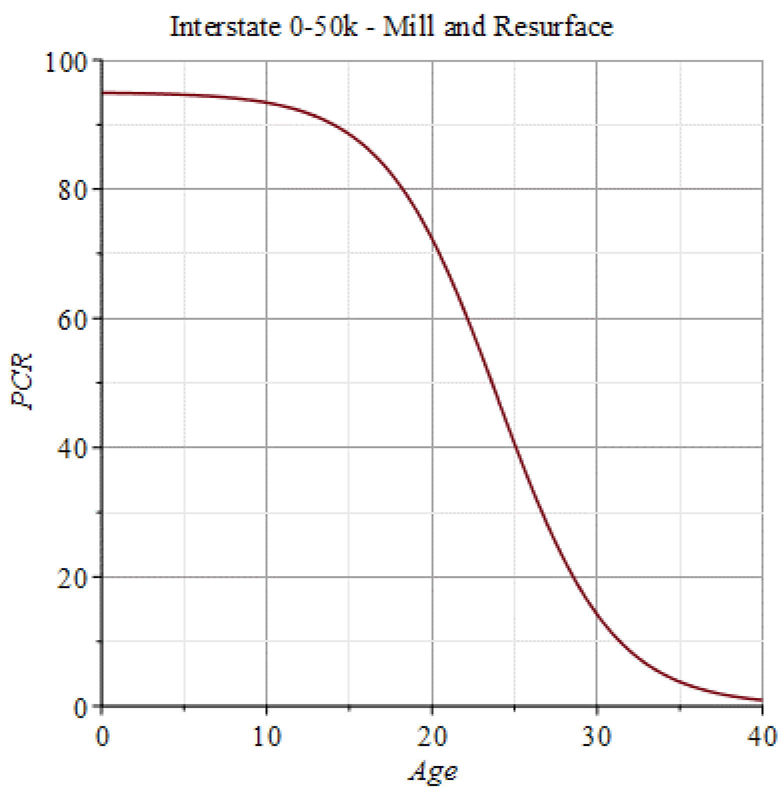
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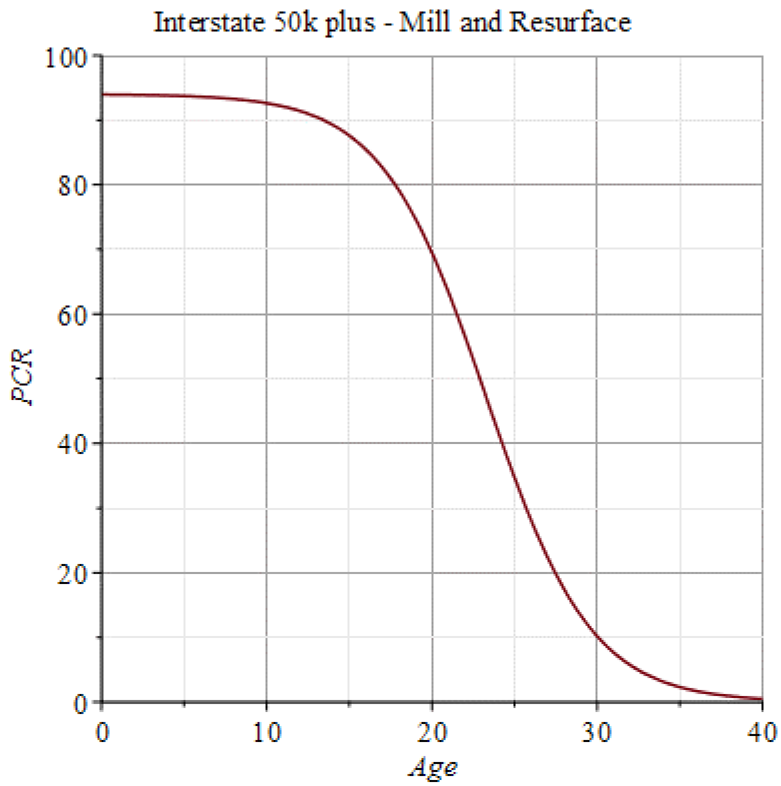
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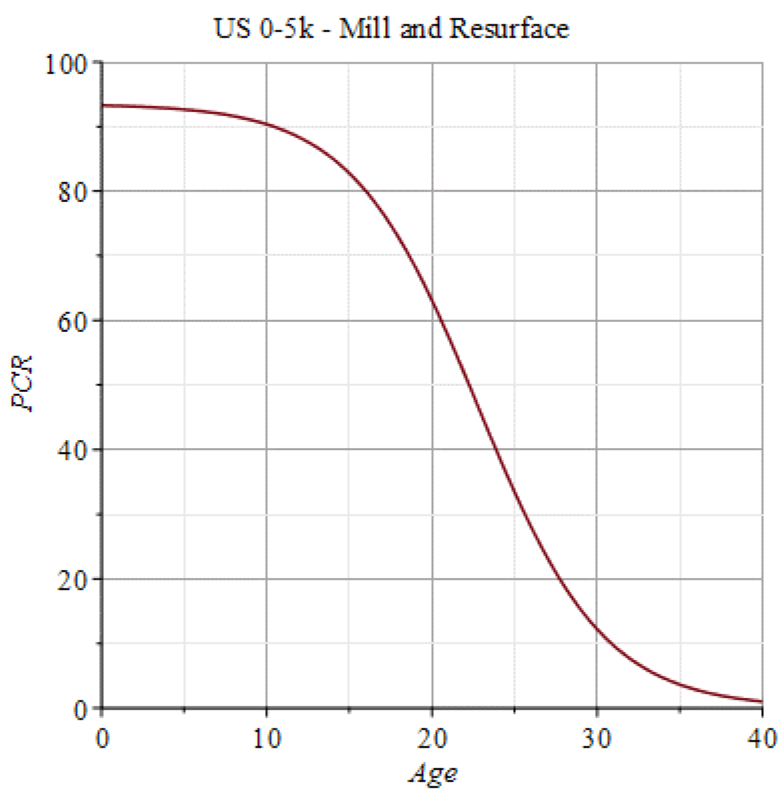
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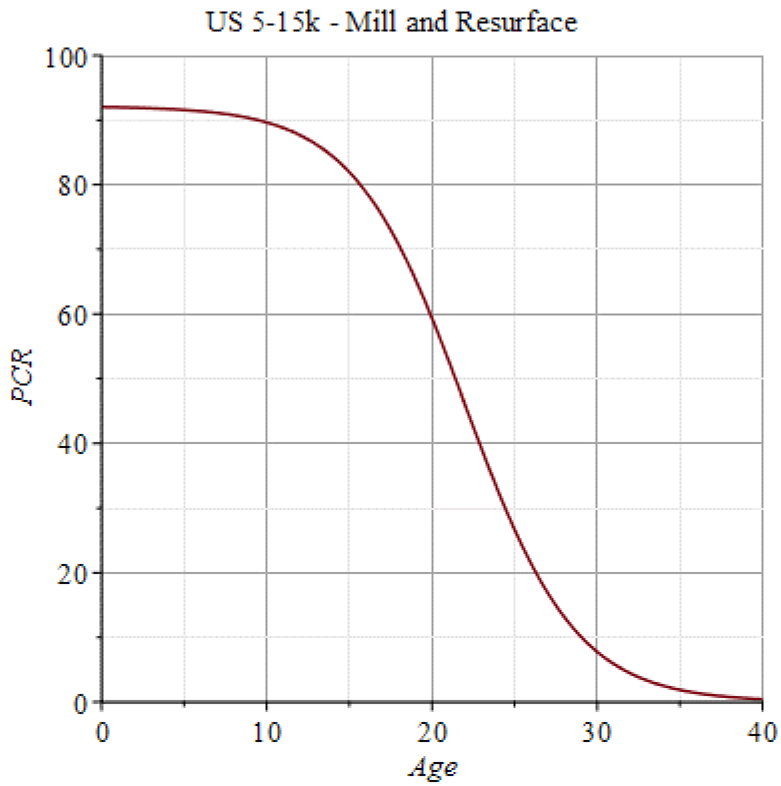
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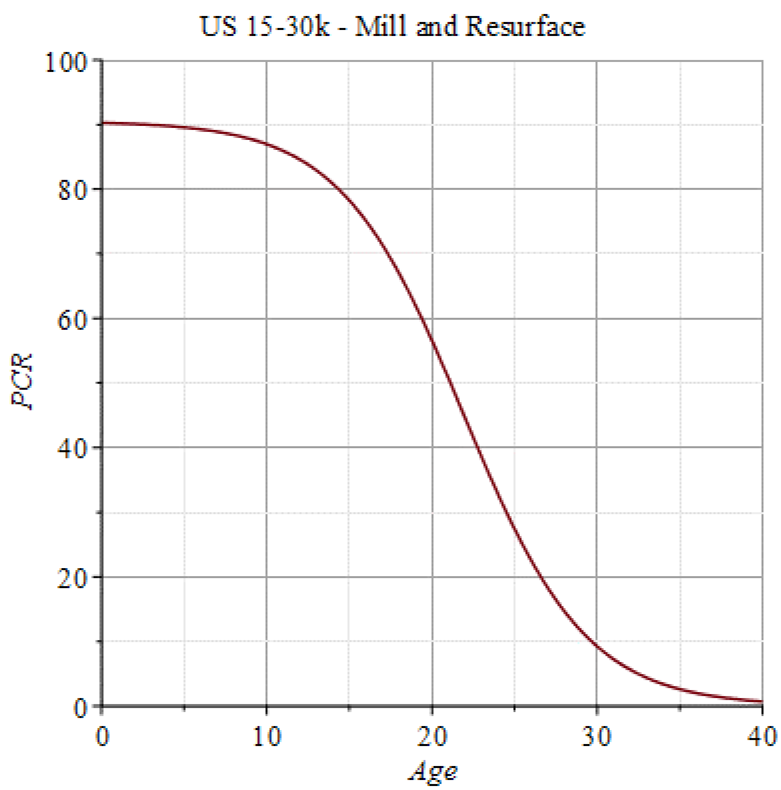
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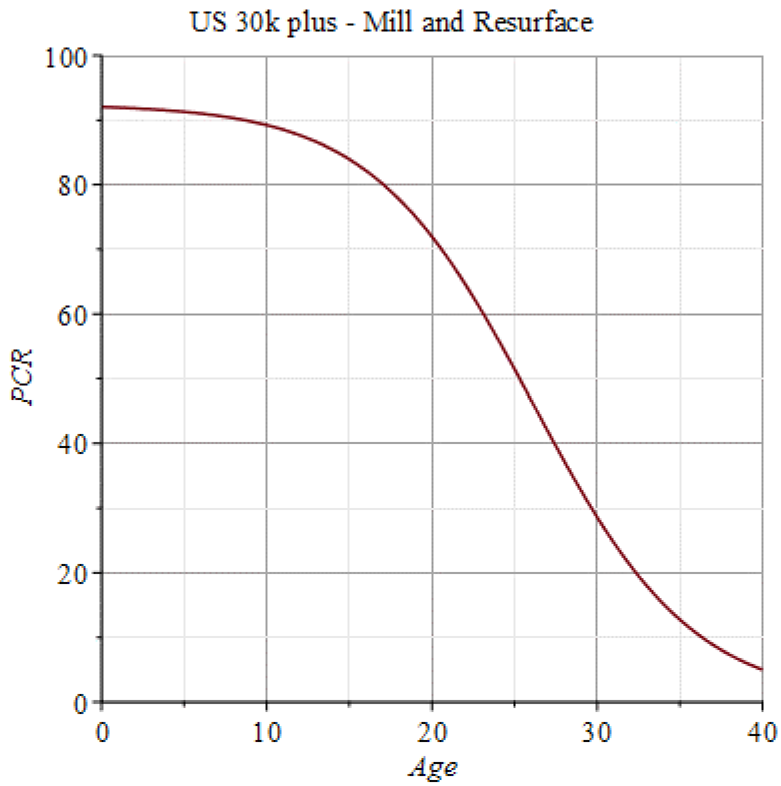
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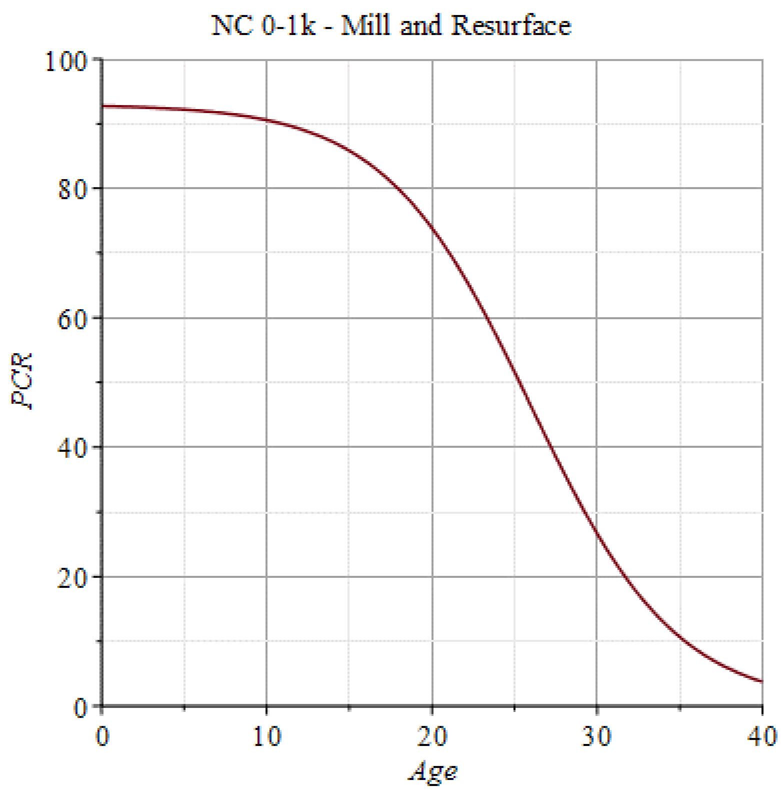
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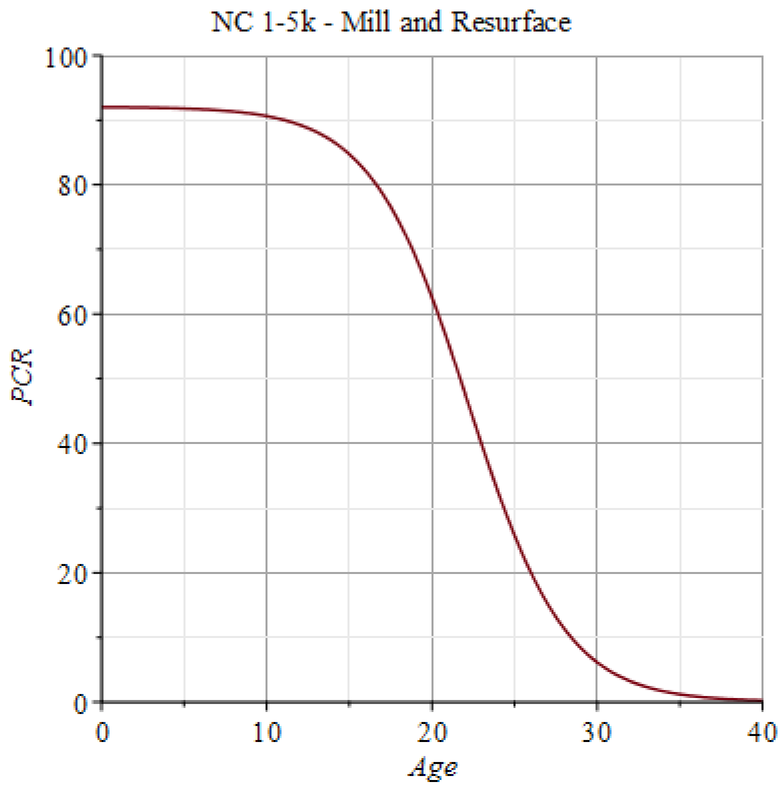
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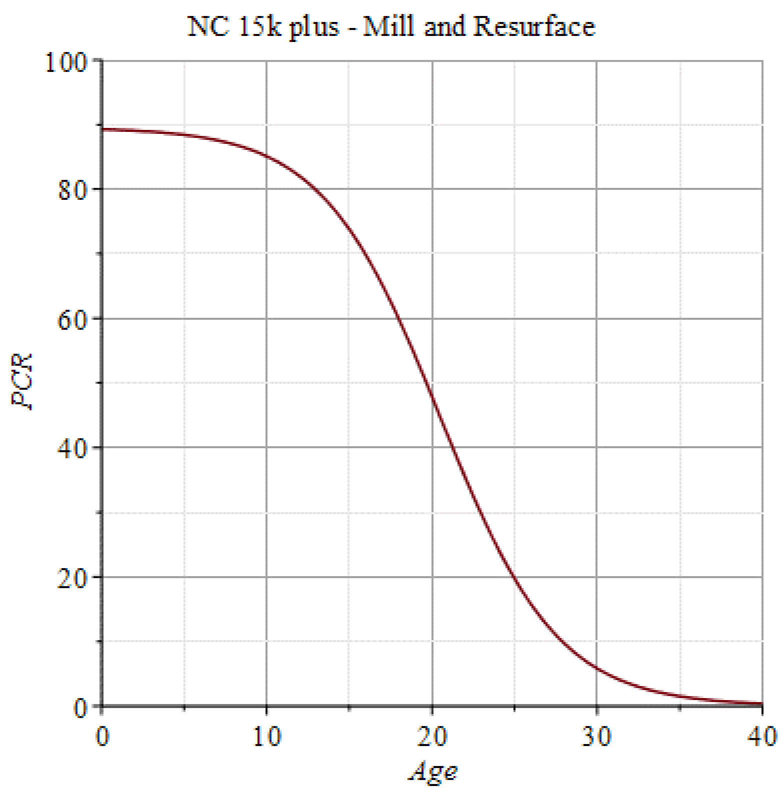
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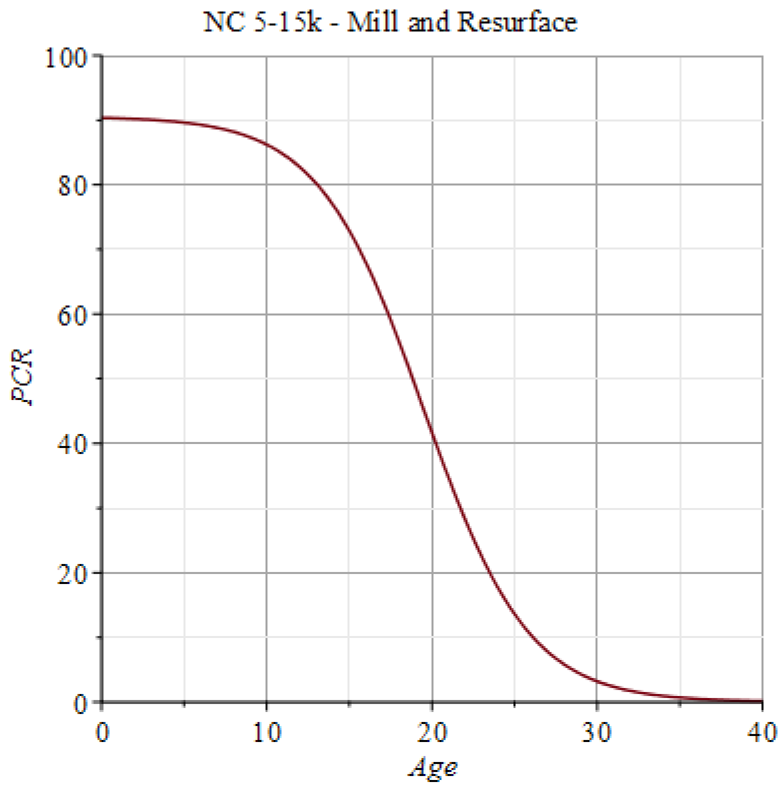
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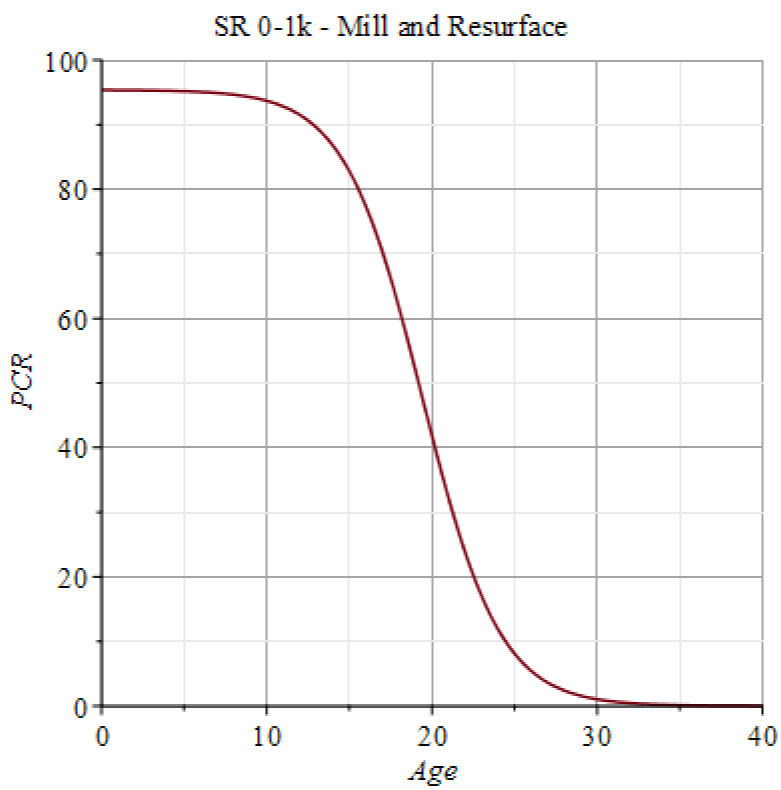
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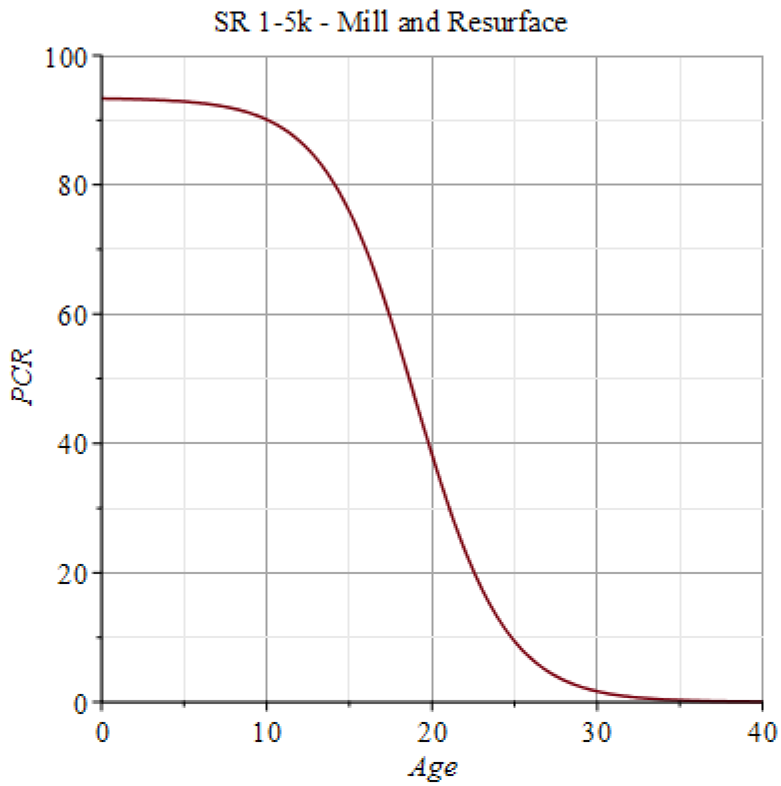
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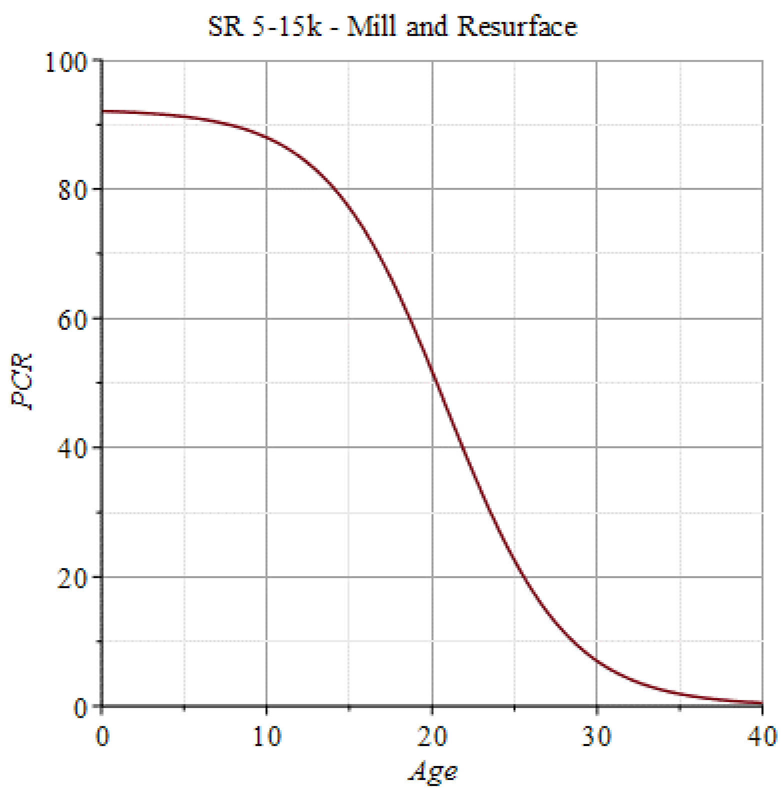
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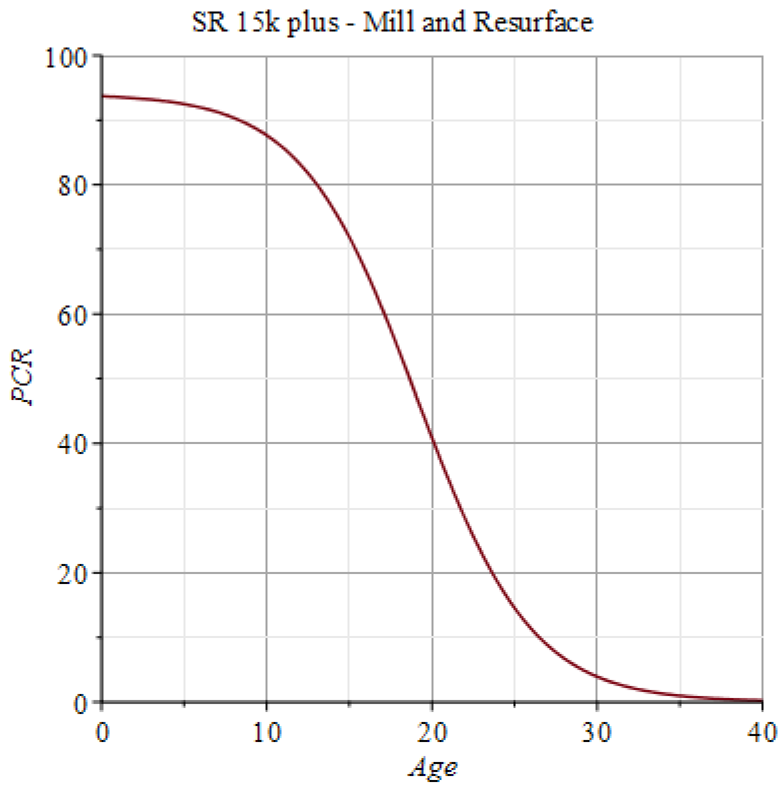
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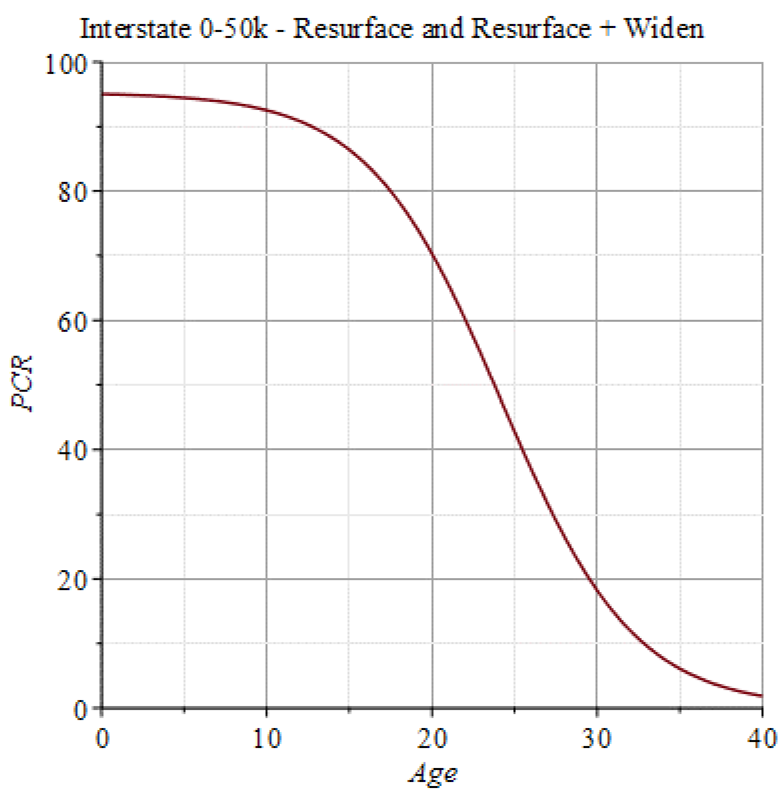
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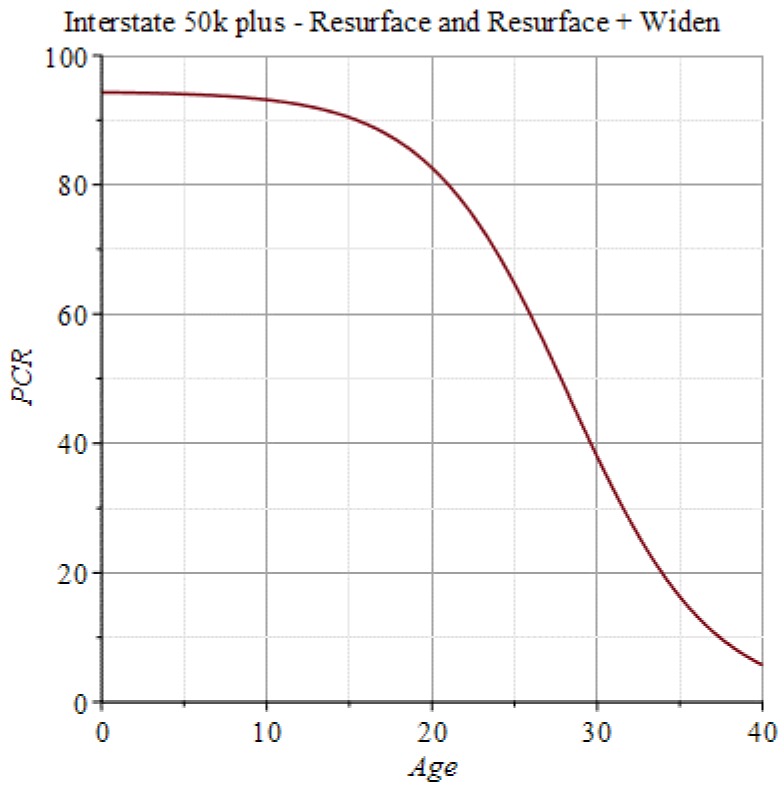
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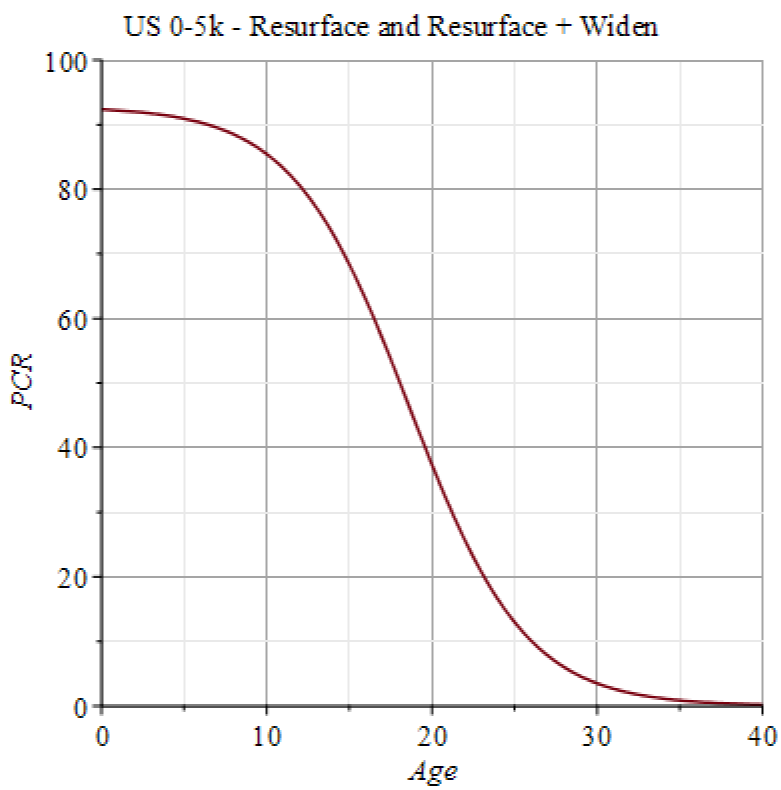
US 0-5k - Resurface and Resurface + Widen
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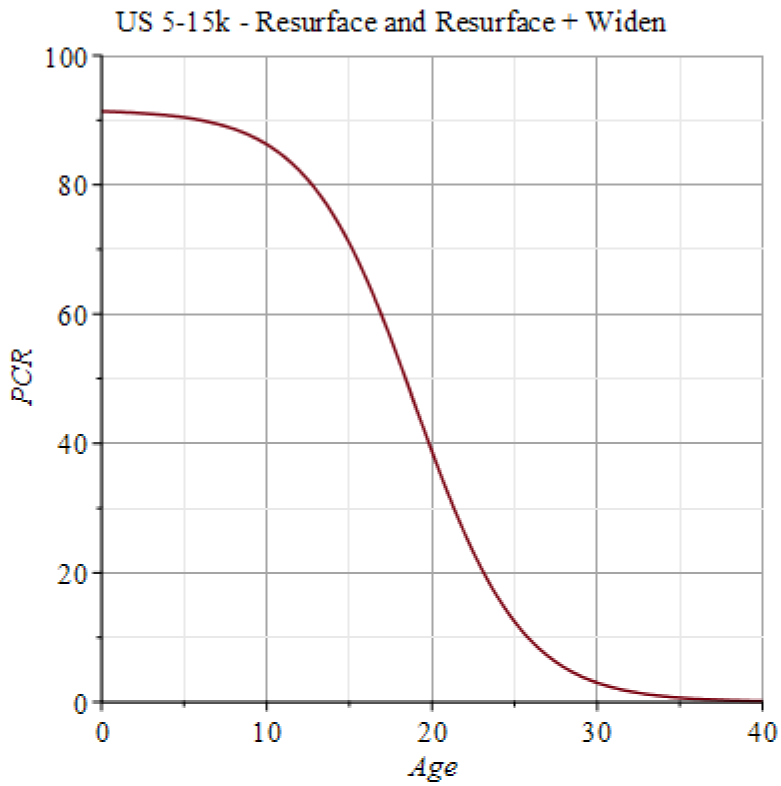

US 5-15k - Resurface and Resurface + Widen
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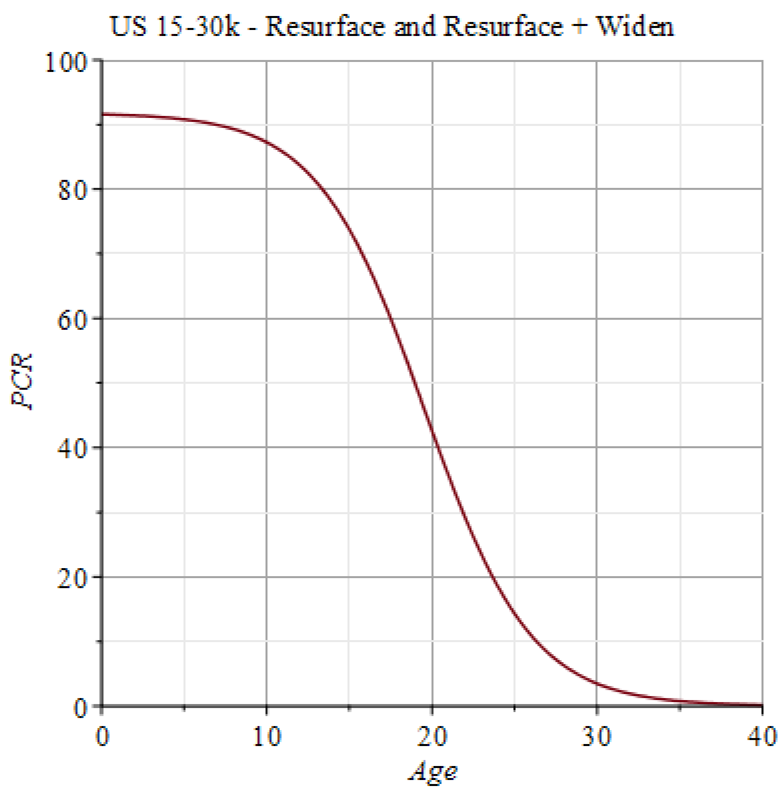

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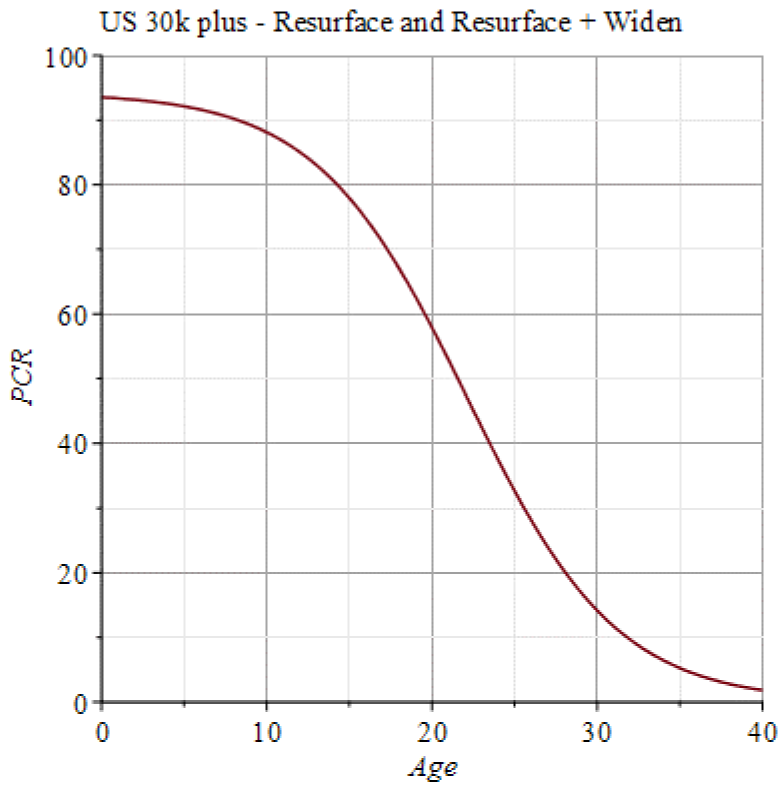
US 30k plus - Resurface and Resurface + Widen
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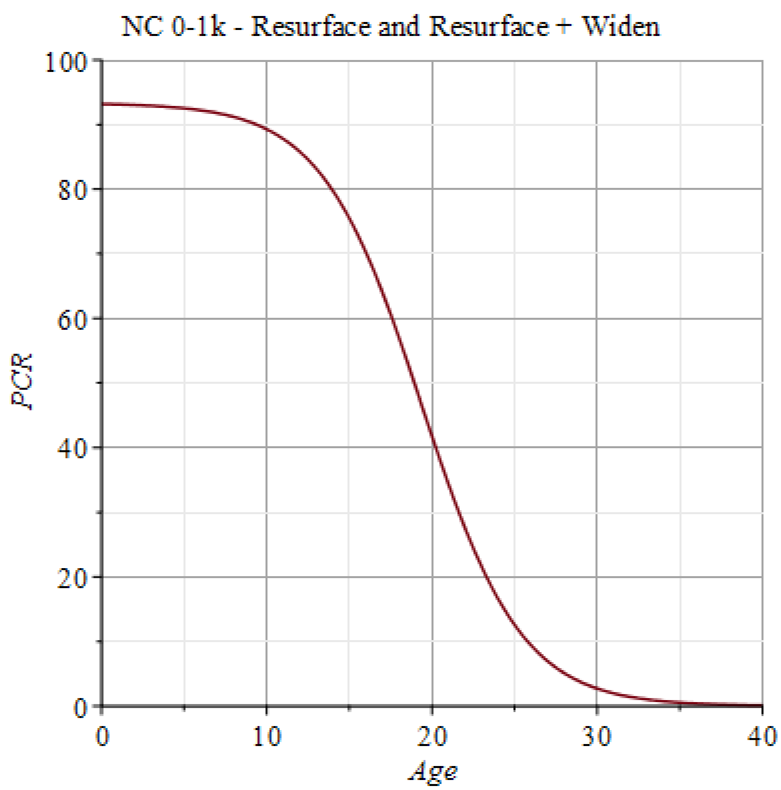
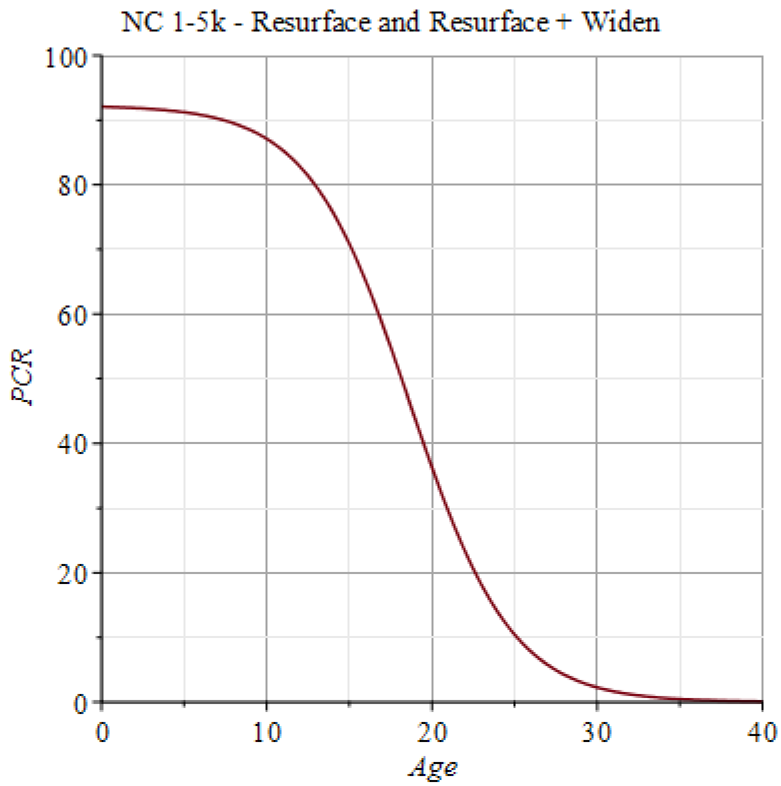
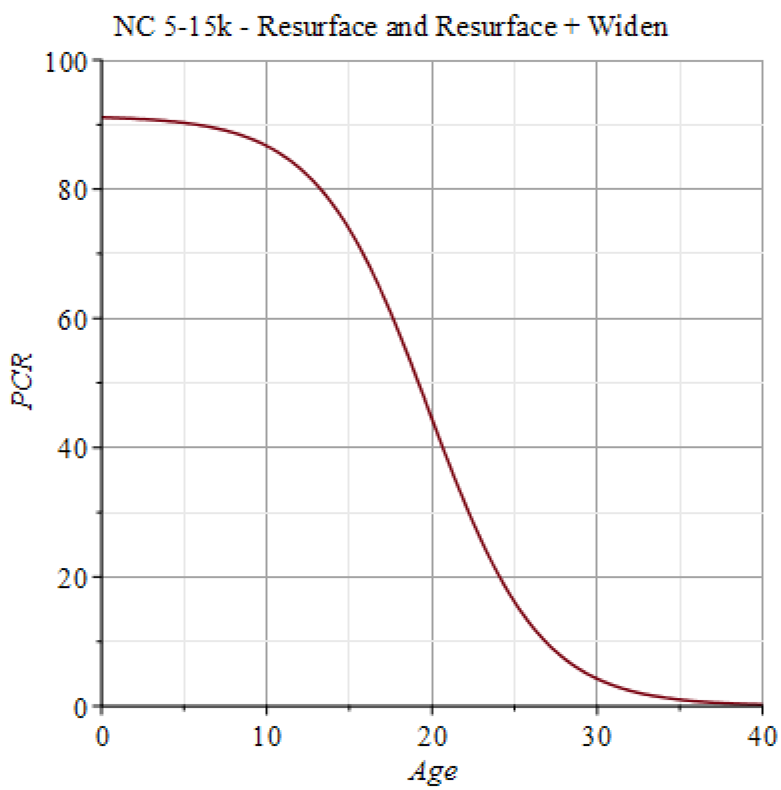
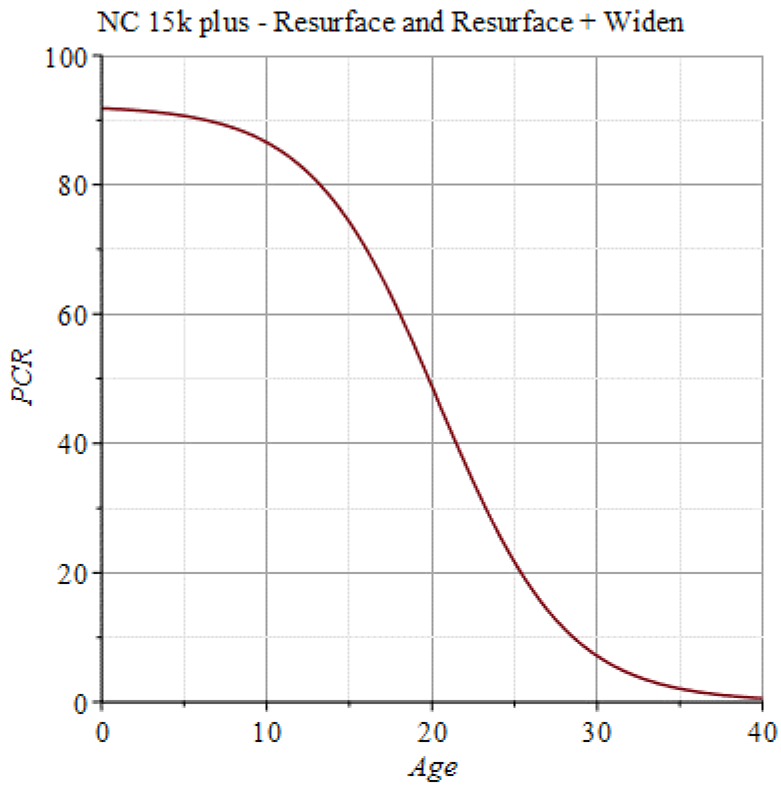
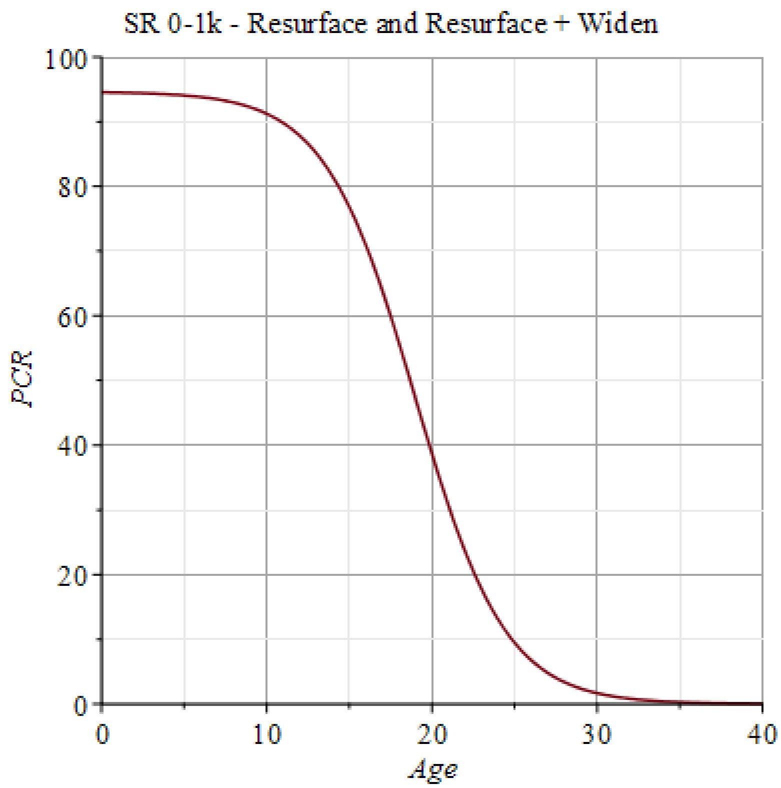
40
Age

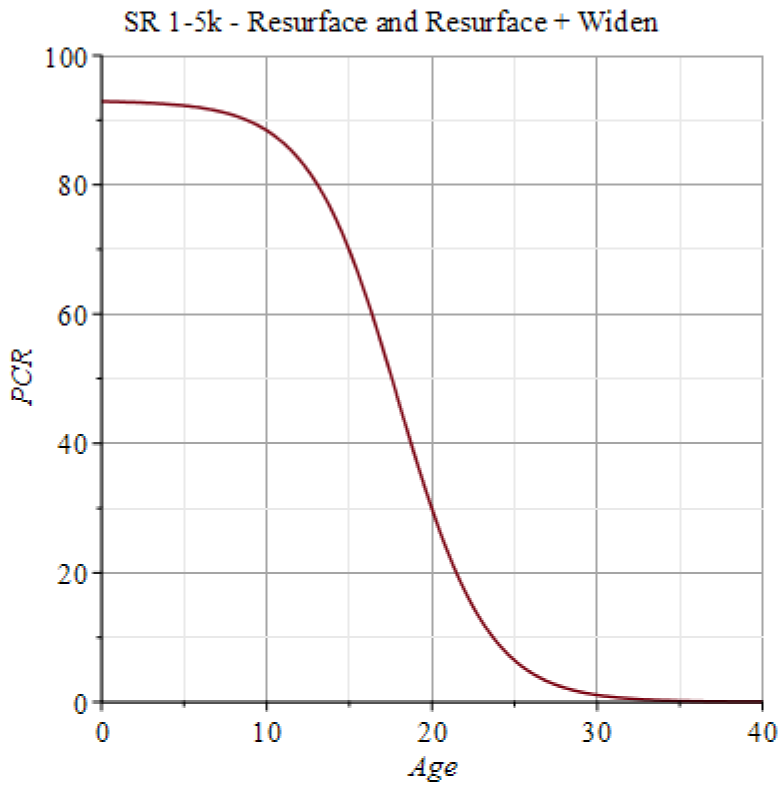

NC 0-1k - Resurface and Resurface + Widen
100
80
60
40
20
0
PCR
0
10
20
30
40
Age

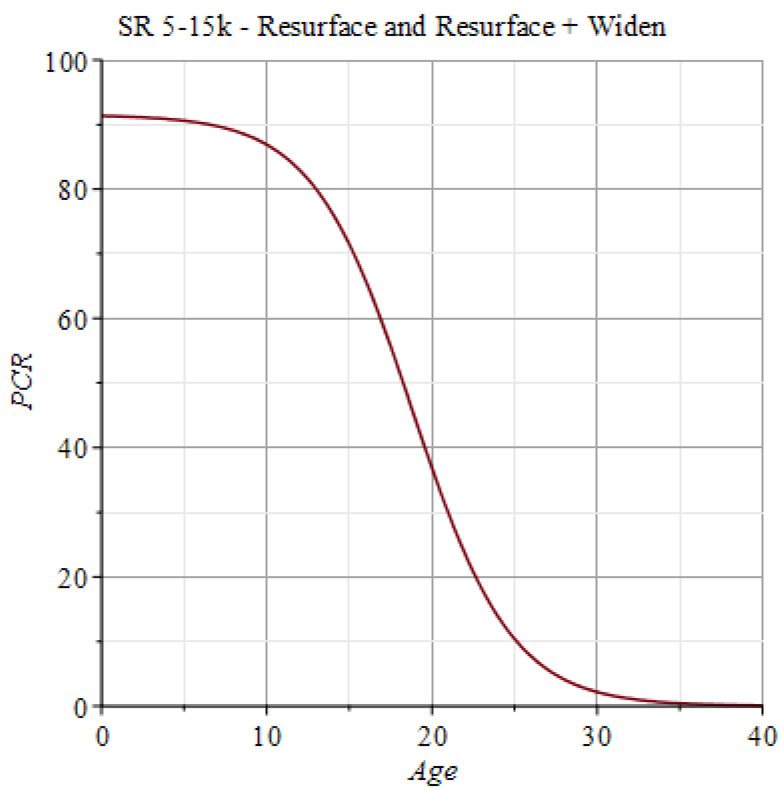

NC 1-5k - Resurface and Resurface + Widen
100
80
60
40
20
0
PCR
0
10
20
30
40
Age

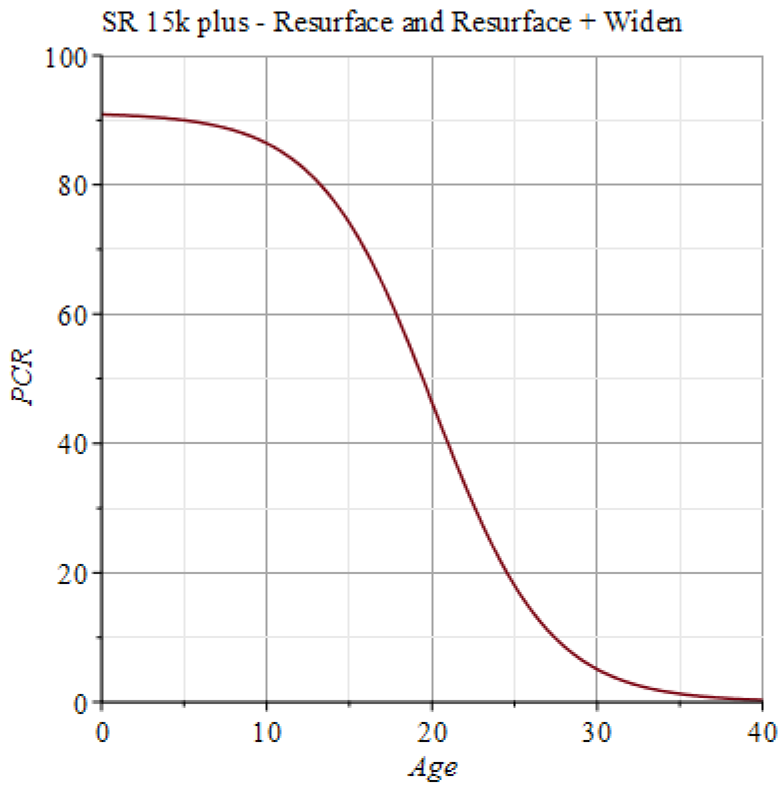

NC 5-15k - Resurface and Resurface + Widen
100
80
60
40
20
0
PCR
0
10
20
30
40
Age

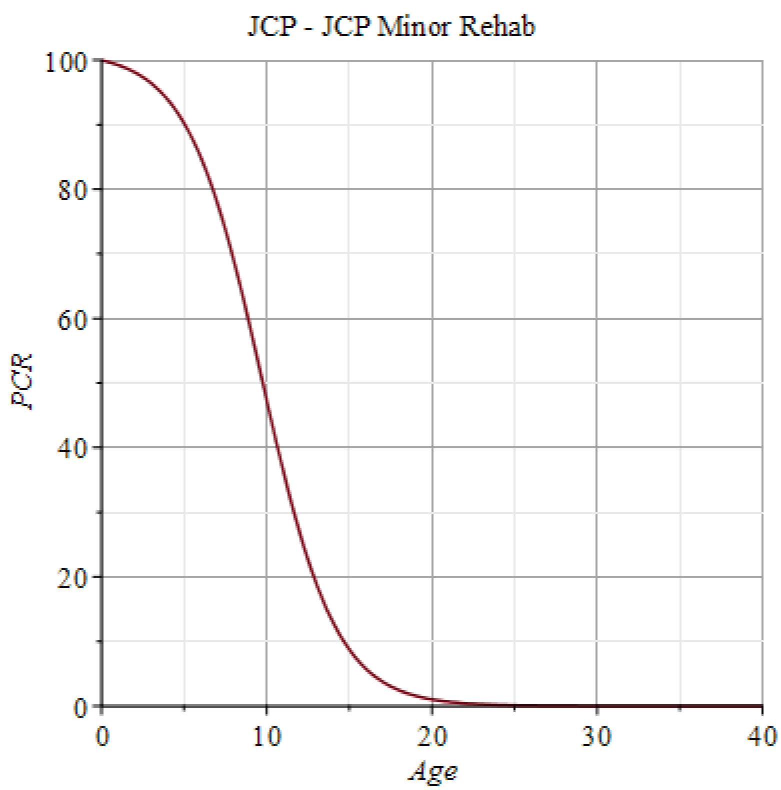

NC 15k plus - Resurface and Resurface + Widen
PCR
Age
0
20
40
60
80
100
0
10
20
30
40

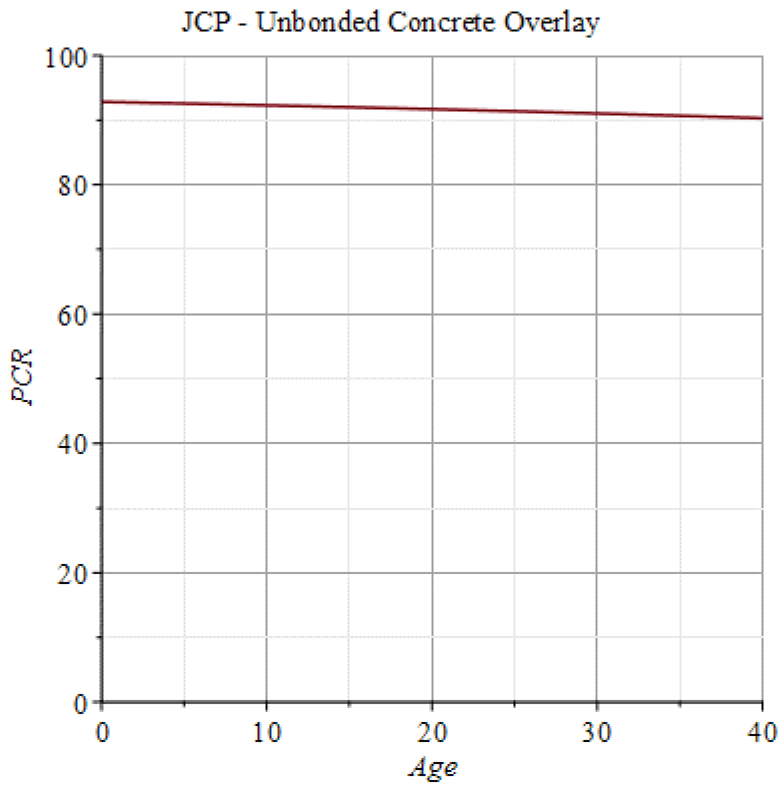

SR 0-1k - Resurface and Resurface + Widen
PCR
Age
0
20
40
60
80
100
0
10
20
30
40

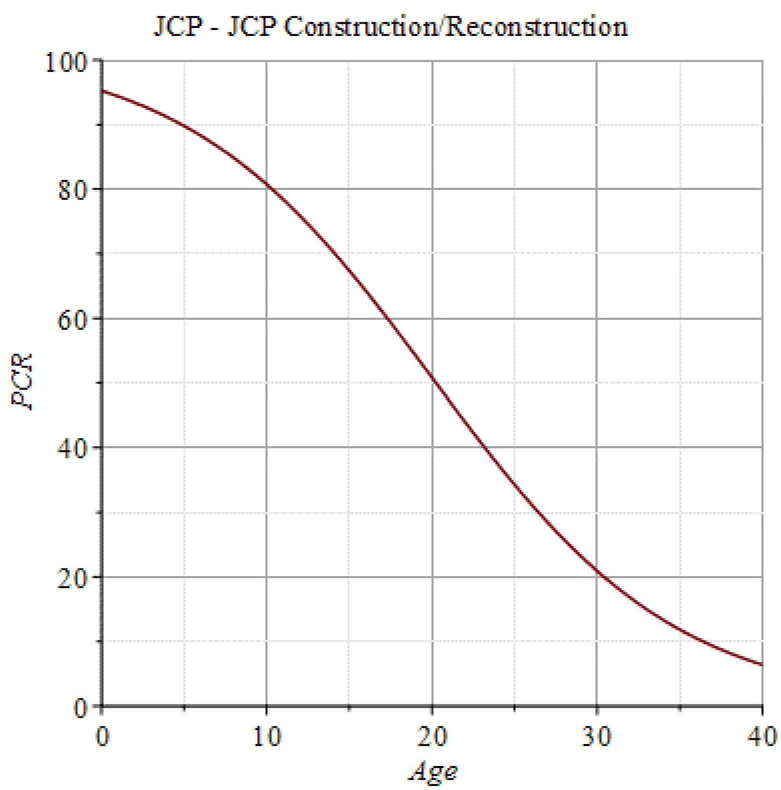

SR 1-5k - Resurface and Resurface + Widen
PCR
Age
0
20
40
60
80
100
0
10
20
30
40


SR 5-15k - Resurface and Resurface + Widen
PCR
Age
0
20
40
60
80
100
0
10
20
30
40

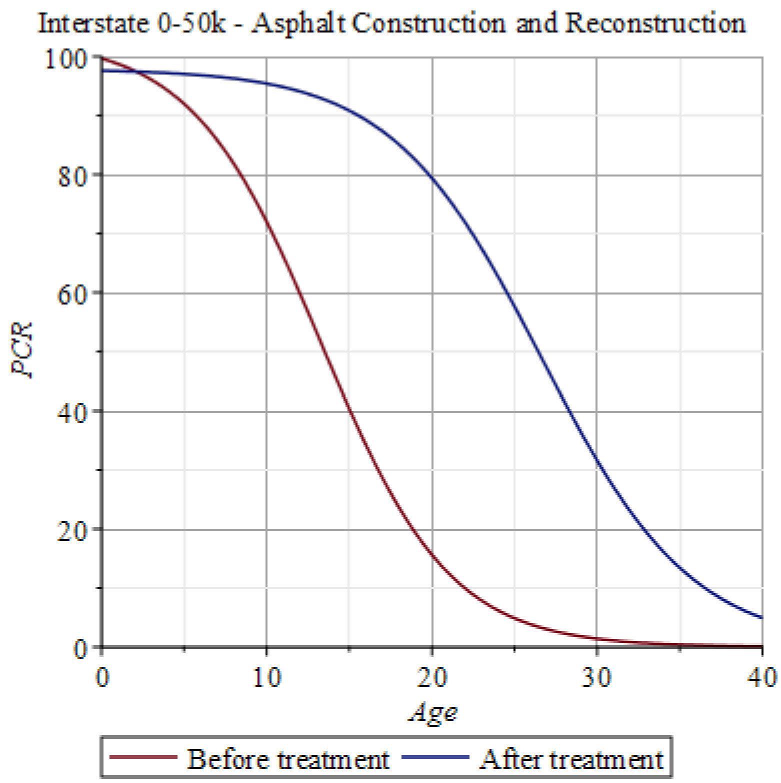

SR 15k plus - Resurface and Resurface + Widen
100
80
60
40
20
0
PCR
0
10
20
30
40
Age

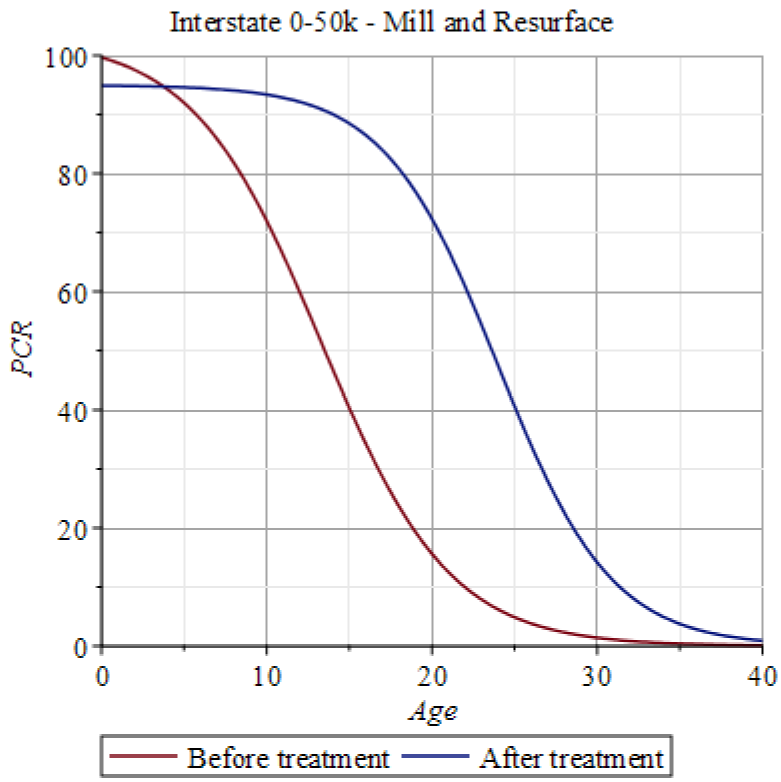

JCP - JCP Minor Rehab
100
80
60
40
20
0
PCR
0
10
20
30
40
Age

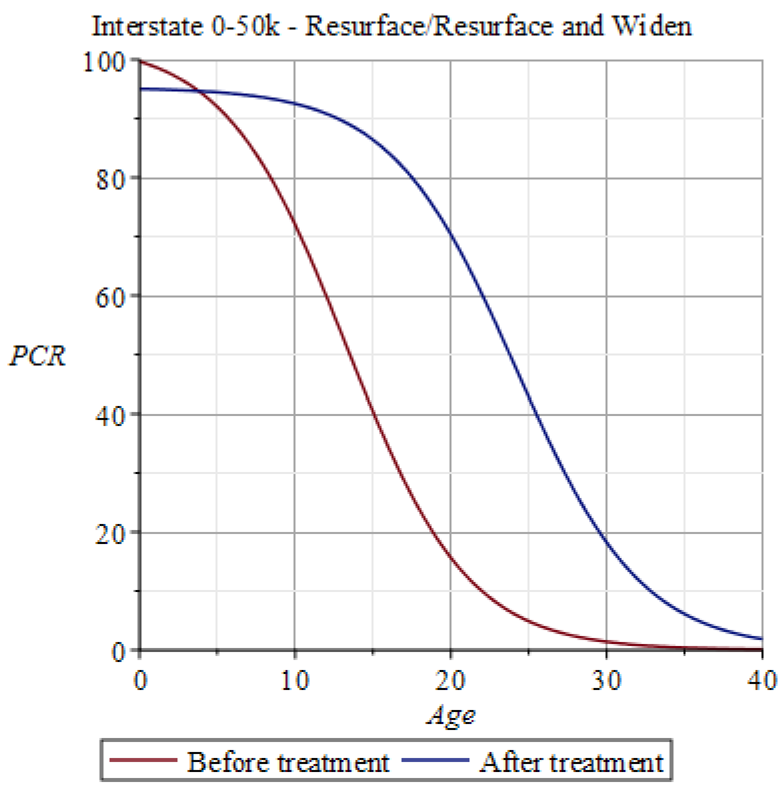

JCP - Unbonded Concrete Overlay
100
80
60
40
20
0
PCR
0
10
20
30
40
Age


JCP - JCP Construction/Reconstruction
100
80
60
40
20
0
PCR
0
10
20
30
40
Age

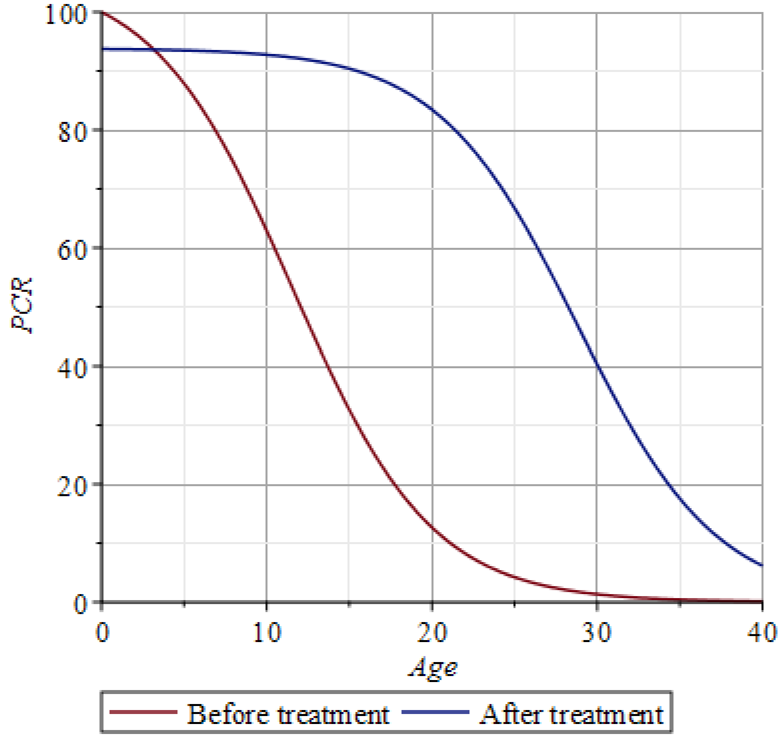
APPENDIX B: COMPARISON OF BEFORE AND AFTER-TREATMENT PERFORMANCE CURVES



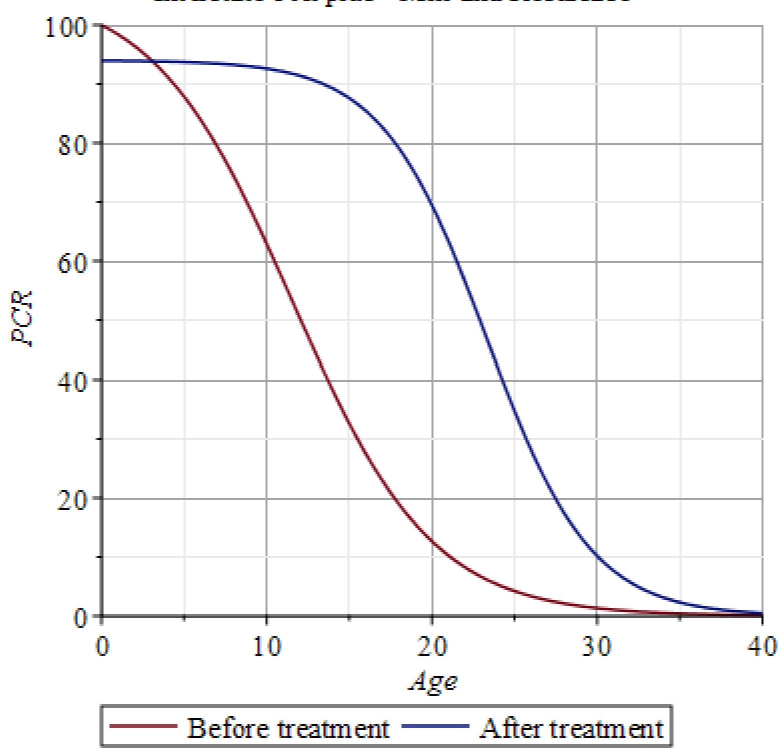

Interstate 0-50k - Mill and Resurface
100
80
60
40
20
0
PCR
0
10
20
30
40
Age
Before treatment
After treatment

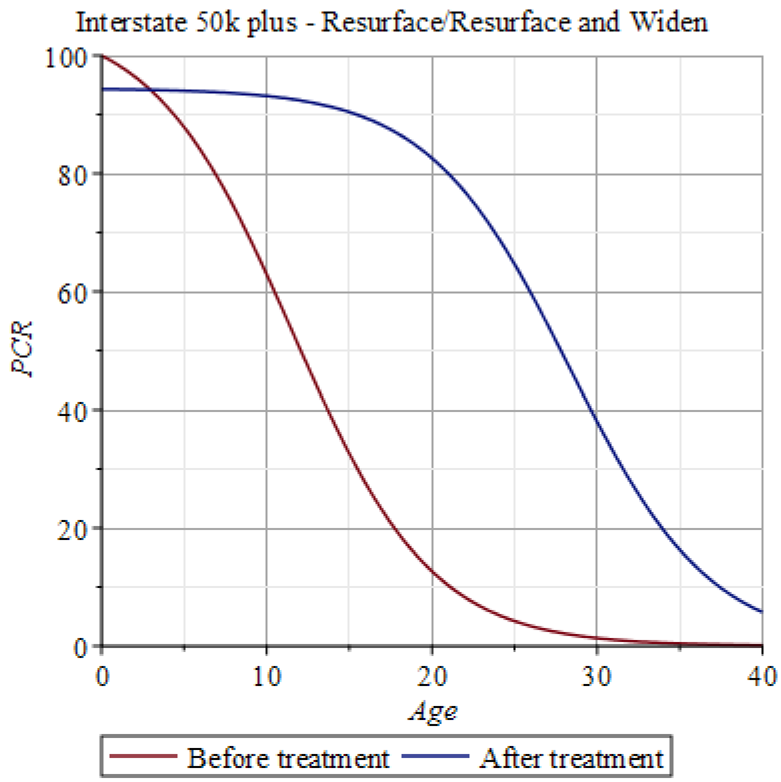

Interstate 0-50k - Resurface/Resurface and Widen
100
80
60
40
20
0
PCR
0
10
20
30
40
Age
Before treatment
After treatment

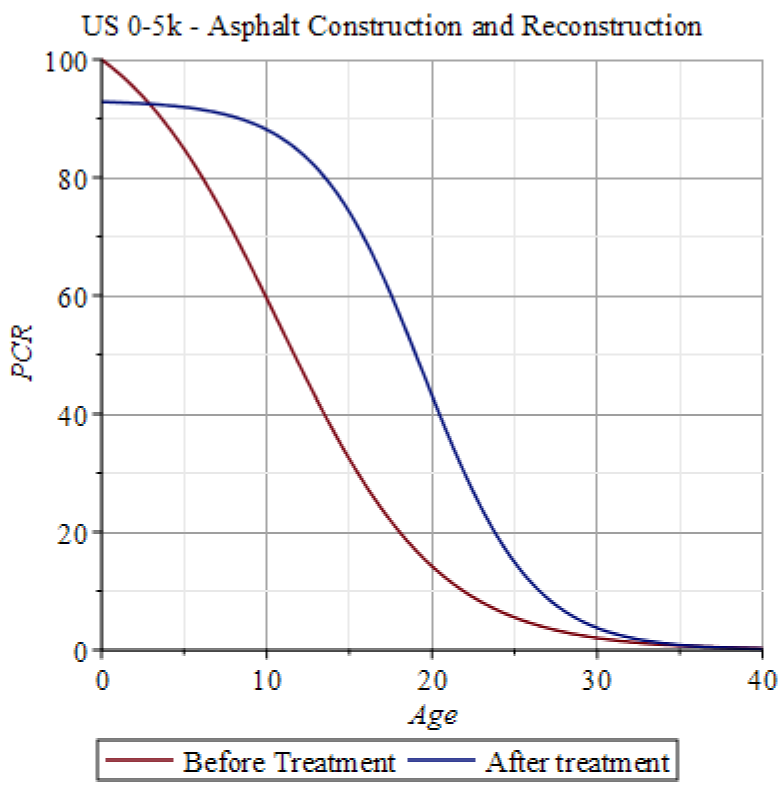
Interstate 50k plus - Asphalt Construction and Reconstruction

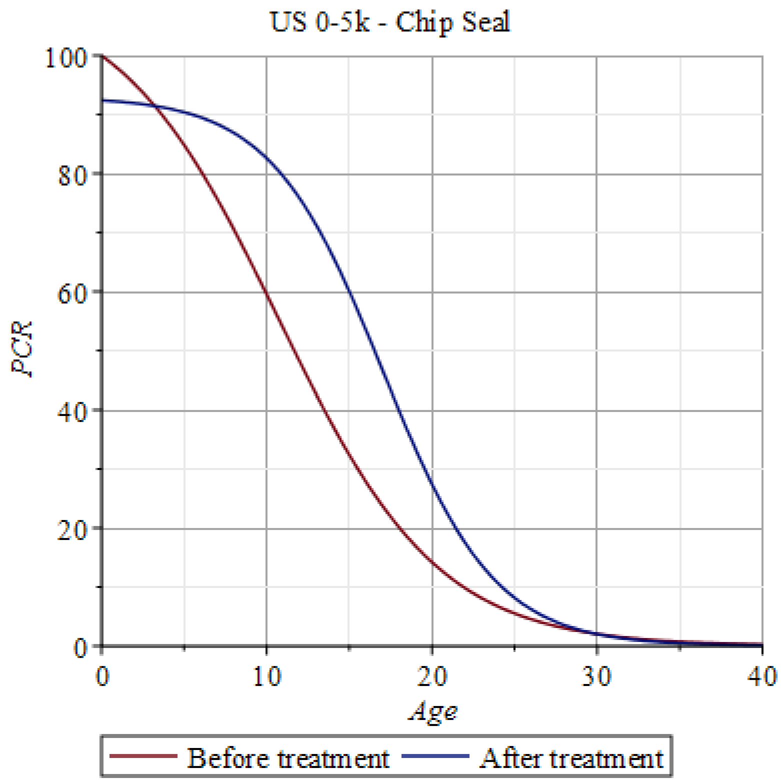


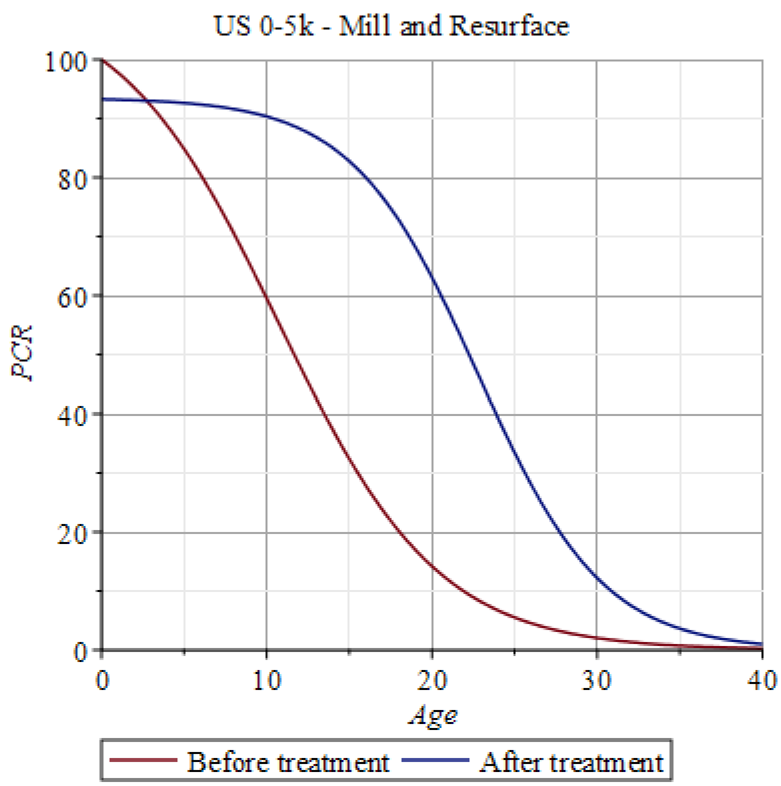
Interstate 50k plus - Mill and Resurface

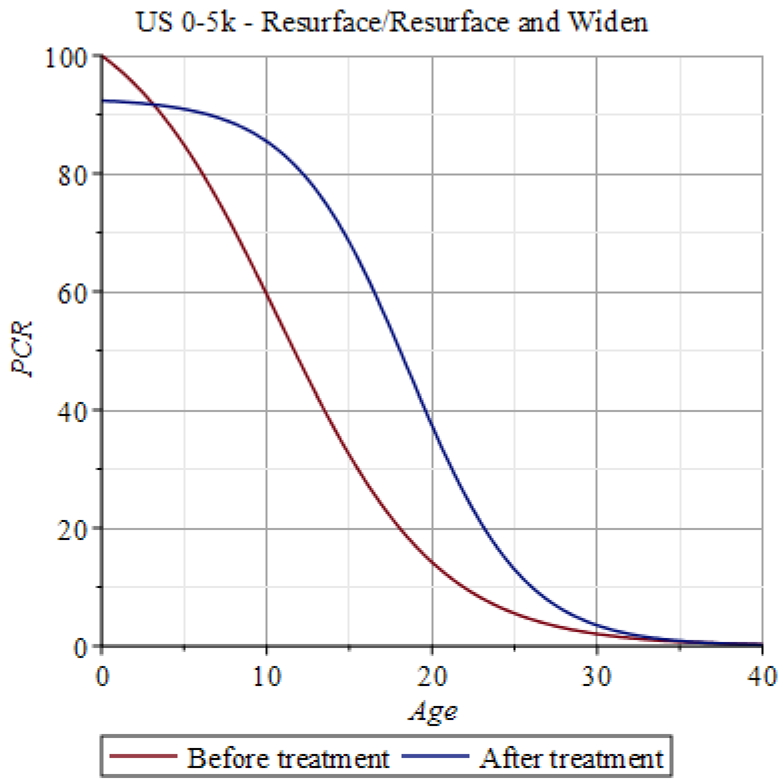


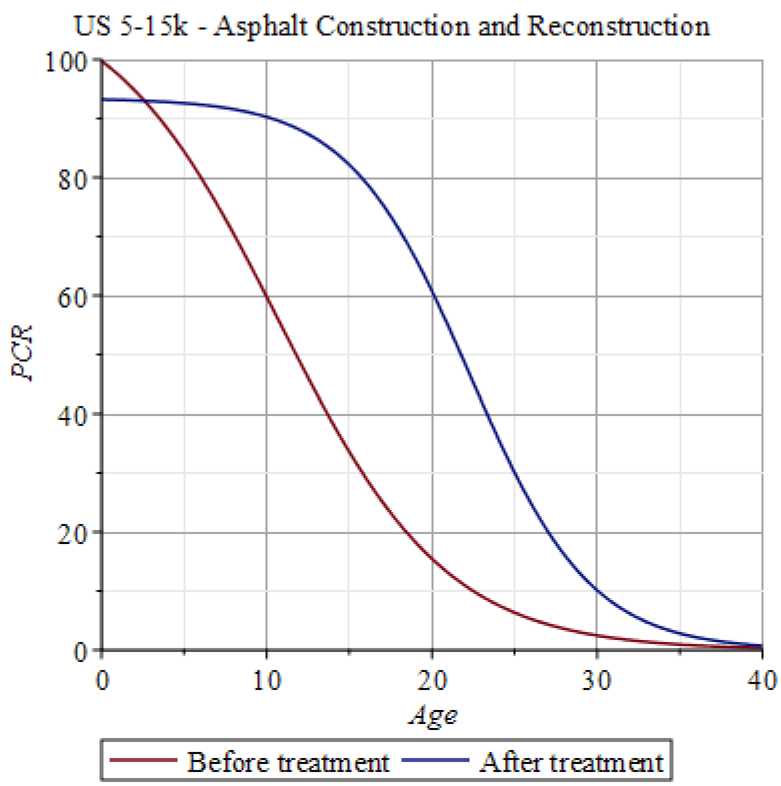

Interstate 50k plus - Resurface/Resurface and Widen
PCR
100
80
60
40
20
0
0
10
20
30
40
Age
Before treatment
After treatment

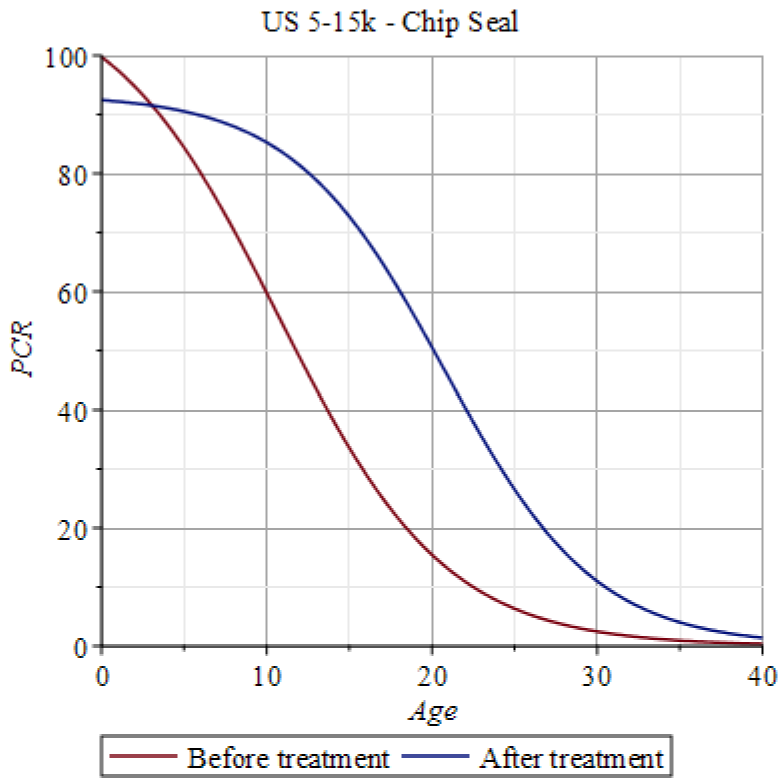

US 0-5k - Asphalt Construction and Reconstruction
PCR
100
80
60
40
20
0
0
10
20
30
40
Age
Before Treatment
After treatment

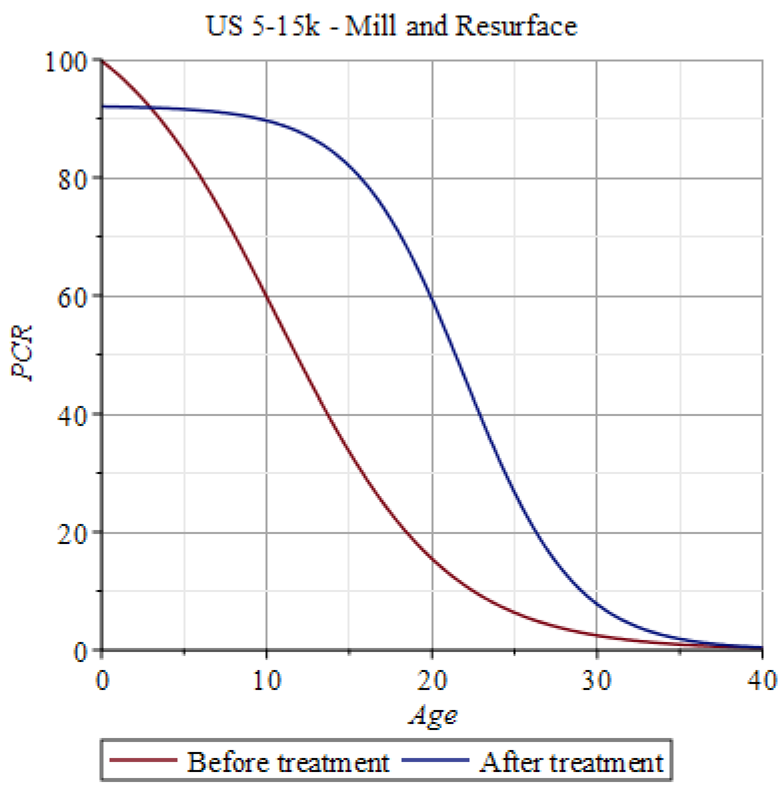

US 0-5k - Chip Seal
100
80
60
40
20
0
PCR
0
10
20
30
40
Age
Before treatment
After treatment

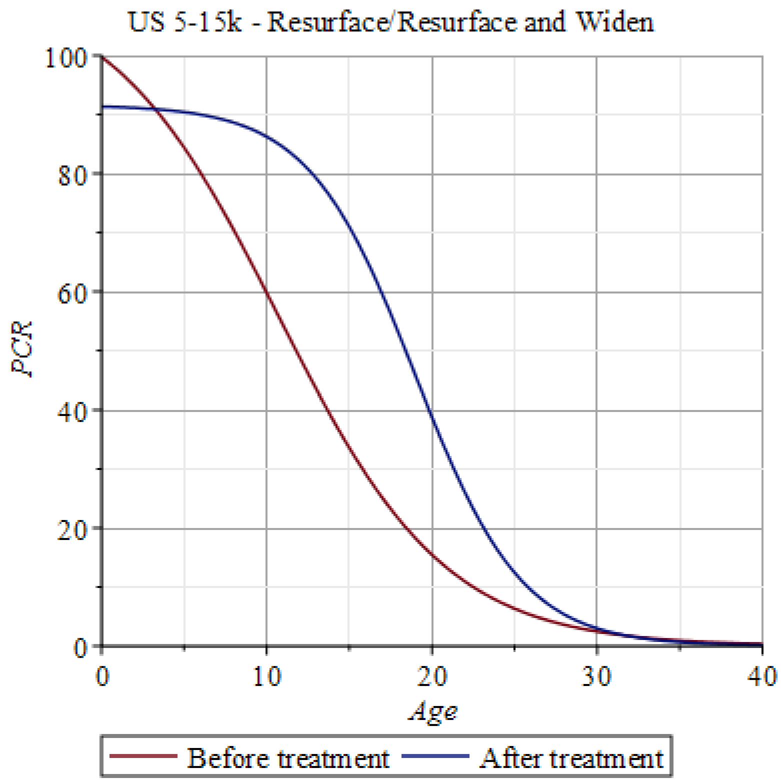

US 0-5k - Mill and Resurface
100
80
60
40
20
0
PCR
0
10
20
30
40
Age
Before treatment
After treatment

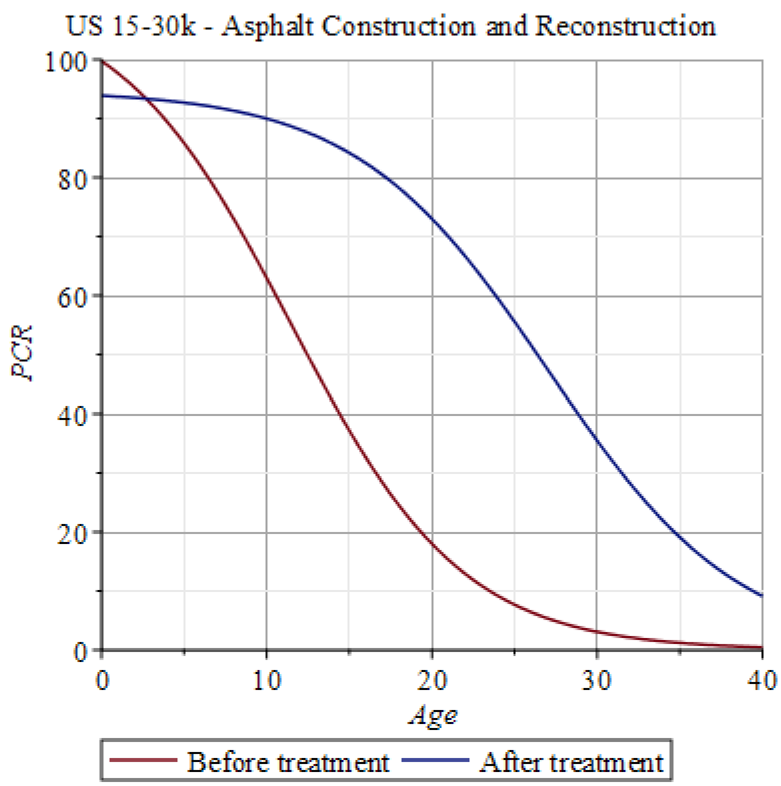

US 0-5k - Resurface/Resurface and Widen
PCR
100
80
60
40
20
0
0
10
20
30
40
Age
Before treatment
After treatment

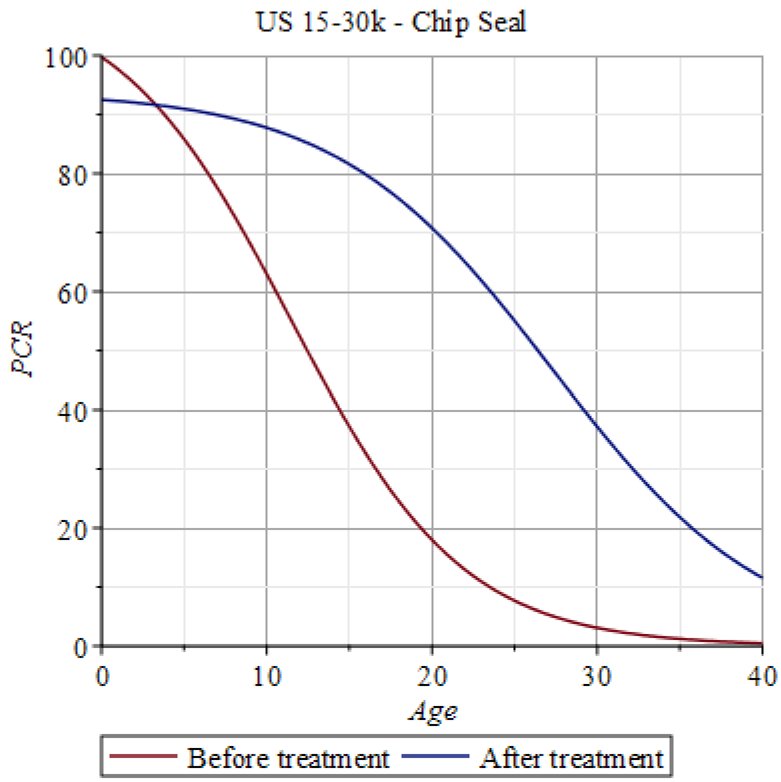

US 5-15k - Asphalt Construction and Reconstruction
PCR
100
80
60
40
20
0
0
10
20
30
40
Age
Before treatment
After treatment

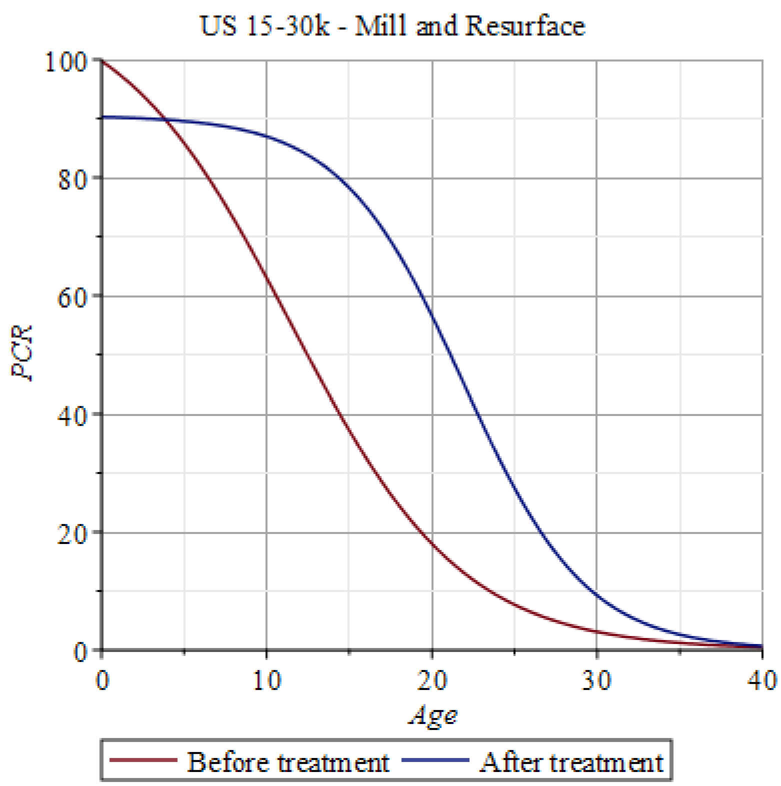

US 5-15k - Chip Seal
PCR
100
80
60
40
20
0
0
10
20
30
40
Age
Before treatment
After treatment

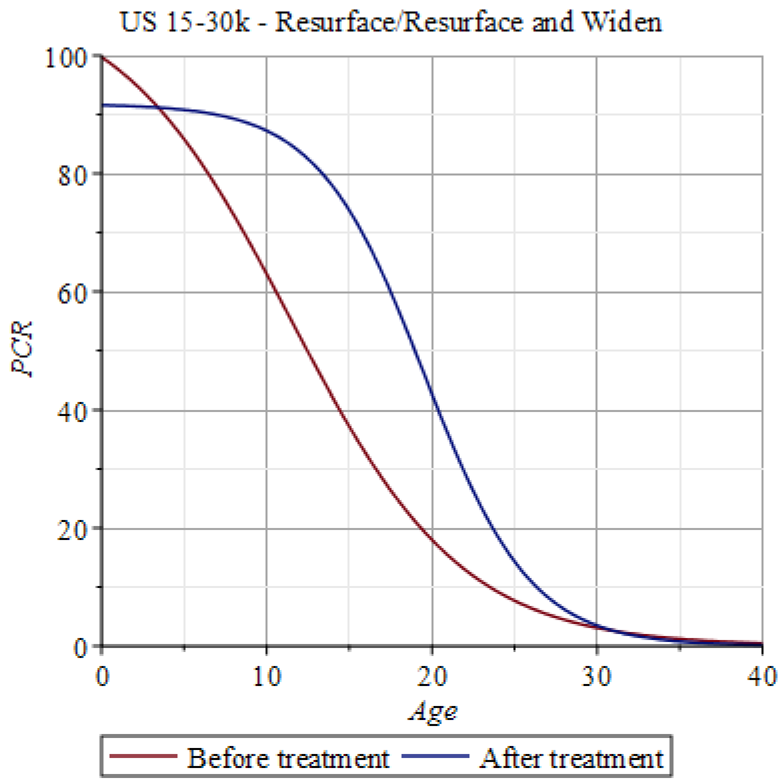

US 5-15k - Mill and Resurface
PCR
100
80
60
40
20
0
0
10
20
30
40
Age
Before treatment
After treatment

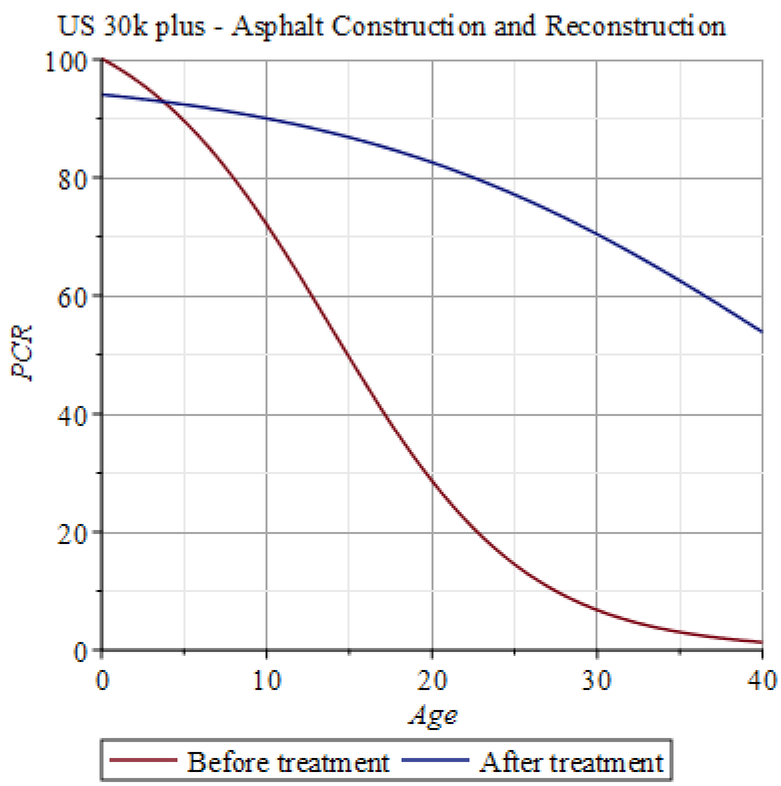

US 5-15k - Resurface/Resurface and Widen
PCR
Age
Before treatment
After treatment

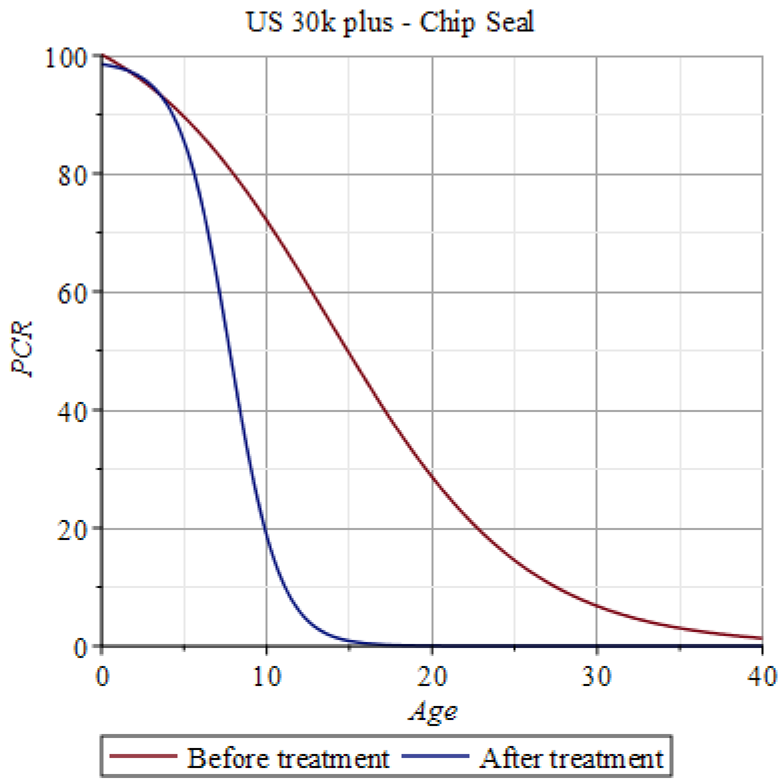

US 15-30k - Asphalt Construction and Reconstruction
PCR
Age
Before treatment
After treatment

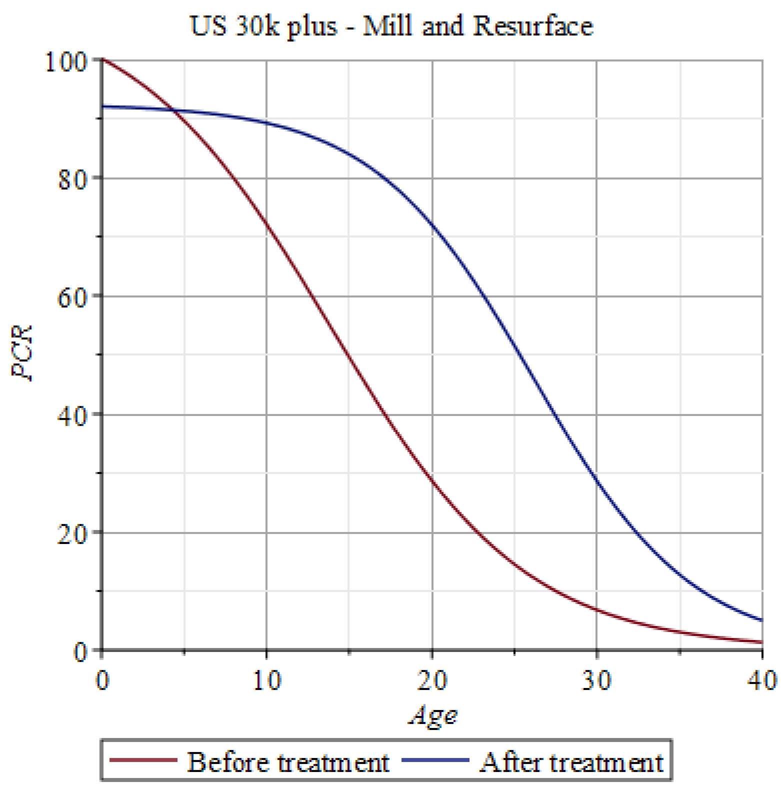

US 15-30k - Chip Seal
100
80
60
40
20
0
PCR
0
10
20
30
40
Age
Before treatment
After treatment

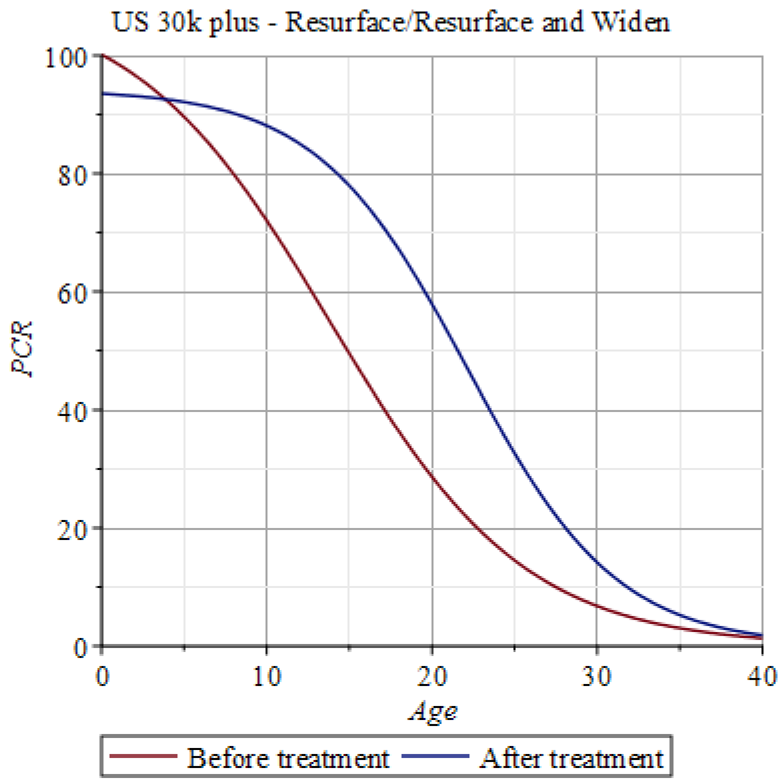

US 15-30k - Mill and Resurface
100
80
60
40
20
0
PCR
0
10
20
30
40
Age
Before treatment
After treatment


US 15-30k - Resurface/Resurface and Widen
PCR
Age
100
80
60
40
20
0
0
10
20
30
40
Before treatment
After treatment

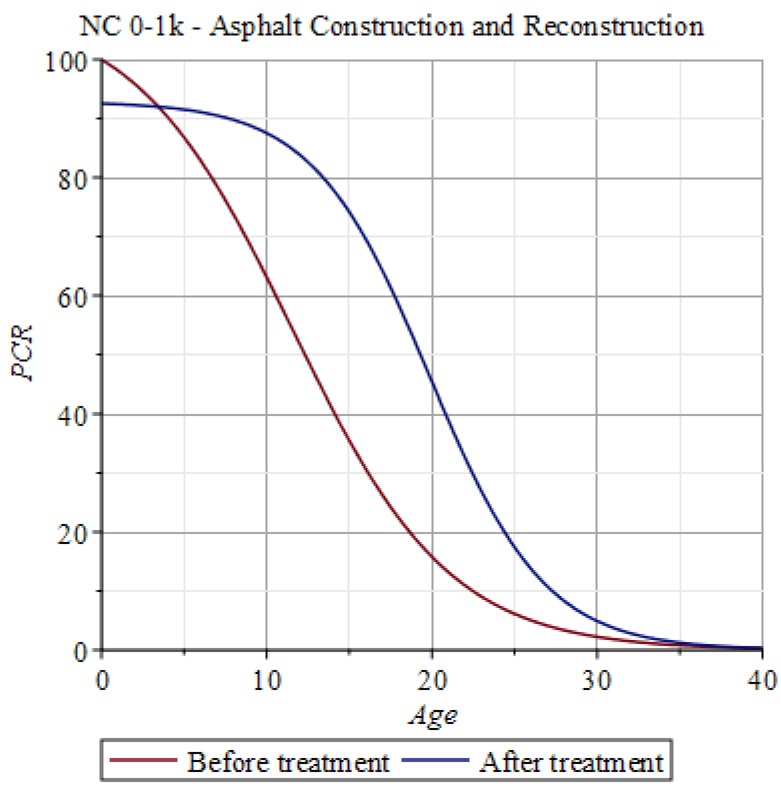

US 30k plus - Asphalt Construction and Reconstruction
PCR
Age
100
80
60
40
20
0
0
10
20
30
40
Before treatment
After treatment


US 30k plus - Chip Seal
100
80
60
40
20
0
PCR
0
10
20
30
40
Age
Before treatment
After treatment

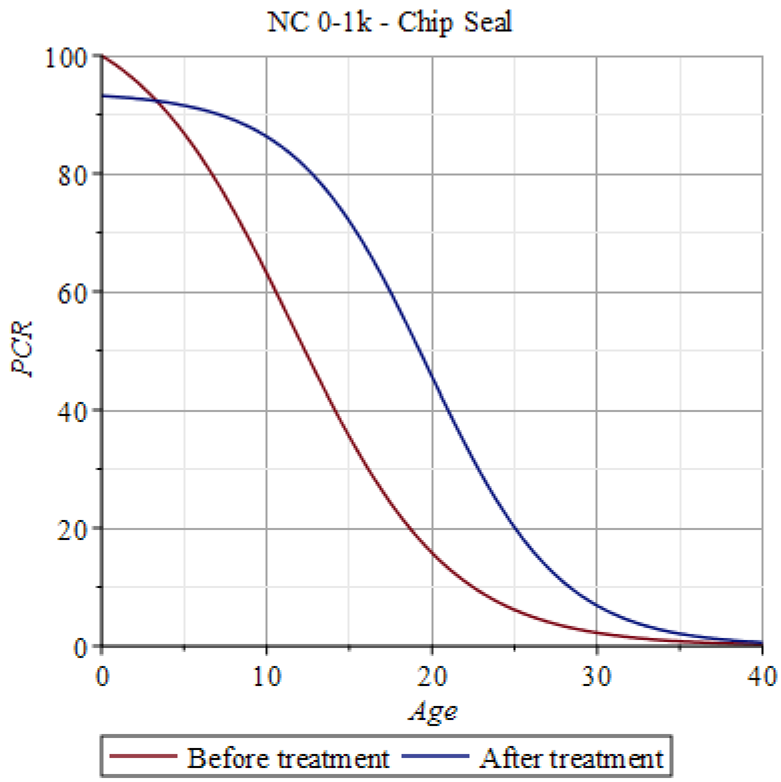

US 30k plus - Mill and Resurface
100
80
60
40
20
0
PCR
0
10
20
30
40
Age
Before treatment
After treatment

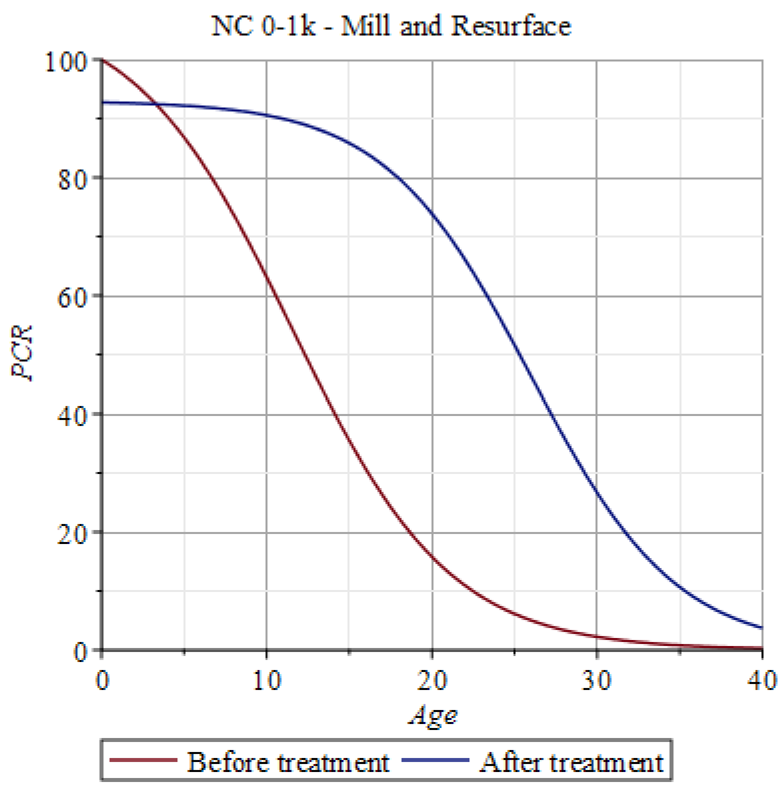


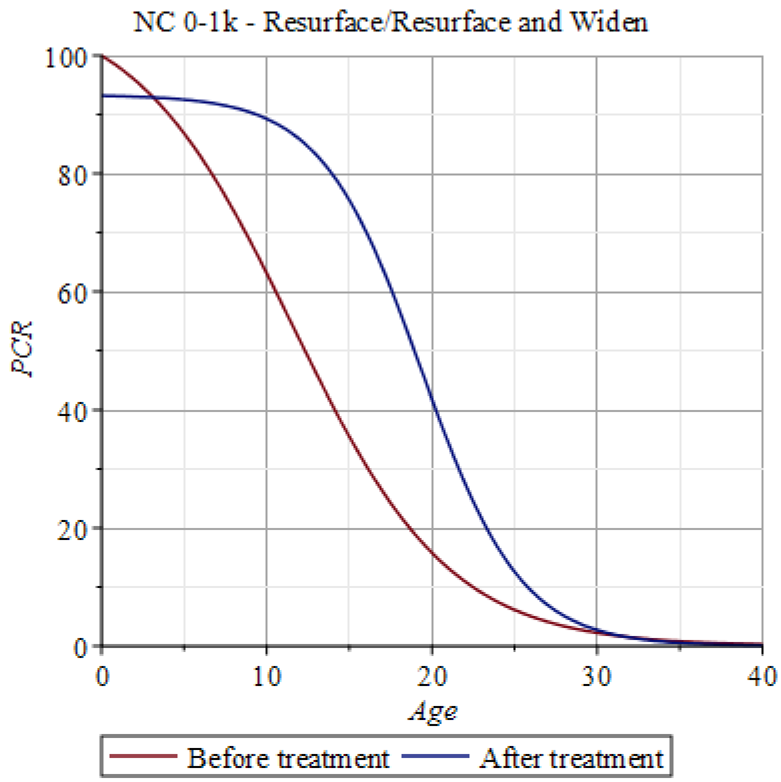
US 30k plus - Resurface/Resurface and Widen
PCR
100
80
60
40
20
0
0
10
20
30
40
Age
Before treatment
After treatment

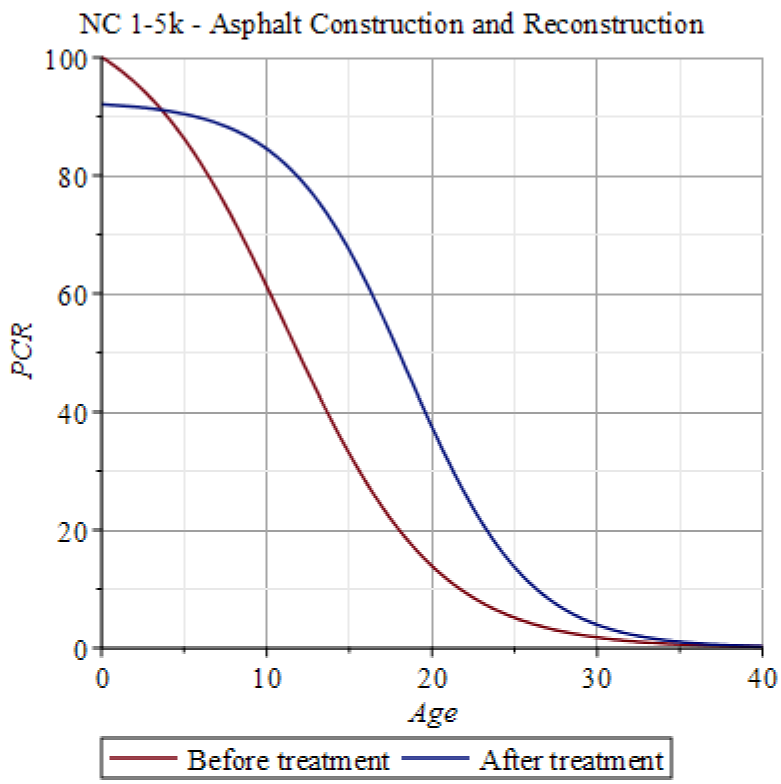


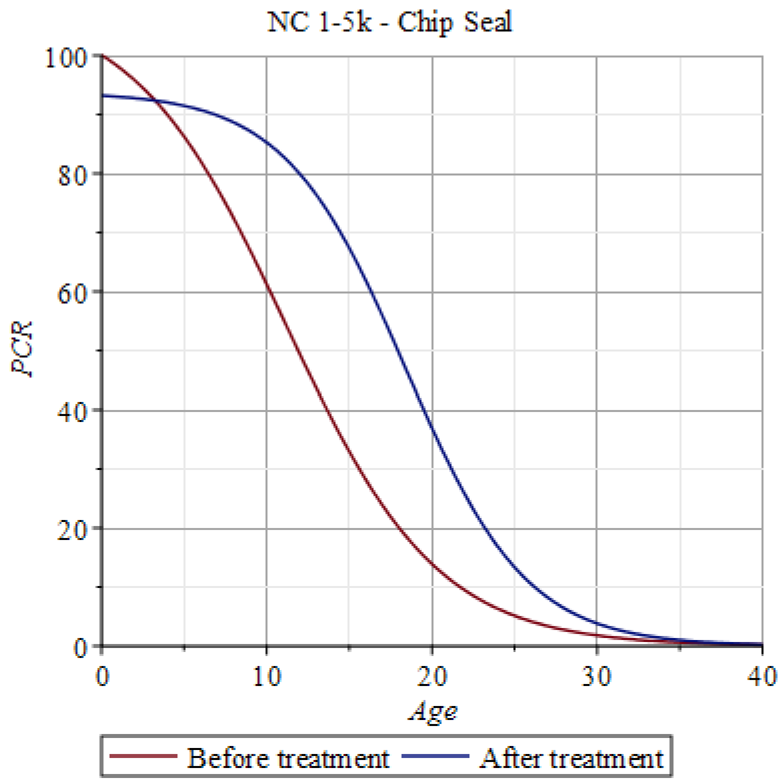
NC 0-1k - Asphalt Construction and Reconstruction
PCR
100
80
60
40
20
0
0
10
20
30
40
Age
Before treatment
After treatment

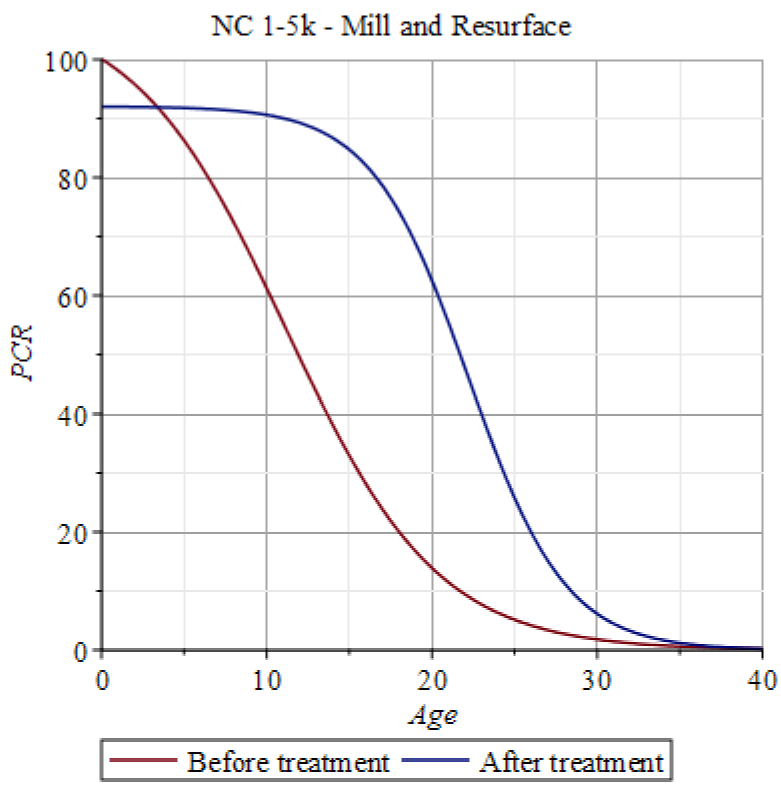

NC 0-1k - Chip Seal
PCR
Age
Before treatment
After treatment


NC 0-1k - Mill and Resurface
PCR
Age
Before treatment
After treatment

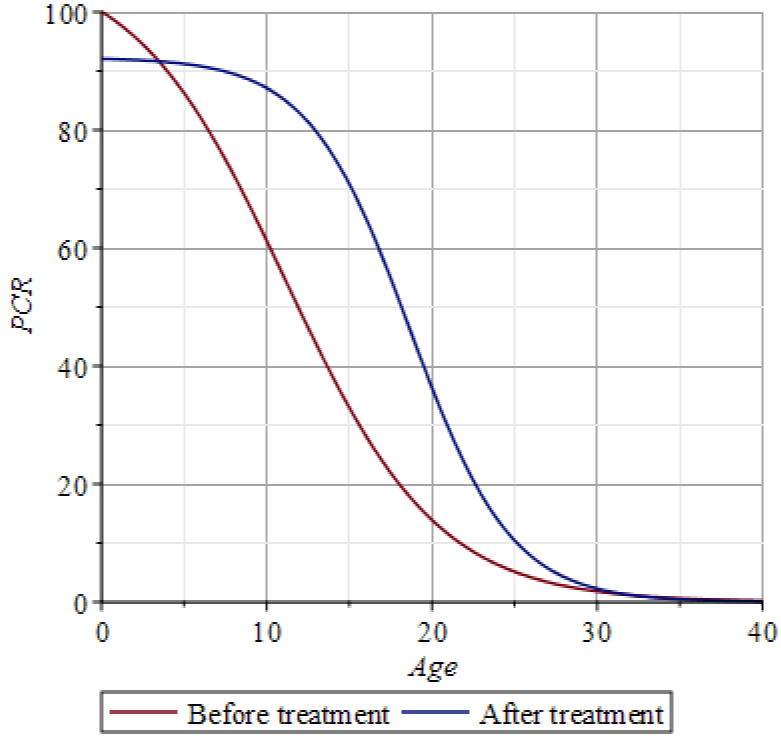

NC 0-1k - Resurface/Resurface and Widen
PCR
Age
0
10
20
30
40
0
20
40
60
80
100
Before treatment
After treatment


NC 1-5k - Asphalt Construction and Reconstruction
PCR
Age
0
10
20
30
40
0
20
40
60
80
100
Before treatment
After treatment

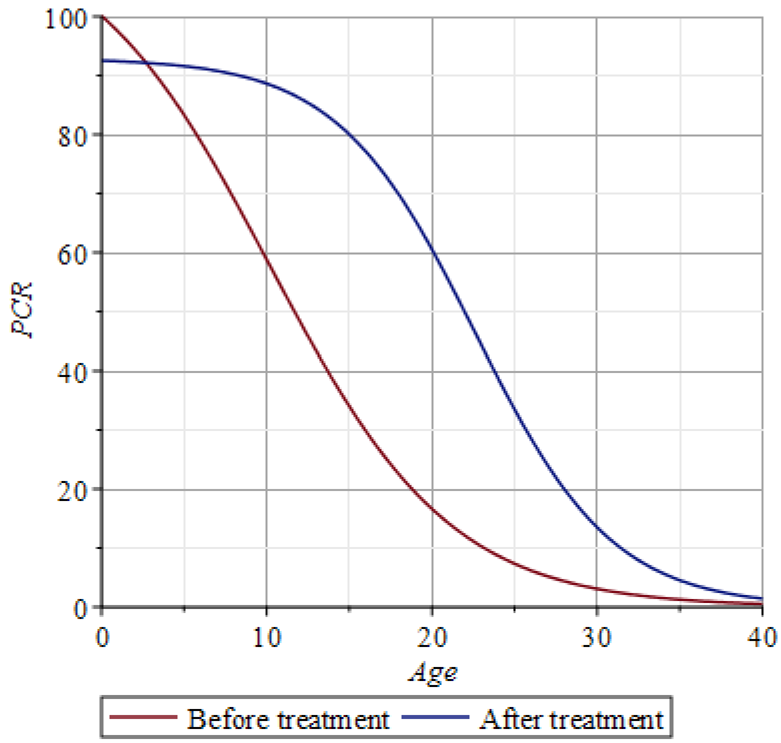

NC 1-5k - Chip Seal
PCR
Age
0
10
20
30
40
0
20
40
60
80
100
Before treatment
After treatment

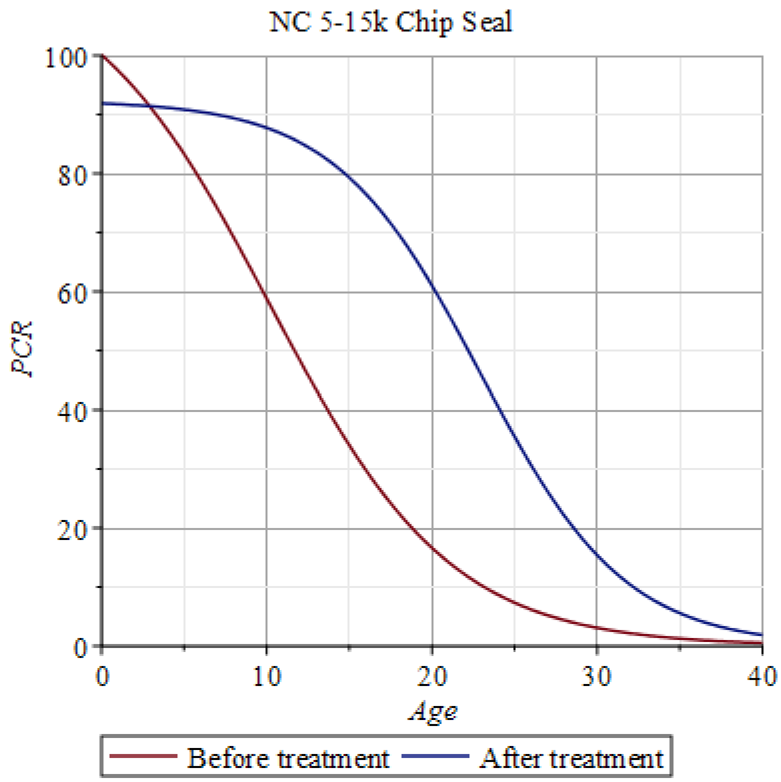

NC 1-5k - Mill and Resurface
PCR
Age
0
10
20
30
40
0
20
40
60
80
100
Before treatment
After treatment

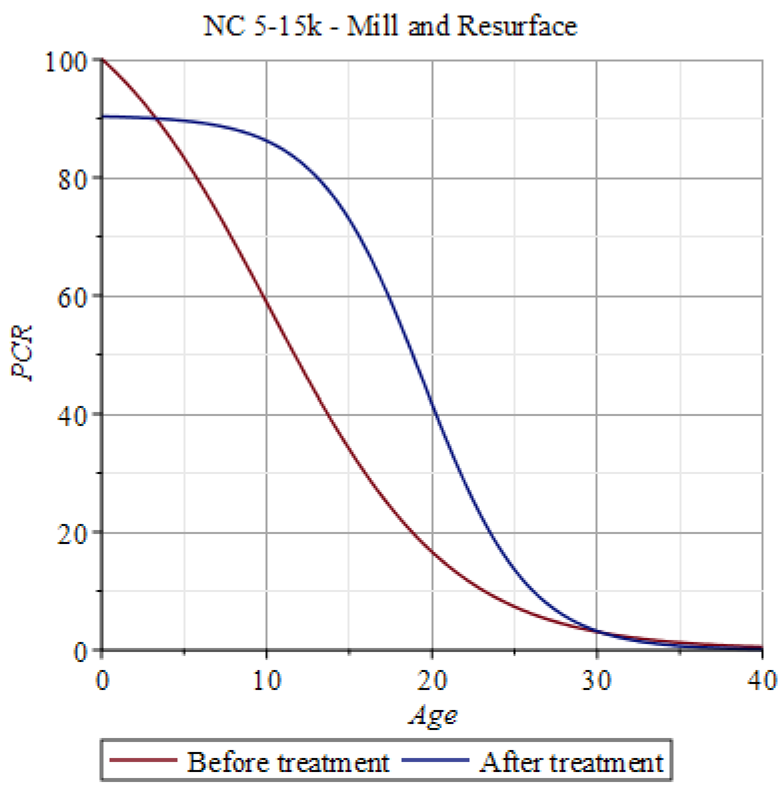
NC 1-5k - Resurface/Resurface and Widen

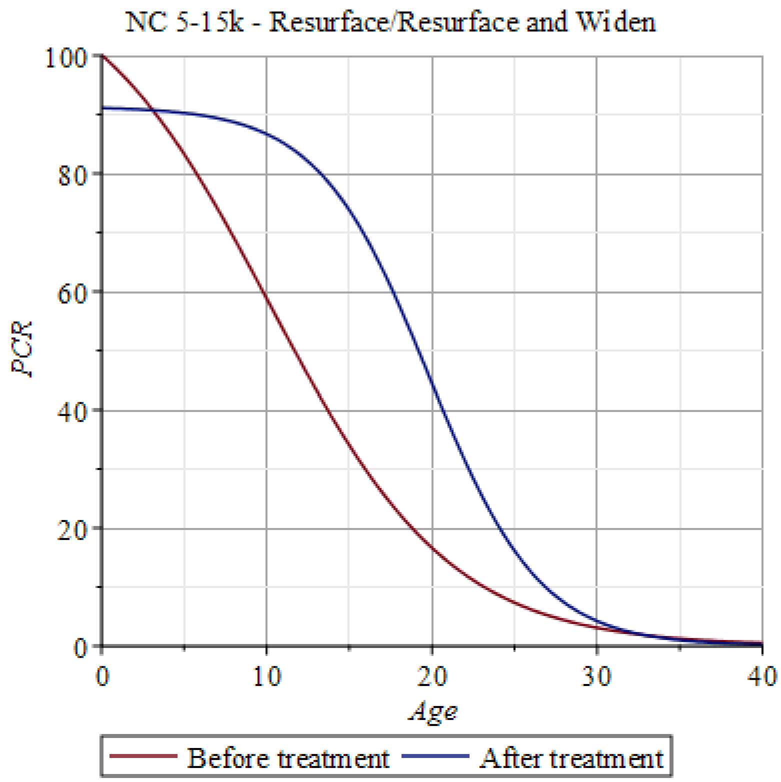


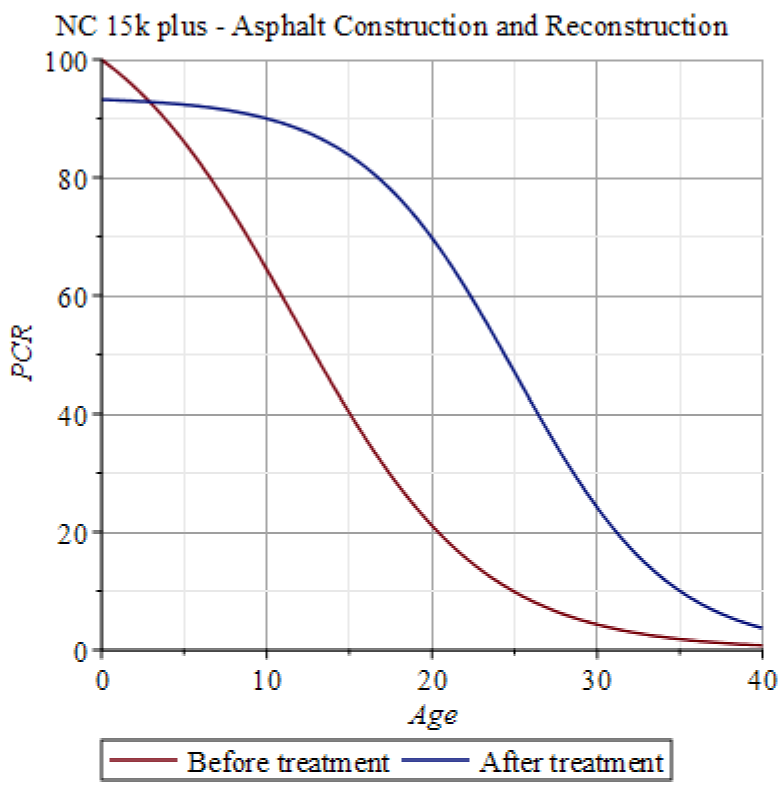
NC 5-15k - Asphalt Construction and Reconstruction

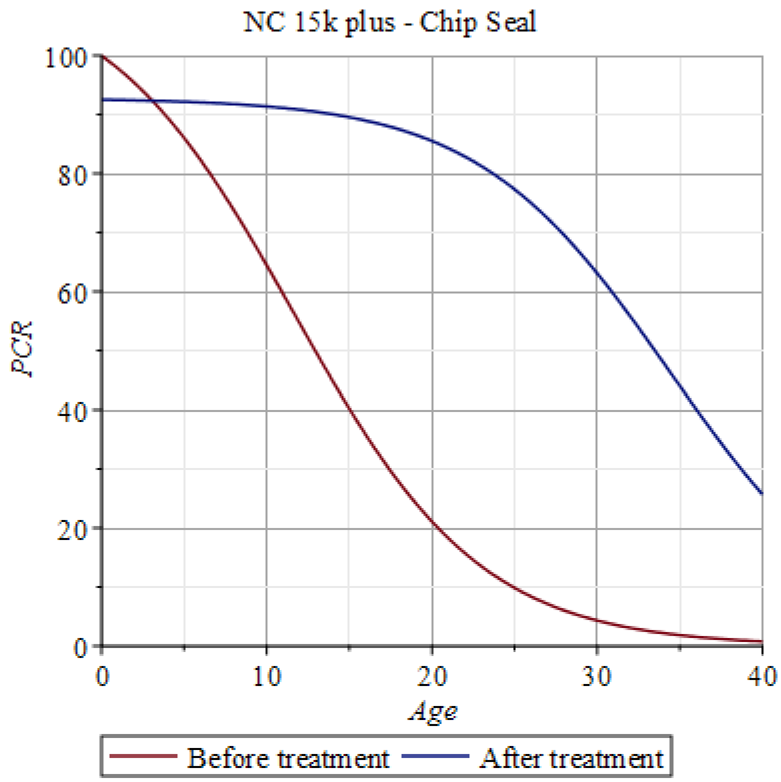


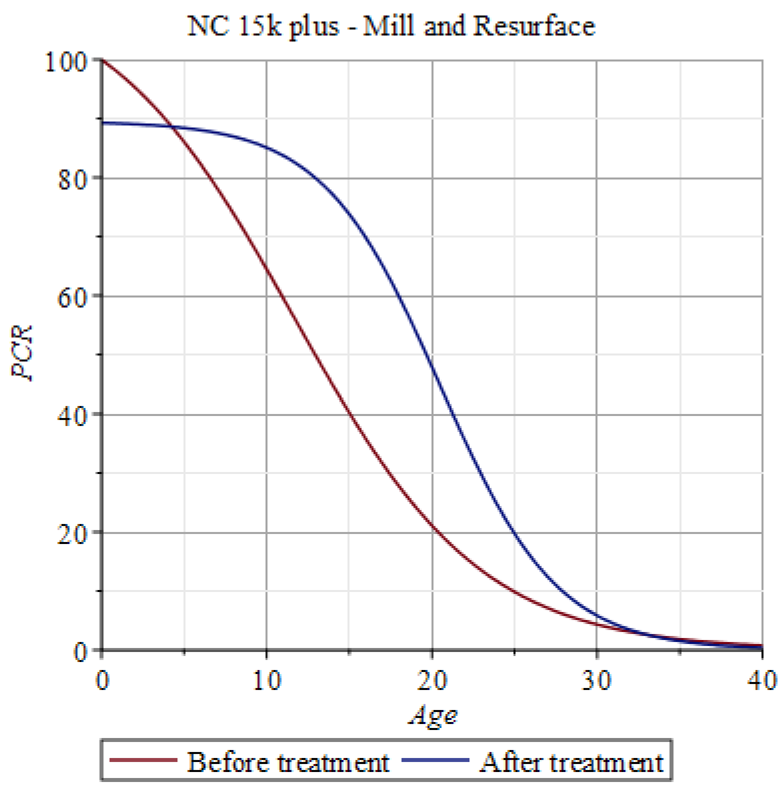

NC 5-15k Chip Seal
100
80
60
40
20
0
PCR
0
10
20
30
40
Age
Before treatment
After treatment

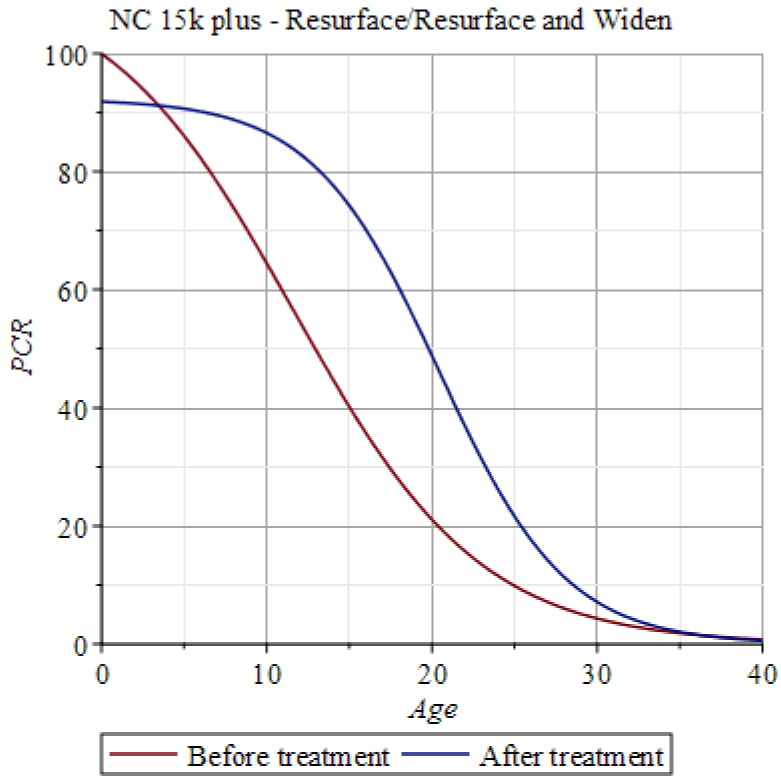

NC 5-15k - Mill and Resurface
100
80
60
40
20
0
PCR
0
10
20
30
40
Age
Before treatment
After treatment

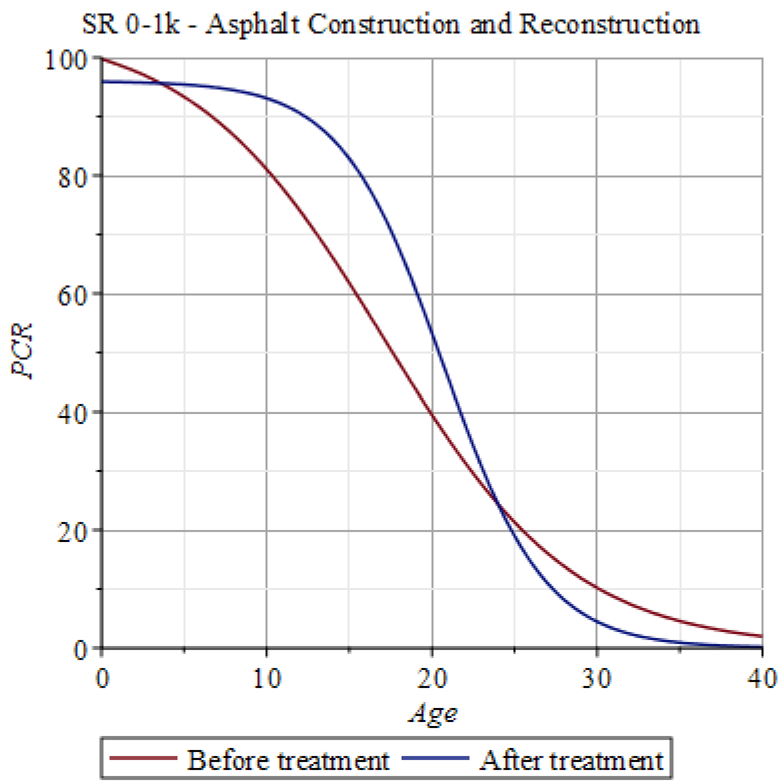

NC 5-15k - Resurface/Resurface and Widen
PCR
Age
0
20
40
60
80
100
10
30
Before treatment
After treatment

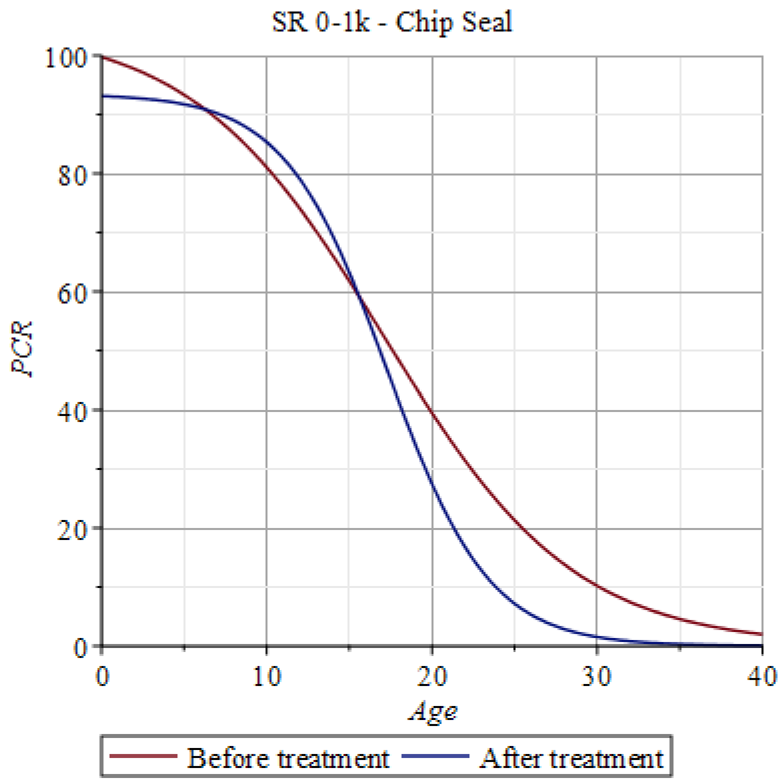

NC 15k plus - Asphalt Construction and Reconstruction
PCR
Age
0
20
40
60
80
100
10
30
Before treatment
After treatment

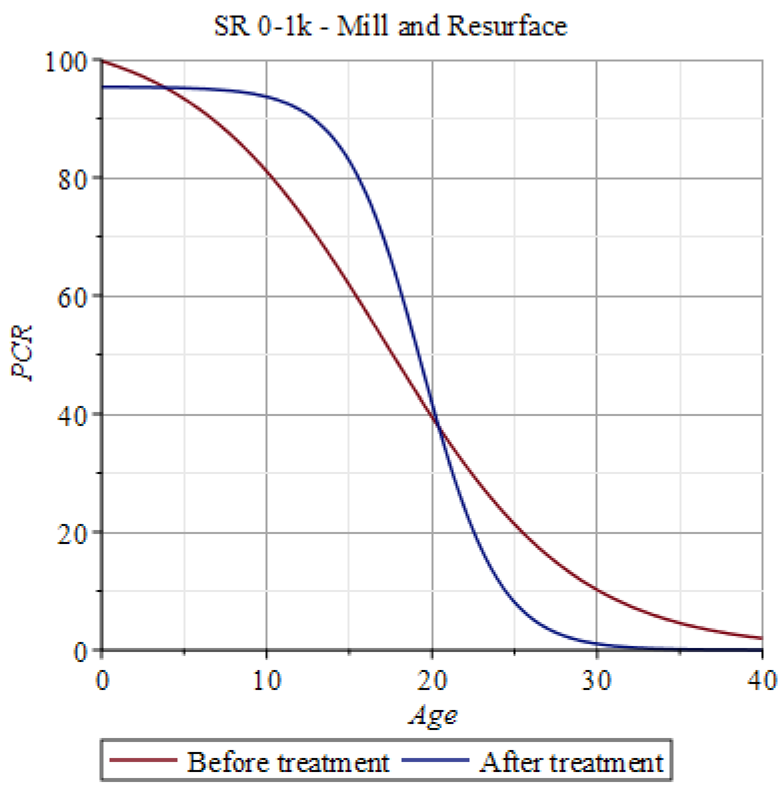

NC 15k plus - Chip Seal
100
80
60
40
20
0
PCR
0
10
20
30
40
Age
Before treatment
After treatment

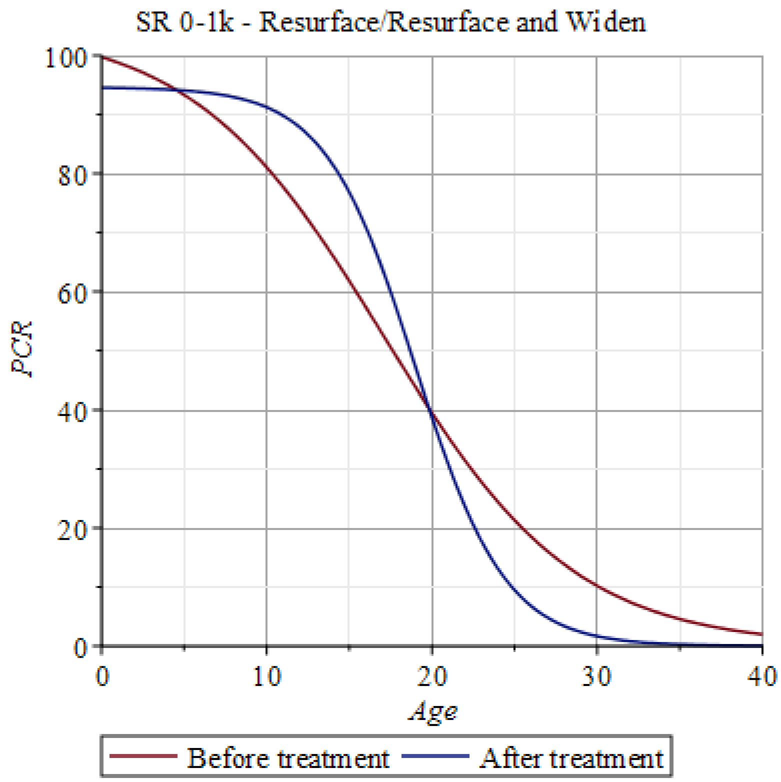

NC 15k plus - Mill and Resurface
100
80
60
40
20
0
PCR
0
10
20
30
40
Age
Before treatment
After treatment

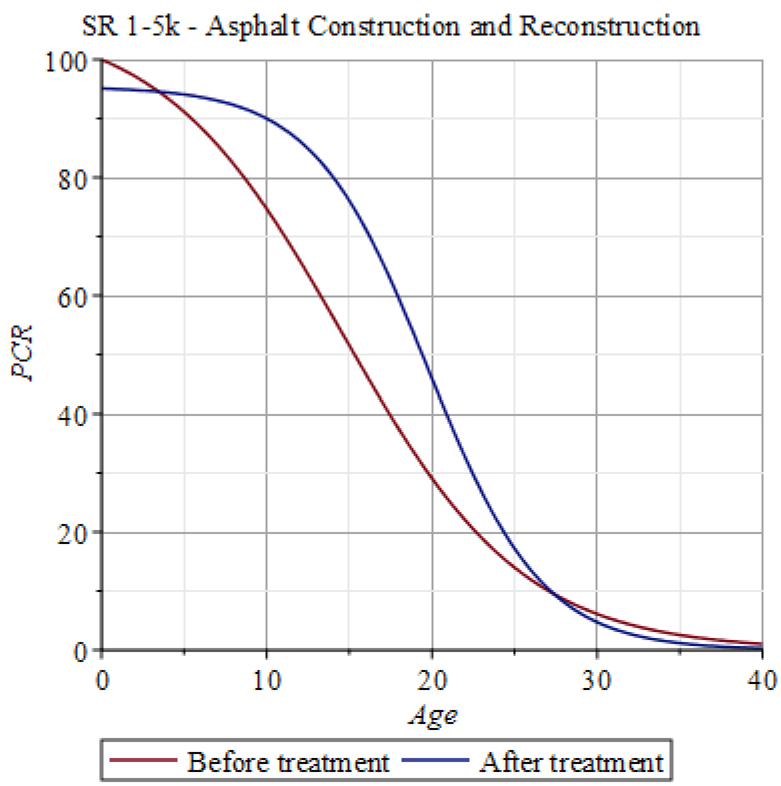

NC 15k plus - Resurface/Resurface and Widen
PCR
Age
0
10
20
30
40
20
40
60
80
100
Before treatment
After treatment

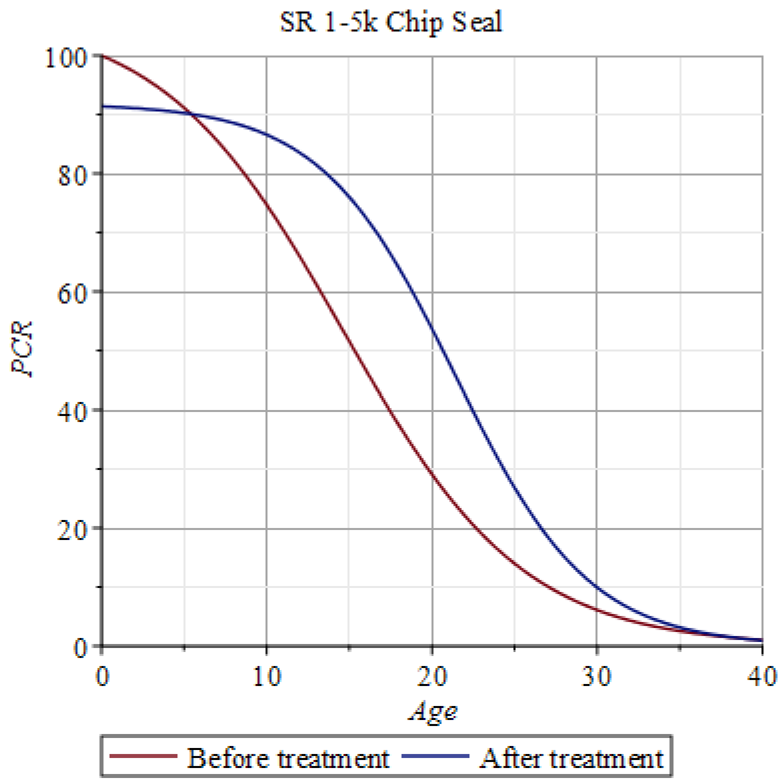

SR 0-1k - Asphalt Construction and Reconstruction
PCR
Age
0
10
20
30
40
20
40
60
80
100
Before treatment
After treatment

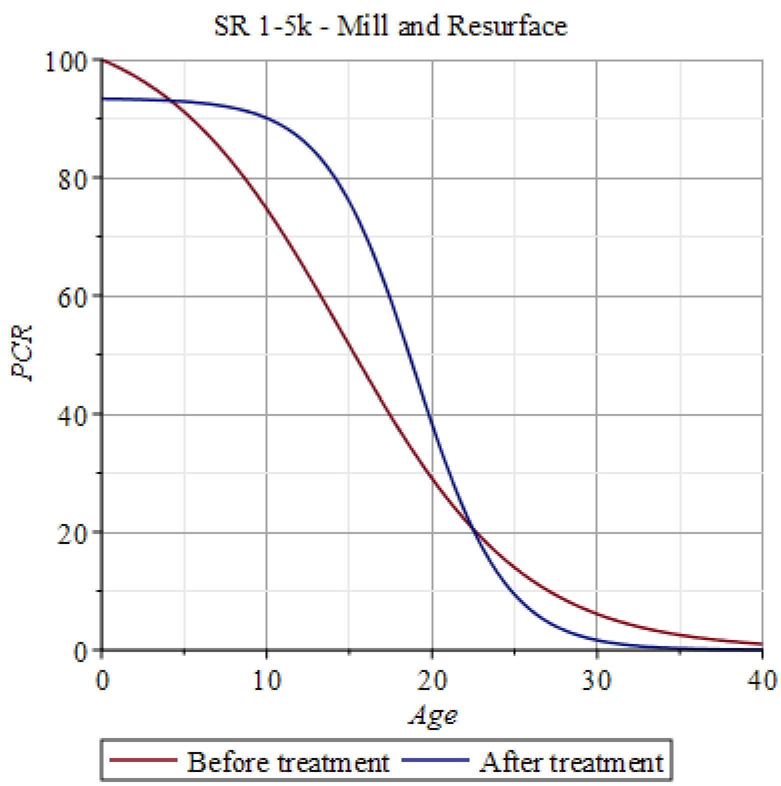

SR 0-1k - Chip Seal
PCR
Age
Before treatment
After treatment

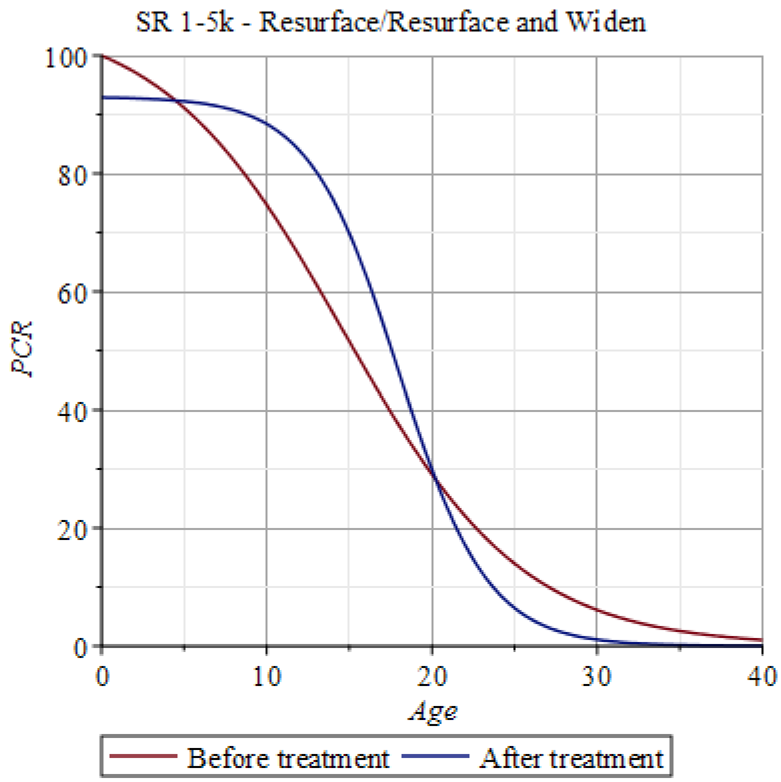

SR 0-1k - Mill and Resurface
PCR
Age
Before treatment
After treatment

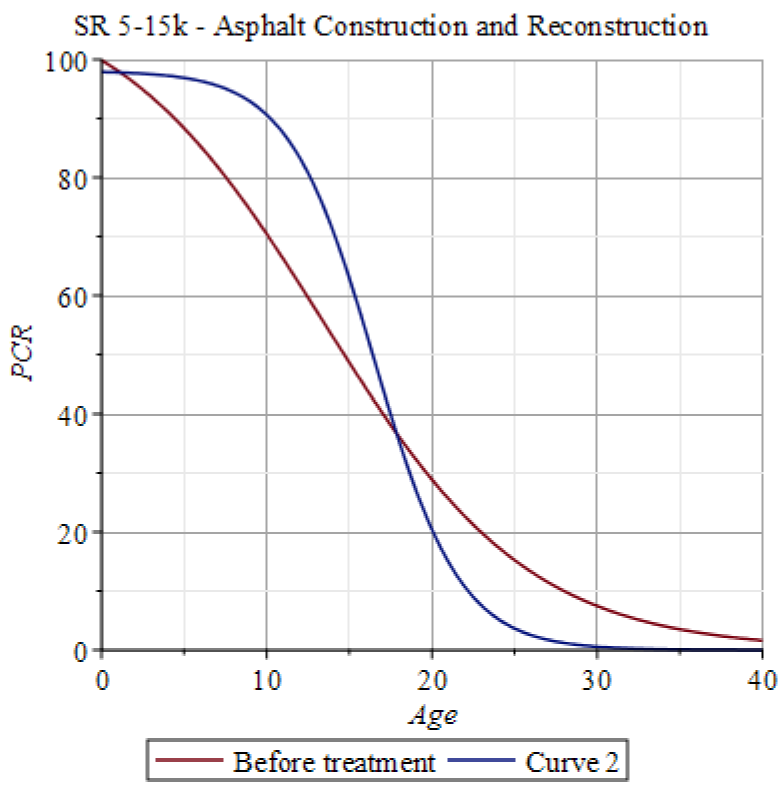

SR 0-1k - Resurface/Resurface and Widen
PCR
Age
0
20
40
60
80
100
10
30
Before treatment
After treatment

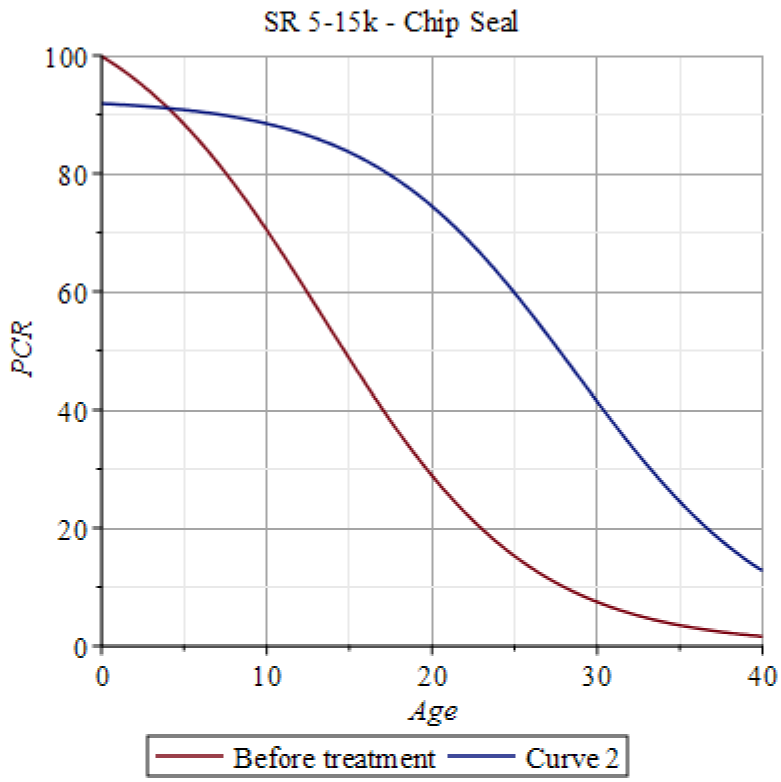

SR 1-5k - Asphalt Construction and Reconstruction
PCR
Age
0
20
40
60
80
100
10
30
Before treatment
After treatment

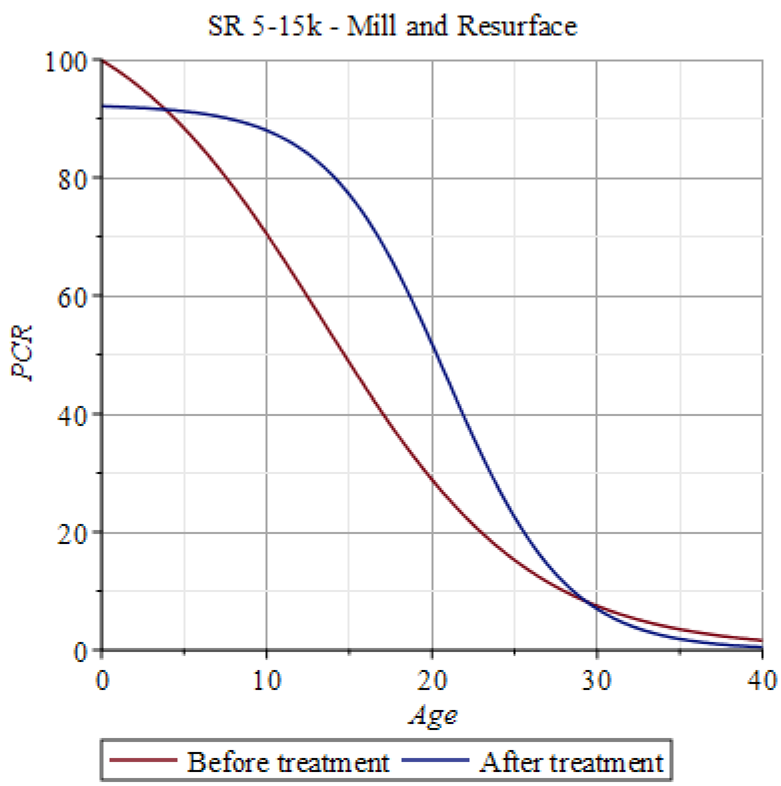

SR 1-5k Chip Seal
PCR
Age
100
80
60
40
20
0
0
10
20
30
40
Before treatment
After treatment

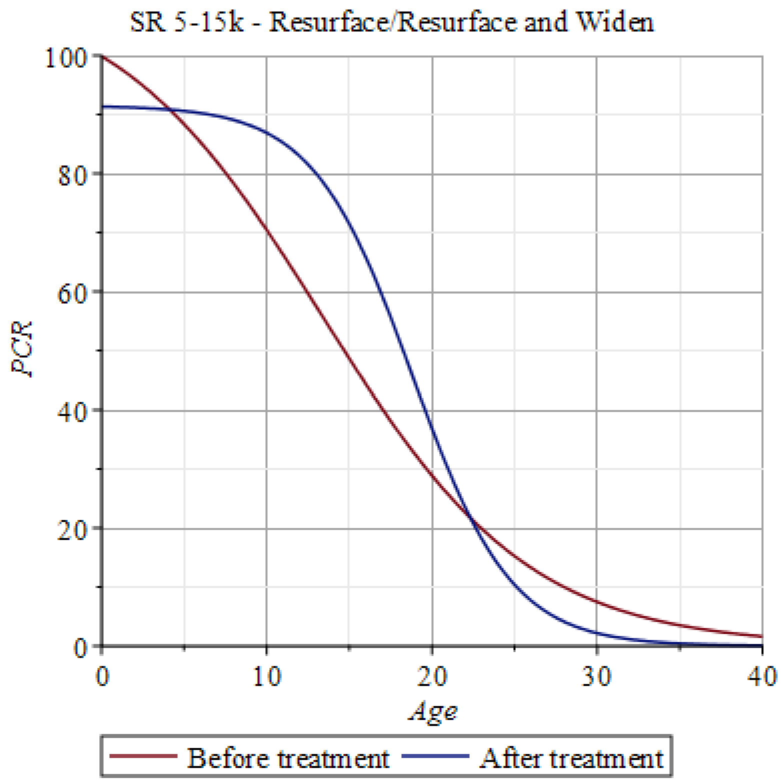

SR 1-5k - Mill and Resurface
PCR
Age
100
80
60
40
20
0
0
10
20
30
40
Before treatment
After treatment


SR 1-5k - Resurface/Resurface and Widen
100
80
60
40
20
0
PCR
0
10
20
30
40
Age
Before treatment
After treatment

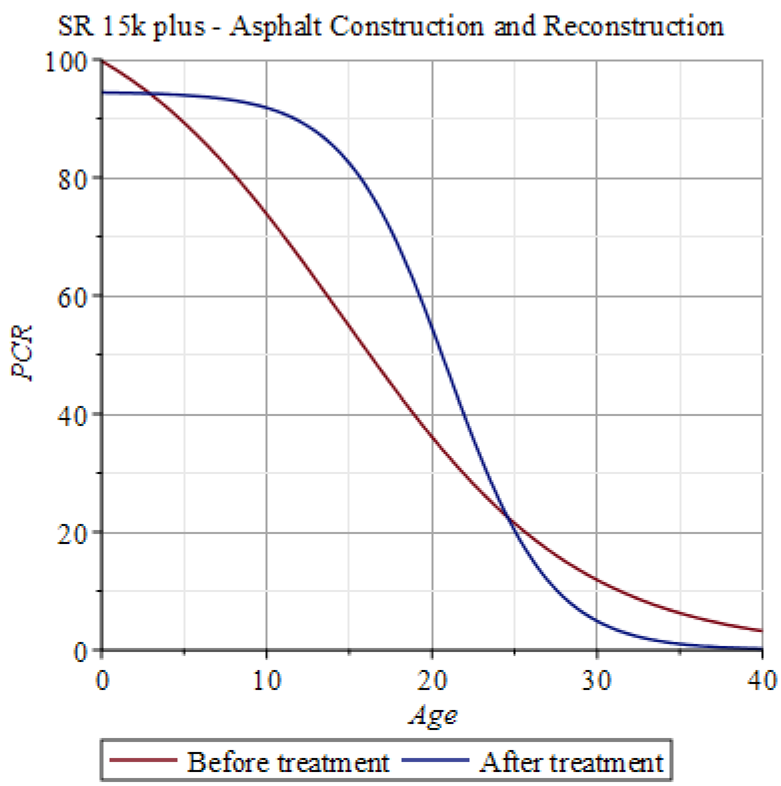

SR 5-15k - Asphalt Construction and Reconstruction
100
80
60
40
20
0
PCR
0
10
20
30
40
Age
Before treatment
Curve 2


SR 5-15k - Chip Seal
100
80
60
40
20
0
PCR
0
10
20
30
40
Age
Before treatment
Curve 2

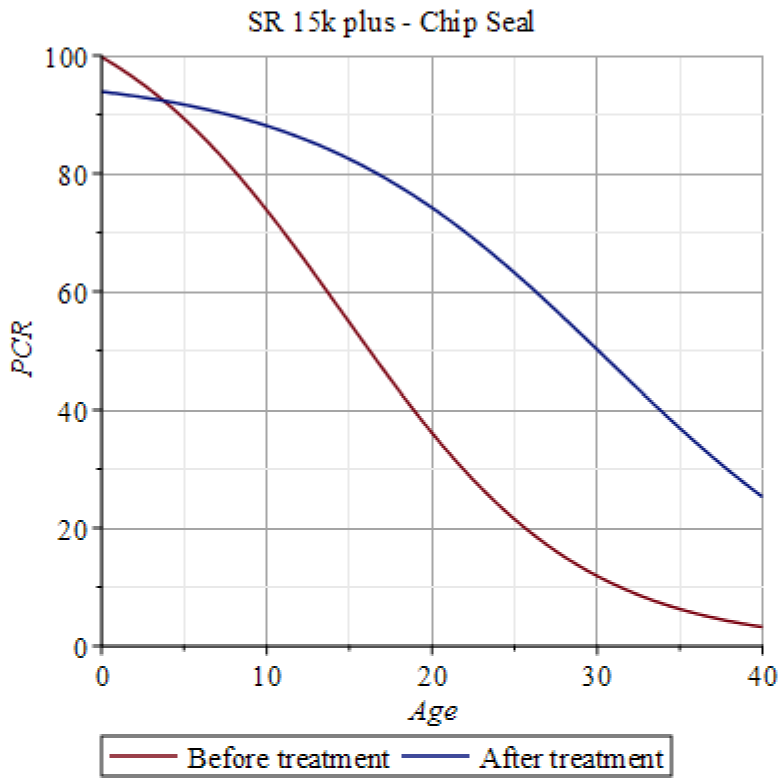

SR 5-15k - Mill and Resurface
100
80
60
40
20
0
PCR
0
10
20
30
40
Age
Before treatment
After treatment

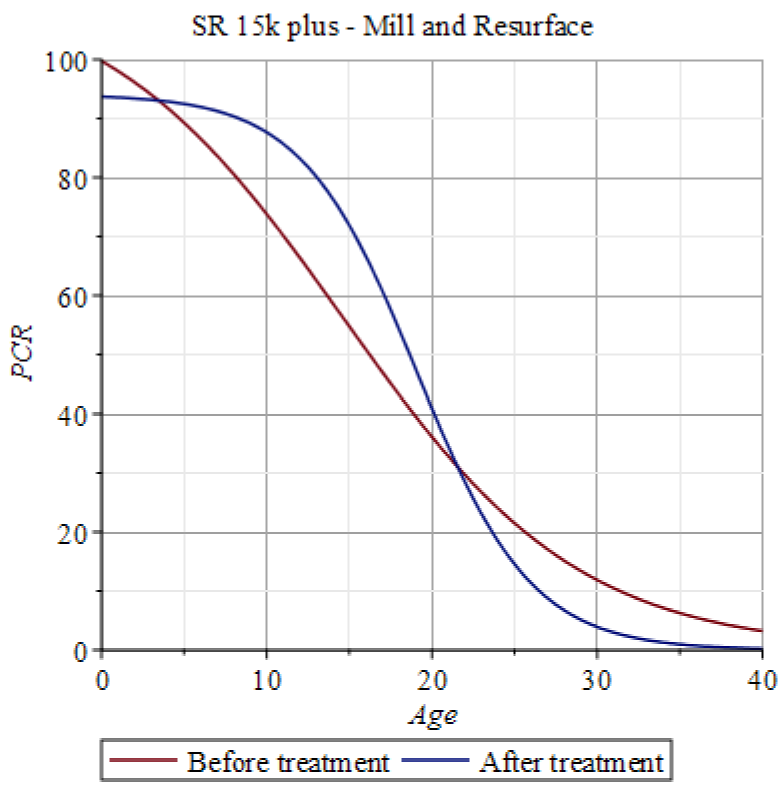


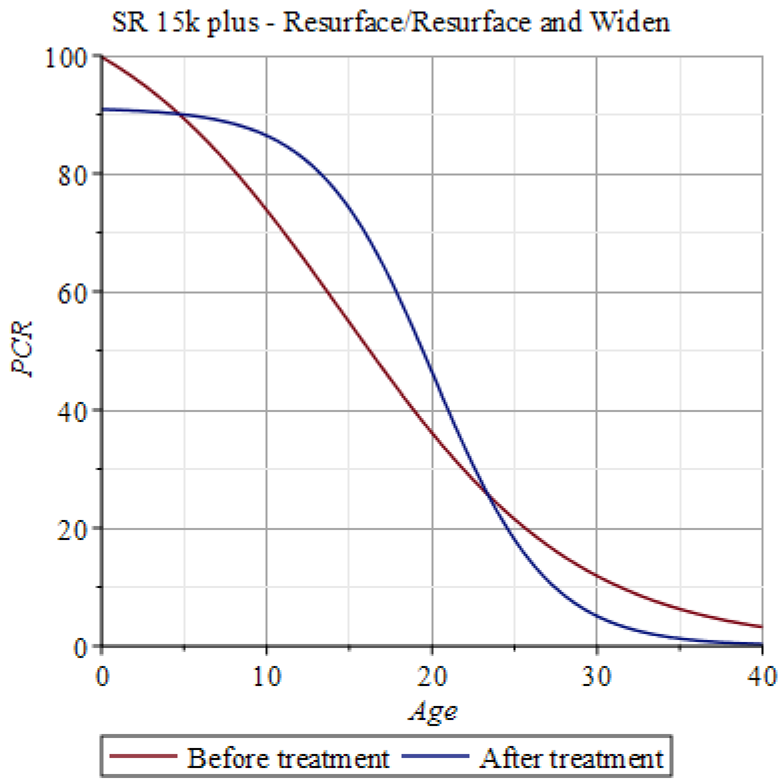
SR 5-15k - Resurface/Resurface and Widen
PCR
Age
0
10
20
30
40
100
80
60
Before treatment
After treatment

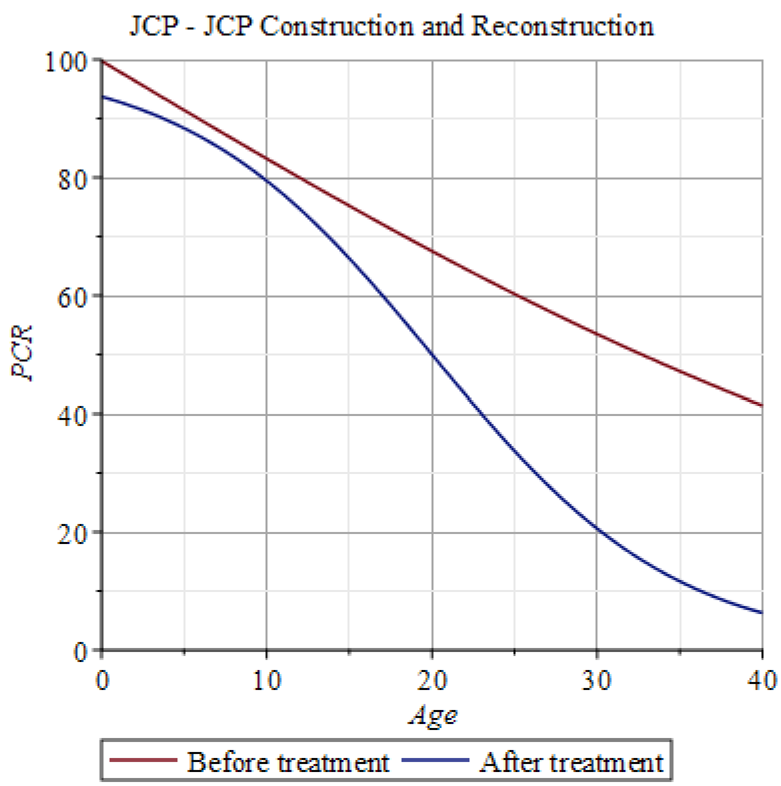


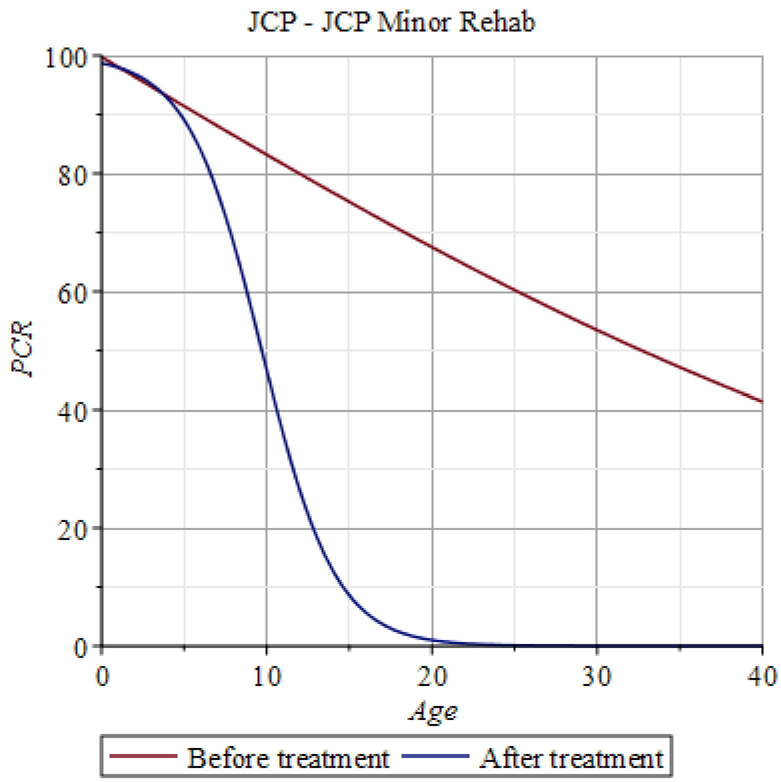
SR 15k plus - Asphalt Construction and Reconstruction
PCR
Age
0
10
20
30
40
100
80
60
Before treatment
After treatment

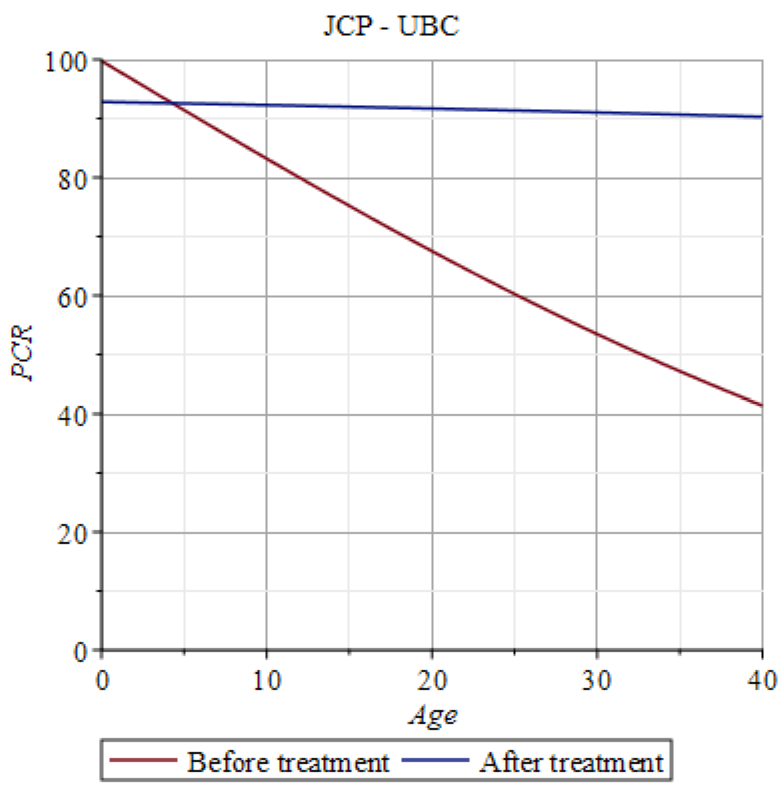

SR 15k plus - Chip Seal
PCR
100
80
60
40
20
0
0
10
20
30
40
Age
Before treatment
After treatment


SR 15k plus - Mill and Resurface
PCR
100
80
60
40
20
0
0
10
20
30
40
Age
Before treatment
After treatment


SR 15k plus - Resurface/Resurface and Widen
PCR
100
80
60
40
20
0
0
10
20
30
40
Age
Before treatment
After treatment


JCP - JCP Construction and Reconstruction
PCR
100
80
60
40
20
0
0
10
20
30
40
Age
Before treatment
After treatment


JCP - JCP Minor Rehab
100
80
60
40
20
0
PCR
0
10
20
30
40
Age
Before treatment
After treatment


JCP - UBC
100
80
60
40
20
0
PCR
0
10
20
30
40
Age
Before treatment
After treatment