12-1-2014

Modeling Pavement Distress Rates within U.S. Air Force Airfields

Lauren Sahagun
University of Nevada, Las Vegas, laurensahagun@gmail.com

MODELING PAVEMENT DISTRESS RATES WITHIN US AIR FORCE AIRFIELDS

By

Lauren K. Sahagun
Captain, USAF

Bachelor of Science in Civil Engineering
United States Air Force Academy
2010

A thesis submitted in partial fulfillment of the requirements for the

Master of Science in Engineering – Civil & Environmental Engineering

Department of Civil and Environmental Engineering
Howard R. Hughes College of Engineering
The Graduate College

University of Nevada, Las Vegas

December 2014

We recommend the thesis prepared under our supervision by

Lauren Sahagun

entitled

Modeling Pavement Distress Rates within U.S. Air Force Airfields

is approved in partial fulfillment of the requirements for the degree of

Master of Science in Engineering -- Civil and Environmental Engineering

Department of Civil and Environmental Engineering and Construction

Moses Karakouzian, Ph.D., Committee Chair

Mohamed Kaseko, Ph.D., Committee Member

Douglas Rigby, Ph.D., Committee Member

Ashok Singh, Ph.D., Graduate College Representative

Kathryn Hausbeck Korgan, Ph.D., Interim Dean of the Graduate College

December 2014

Abstract

Through the review of Pavement Condition Index (PCI) surveys completed at Air Force installations scattered across the continental United States, pavement engineers at the Air Force Civil Engineer Center propose that the predominant factor contributing to pavement distress development is climate. They suggest that within each pavement distress type (i.e. alligator cracking, rutting, spalling, etc.) a geographic pattern exists that is strongly correlated to the conventional climate zones within the US. Knowledge of these geographic patterns would equip pavement engineers and asset managers with a powerful tool to develop purposeful maintenance strategies specific to each distress type.

The following approach was used to evaluate the hypothesis that climate is the predominant pavement distress contributor. First the AF Roll-up Database, housing over 50,000 lines of pavement distress data, was distilled using an original process designed to combine like distresses while accounting for age and size of the pavement upon which the distress occurs. The process effectively reduced the 50,000 lines of distress data to a format that could be used to perform krig analysis. Krig analysis was performed upon the distilled pavement distress data to develop a pavement behavior model for asphalt cement (AC) and portland cement concrete (PCC) runways. Regression analysis and further krig analysis were conducted for each distress type within the presented pavement models to identify if the distress behavior varies between the zones of the models. The combined regression and krig analysis provided insight into the overall pavement behavior for AC and PCC runways and illustrated which zone was more susceptible to specific pavement distresses.

The investigation showed that some distresses display a strong geographic pattern while others are more widespread. The model created in this research to assess the geographic patterns embedded within the distress data and the krig analysis used to uncover these patterns are both

based on a derivation of the PCI deduct value, which contains within it all five pavement deterioration factors (climate, maintenance strategy, traffic load, construction history and pavement structure). This research shows that there is a relationship between pavement distress and climate; however, an investigation of patterns within the other four pavement deterioration factors must be conducted before the conclusion can be made that it is the predominant factor. The data consolidation process and pavement behavior models presented here provide a framework to conduct the additional analysis.

Table of Contents

Page

List of Tables

Page

List of Figures

Chapter 1 Introduction

1.1 Background

The United States Air Force contains 1.6 billion square feet of concrete and asphalt pavement in its real property inventory across 166 Air Force installations worldwide. The airfield pavement portion of the inventory alone has a plant replacement value of more than $27 billion and requires millions of dollars in annual maintenance. The Budget Control Act enacted by the United States Congress in 2011 requires the Department of Defense (DoD) to reduce its expenditures by approximately $487 billion over the next 10 years (Defense Budget, 2012). This budget cut has forced Air Force engineers and asset managers, at all administrative levels, to reconsider their strategic approach to facility and infrastructure asset management.

The Air Force Civil Engineer Center (AFCEC) is responsible for strategic and long-term pavement management at the combined, joint, major command and installation levels. To manage the Air Force pavement inventory, AFCEC developed the Air Force Pavement Evaluation Program (AFPEP). AFPEP determines each installation's current pavement condition and works to strategically allocate restoration and modernization funds to address future pavement and mission needs (AFCEC webpage). The Pavement Evaluation Program obtains compiles, and reports pavement strength, condition, and performance through a rotation of pavement inspections, evaluations and tests to determine each installation's pavement condition (AFI32-1041, 2013). From these inspections, evaluations and tests, engineers and asset managers are able to determine the operational condition of the pavement, develop and prioritize sustainment, restoration and modernization projects and determine whether additional pavement investigation is necessary.

One of the inspections used by AFCEC to evaluate the pavement's structural and operational integrity is the Pavement Condition Index (PCI) Survey. The results of these inspections are the catalyst and the basis of which this research has been conducted. From the compiled results of the PCI surveys, pavement engineers at AFCEC-East, located at Tyndall Air Force Base, Florida, have noticed what they believe to be climatological trends within the pavement distress data. From these observations, they postulate that climate is the predominant contributing factor of pavement distresses.

To test their hypothesis, they partnered with the Air Force Institute of Technology (AFIT), located at Wright-Patterson Air Force Base, Ohio, to conducted research into the relationship between climate and pavement deterioration rates. The objective of that research was to answer the question: "How can climate regions, within the United States, be used to understand and quantify the effects of climatic conditions on the deterioration rates of airfield pavements?" (Meihaus, 2013). The research accomplished by AFCEC and AFIT used precipitation and temperature data collected from 1982-2011 at 1,700 National Oceanic and Atmospheric Administration, National Weather Service, and Federal Aviation Administration weather stations scattered across the United States to develop a climate model. The climate model included the four climate zones depicted in Figure 1. They worked with engineers at U.S. Army Cold Regions Research and Engineering Laboratory to develop the break points delineating freeze and no-freeze zones and wet and dry zones (Meihaus, 2013). The break point used to define a "wet" zone from a "dry" zone was 25 inches of annual precipitation and the criterion used to delineate between a "freeze" climate and a "no freeze" climate was 750 freezing degree days. A freezing degree day is defined as the temperature of the mean daily air temperature from 0°C (Assel, 1980). The four climate zones were "freeze_dry", "freeze_wet", "no freeze_dry", and no freeze_wet". After the climate model was developed the research used PAVER™, a pavement management software program originally developed in the 1970s to assist the DoD in managing its large pavement inventory, to calculate the pavement deterioration rates within each family of pavement (Colorado State, 2014). These deterioration rates were then statistically examined against other deterioration rates at bases within each of the four proposed climate zones. The investigation concluded that aprons typically deteriorate faster than taxiways and taxiways deteriorate faster than runways for the same pavement type. It also found that asphalt concrete (AC) and asphalt-over-asphalt concrete (AAC) pavements deteriorate much faster than portland cement concrete (PCC) pavements for the same pavement use and finally that the "freeze_dry" climate zone had the highest rate of deterioration for all pavement families (small exception of AC/AAC runways) as seen in Tables 1 and 2 (Meihaus, 2013).

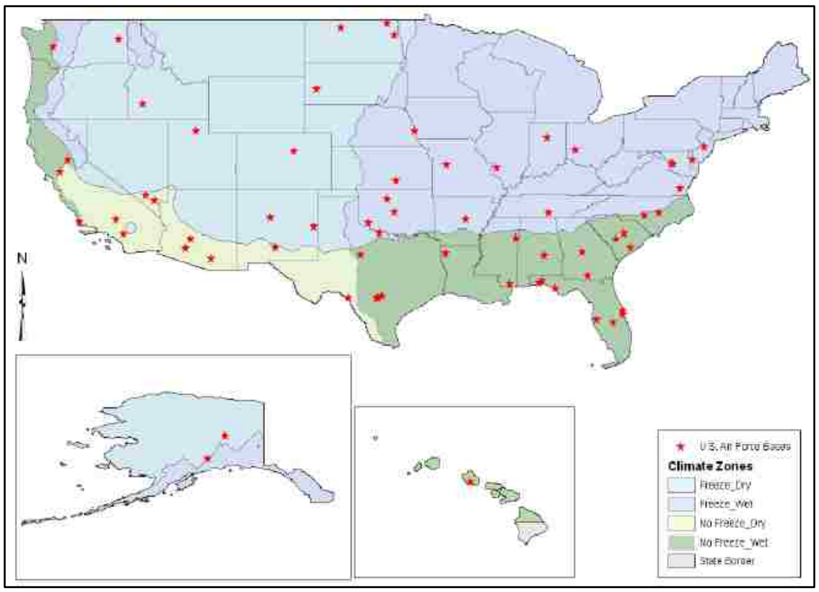


Figure 1: Precipitation and Temperature Based Climate Model Proposed by AFIT

	AC/AAC (AC AGE RESTRICTED) Average Rate of Deterioration		
Climate Zone	**Runway**	**Taxiway**	**Aprn**
No Freeze_Wet	2.1342	1.7229	1.8735
No Freeze_Dry	2.4213	1.8043	1.9540
Freeze_Wet	2.4110	1.8843	N/A
Freeze_Dry	2.4170	2.1053	2.3775
Overall	2.31677	1.864	2.0205

Table 1: Average Rate of Deterioration for RW, TW and Aprons in each of the Four Climate Zones Proposed by AFIT-AC/AAC

	PCC		
	Average Rate of Deterioration		
Climate Zone	**Runway**	**Taxiway**	**Aprn**
No Freeze_Wet	0.5121	0.5799	0.7069
No Freeze_Dry	0.6004	0.4599	0.6434
Freeze_Wet	0.7347	0.7635	0.7695
Freeze_Dry	0.9851	0.8515	1.0048
Overall	0.65809	0.6445	0.76326

Table 2: Average Rate of Deterioration for RW, TW and Aprons in each of the Four Climate Zones Proposed by AFIT-PCC

As follow-on research to the investigation of climate and deterioration rates accomplished by AFIT, pavement engineers at AFCEC-East requested an investigation of distress patterns within the four proposed climate regions be accomplished. Specifically, they wanted to know which distress types were most prevalent in each of the four climate zones. This knowledge would provide them with valuable information to use during pavement maintenance planning and asset allocation, for example if they know alligator and longitudinal/transverse cracking are more prevalent in "freeze_wet" climates then they can proactively allocate funds to address these distresses at Air Force installations located within the "freeze_wet" climate zone.

1.2 Problem Statement

Through the review of PCI surveys completed at Air Force installations scattered across the continental United States, pavement engineers at AFCEC-East have noticed a relationship between the occurrence of specific pavement distresses and the geographic location where they occur. They propose that within each pavement distress type (i.e. alligator cracking, longitudinal and transverse cracking, spalling, etc.) a geographic pattern exists that is strongly related to the climate zones within the United States. To assess the validity of this suggestion an analysis of patterns within specific pavement distress types must be conducted from a geographic and climatological vantage. This research effort aims to aid pavement engineers and asset managers to design and further develop maintenance strategies to combat distress type and plan for region specific pavement deterioration behavior.

1.3 Research Objectives

The objective of this research is to investigate the existence of geography and/or climate induced patterns in airfield pavement distresses. To accomplish this investigation the following questions must be addressed:

1) Is a climate model based upon precipitation and temperature data appropriate for use to evaluate the relationship between climate and pavement deterioration behavior at the individual pavement distress level?
2) Does a pattern emerge considering only the geographic location of specific pavement distresses?
3) If a geographic or climatological pattern does not emerge what other factors should be considered as contributing to the development of the surveyed pavement distresses?

Chapter 2 Literature Review

2.1 Pavement Management System

A deliberate and purposeful approach to pavement management is essential for prolonged airfield pavement life and uninterrupted mission completion. In 2013 the U.S. Air Force accomplished over 5.9 million sorties (ATAR, 2013). Airfield managers, pavement engineers and asset managers at all levels work together to ensure airfield pavements can safely support each and every one of those flying missions through use of a Pavement Management System (PMS). A PMS effectively provides a systematic and consistent method for identifying maintenance and repair (M&R) requirements, highlights requirement priorities and provides a framework for scheduling maintenance actions while optimizing cost and time (Shahin, 2005). Figure 2 shows an idealized conceptual illustration of a pavement condition life cycle as described by M.Y. Shahin (2005). The illustration shows two important concepts of the PMS. The first is that a pavement's rate of deterioration (ROD) is not constant. Initially the ROD is very rapid; after the initial drop in pavement condition the ROD levels off for a number of years until it undergoes a second rapid decrease in pavement condition. The second major take away from this illustration is that if maintenance action is accomplished to rehabilitate the pavement before the second rapid decrease in pavement condition occurs then the overall cost of the rehabilitation is much less than if the rehabilitation is accomplished after the second major drop (Shahin, 2005). AFCEC aims to assist pavement engineers and asset managers at the major command and base levels in creating a PMS for each part of the pavement inventory as outlined in the following steps.

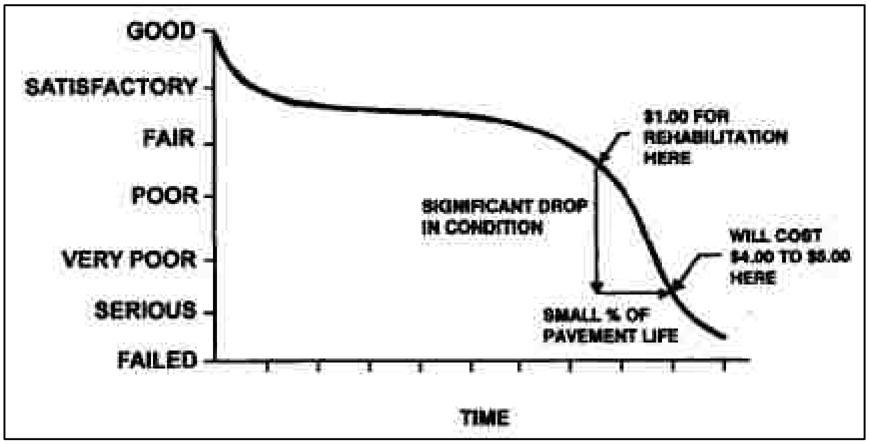


Figure 2: Conceptual Illustration of Pavement Condition Life Cycle (Shahin, 2005)

2.1a Pavement Family Identification

The first step in establishing a PMS is classifying the pavement within the system. The pavement network is the highest level of classification within the pavement system. Shahin defines a pavement network as, “a logical grouping of pavements for M&R management” (2005). Examples of pavement networks within an Air Force installation are airfield pavement, roadways and parking lots. Another way to create networks within an Air Force installation is to delineate between roadways associated with the base and roadways associated with family housing. For this research, the pavement network is set as the airfield pavement at each AF installation (Figure 3). Within a pavement network is a pavement branch. Each branch is readily identifiable and has a unique use. This research is focused on the pavement behavior of only the runway branch within the installation’s airfield network. The smallest classification within a pavement system is a pavement section. A pavement section is created when the pavement characteristics within a branch are not consistent. For example within a runway branch the first and last 1,000 feet may be constructed of PCC to withstand the force induced by take-offs and landings where the middle portion which is designed for loads at higher speeds is constructed with AC. Pavement characteristics to consider when defining sections are: pavement structure, construction history, traffic, pavement function, drainage, condition and size (Shahin, 2005).

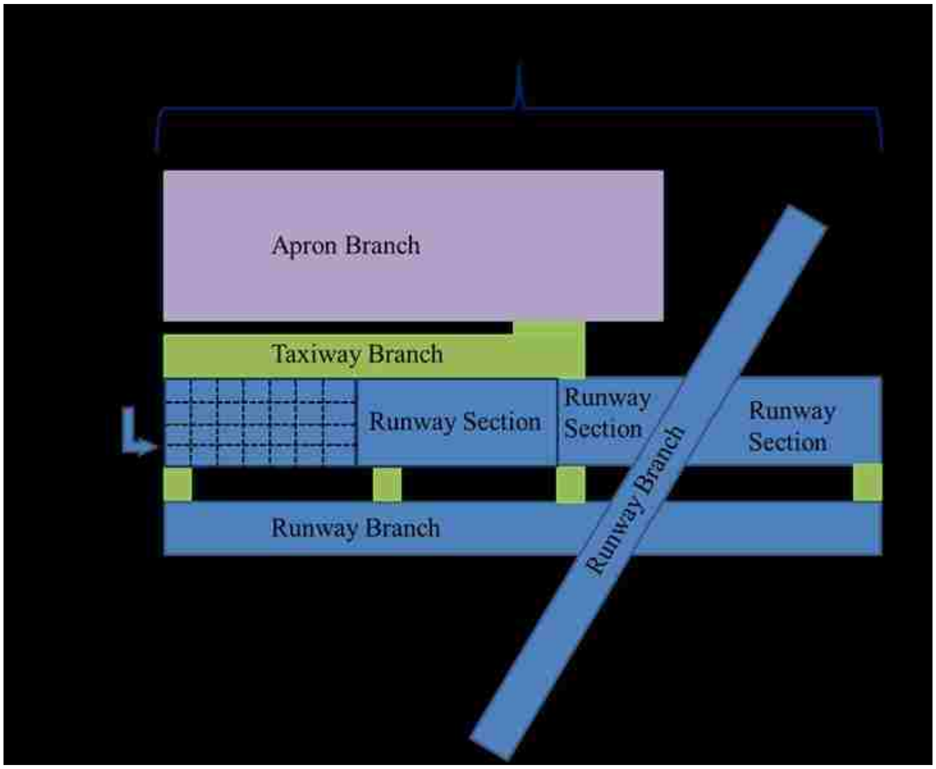


Figure 3: Pavement Family Illustration

2.1b Pavement Condition Index

The second major component of a PMS is assessing the current condition of the pavement within the system and predicting how it will behave in the future. For the condition of one pavement network to be compared to another pavement network an objective and repeatable rating system must be used across all networks under consideration. The rating system used by AFCEC to standardize condition assessments across all Air Force installations is the Pavement Condition Index (PCI) which was developed by the U.S. Army Corps of Engineers in the 1970s and has been published as American Society for Testing and Materials (ASTM) standard, D5340 (Shahin, 2005). Other agencies that use the PCI to assess the condition of their pavement systems include: the U.S. Navy, U.S. Army, the Federal Aviation Administration and the Federal Highway Administration (Colorado State, 2014).

The PCI is a numerical index, ranging from 0-100, where a rating of 100 corresponds to a pavement in perfect condition and a rating of 0 corresponds to a failed pavement (Figure 4).

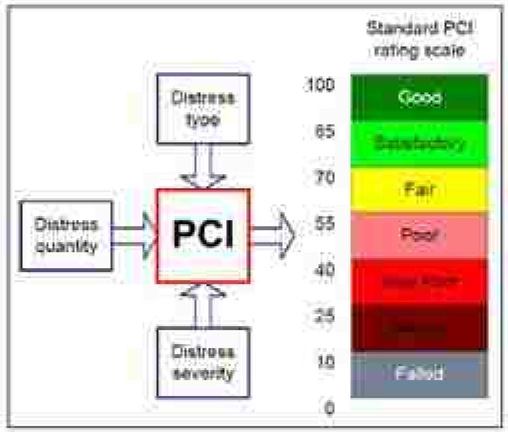


Figure 4: Pavement Condition Index (PCI) Rating Scale (Colorado State University, 2014)

Calculation of the PCI is based on the results of a visual condition inspection, called the PCI Survey. The PCI Survey is used to identify distress type, severity, and quantity caused by aircraft loadings, vehicle traffic and environmental conditions and is conducted approximately every five years, by contracted personnel, at all main operating bases and auxiliary fields belonging to the Unites States Air Force (AFI32-1041, 2013). The pavement distress information collected during PCI Surveys provides insight into the cause of the pavement deterioration and is the basis on which this research is conducted (Shahin, 2005).

2.2 PCI Survey and Calculation Procedures

Outlined in the following section is a discussion of the procedures used to conduct each PCI Survey and to calculate the PCI of each pavement section within the surveyed networks. It is important to highlight that the scope of this research does not include original survey data or PCI calculations. All distress data was collected during PCI surveys over the past 16 years and all PCI values were calculated with the PAVER™ software. Although the data used to perform the analysis was provided in full by AFCEC, it is crucial to understand how the surveys are conducted and how the PCI values are calculated in order to understand how the data was manipulated to form the pavement models used to draw conclusions about the relationship between pavement distress patterns and climate.

2.2a PCI Survey Procedures

When calculating the PCI of a pavement section the survey team first divides the pavement section into sample units. A pavement sample unit is a subdivision of a pavement section that has a defined standard size and is created solely for the purpose of pavement inspection (ASTM D5340, 2011). The standard size for PCC airfield pavement is 20 contiguous slabs (+/- 8 slabs if the total number of slabs in the section is not evenly divisible by 20, or to accommodate specific field conditions) and 5,000 contiguous square feet for AC airfield pavement (+/- 2,000 square feet if the section is not evenly devisable by 5,000) (ASTM 5340, 2011). The minimum number of sample units that must be inspected by the survey team within a given section, to estimate the PCI of the section within a 95% confidence interval, is calculated using the formula below (Equation 1) and rounding up to the nearest whole number:

$$n = \frac{Ns^2}{\left(\left(\frac{e^2}{4}\right)(N-1)+s^2\right)} \qquad \text{(Eq 1)}$$

where:

e= acceptable error in estimating the section PCI. Typically, *e*=+/- 5 PCI points,

s= standard deviation of the PCI of one inspection sample unit to another within a given section and,

N= total number of sample units in the section.

Once the minimum number of sample units to be inspected has been calculated, the sequence of sample units that are inspected within the section must be determined to achieve a systematic random sampling of the pavement units. In order to achieve a systematic random sampling the first sample unit to be inspected is selected at random from sample units 1 through *i* where *i* is the spacing interval of the units to be sampled and is calculated with the following formula (Equation 2):

$$i = \frac{N}{n} \quad \text{(Eq 2)}$$

where:

N= total number of sample units in the section, and

n= number of sample units to be inspected.

Once the survey team selects the first sample to be inspected every successive pavement sample at spacing interval (*i*) is also inspected (ASTM D5340, 2011). Additional sample units can be inspected when non-representative distresses are observed. An additional sample is inspected when there exists very poor or very excellent samples that are unusual to the rest of the section and where sample units contain an unusual distress such as a utility cut (ASTM D5340, 2011). These additional sample units are selected by the survey team and could vary based on the experience and judgment of the given inspector. When additional units are included in the survey, the section PCI calculation is altered slightly to prevent biasing the PCI of the entire section (Shahin, 2005).

The procedures used to perform the PCI surveys are explicit to each pavement type and can be referenced in full detail in ASTM D5340.

2.2b Calculating the PCI

Before the PCI for a given pavement section can be calculated, the PCI for each inspection sample unit within that section must first be calculated. The PCI is calculated using PCI deduct values which are weighing factors used to account for the degree of impact that each combination of distress type, severity and density has on the overall pavement condition (Shahin, 2005). PCI deduct values range from 0-100 and increase in negative effect on the pavement condition as the deduct value increases. The PCI for each pavement sample unit is calculated by summing the PCI deduct values per each unique combination of distress type and severity for that sample unit, correcting for the number and value of deducts, and subtracting from 100.

2.2b.1 The steps for calculating a sample unit's PCI for asphalt surfaced airfield pavement are as follows:

Step 1: Determine PCI deduct values

1a. For each pavement distress type (Table 3) at each level of severity (high, moderate, low), sum the quantity of distress measured in square feet (square meters), linear feet (meters), or number of occurrences, depending on the propagation nature of distress type.

Asphalt Surfaced Airfields		Portland Cement Concrete Airfields	
Distress	Distress Description	Distress	Distress Description
41	Alligator cracking	61	Blowup
42	Bleeding	62	Corner break
43	Block cracking	63	Linear cracking
44	Corrugation	64	Durability cracking
45	Depression	65	Join seal damage
46	Jet blast	66	Small patch
47	Joint reflection/cracking	67	Large patch/utility cut
48	Long and trans cracking	68	Popouts
49	Oil spilage	69	Pumping
50	Patching	70	Scaling/crazing
51	Polished aggregate	71	Faulting
52	Weathering/raveling	72	Shattered slab
53	Rutting	73	Shrinkage cracking
54	Shoving	74	Joint spalling
55	Slippage cracking	75	Corner spalling
56	Swelling		

Table 3: Distress Code Definition Chart (Shahin, 2005)

1b. Calculate the percentage of density per sample unit for each distress type and severity by the total area of the sample unit. For example, if inspection Sample Unit A has 50 square feet of alligator cracking and the total area of Sample Unit A is 5,000 square feet then the distress density would be 1% ($\frac{50SF}{5{,}000SF} * 100$).

1c. Use the distress specific deduct curves found in ASTM 5340 to determine the PCI deduct value. Figure 5 shows an example deduct curve for distress type 41, "alligator cracking" (Shahin, 2005). To continue the example used in Step 1b; if the 50 SF of alligator cracking is considered "low" severity then the deduct value calculated using this curve would be 20 points.

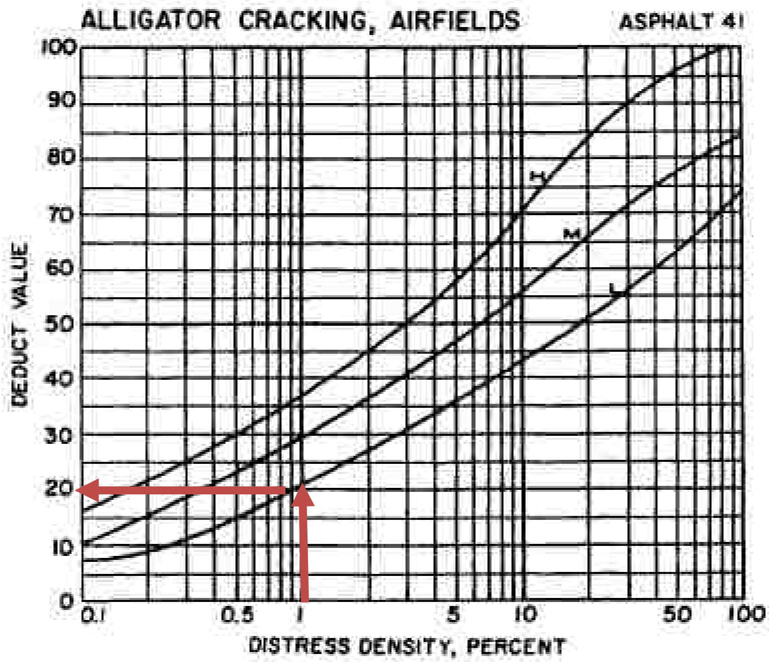


Figure 5: Flexible Pavement Deduct Value, Distress 41, Alligator Cracking (Shahin, 2005)

Step 2: Determine the maximum allowable number of deducts (m)

2a. For airfield pavements, if one or fewer individual deduct values is greater than 5.0, the total deduct value is used in place of the maximum corrected deduct value (CDV), described in Step 3 and the PCI calculation is complete. If more than one individual deduct value is greater than 5.0, then the following steps are required:

2b. List the individual deduct values from largest to smallest.

2c. Use Figure 6 and Equation 3 to determine the allowable number of deducts (note: equation and figure are specific to airfield pavements).

$$m_i = 1 + (\frac{9}{95})(100 - HDV_i) \qquad \text{(Eq 3)}$$

where:

m_i= allowable number of deducts, including fractions, for sample unit *i*, and

HDV_i= highest individual deduct value for sample unit *i*.

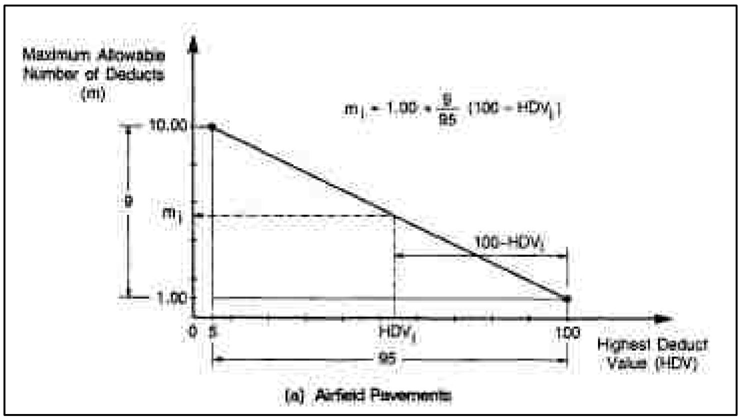


Figure 6: Determination of Maximum Allowable Deducts (m) (Shahin, 2005)

2d. The number of individual deduct values is curtailed at m deducts. If fewer than m deducts exist then all deduct values are included.

Step 3: Determine the maximum corrected deduct value (CDV)

3a. Find q by counting the number of individual deducts greater than 5.0.

3b. Sum all individual deducts to find the total deduct value (TDV).

3c. Use the appropriate correction curve to find the CDV using q and the TDV (Figure 7).

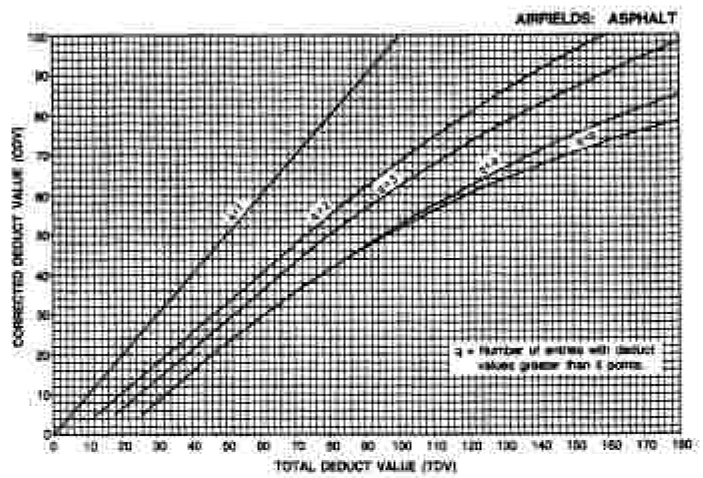


Figure 7: Correction Curve for Asphalt Cement Airfield Pavement (Shahin, 2005)

3d. Reduce the smallest individual deduct value greater than 5.0 to 5.0 and repeat Steps 3a through 3c until q is equal to 1.

3e. The maximum CDV is the largest of the CDVs determined.

Step 4: Calculate the sample unit PCI by subtracting the maximum CDV from 100.

2.2b.2 The steps are very similar for calculating the PCI for a sample unit of PCC pavement as they are for flexible pavement and are as follows:

Step 1: Determine deduct values

1a. For each combination of distress type and severity level, sum the number of slabs in which they occur.

1b. Obtain the percentage of density per sample unit for each distress type and severity level by dividing the number of affected slabs from Step 1a by the total number of slabs in the sample unit and multiplying by 100.

1c. Use the appropriate deduct curve (found in ASTM 5340) to determine the deduct value for each distress type and severity level combination (Shahin, 2005)

Steps 2 through 4 are the same for calculating PCI for concrete pavement as they are for asphalt pavement and have been explained in the previous section.

2.2c Calculating the PCI for a Section Using Inspection Sample Unit PCIs

If all sample units are selected using the technique prescribed in ASTM D5340 and previously detailed and are of equal size, the PCI for the section can be estimated by averaging the PCIs of each sample unit within that section. If the inspected samples were not of equal size then the average PCI should be estimated using an area weighted averaging technique. Similarly, if additional samples were surveyed, the PCI calculation should account for the additional sample units. Specific equations for calculating the PCI of the section in these aforementioned circumstances can be found in ASTM 5340.

Chapter 3 Assumptions

As previously mentioned; the inspection data and PCI calculations collected over the past 50 plus years is maintained by AFCEC and was made available for this research effort in the form of an Access database. This research uses that data to evaluate if a relationship between climate and distress occurrences exists within the continental United States. Assumptions of the research have to be defined because the data used was collected by a third party.

The first assumption of this research is that the rate of sampling within each pavement section follows the minimum sampling procedures outline in ASTM D5340 *Standard Test Method for Airport Pavement Condition Index Surveys* and is consistent across all PCI surveys. This assumption has to be made because the data set only includes instances of a distress finding. It does not include pavement sections that were inspected but did not contain a pavement distress, meaning the data does not include sampling rate for sections of pavement void of distresses; therefore the data is insufficient to quantify if the sampling rate is consistent across the survey process. The PCI surveys were completed by four different contractors. An assumption is made that the expertise is similar between the four contractors and all PCI survey findings would be comparable for any given inspection between the four contractors. However, the statistical analysis conducted on the data accounts for the variance between the four contracts. This statistical analysis is described in detail in Chapter 6, Results and Analysis. The third assumption that was made is that the PCI is returned to 100 at the time of the last major/global renovation. This assumption is necessary because reliable maintenance records for each section of airfield pavement is not available and so the only method to reasonably estimate the pavement's deterioration behavior over time is to assume the condition was returned to 100 on the date of the last major/global renovation and assess the change in condition at the last inspection since renovation occurred. These assumptions were necessary to make in order to draw reasonable conclusions from the data source.

Chapter 4 Data Source

The data used in this research is the result of PCI Surveys conducted by 4 different Air Force contracts over the past 16 years. The data is housed in an Access database titled “AF Roll-up Database” and consists of over 50,000 lines of distress data from Air Force installations across the globe. The data fields pulled from the database and a description of each are outlined in Table 4 below.

Data Field Title	Description
Name	Air Force Installation Name Example: Altus AFB, Nellis AFB
Branch Area	Total area of the branch in square feet
Branch Use	Runway, taxiway, apron, etc.
Branch ID	Specific name assigned to branch Example: RW1028
Sections	Number of sections with in specified branch
Section ID	Similar to Branch ID
Section True Area	Total area of section in square feet
Surface Type	PCC, AC, AAC, APC
Years Since Global/Major Work	Years since the pavement section’s PCI was returned to 100
Sample Units Inspected	Within the section number of sample units that were surveyed
Total Sample Units in Section	Number of pavement samples the section was broken into for the purposes of inspection (based on procedure outlined in ASTM 5340)
Distress Code	Code assigned by PAVER TM that represents a specific pavement distress (Table 3)
Distress Description	Alligator cracking, rutting, popout, weathering, etc.
Distress Mechanism	Force that causes the distress Example: climate, load, other
PCI Deduct	Calculated value representing the impact the distress has on the section’s overall condition
PCI	Numerical value between 0-100 associated with pavement section’s condition

Table 4: Data Fields within AF Roll-up Database Used in Research

Chapter 5 Methodology

The following methodology was used to assess if the distress occurrences recorded during PCI Surveys contain an embedded geographic or climatological pattern. Regression analysis was conducted between the PCI deduct values and pavement age, measured in years since the last major/global renovation, for each unique combination of pavement type and distress type within runway pavements for each of the four climate zones presented by AFIT. The following graphs are a few examples of the regression analysis conducted on PCC runways (see Appendix A for additional regression analysis performed on AC, AAC and APC runways).

5.1 Regression Analysis

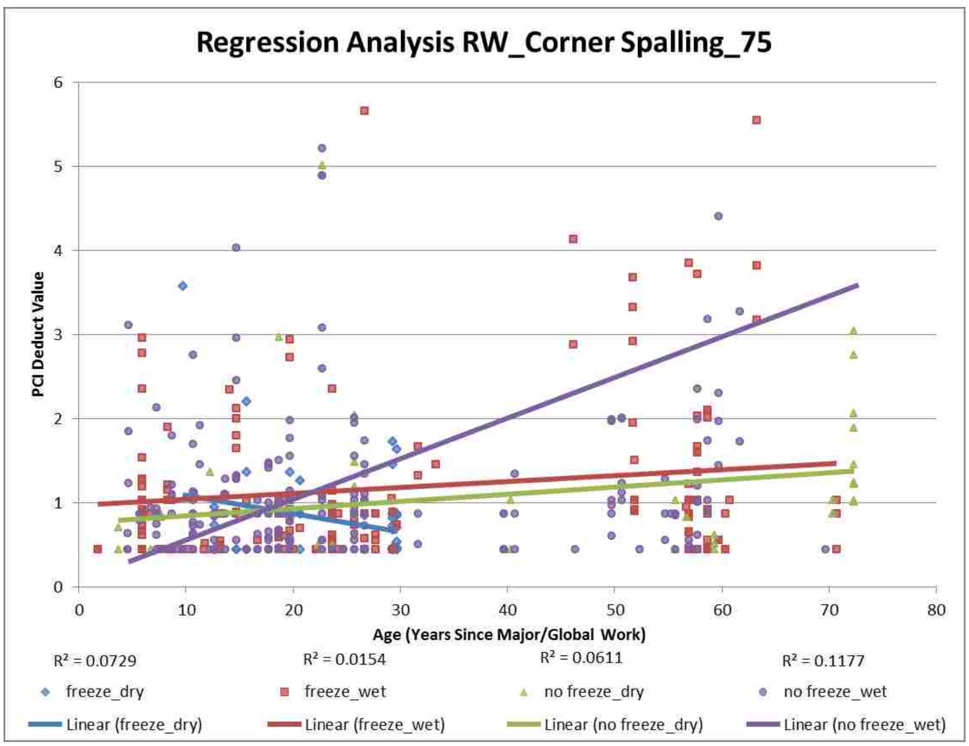


Figure 8: Regression Analysis PCC Runway-Distress Code 75, AFIT Climate Model

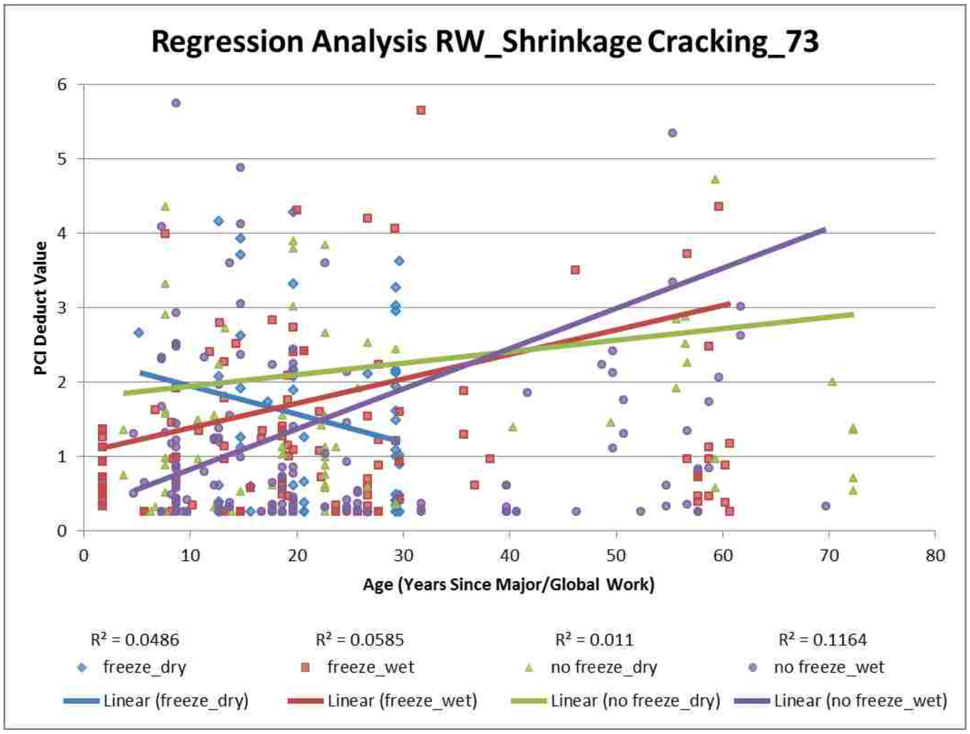


Figure 9: Regression Analysis PCC Runway-Distress Code 73, AFIT Climate Model

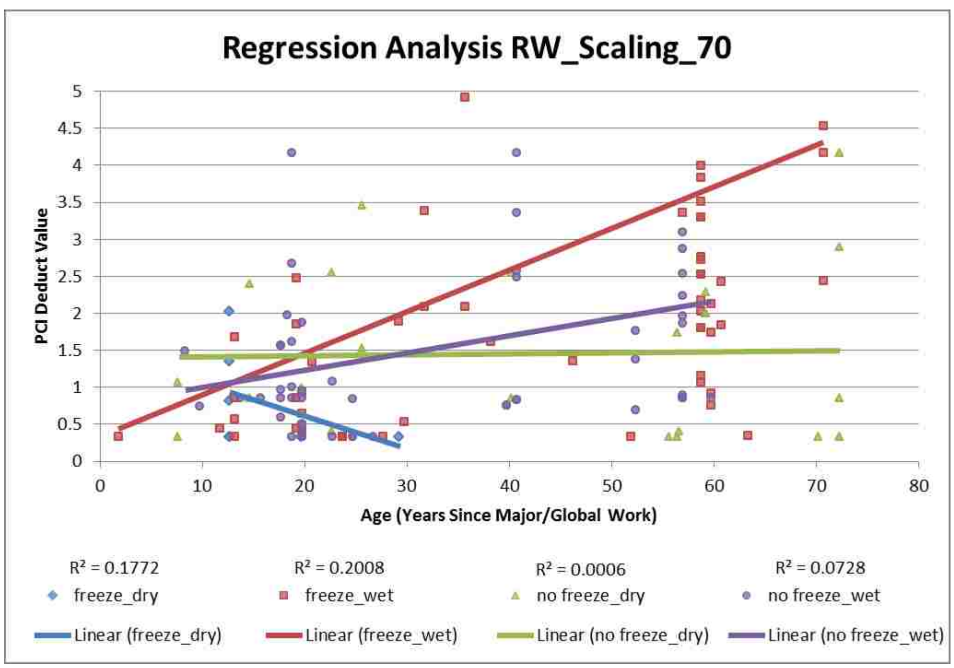


Figure 10: Regression Analysis PCC Runway-Distress Code 70, AFIT Climate Model

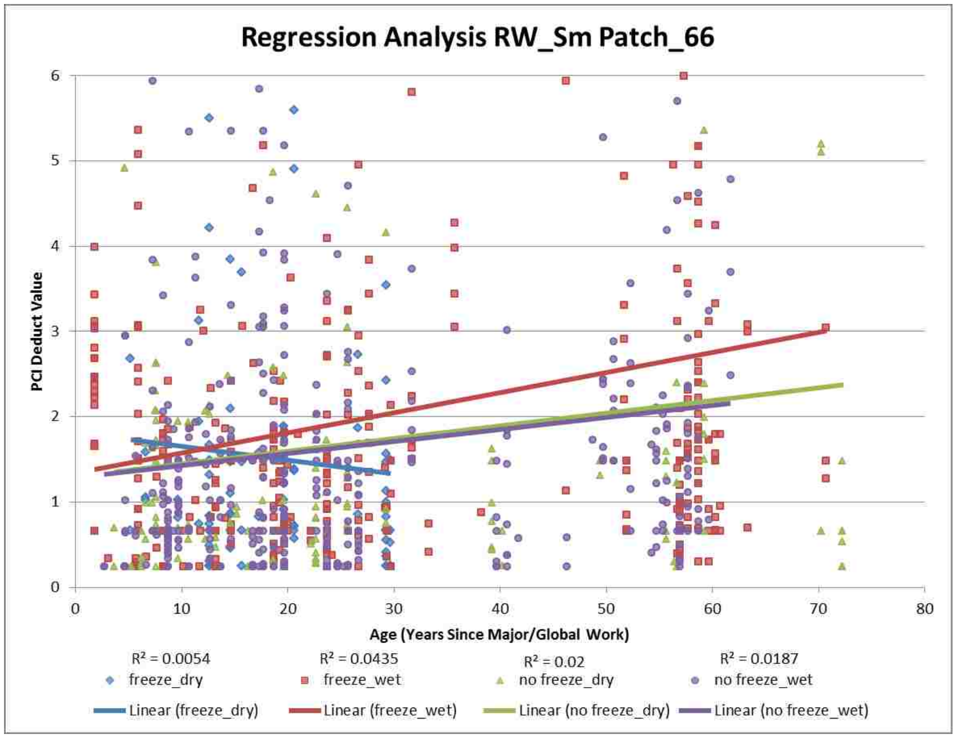


Figure 11: Regression Analysis PCC Runway-Distress Code 66, AFIT Climate Model

After conducting these regression analyses the most glaring issue is the R^2 values. The R^2 value is a numerical representation of how well the data fits a linear model. The closer the R^2 values is to 1.0 the better the data "fits" the model. The highest R^2 value of the distress data presented in Figures 8-11 is 0.2, which is very small and suggests that there is very little correlation between the proposed climate zones and the distress data. The second damming trend is shown by the linear regression trend lines. It should be noted that because the R^2 values are very small, suggesting little correlation between the comate zones and the distress data, the linear regression trend lines associated with each climate zone are not strong representations of the distress data. However, the trend lines do suggest a notion of the distress propagation with time, which is why they were included in the paper rather than being discarded completely. The trend that is observed in the proposed "freeze_dry" climate zone should be highlighted. This trend is common in the following distress specific PCI deduct values within PCC runway pavement sections: corner spalling (75), joint spalling (74), shrinkage cracking (73), scaling (70), large patch/utility cut (67), small patch (66), joint seal damage (65), durability cracking (64), and linear cracking (63). The trend observed in the suggested "freeze_dry" climate zone is also observed in the flexible pavement data (see Appendix A). What this trend suggests for pavements located in the proposed "freeze_dry" climate zone, is that as more time lapses between the date of the last major/global renovation and the PCI survey, the PCI deduct value actually decreases without any additional maintenance action. This trend is not consistent with any conventionally known pavement behavior and begs the question of "why does pavement in the "freeze_dry" climate behave in this nature?" A reasonable conclusion from this regression analysis is that the pavement located in the proposed "freeze_dry" climate zone actually belongs to another climate or that perhaps an alternative modeling approach should be investigated. Performing this regression analysis on runway pavements answered the research objective (1) to investigate whether the AFIT climate model coulds be used to relate individual pavement distresses to U.S. climate behavior. The conclusion is that the pavement behavior in the "freeze_dry" climate zone necessitates an alternative model for the consideration of distress pattern as it relates to geography and/or climate.

5.2 Model Approach

Rather than trying to force the distress data into a predeveloped climate model and then perform isolated geostatistical analysis within each zone of the model; a pavement behavior model was created by kriging the distress data as it naturally occurs and assessing if any geographic patterns imbedded within the distress data developed that could then be compared to conventional climate models. Key to utilizing this model is understanding that all distress contributors (i.e. traffic load, climate, maintenance history, construction and pavement structure (Haas, 2001)) are woven into the geographic manifestation of the model because the value used to krig with is a derivation of the PCI deduct value. An explanation of the PCI deduct value used to krig with is presented in Section 5.4.

5.3 Kriging

Kriging is a statistical method used to predict the value of an unknown point using the measured values and weighted distances of nearby points. Spatial autocorrelation, which is based on Tobler's first law of geography stating that things that are closer together are more alike than things that are far apart, is the term used to describe the inherent relationship between the geographic distance between measured points within a space and the distribution of the size or magnitude of each measured point within that space (McCoy & Johnston, 2002). A semivariogram is used to fit a mathematical function that models the autocorrelation between the measured points. The mathematical model is then used to make a value prediction at an unknown point. The semivariogram is created by plotting the distance between two points against their variation (difference squared) for each possible combination of point-pairs within the space. Often there are many pairs of points within the space and the processing becomes very lengthy. To speed the processing up, the whole space is divided into a set number of lag bins and the average variation between the point-pairs within each lag is used to create an empirical semivariogram. The lag size is the distance of the whole space divided by the number of lag bins. There are different methods of fitting a mathematical model to the semivariogram plot. The methods include: Circular, Spherical, Exponential, Gaussian and Linear and each is designed to model different types of phenomenon more accurately (McCoy & Johnston, 2002). In this research, Spherical modeling was used because it works well when there is a progressive decrease of autocorrelation to a certain distance when the autocorrelation is reduced to zero. Once the semivariogram model is fit to the data, the predictive surface can be created by kriging in one of two ways: Ordinary Kriging or Universal Kriging. Ordinary Kriging was used in this research because Universal Kriging assumes that there is an overriding trend within that data, such as differing survey techniques between PCI Surveys that can be mathematically modeled, that is not an assumption of this research. An easy way to think about what kriging does is to consider a blanket drapped over a number of balls of differing diameters. The measured values would be the height of each ball and the krig analysis would use those heights to attempt to predict the height of the blanket spanning each pairing of balls. As the number of balls increases the accuracy of the semivariogram model increases and the resultant krig layer is more representative of the shape of the blanket.

5.4 Distilling the Data-Road to Krig Layer

The Air Force Roll-up Database contains distress data for over 50,000 surveyed pavement distresses. The largest component of this research was developing a method to distill the Roll-up Database from 50,000 plus distress instances down to a concentrated list, representative of the whole database so that the kriging analysis could be applied, via the geospatial tools within ArcMap an application of ArcGIS.

The first refinement was to filter out distress data outside the range of this investigation. That included isolating and removing: Air Force installations located outside of the continental United States (including removing installations located in Alaska and Hawaii), non-runway pavement branches, pavement types other than asphalt cement (AC), asphalt-over-asphalt cement (AAC), asphalt-over-portland cement concrete (APC) and Portland cement concrete (PCC) and finally filtering to only include distress data for distress types listed in Table 3. After these filters were performed the data set included more than 6,400 instances of distress data occurring at 77 installations.

The second step in distilling the data was to break it into sub data sets, specific to, pavement type and distress code. For example the PCI deduct value representative of an instance of alligator cracking (Distress Code 41), occurring on an asphalt cement (AC) runway (RW) was only considered with other PCI deduct values of the same distress type and pavement family.

Once these data groups were created, each line of data (representing one distress occurrence) was assigned a latitude and longitude corresponding to the Air Force installation at which it occurred. This data was then fed into ArcMap and displayed as x,y data in a point shapefile. This approach proved problematic because if a specific pavement distress occurred in more than one section or at different severity levels within the same pavement family at any given air field then coincidental points were created within ArcMap. Coincidental points are different data points with the same x,y coordinates. In the above ball and blanket example, a coincidental point would be comparable with trying to have two balls in the exact same location. This is a problem in geospatial processing because the software can only consider one of the points at a time and so tries to simplify the coincidental points by using only the largest point value, the smallest point value, taking an average of all point values or by deleting the points to perform the spatial analysis. An alternative method was needed to accurately represent the data because by simplifying the coincidental points to a maximum or a minimum, etc. the differences in frequency of distress occurrence between airfields were lost. The method described in the following text was created in an effort to maintain the integrity of each distress occurrence while still removing the coincidental points.

The following example is included to illustrate the process used in this research to combine all PCI Deduct values for each unique combination of runway pavement type and distress type. Table 5 is an excerpt of distress data from the AF Roll-up Database. It represents every instance of pavement distress code 66, “small patch”, occurring on PCC runways at Andrews Air Force Base (AFB). This distress occurs 21 times (each line of data represents the combined PCI deduct at each severity level, H, M, L of all sample units within a pavement section) across two different branches (Runway 01R/19L and Runway 01L/19R). Figures 12 is a conceptual illustrations of the two runways represented in Table 5 and Figure 13 depicts the breakdown of section areas within each of the two branches. If the data was fed directly into ArcMap as it appears in the AF Roll-up Database, the software would try to simplify the 21 coincidental points into one point. To circumvent this undesirable simplification the PCI deduct values were summed to create one value that encompassed each individual distress occurrence. Before they could be summed they first needed to be normalized to account for differing pavement age and pavement size.

latitude	longitude	Name	Branch Area	Branch Use	BranchID	Sections	SectionID	Section True Area	Surface Type - Current	Years Since Global/Maj Work	Sample Units Inspected	Total Sample Units in Section	Distress Code	Distress Description	Distress Mechanism	PCI Deduct	PCI
38.79	-76.88	Andrews AFB	1477295	RUNWAY	RW-01R/19L	16	R15C	30011	PCC	5.70	8	9	66	SMALL PATCH	Other	.243	98
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R20A1	39410	PCC	1.80	5	5	66	SMALL PATCH	Other	3.048	94
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R20A2	59114	PCC	1.80	10	10	66	SMALL PATCH	Other	3.030	95
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R21A1	40000	PCC	1.80	5	5	66	SMALL PATCH	Other	2.447	97
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R21A2	60000	PCC	1.80	10	10	66	SMALL PATCH	Other	2.367	97
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R22C1	71928	PCC	1.80	9	9	66	SMALL PATCH	Other	2.802	95
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R22C2	107891	PCC	1.80	18	18	66	SMALL PATCH	Other	3.982	93
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R23C1	104000	PCC	1.80	13	13	66	SMALL PATCH	Other	2.281	97
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R23C2	156001	PCC	1.80	26	26	66	SMALL PATCH	Other	3.426	96
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R24C1	245568	PCC	1.80	31	31	66	SMALL PATCH	Other	2.462	96
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R24C2	368352	PCC	1.80	62	62	66	SMALL PATCH	Other	.660	97
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R24C2	368352	PCC	1.80	62	62	66	SMALL PATCH	Other	2.231	97
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R25C1	102700	PCC	1.80	13	13	66	SMALL PATCH	Other	1.678	95
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R25C2	154051	PCC	1.80	26	26	66	SMALL PATCH	Other	2.684	96
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R26C1	63969	PCC	1.80	8	8	66	SMALL PATCH	Other	1.647	97
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R26C2	95954	PCC	1.80	16	16	66	SMALL PATCH	Other	2.680	96
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R27A1	40000	PCC	1.80	5	5	66	SMALL PATCH	Other	2.447	97
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R27A2	60000	PCC	1.80	10	10	66	SMALL PATCH	Other	.660	97
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R27A2	60000	PCC	1.80	10	10	66	SMALL PATCH	Other	2.129	97
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R28A1	37767	PCC	1.80	5	5	66	SMALL PATCH	Other	2.447	97
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R28A2	56651	PCC	1.80	10	10	66	SMALL PATCH	Other	3.118	96

Table 5: Example of Data Used to Create Pavement Model

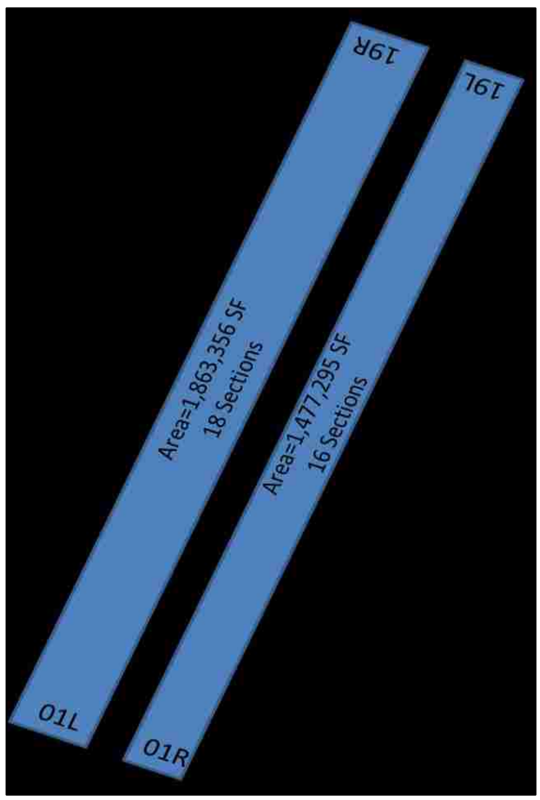


Figure 12: Andrews AFB Runway 01L/19R and 01R/19L, PCC

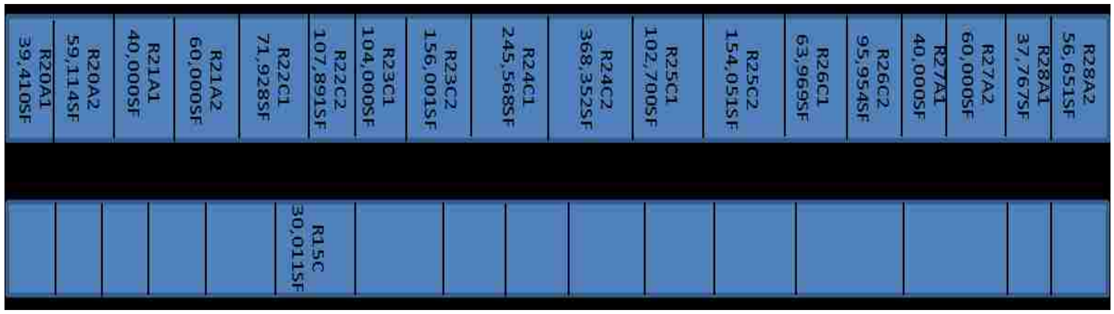


Figure 13: Andrew AFB RW 01L/19R and 01R/19L Depicting Sections and Section Areas (conceptual illustration, actual section layout may differ)

5.4a Normalizing for Age and Pavement Size

Step 1: Account for the pavement section age by creating a rate (PCI deduct/yrs since major/global reno).

The PCI deduct values could not be summed without considering the age of each individual pavement section. The deterioration behavior that causes a PCI deduct of 5 in a 10 year old section of pavement is not the same as the deterioration behavior that causes a PCI deduct of 5 in a 5 year old section of pavement. The purpose of the pavement model that this research is driving towards is to model the typical or average behavior of runway pavement which is why this consideration of rate of deterioration, or PCI deduct points per year, must be made. Creating this rate does two things: first it puts all PCI deduct values on the same nominal scale in order to compare them equally, and the second is that it helps highlight the airfields at which specific distresses are propagating faster than others. The PCI deduct rate is calculated for each line of data using Equation 4.

$$PCI\_Deduct_{Rate} = \frac{PCI\_Deduct}{years\_\sin ce\_major/global\_renovation} \qquad \text{(Eq 4)}$$

To continue the Andrews AFB illustration the PCI deduct rates have been calculated for each line of data from Table 5 and displayed in the column titled "PCI Ded/Years MR" in Table 6 below.

latitude	longitude	Name	Branch Area	Branch Use	BranchID	Sections	SectionID	Section True Area	Surface Type - Current	Years Since Global/Maj Work	Sample Units Inspected	Total Sample Units in Section	Distress Code	PCI Deduct	PCI Ded/Years MR
38.79	-76.88	Andrews AFB	1477295	RUNWAY	RW-01R/19L	16	R15C	30011	PCC	5.70	8	9	66	.243	0.04
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R20A1	39410	PCC	1.80	5	5	66	3.048	1.69
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R20A2	59114	PCC	1.80	10	10	66	3.030	1.68
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R21A1	40000	PCC	1.80	5	5	66	2.447	1.36
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R21A2	60000	PCC	1.80	10	10	66	2.367	1.31
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R22C1	71928	PCC	1.80	9	9	66	2.802	1.56
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R22C2	107891	PCC	1.80	18	18	66	3.982	2.21
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R23C1	104000	PCC	1.80	13	13	66	2.281	1.27
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R23C2	156001	PCC	1.80	26	26	66	3.426	1.90
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R24C1	245568	PCC	1.80	31	31	66	2.462	1.37
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R24C2	368352	PCC	1.80	62	62	66	.660	0.37
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R24C2	368352	PCC	1.80	62	62	66	2.231	1.24
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R25C1	102700	PCC	1.80	13	13	66	1.678	0.93
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R25C2	154051	PCC	1.80	26	26	66	2.684	1.49
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R26C1	63969	PCC	1.80	8	8	66	1.647	0.91
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R26C2	95954	PCC	1.80	16	16	66	2.680	1.49
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R27A1	40000	PCC	1.80	5	5	66	2.447	1.36
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R27A2	60000	PCC	1.80	10	10	66	.660	0.37
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R27A2	60000	PCC	1.80	10	10	66	2.129	1.18
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R28A1	37767	PCC	1.80	5	5	66	2.447	1.36
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R28A2	56651	PCC	1.80	10	10	66	3.118	1.73

Table 6: PCI Deduct Rate Calculation

Step 2: Normalize the PCI deduct rate for size of the pavement section it represents.

Each line of data in the AF Roll-up Database represents the total PCI deduct value for a given distress at a specific severity level for the entire pavement section (Ex. Low severity, small patch, in section R15C). To calculate the PCI deduct value for the whole section, each section within a branch is divided into a number of inspection sample units following the procedures outlined in ASTM D5340 (Figure 3). Each inspection sample unit where the distress occurs will have a PCI deduct value assigned to it following the steps previously outlined in Chapter 2. Once the entire section has been surveyed, one PCI deduct value is calculated using either a straight average of the PCI deduct values of each individual inspection sample or if the size of each inspection sample differs or if additional sample units were needed then an area weighted average is used to calculate the PCI deduct for the whole section. As the area of the section increases so does the minimum number of inspection sample units required by ASTM D5340.

Each PCI deduct value in the database represents a pavement section of a unique size (Reference Table 5 and Figure 13). A weighted average was used to combine the PCI deduct values from each pavement section to account for variations in size. The weighted average was calculated with Equation 5 and displayed for each line of data, for the Andrews AFB example, in Table 7 below.

$$RWA_{age\&siz} = \frac{1}{AreaRWA}\left[\frac{PCIded_{\sec A1}}{Yrs\_\sin ce\_MR}*(AreaSec'tA1)+\frac{PCIded_{\sec tA2}}{yrs\_\sin ce\_MR}*(AreaSec'tA2)+...\right] \quad \text{(Eq 5)}$$

and

$$RWB_{age\&size} = \frac{1}{AreaRWB}\left[\frac{PCIded_{\sec tB1}}{yrs\_\sin ce\_MR}(AreaSec'tB1)+...\right]$$

latitude	longitude	Name	Branch Area	Branch Use	BranchID	Sections	SectionID	Section True Area	Surface Type - Current	Years Since Global/Maj Work	Sample Units Inspected	Total Sample Units in Section	Distress Code	PCI Deduct	PCI Ded/Years MR	Branch PCI Deduct
38.79	-76.88	Andrews AFB	1477295	RUNWAY	RW-01R/19L	16	R15C	30011	PCC	5.70	8	9	66	.243	0.04	0.000866
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R20A1	39410	PCC	1.80	5	5	66	3.048	1.69	1.518801
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R20A2	59114	PCC	1.80	10	10	66	3.030	1.68	
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R21A1	40000	PCC	1.80	5	5	66	2.447	1.36	
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R21A2	60000	PCC	1.80	10	10	66	2.367	1.31	
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R22C1	71928	PCC	1.80	9	9	66	2.802	1.56	
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R22C2	107891	PCC	1.80	18	18	66	3.982	2.21	
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R23C1	104000	PCC	1.80	13	13	66	2.281	1.27	
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R23C2	156001	PCC	1.80	26	26	66	3.426	1.90	
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R24C1	245568	PCC	1.80	31	31	66	2.462	1.37	
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R24C2	368352	PCC	1.80	62	62	66	.660	0.37	
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R24C2	368352	PCC	1.80	62	62	66	2.231	1.24	
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R25C1	102700	PCC	1.80	13	13	66	1.678	0.93	
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R25C2	154051	PCC	1.80	26	26	66	2.684	1.49	
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R26C1	63969	PCC	1.80	8	8	66	1.647	0.91	
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R26C2	95954	PCC	1.80	16	16	66	2.680	1.49	
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R27A1	40000	PCC	1.80	5	5	66	2.447	1.36	
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R27A2	60000	PCC	1.80	10	10	66	.660	0.37	
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R27A2	60000	PCC	1.80	10	10	66	2.129	1.18	
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R28A1	37767	PCC	1.80	5	5	66	2.447	1.36	
38.79	-76.88	Andrews AFB	1863356	RUNWAY	RW-01L/19R	18	R28A2	56651	PCC	1.80	10	10	66	3.118	1.73	

Table 7: PCI Deduct Value for each Runway

Step 3: Combine each branch PCI deduct to calculate PCI deduct value representing the average distress specific deterioration behavior for the entire RW.

To combine the PCI deduct values specific to each branch within an airfield one more area weighted average must be accomplished. This is necessary because the areas of each branch within a network can vary drastically. In the Andrews AFB example the two runways differ by 400,000 square feet; however, this difference can be more than 1 million square feet at other airfields. The area weighted average to account for varying branch size within a network is calculated with Equation 6 below.

$$PCI\_Deduct_{age\&size} = \frac{\sum\left((RunwayA_{age\&size})AreaRunwayA + (RunwayB_{age\&size})AreaRunwayB\right)}{\sum((AreaRunwayA + AreaRunwayB) + ...)} \quad \text{(Eq 6)}$$

Completing this process consolidates the 6,400 plus lines of RW pavement distress data to one normalized PCI deduct value representing each distress' average deterioration behavior for each of the four runway pavement types at each AF installation. The value representing the deterioration behavior of PCC runway pavement at Andrews AFB caused by small patching (Distress Code 66) is 0.8475 points/yr. This value eliminates each of the 21 coincidental points while still representing the deterioration to the pavement caused by each. Consolidating the Rollup Database was the first step toward answering the second research objective of relating distress location to climate or geographic region.

Chapter 6 Results and Analysis

6.1 Developing the Models

The following four maps were created using the normalized PCI deduct values described in the previous chapter. Each map was created by summing the normalized PCI deduct values for all distress types and then kriging the combined PCI deduct value. Mapping all distresses at once provides insight into the average deterioration behavior of the pavement as a whole. This deterioration behavior is illustrated by the geographic patterns seen in the following four pavement type specific models.

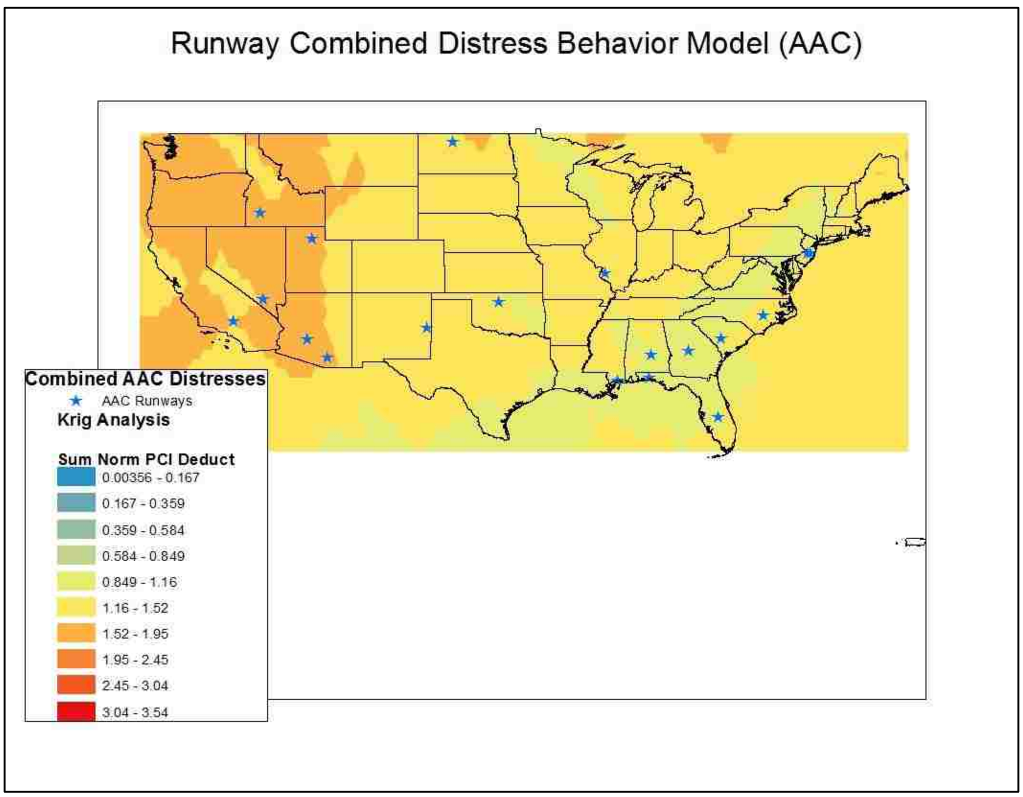


Figure 14: Krig Image of Normalized PCI Deduct Values for all Distress Types on AAC Runways

Figure 14, depicting average distress behavior in asphalt-over-asphalt (AAC) runways, shows that airfields in the Western third of the United States tend to have high normalized PCI deduct values, followed by the second highest normalized PCI deduct values in the middle third of the U.S. and finally lowest in the Eastern third of the U.S. However, there are very few data points located within the middle third of the U.S. which introduces doubt into the strength of the model. This research considered a total of 77 installations scattered across the entire United States which spans more than 3.1 million square miles (not including Alaska and Hawaii). Of those 77 installations only 19 contain AAC runway pavement sections. ASTM D5922-96 *Standard Guide for Analysis of Spatial Variation in Geostatistical Site Investigation* recommends at least 20 paired data values be available for each lag. This data set is right on the edge of the numerical recommendation made by the ASTM; however, the area the krig analysis considers is so large that 19 measured values spread across 3 million square miles leaves large spans between measured points where the variation in normalized PCI deduct value cannot be predicted with a high level of confidence. Referring back to ball and blanket example, if the footprint of the blanket is very large and it is held up with only a few balls it is very hard to predict the height of the blanket between the balls. The krig image presented in Figure 14 shows the trends that exist within the data; however, due of the lack of measured points, no additional analysis was performed on the data for AAC runway pavement sections because any conclusions that may be drawn would be based on an uncertain model.

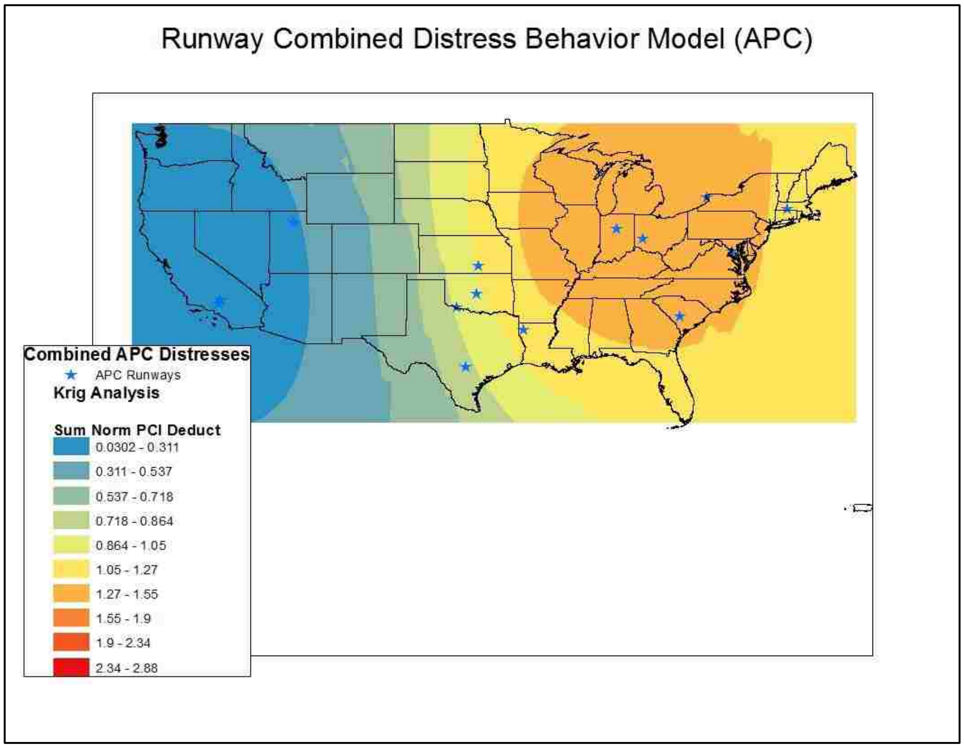


Figure 15: Krig Image of Normalized PCI Deduct Values for all Distress Types on APC Runways

Figure 15, depicting distress behavior in asphalt-over-portland cement concrete (APC) runways, shows a progressive increase in detrimental distress behavior in an eastward trend. However, the data only includes 12 AF installations where APC runway pavement occurs. For the sample size deficiency discussed above this krig image was created to investigate the geographic trend within the data but no additional analysis was conducted.

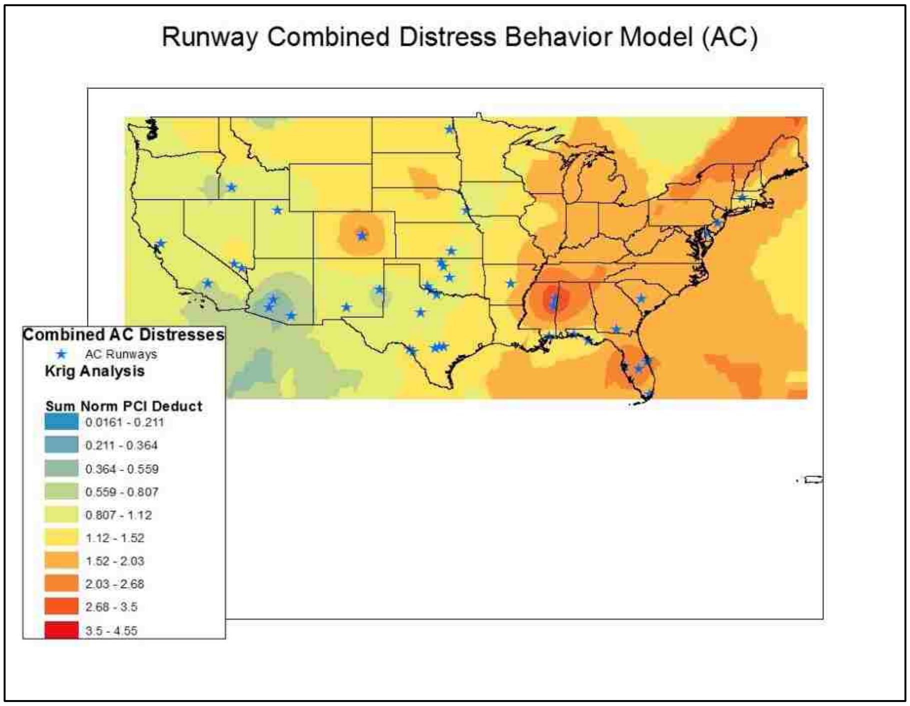


Figure 16: Krig Image of Normalized PCI Deduct Values for all Distress Types on AC Runways

The krig image displayed in Figure 16 is the result of kriging the normalized PCI deduct values for the combination of all pavement distresses at 45 AF installations. There is a strong eastern trend in the magnitude of the normalized PCI deduct values. The map suggests that the distress behavior, represented by the normalized PCI deduct value used to krig upon, is 2.5-3.5 times larger in asphalt cement runways located in the Eastern U.S. than in the Western U.S. This trend is very different than the trend seen in Figure 17, which illustrates the combined distress behavior of PCC runways. The krig image was produced by kriging the normalized PCI deduct value for all distresses occurring on PCC runways at 58 AF installations across the U.S. The krig image reveals two distress behavior zones embedded within the data. The higher distress behavior occurs in the Western region of the U.S. and the smaller distress behavior occurs in the Eastern region of the U.S. The magnitude of the distress behavior at airfields in the Western/Northwestern region of the U.S. is almost 3.5 times the size of the distress behavior at airfields in the Eastern region of the U.S. The trends within PCC runway pavement are almost exactly opposite those of

AC runway pavement; however, attention should be paid to the difference in the scales used in each krig image, the AC scale ranges from 0-4.55 PCI deduct points per year whereas the PCC scale ranges from 0-2.37 PCI deduct points per year. Meaning that overall the PCI deduct values in PCC RW pavements are much smaller than those of AC RW pavements.

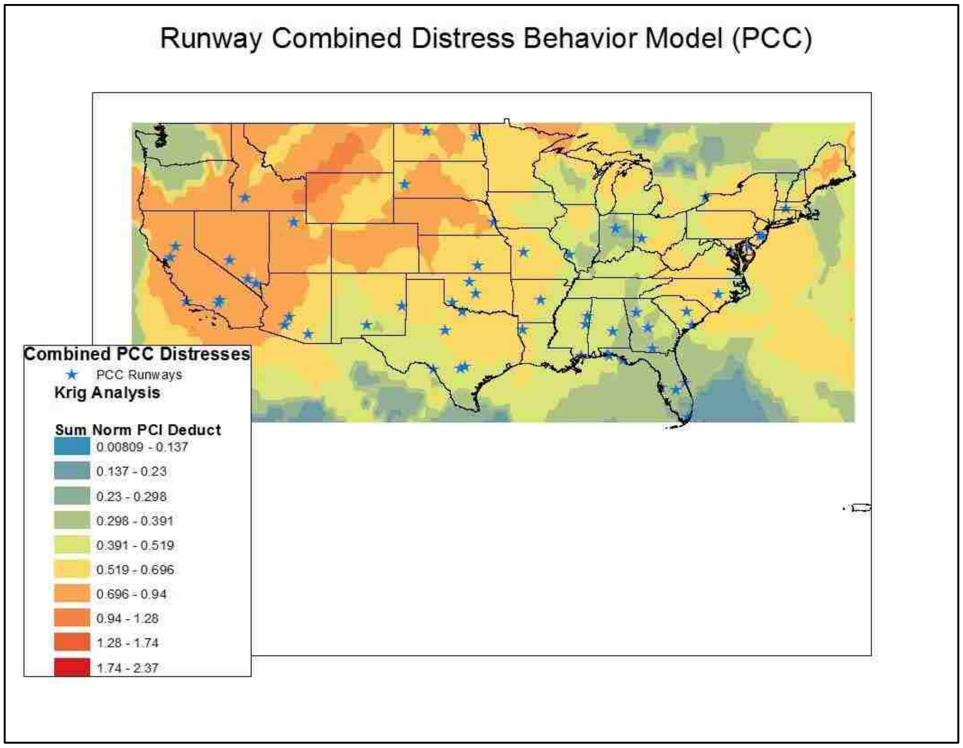


Figure 17: Krig Image of Normalized PCI Deduct Values for all Distress Types on PCC Runways

From the results of the krig analysis completed on each of the four runway pavement types, facilitated the following pavement distress based models for AC and PCC runways pavements (Figures 18 and 19 respectively). Notice the line of demarcation between Zone 1 and Zone 2 is almost exactly the same in each pavement model and that the predominant distress behavior trends to the East for AC runway pavements while it trends to the West for PCC runway pavements.

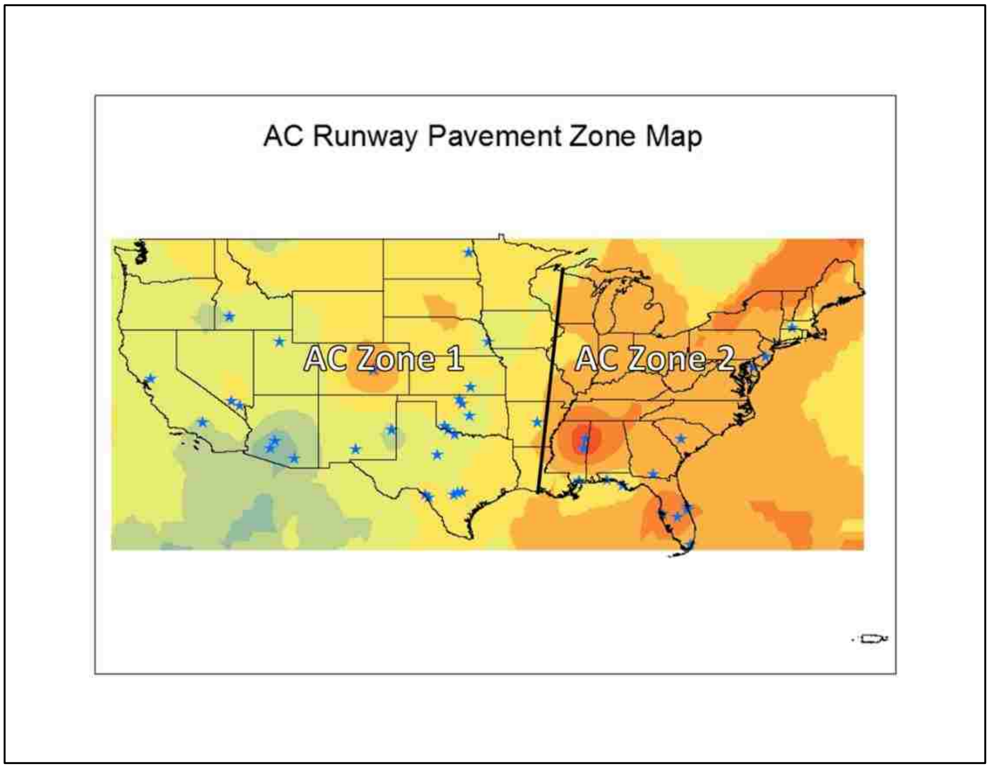


Figure 18: AC Runway Model, Based on Average Distress Behavior

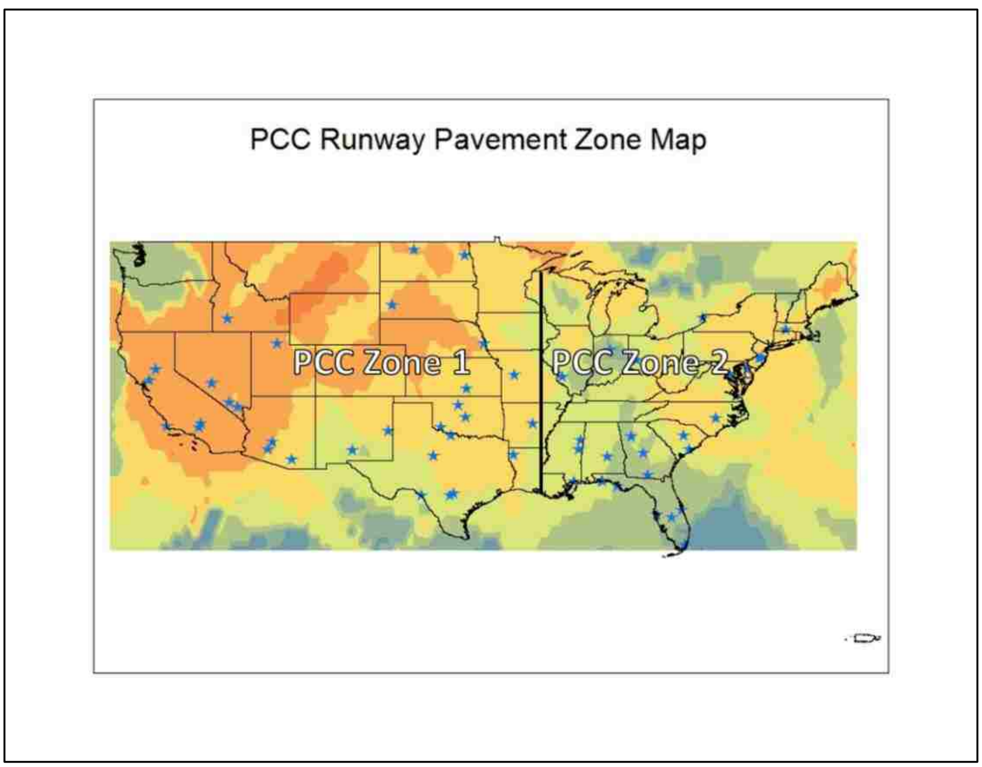


Figure 19: PCC Runway Model, Based on Average Distress Behavior

6.2 Statistical Investigation of Proposed RW Models Based on Average Deterioration Behavior

A statistical investigation was completed to determine if the deterioration behavior of the RW pavement in AC Zone 1was statistically different than the pavement in AC Zone 2; as well as, between PCC Zone 1 and PCC Zone 2. A Two-Sample t-Test was used to perform this assessment. A Two-Sample t-Test is often used to compare the means of the observations within two sample groups; in this case the Two-Sample t-Test was used to compare the mean value of the normalized PCI deduct values between Zone 1 and Zone 2 for PCC and AC runway pavements. If the test determines that there is no significant statistical difference between the observation means of each group then the null hypothesis, $\mu_1 = \mu_2$, is accepted and if the test concludes that the sample means do not equal each other, $\mu_1 \neq \mu_2$, then the null hypothesis is rejected and the conclusion is that the two groups are statistically different. The test assumes three criteria are met. The first is that each group is a sample of a distinct population; for this research the assumption is made that the pavement deterioration behavior recorded for the inspection sample units is representative of the pavement deterioration behavior for the whole runway. The second criterion is that the observations in each group are independent of the other group and the last is that there is a normal distribution of observations within each group (Hayter, 2007). The following is the statistical analysis completed with miniTab.

Two-Sample t-Test and Confidence Interval: AC Zone 1, AC Zone 2

Two-sample t-Test for AC Zone 1 vs AC Zone 2

	N	Mean	StDev	SE Mean
AC Zone 1	30	1.114	0.869	0.16
AC Zone 2	15	1.99	1.41	0.36

Difference = mu (AC Zone 1) - mu (AC Zone 2)
Estimate for difference: -0.877
95% CI for difference: (-1.710, -0.045)
t-Test of difference = 0 (vs not =): T-Value = -2.21 P-Value = 0.040 DF = 19

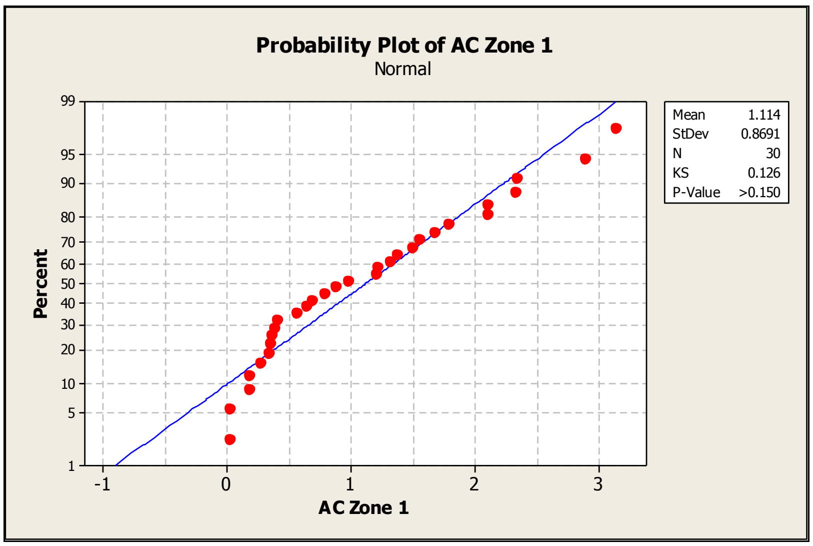


Figure 20: Probability Plot of AC Zone 1

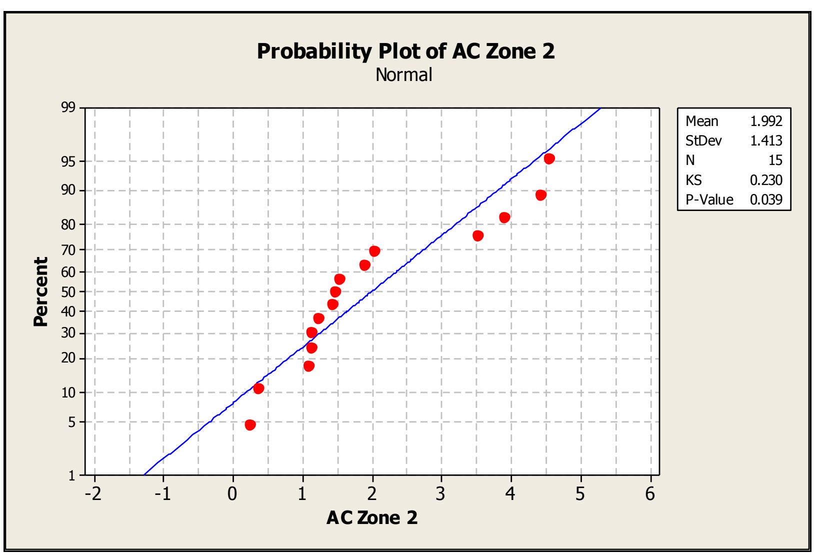


Figure 21: Probability Plot of AC Zone 2

Since the sample distress data for AC Zone 1 plots along the normal distribution based line, and the P-value of the Kolmogorov-Smirnov test of normality > .05, AC Zone 1 sample is normally distributed. AC Zone 2 sample is borderline normal (P-value = .04).

Two-Sample t-Test and Confidence Interval: PCC Zone 1, PCC Zone 2

Two-sample t-Test for PCC Zone 1 vs PCC Zone 2

	N	Mean	StDev	SE Mean
PCC Zone 1	31	0.665	0.560	0.10
PCC Zone 2	27	0.409	0.375	0.072

Difference = mu (PCC Zone 1) - mu (PCC Zone 2)
Estimate for difference: 0.256
95% CI for difference: (0.007, 0.504)
T-Test of difference = 0 (vs not =): T-Value = 2.07 P-Value = 0.044 DF = 52

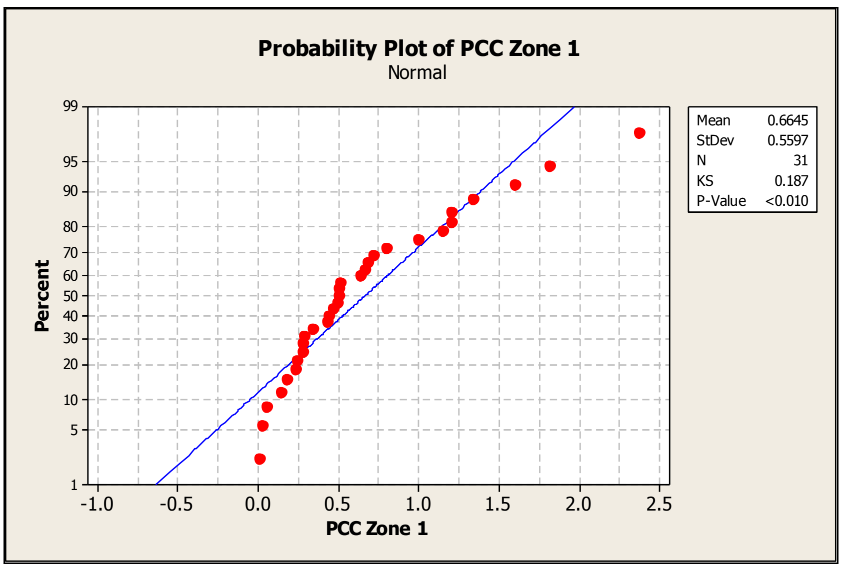


Figure 22: Probability Plot of PCC Zone 1

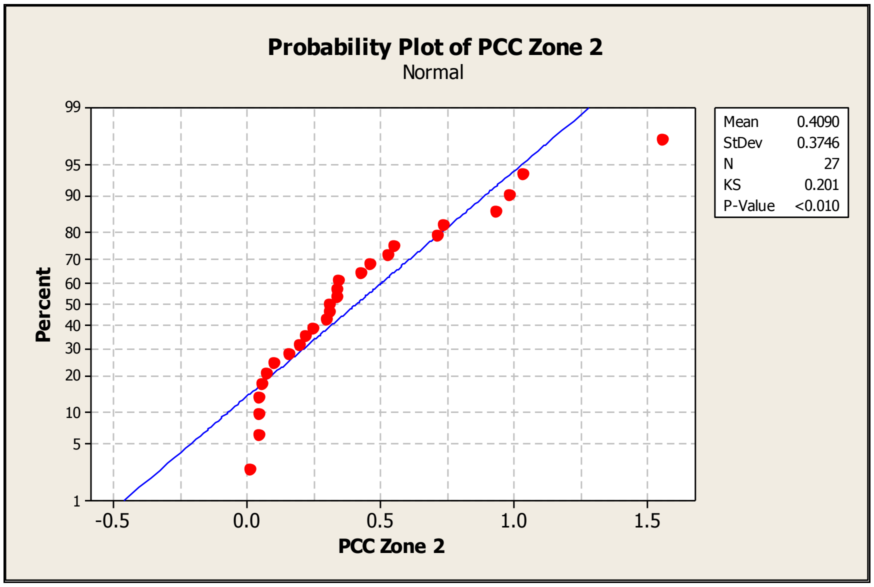


Figure 23: Probability Plot of PCC Zone 2

Since the sample distress data in PCC Zone 1 and Zone 2 do not plot along the normal distribution based line, and the P-value of the Kolmogorov-Smirnov test of normality < .05, the PCC sample data is non-normally distributed. For this reason, the non-parametric Mann-Whitney test was used to compare the true medians of both AC and PCC samples.

Mann-Whitney Test and Confidence Interval: AC Zone 1, AC Zone 2

	N	Median
AC Zone 1	30	0.925
AC Zone 2	15	1.466

Point estimate for ETA1-ETA2 is -0.740
95.0 Percent CI for ETA1-ETA2 is (-1.341,-0.003)
W = 608.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0497

Mann-Whitney Test and Confidence Interval: PCC Zone 1, PCC Zone 2

	N	Median
PCC Zone 1	31	0.5068
PCC Zone 2	27	0.3111

Point estimate for ETA1-ETA2 is 0.1873
95.0 Percent CI for ETA1-ETA2 is (-0.0141,0.3967)
W = 1035.0
Test of ETA1 = ETA2 vs ETA1 not = ETA2 is significant at 0.0614

The true medians of pavement samples in each zone of both pavement models are not equal (AC at 5%, PCC at 10%) and indicate that the pavement deterioration behavior differs between the zones.

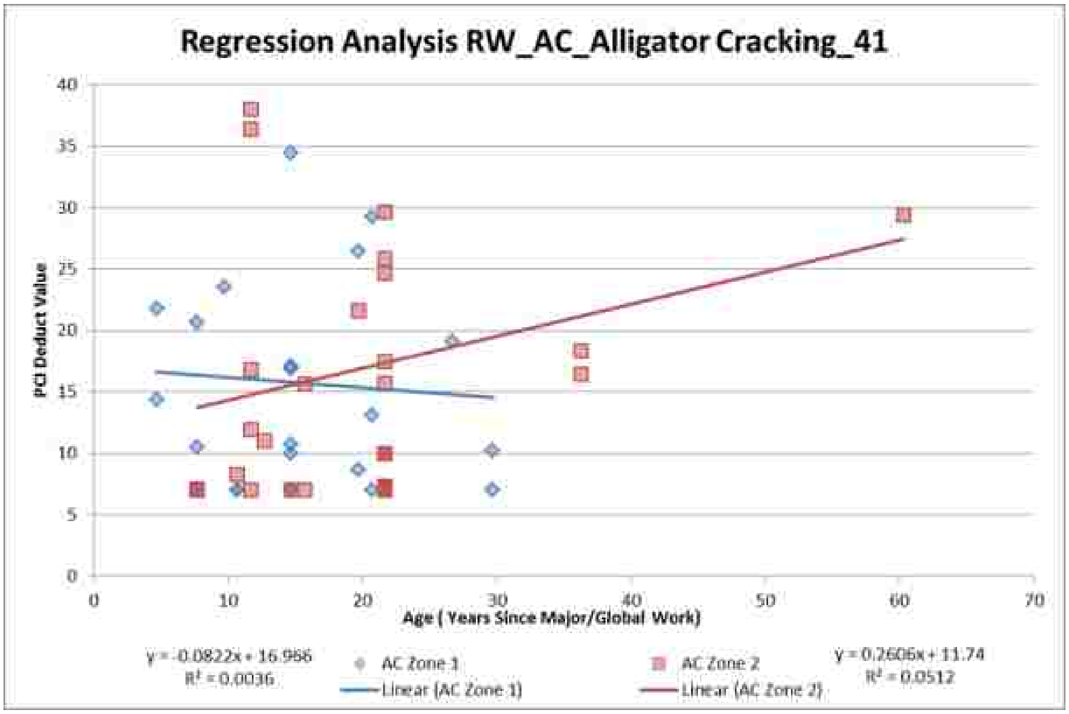
After establishing that Zones 1 and 2 in each pavement model were statistically different than each other, through application of a two-sided t-test and Mann-Whitney test, regression analysis was conducted for each distress type occurring within each model.

6.3 Regression Analysis of Distress Behavior within Each Pavement Model

Conducting a second round of regression analysis on the PCI deduct values within each zone of the pavement models provides insight in the following three ways. First it answered the questions, what is the distress specific pavement behavior between the two zones? Based on that analysis, which pavement distresses have the largest impact on the runway pavement in each of the zones? Second, the regression analysis provides a quantitative evaluation of how well the model data fits the regression model (through the R^2 value). For example, in the case of y=x the R^2 value is 1 because the linear regression fits the data exactly. As the scatter within the data increase the R^2 value decreases. Plotting the raw PCI deduct values against the pavement section age (calculated from years since major/global work) for each distress type facilitates the calculation of R^2 and provides insight into the strength of the proposed pavement distress behavior based model for AC and PCC runways. The last reason to conduct regression analysis on data within the new model is to evaluate if it is an improvement from the original, climate based model.

6.4 Distress Type Krig Analysis

Krig analysis was also conducted for each distress type occurring on AC and PCC runways. The value used to krig upon is the normalized PCI deduct value calculated following the process model presented in Section 5.4a. The combined analysis of the regression analysis and the krig analysis presents insight into the overall deterioration behavior of each distress. The factors effecting pavement condition (traffic load, climate, maintenance history, construction and pavement structure) are contained within the PCI deduct value (Haas, 2001). The value used to krig upon is a derivation of the PCI deduct value; therefore, the geographic pattern that emerges from the krig analysis is resultant of all 5 factors. The krig images help to investigate the second research objective of determining if there is a correlation between the geographic distress patterns and climate. A consolidated analysis of the regression and krig analysis conducted for each distress type can be found in Appendix C. The individual distress analyses are included in Tables 8-23.



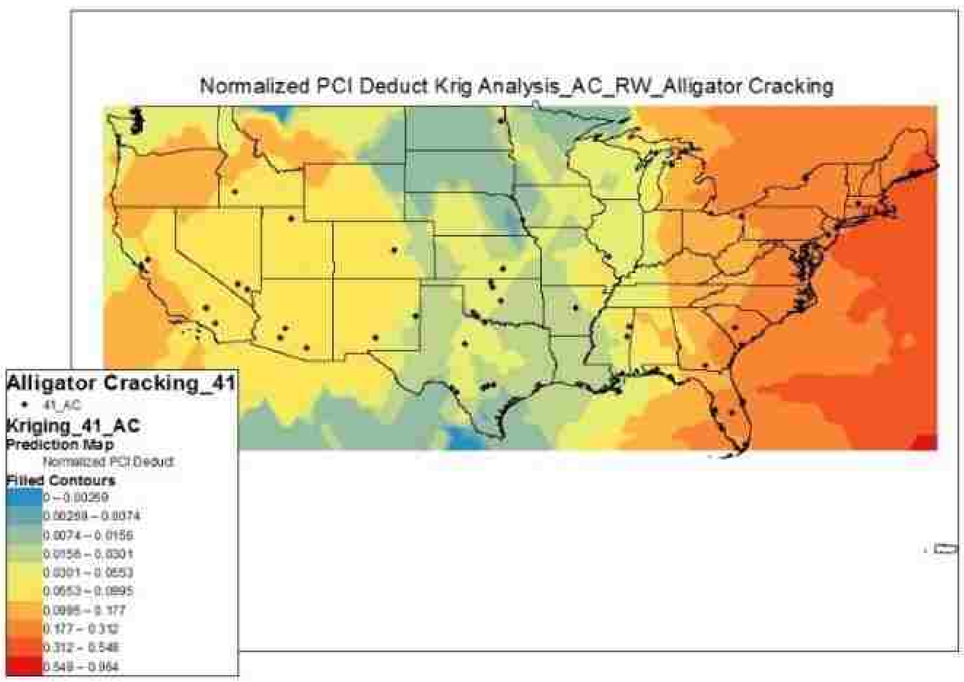
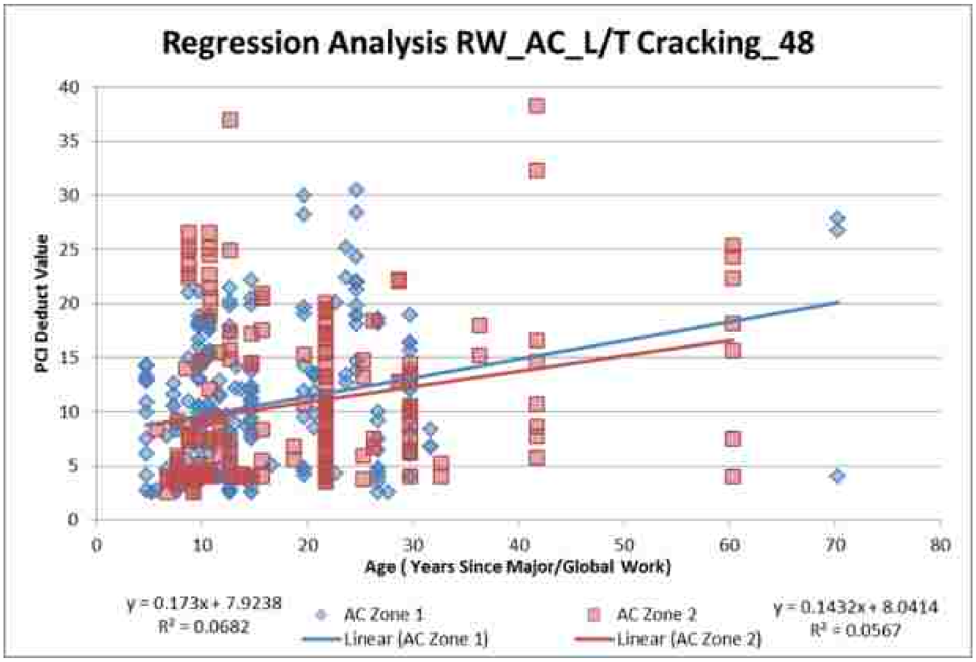


Table 8: Analysis of Alligator Cracking in AC Runways



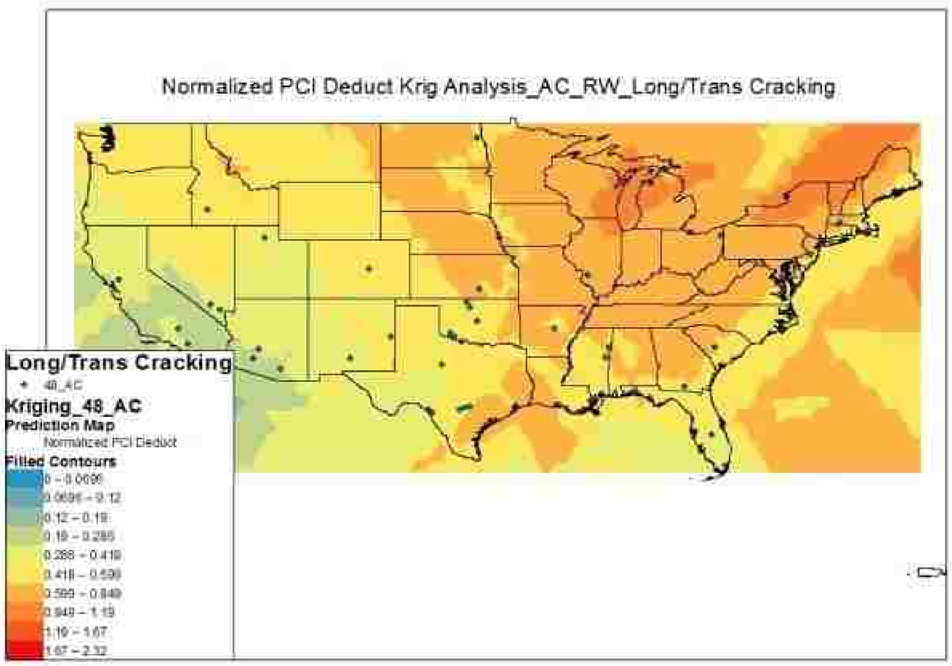
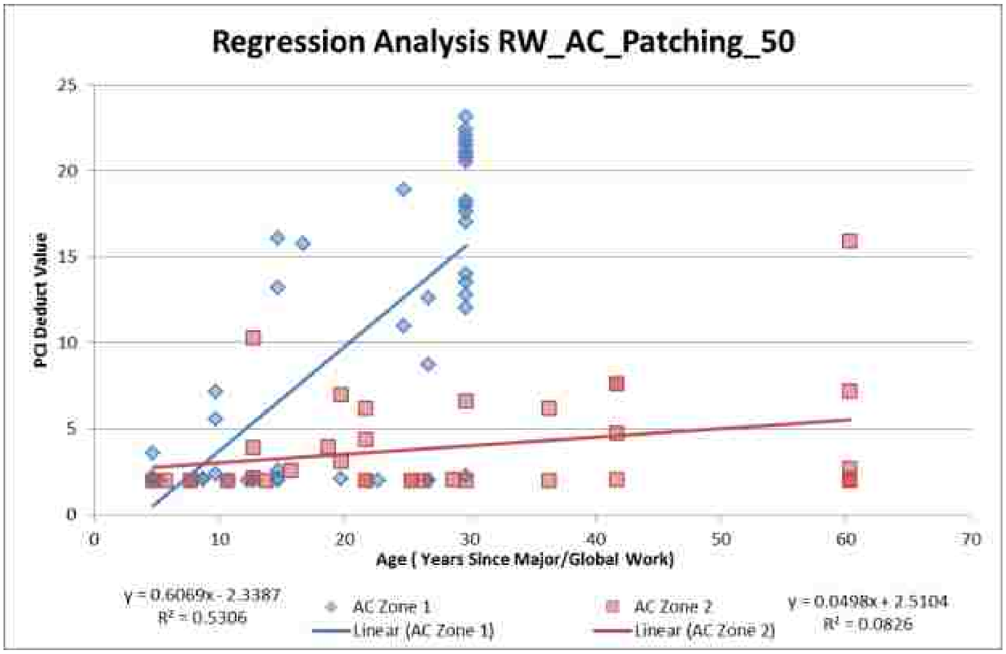


Table 9: Analysis of Long/Trans Cracking in AC Runways



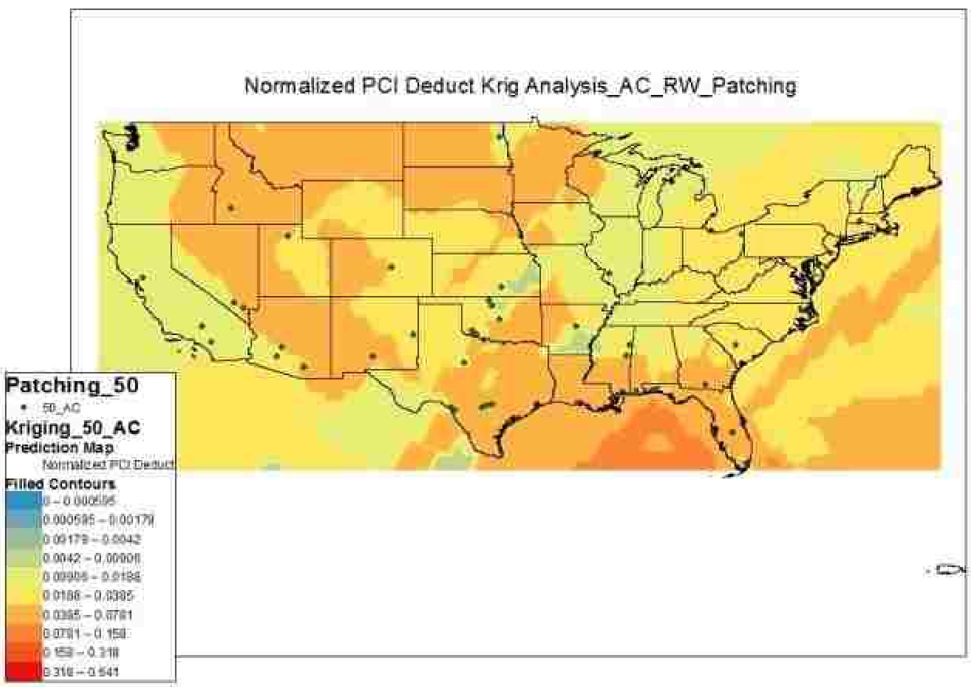
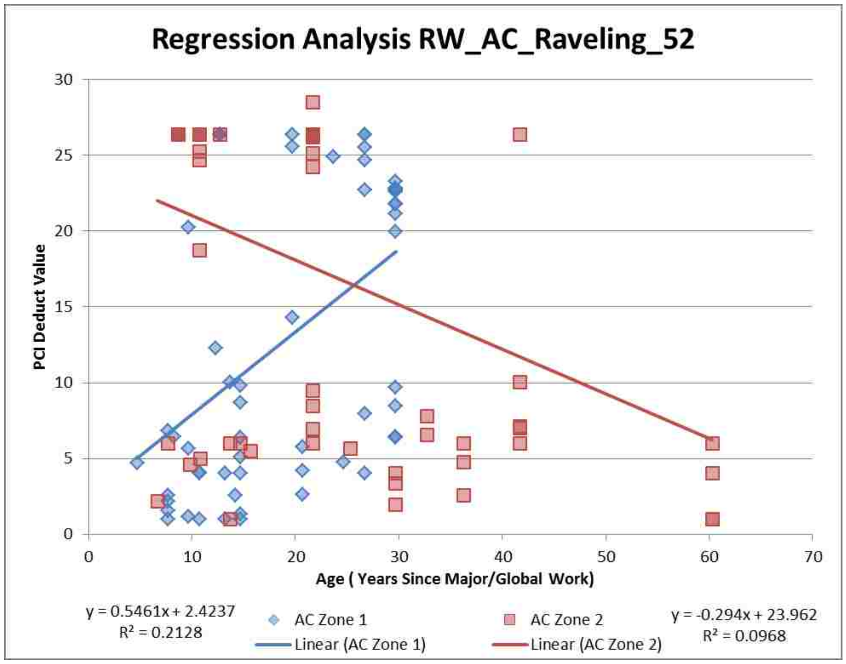


Table 10: Analysis of Patching in AC Runways



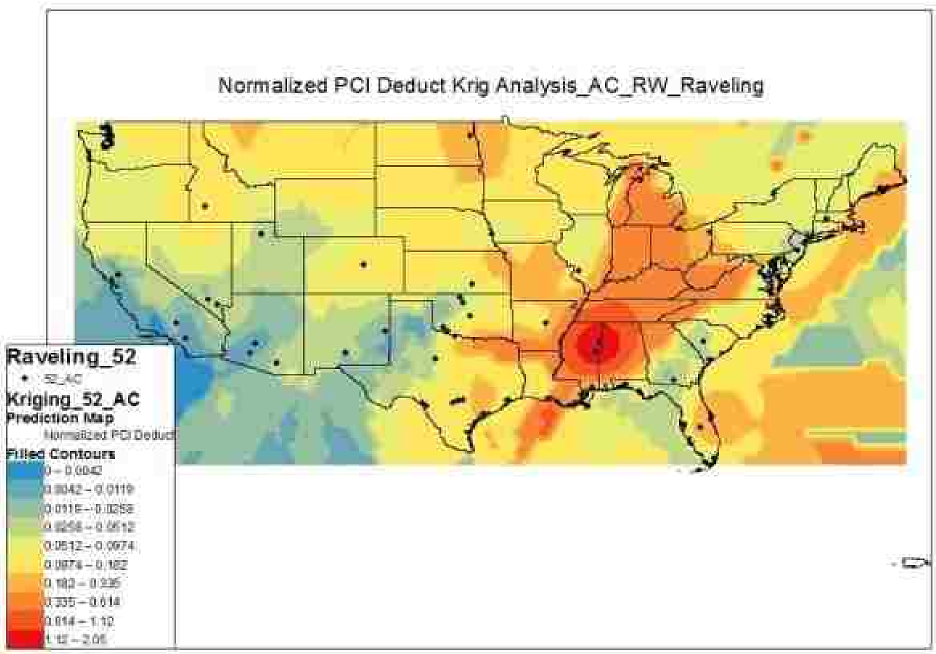
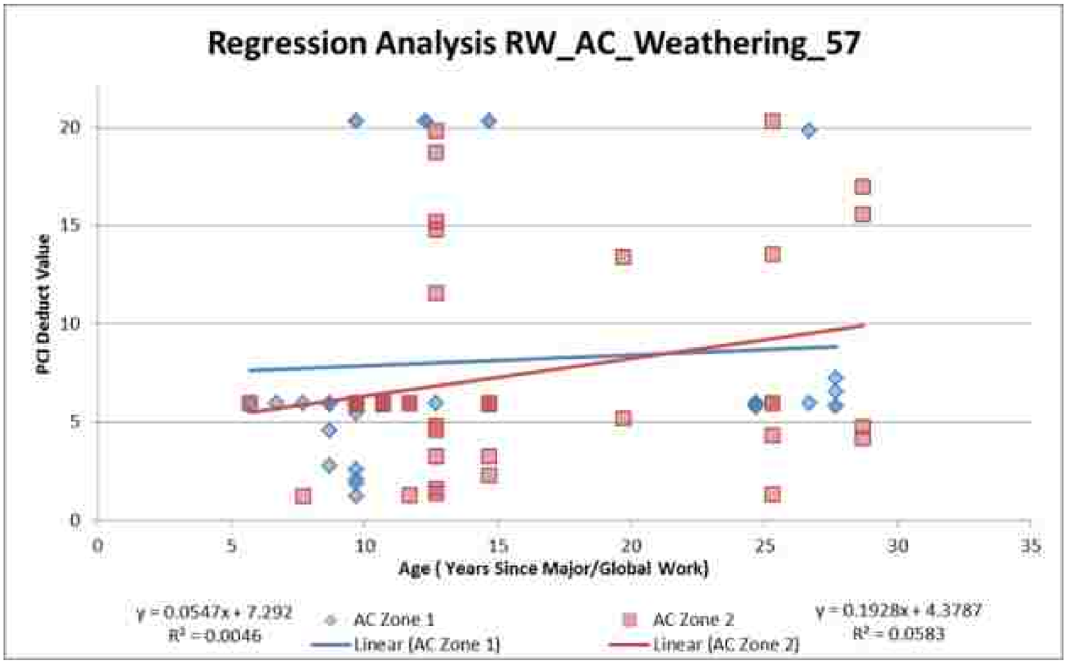


Table 11: Analysis of Raveling in AC Runways



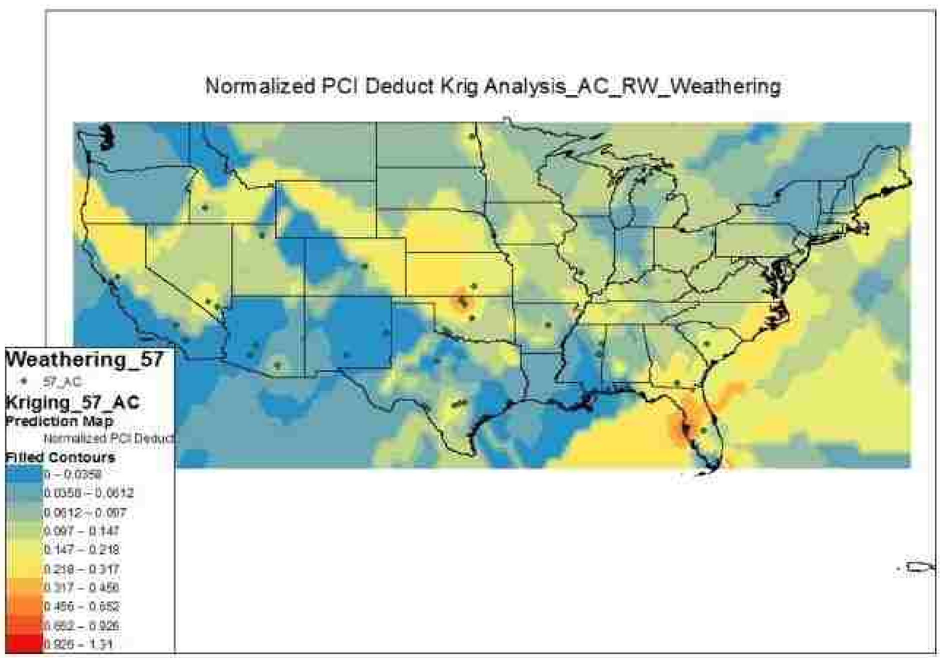
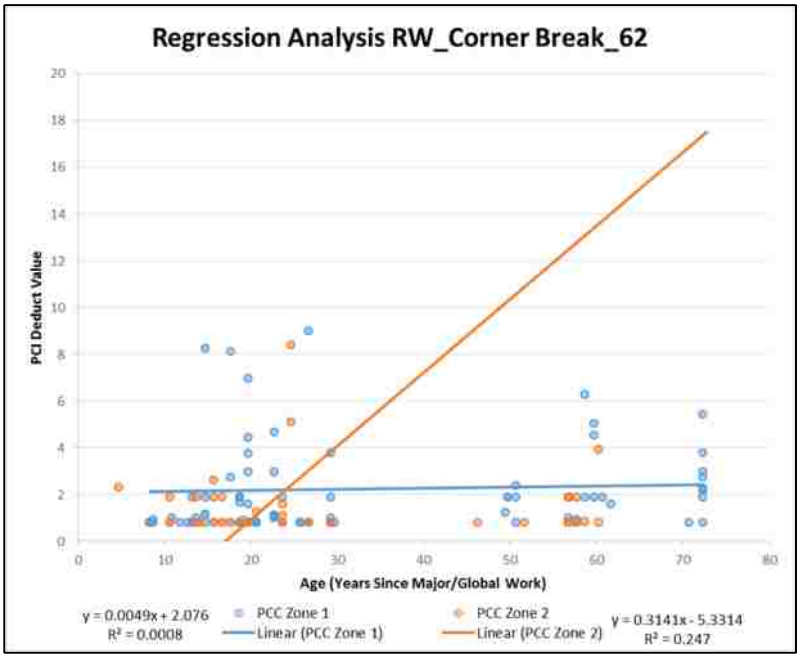


Table 12: Analysis of Weathering in AC Runways



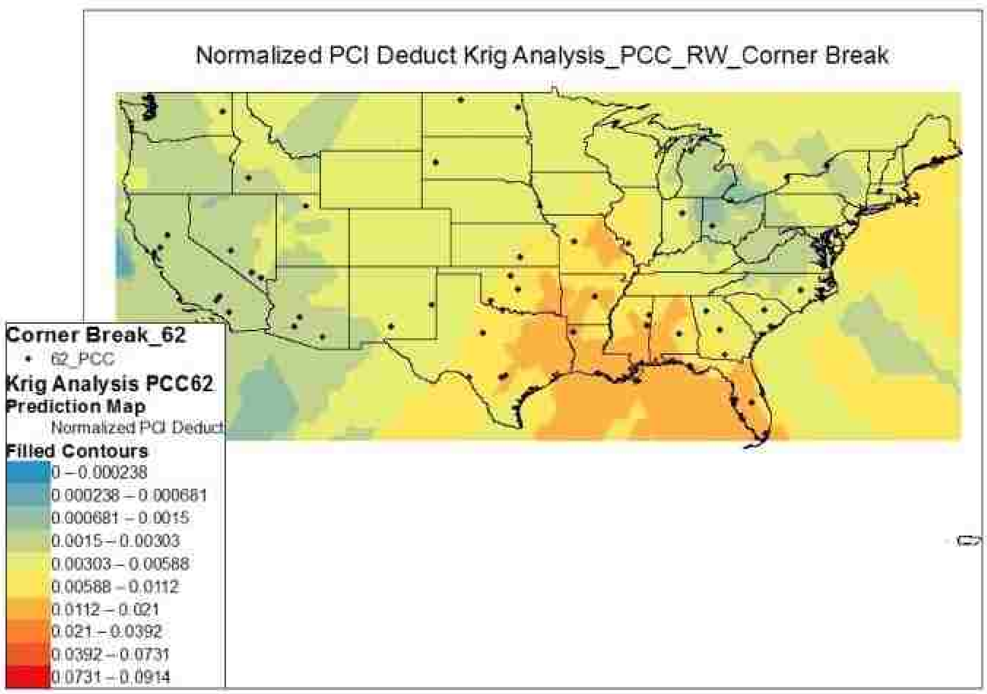
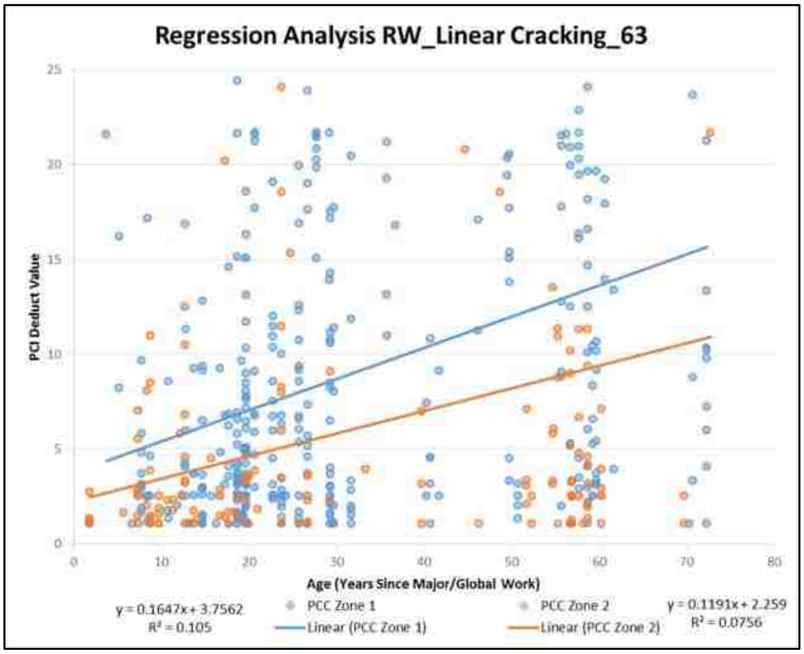


Table 13: Analysis of Corner Breaks in PCC Runways



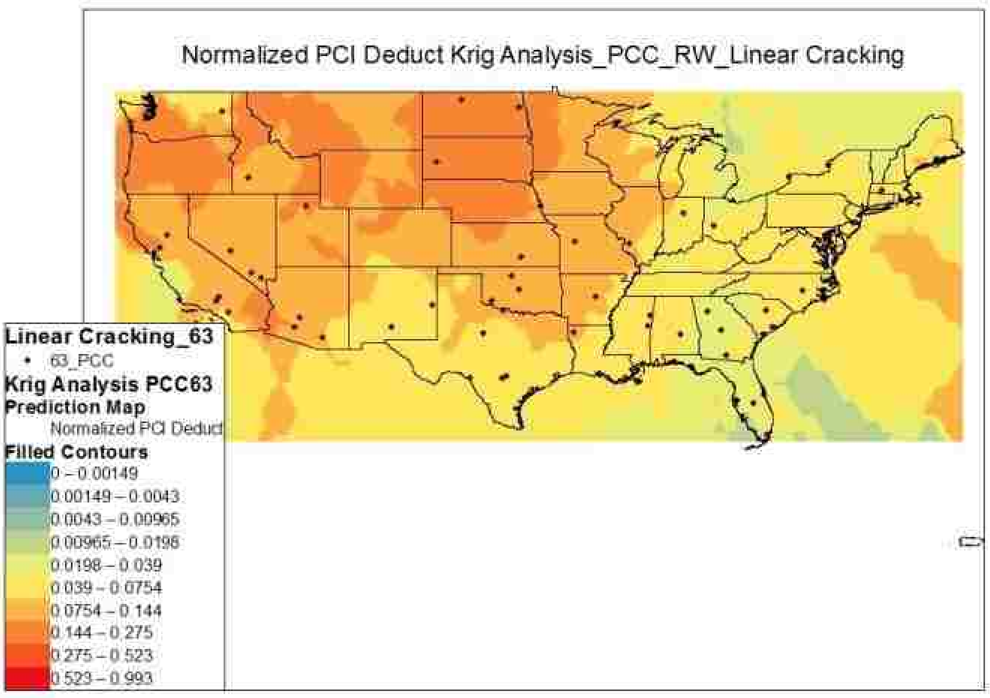
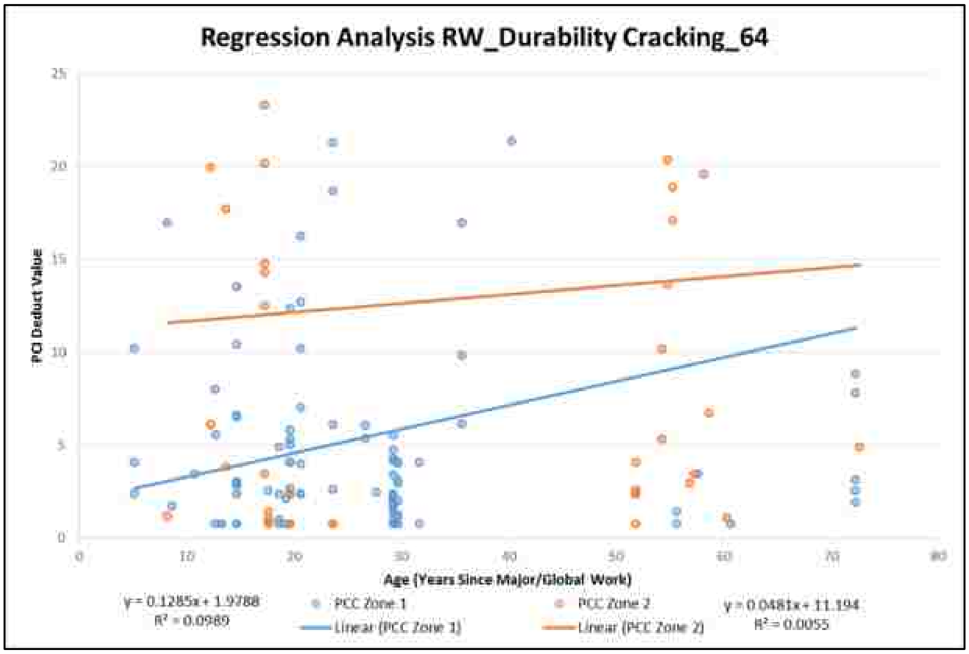


Table 14: Analysis of Linear Cracking in PCC Runways



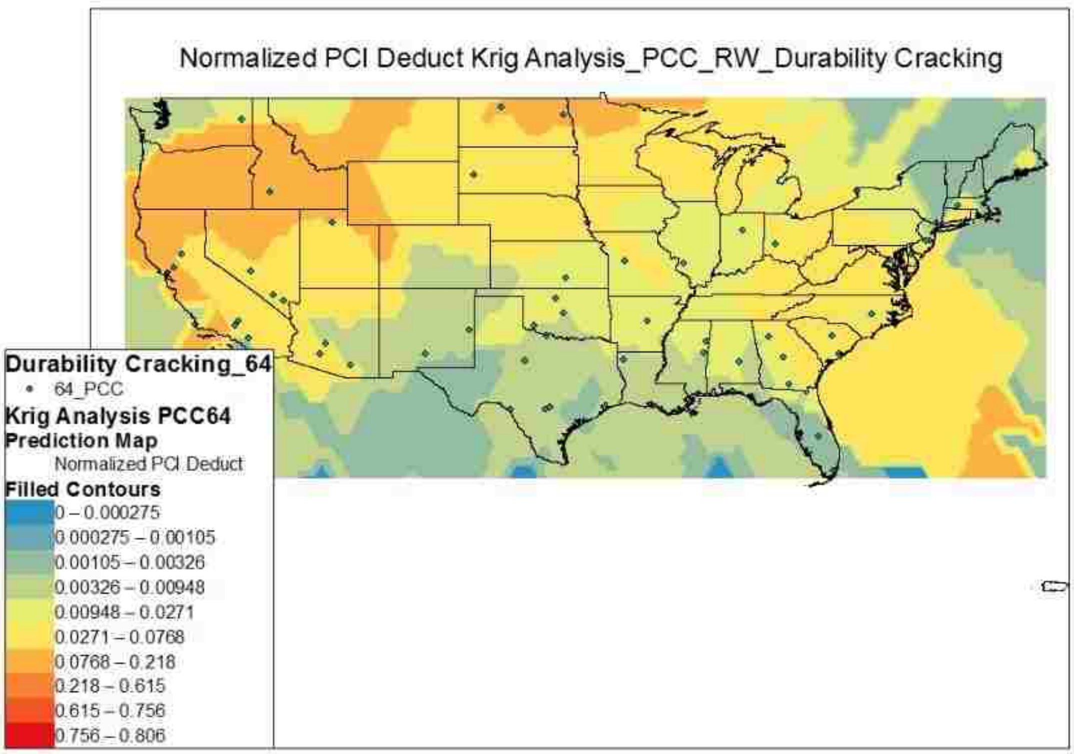
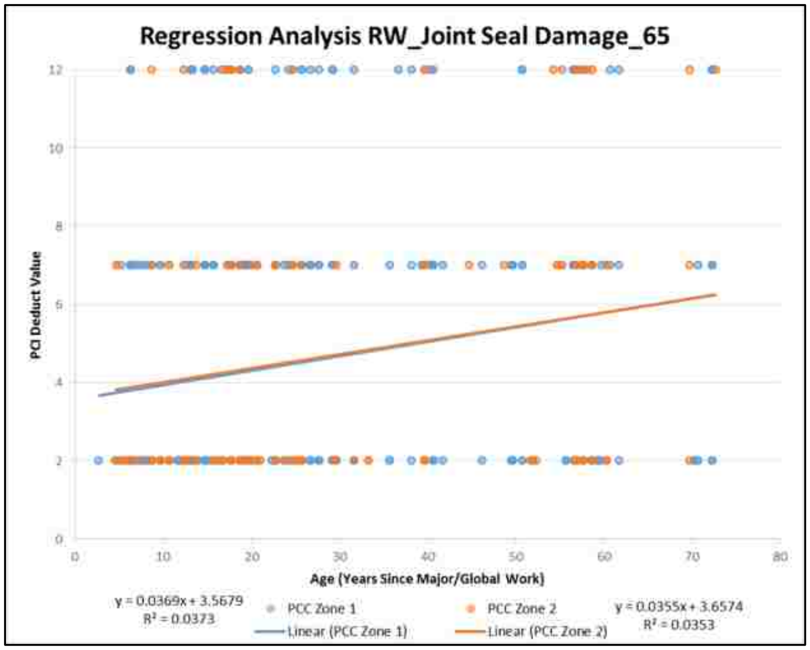


Table 15: Analysis of Durability Cracking in PCC Runways



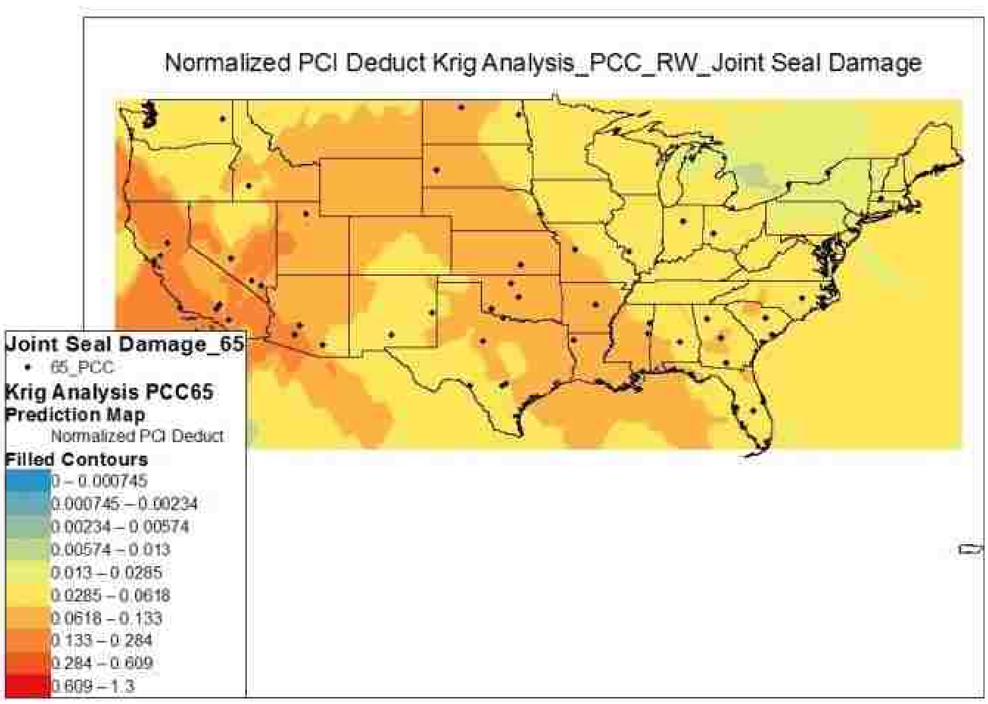
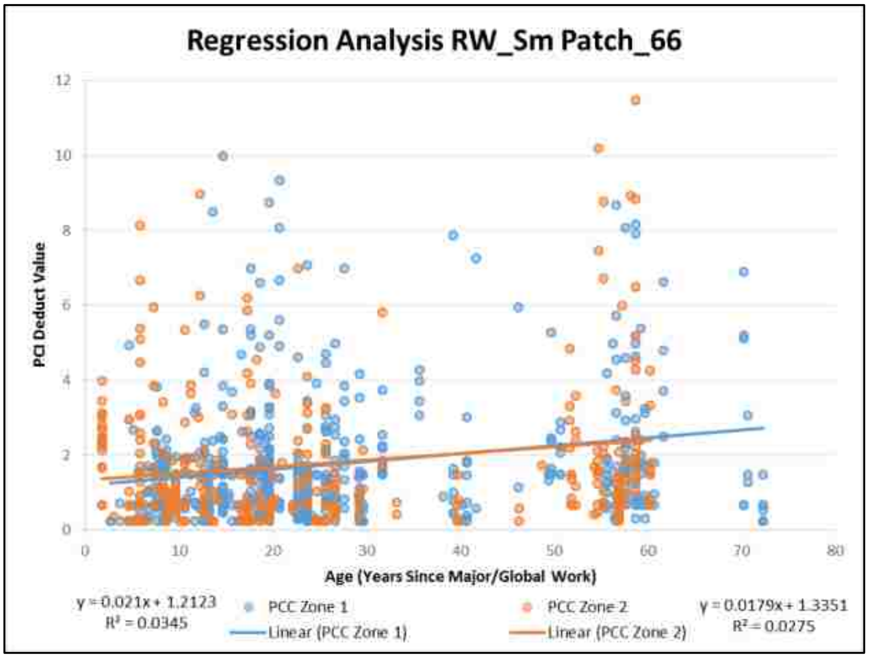


Table 16: Analysis of Joint Seal Damage in PCC Runways



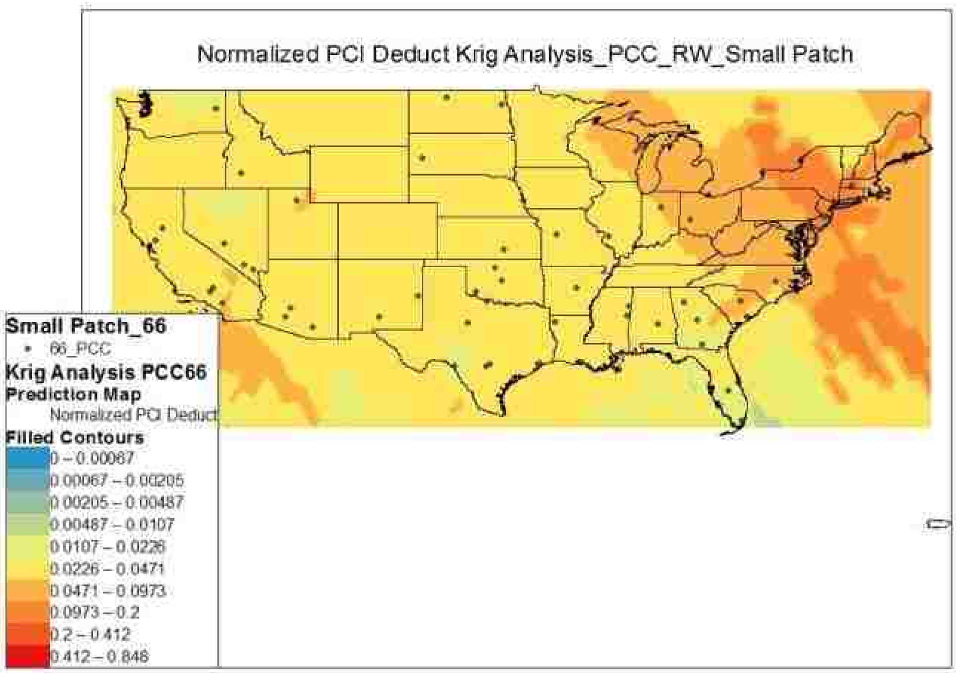
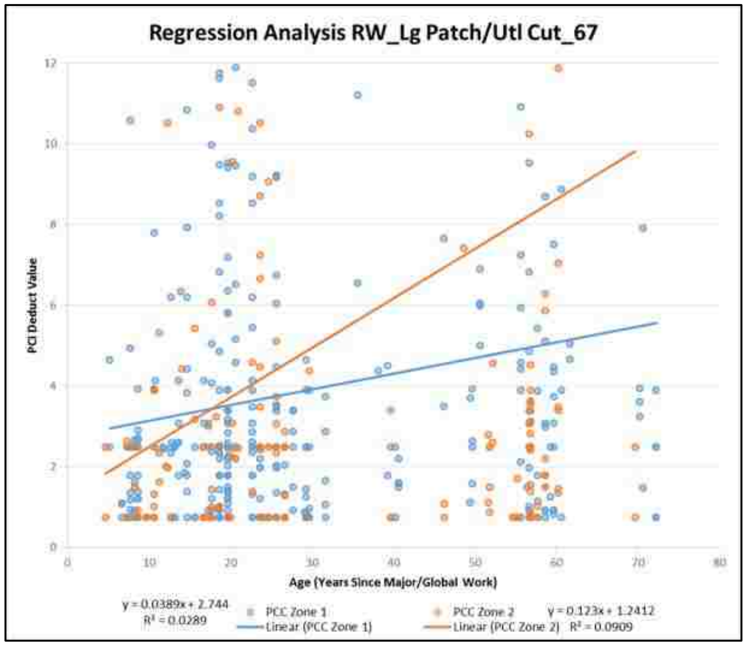


Table 17: Analysis of Small Patching in PCC Runways



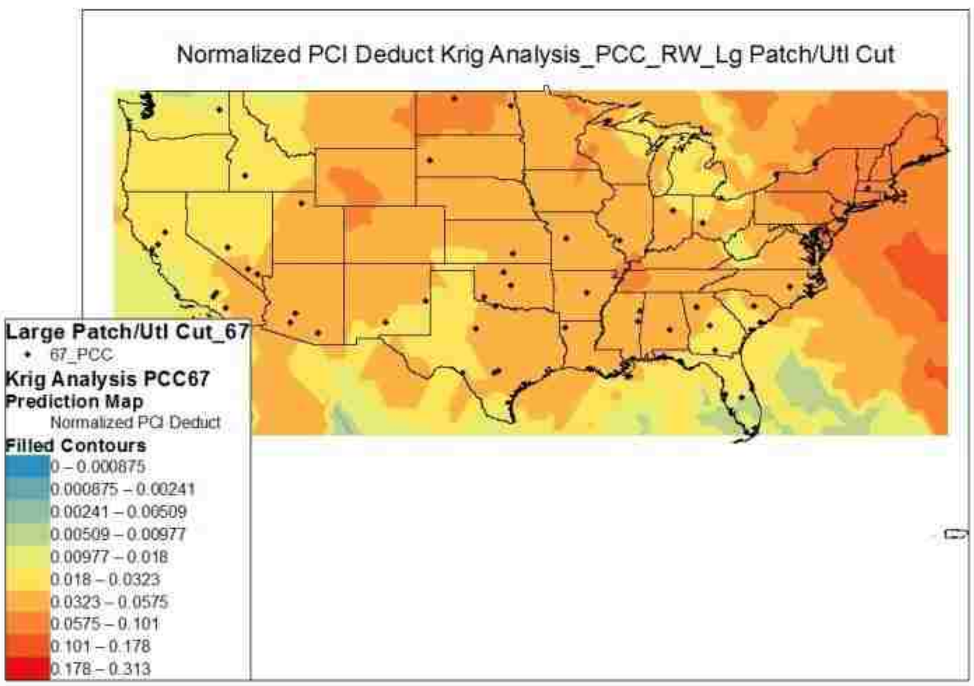
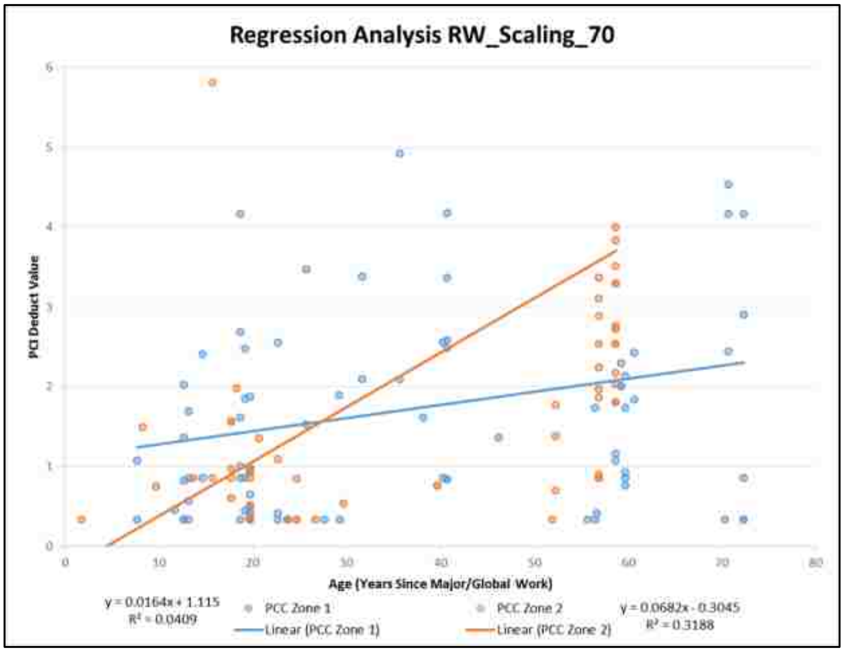


Table 18: Analysis of Large Patching in PCC Runways



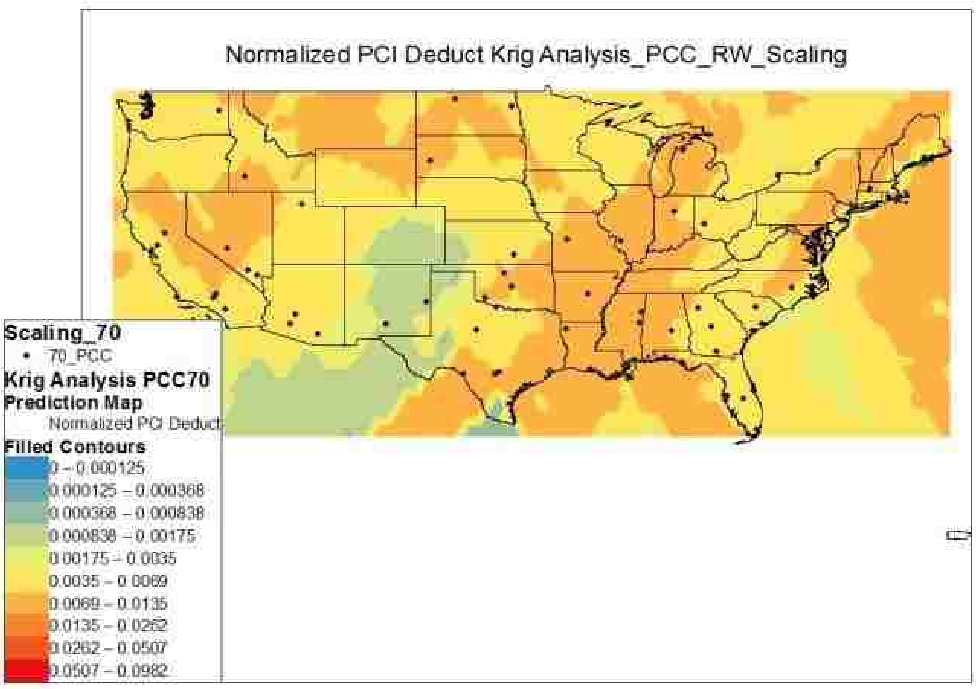
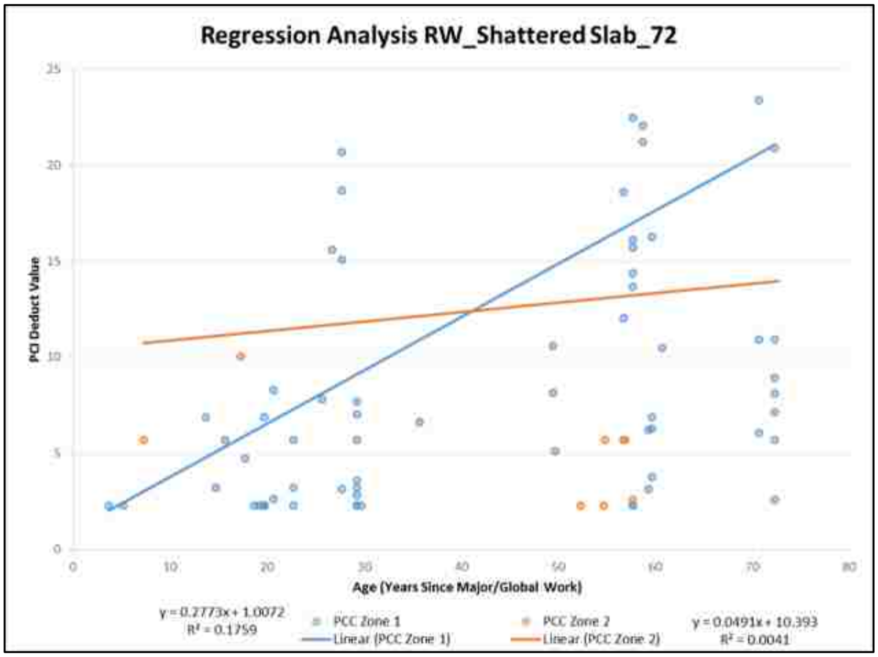


Table 19: Analysis of Scaling in PCC Runways



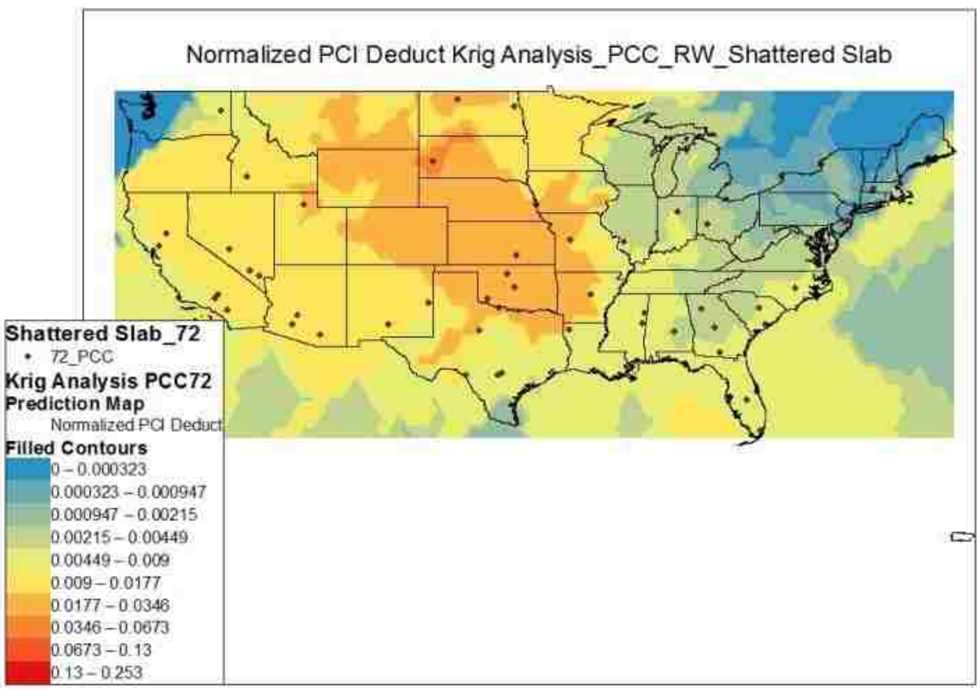
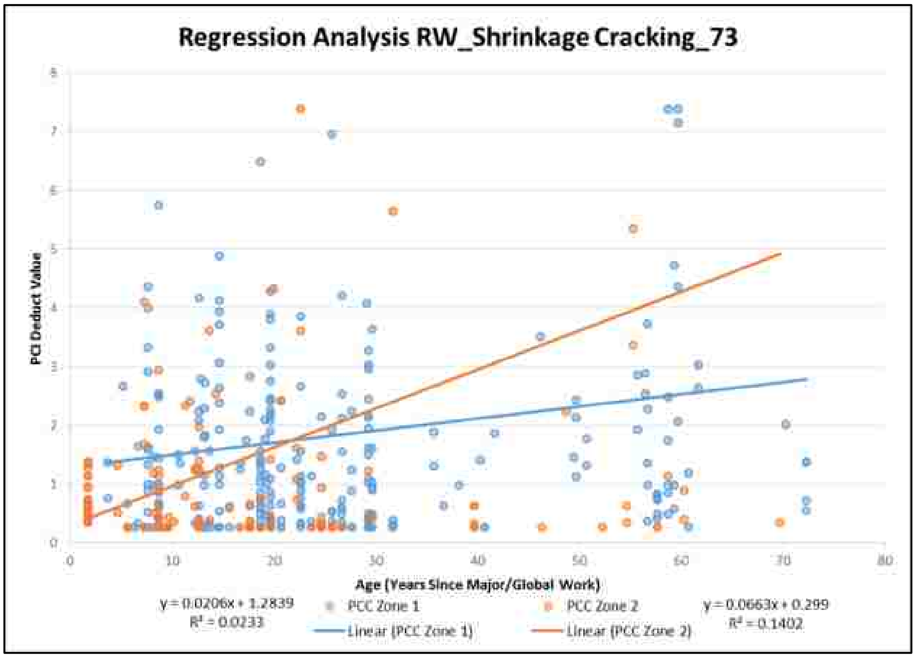


Table 20: Analysis of Shattered Slabs in PCC Runways



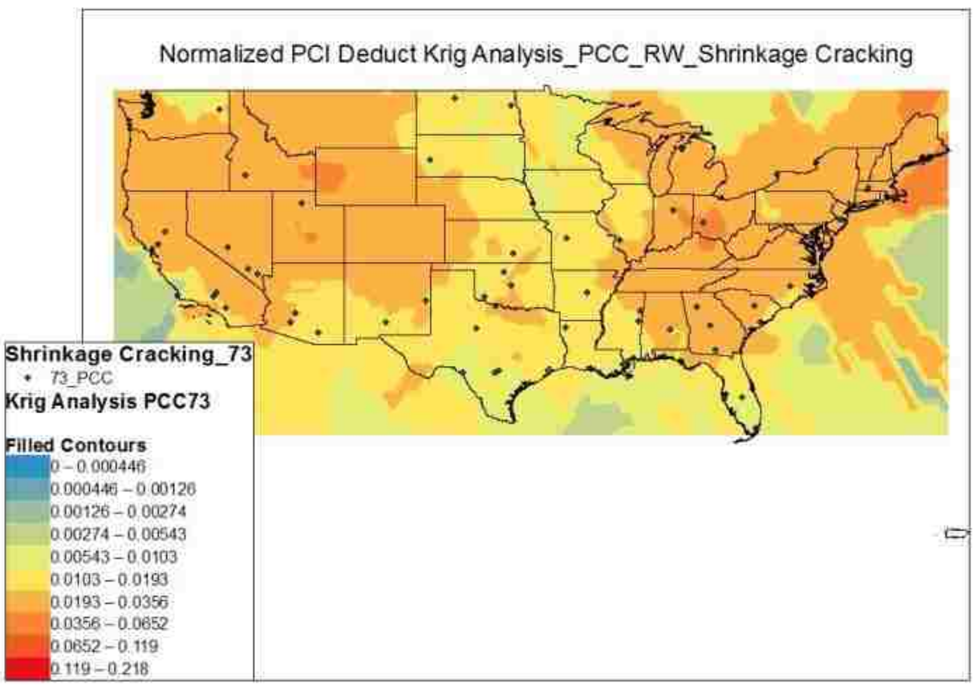
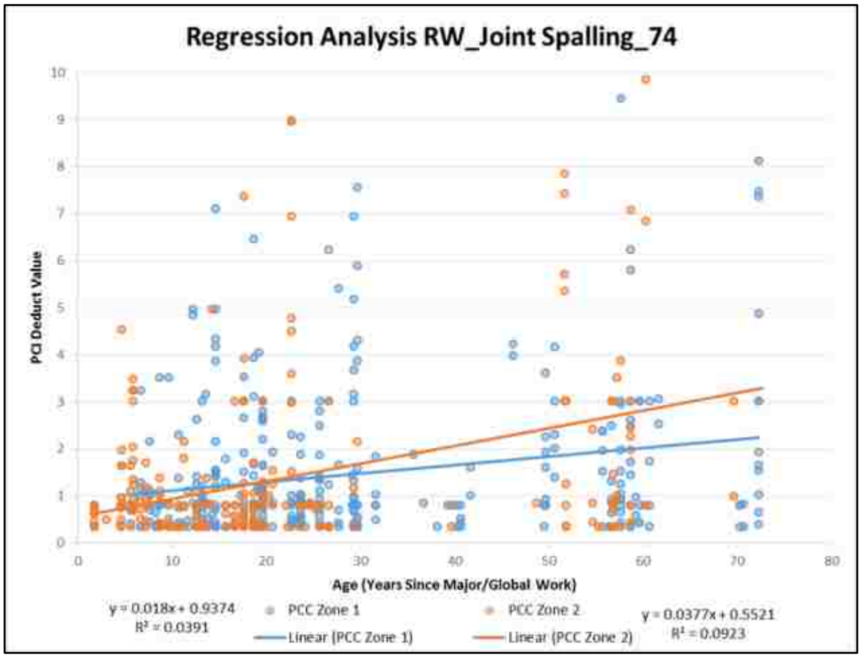


Table 21: Analysis of Shrinkage Cracking in PCC Runways



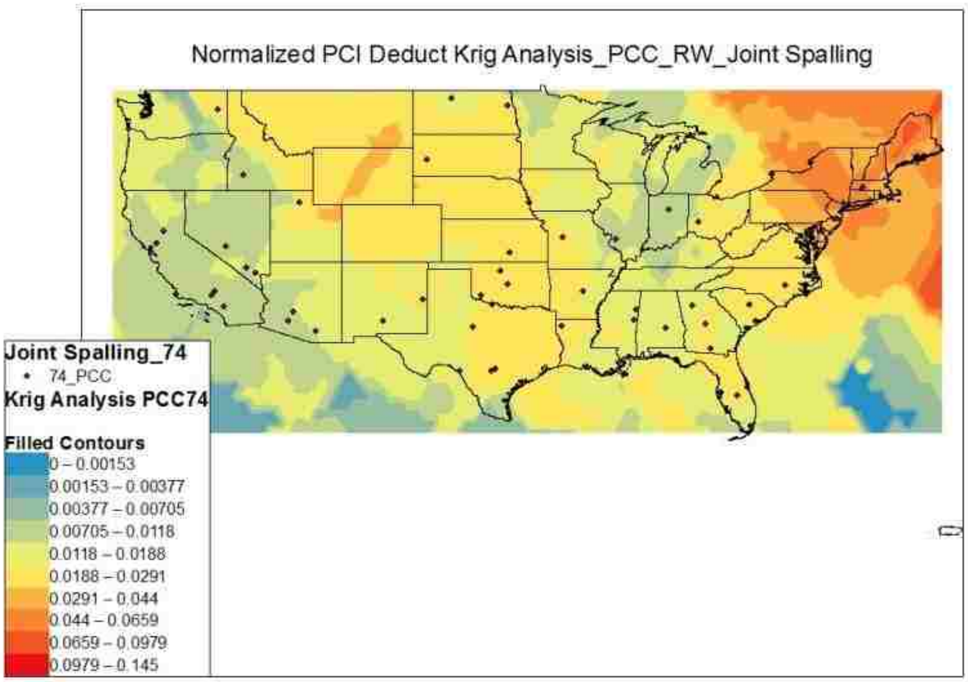
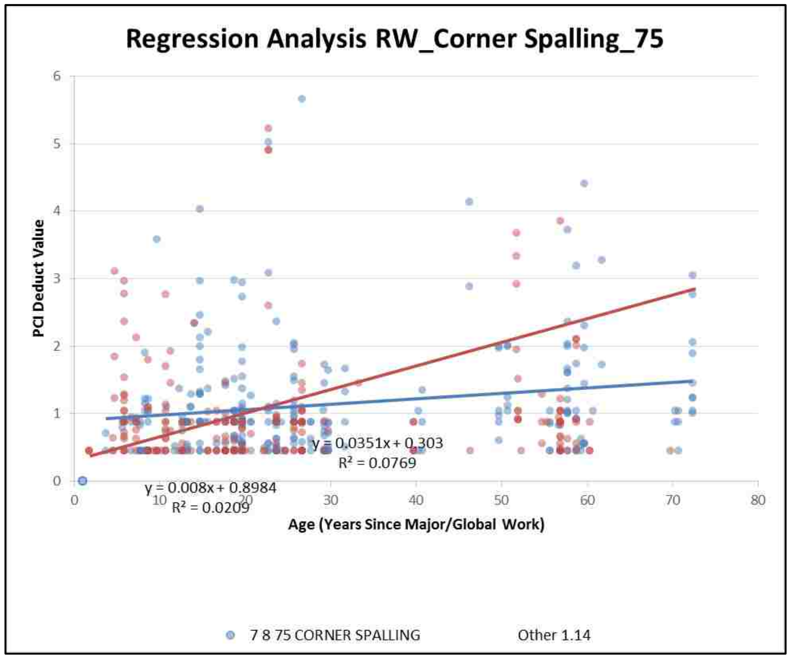


Table 22: Analysis of Joint Spalling in PCC Runways



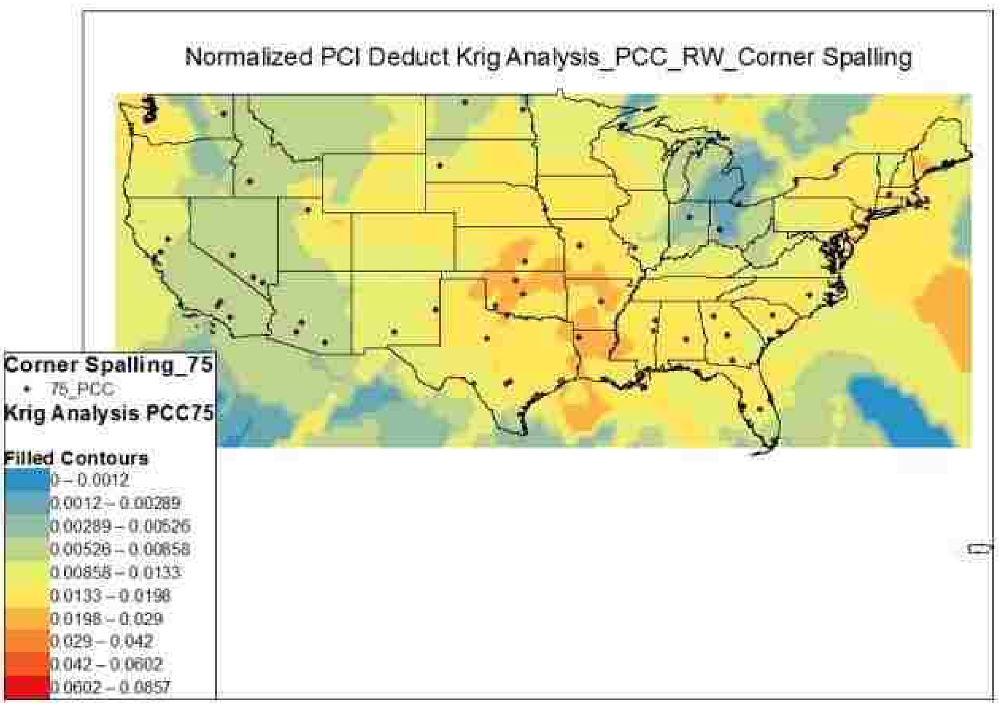


Table 23: Analysis of Corner Spalling in PCC Runways

6.5 Major Take Aways from Analysis

The regression slopes are not the same as pavement deterioration rates but they do provide insight into how the distress propagates over time. They are useful to consider because they suggest how fast the distress develops in each pavement behavior zone and they illustrate which zone has the more dominant distress behavior. The following observations were made by considering the regression slopes and krig images.

Distress 52, raveling, demonstrates the largest deterioration behavior in AC Zone 1, Distresses 41, alligator cracking and 52, raveling exhibit the largest deterioration behaviors in AC Zone 2. Distresses 63, linear cracking and 72, shattered slab demonstrate the largest deterioration behaviors in PCC Zone 1 while Distresses 62, corner break and 67, large patch/utility cut exhibit the largest deterioration behaviors in PCC Zone 2. Distresses like 66, small patch, 70, scaling, 74, joint spalling and 75, corner spalling where there is very little difference in the deterioration behavior across both zones strongly suggest that these distresses are not correlated to climate. These distresses all happen to be specific to PCC runways which may suggest that PCC pavement is less affected by climate than AC runway pavement. Outliers throughout the regression and krig analysis tended to be at auxiliary and reserve bases or at bases with high traffic. These outliers suggest that distresses are the result of the combination of climate, traffic load and maintenance strategy. PCC runway pavement tends to perform better in PCC Zone 2 while AC runway pavements tend to perform more favorably in AC Zone 1. This knowledge suggests that airfield planning should consider AC construction in the Western U.S. and PCC construction in the Eastern U.S. Although, overall PCC deterioration behavior tends to be smaller than AC deterioration behavior across both zones. The regression analysis on the pavement deterioration behavior based model did provide a better fit of the PCI deduct data than the climate based model proposed by AFIT; however, the R^2 values, representing how well the model fits the data, were still small. The small R^2 values suggest additional analysis should be conducted to investigate if there are alternative trends within the data which may provide a better “fit”. Suggestions of additional areas of analysis are described in the recommendations portion of this paper and conclusions of the analysis are made below.

Chapter 7 Conclusions

This research draws the following conclusions:

- Regression analysis performed on each distress type in the four proposed climate zones showed pavement behavior that improved with time in the "freeze_dry" zone. This trend is contradictory to all conventional knowledge of pavement behavior and was enough evidence to conclude that the proposed model based on precipitation and temperature data was not appropriate to use to evaluate pavement behavior at the individual distress level.
- The process model developed to distill the AF Roll-up Database is an effective method to consolidate the data so that analytic tools can be applied to evaluate embedded data trends.
- Krig analysis performed on the summation of all pavement distresses showed a distinct geographic difference in the pavement deterioration behavior of both AC and PCC runways. Deterioration behavior tends to be more severe in the Eastern U. S. in AC runway pavements and more severe in the Western U.S. for PCC runway pavements.
- Krig analysis performed at the individual distress level showed that some distresses occur in more defined geographic regions than others. Examples of these distress types include raveling, linear cracking and joint seal damage. However, this conclusion does not directly correlate these more location specific distresses to climate causation because the geographic pattern was uncovered using a derivation of the PCI deduct value which includes in it all five pavement distress contributing factors.
- Examples of distresses that did not show a strong geographic pattern include alligator cracking and corner breaking. The analysis showed that traffic load and maintenance strategy seemed to play a large role in the development of these distresses.

Without additional investigation of potential patterns within the other four pavement deterioration factors this research cannot confirm the hypothesis that climate is the predominant contributing factor. The data consolidation process model and pavement behavior models presented here provide a framework to conduct the additional analysis.

Chapter 8 Recommendations

The process model presented in the research to consolidate the section PCI deduct values in order to perform geostatistical analysis only accounted for age and size (area) of the pavement sections tied to each pavement distress. Additional consideration should be paid to other characteristics of the pavement sections such as thickness, length and width of the pavement slabs, mix design, etc. The regression analysis conducted on the pavement models showed an improvement in correlation between PCI and age within each zone from the regression analysis performed on the climate based model; however, the R^2 values were still very small which indicates the models can be improved further.

The same approach used for runway pavement analysis should be applied to the taxiway and apron distress data within the AF Roll-up Database. If the same trends uncovered in the runway pavement analysis are uncovered in the taxiway and apron data then a clearer picture of how climate relates to pavement distress can be drawn. The analysis will also equip pavement engineers and asset managers with a valuable map that forecasts how pavement distresses will develop in taxiways and aprons.

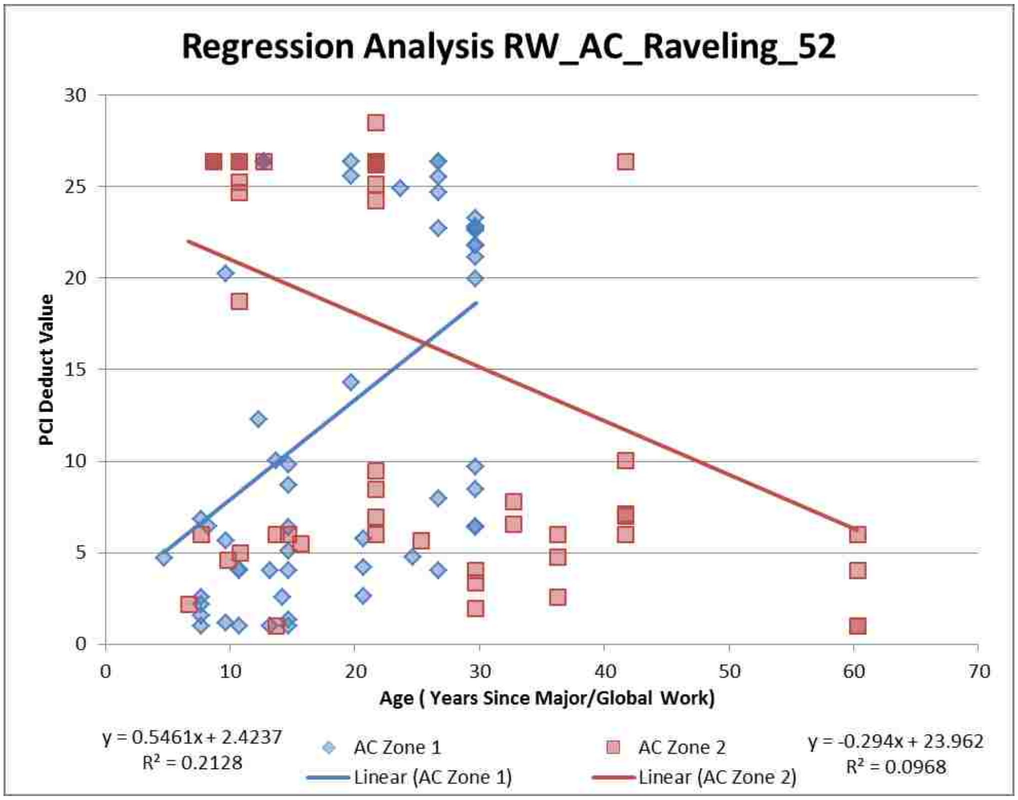
Many of the distress types could not be analyzed in this research because there was not enough data to draw reliable conclusions from. Consideration should be made to including distress data from non AF installations (i.e. municipal airports, private airports, international airports, etc.). While an investigation of the survey techniques used to inspect the pavement would have to be completed, this additional data may allow for a larger sample size for some of the less frequent distress types.

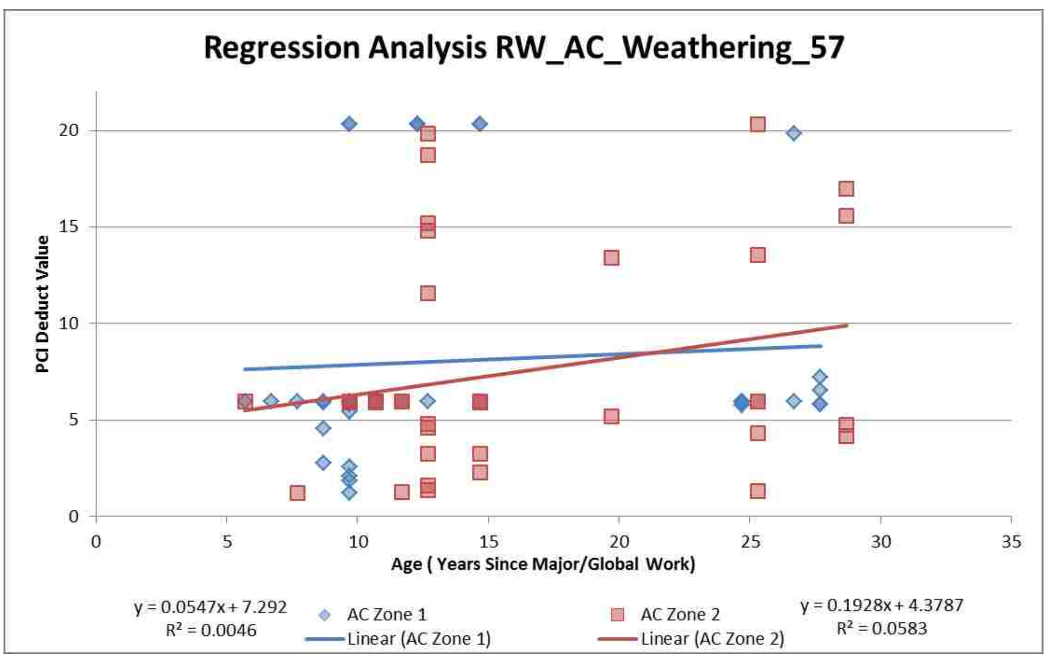
The PCI survey data does not include data for pavement sections void of pavement distress. Although recording this data would increase the scope of the survey, the data would be very valuable to conduct further analysis of correlations between the physical characteristics of the pavement sections and the occurrence of pavement distresses. It would also strengthen any additional statistical analysis of the AF Roll-up Database.

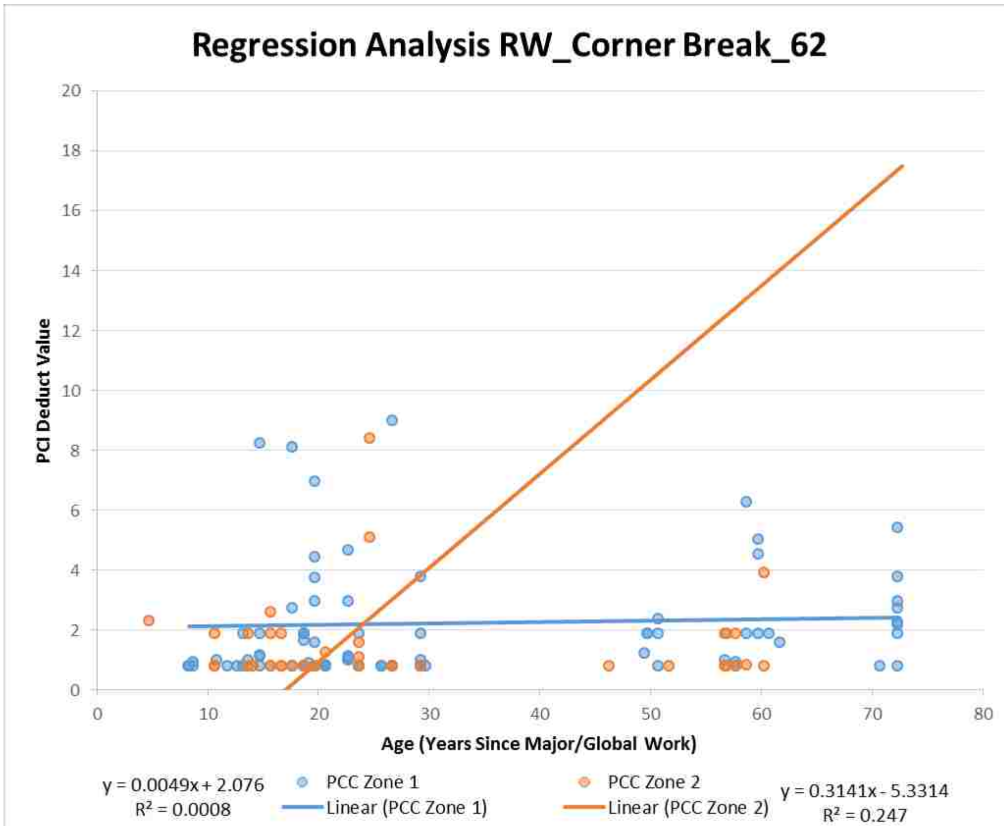
As mentioned many times, consideration of maintenance strategy, traffic load, construction history and pavement structure should be made before making a conclusion about the predominant distress contributor. During the course of this research attempts were made to acquire aircraft traffic information for each of the AF installations under consideration. However, the only data the AF tracks is the total annual number of aircraft operations at each installation in a document called the USAF Air Traffic Activity Report. The report does not include the total number of operations performed by each type of aircraft at each installation. This data would allow for analysis of traffic load to be conducted with the data in the AF Roll-up Database. For example analysis could be conducted to see if rutting is more prevalent at bases where cargo planes or at bases where fighter planes are the predominant aircraft. Which would help to piece together the full distress analysis picture.

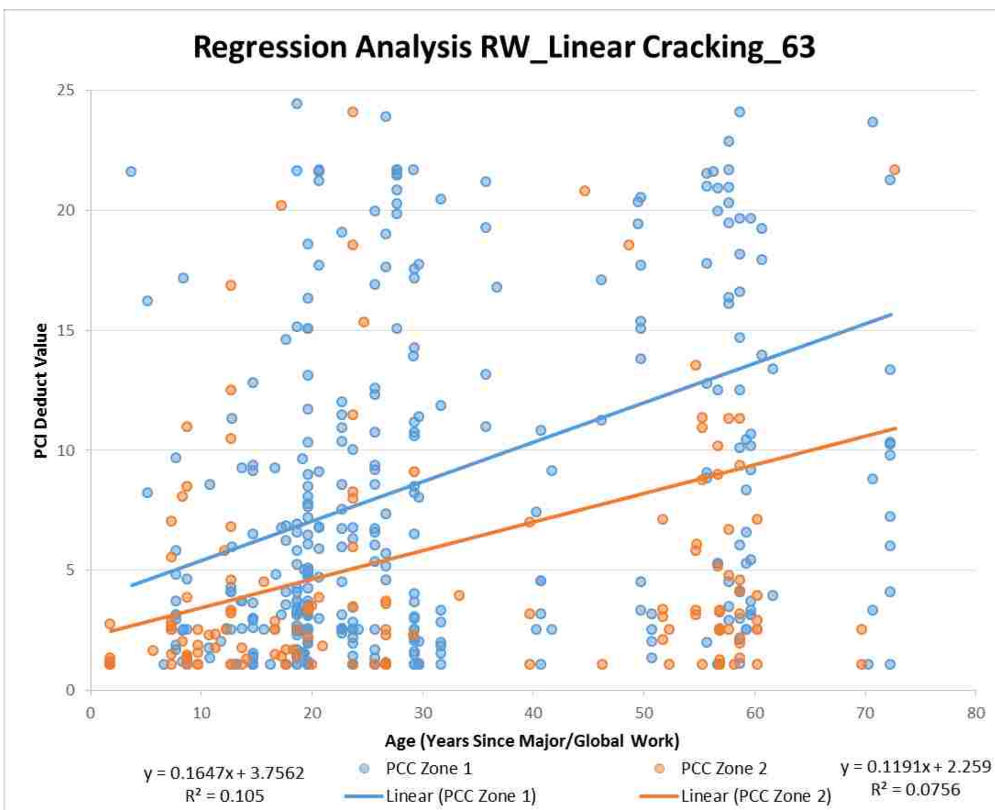
Other valuable pieces of this puzzle are to evaluate the maintenance strategy at each installation or perhaps within each major command. This could be done using dollars spent at each installation in annual airfield maintenance. Again, this data is not readily available but would be very beneficial for modeling and forecasting the pavement behavior.

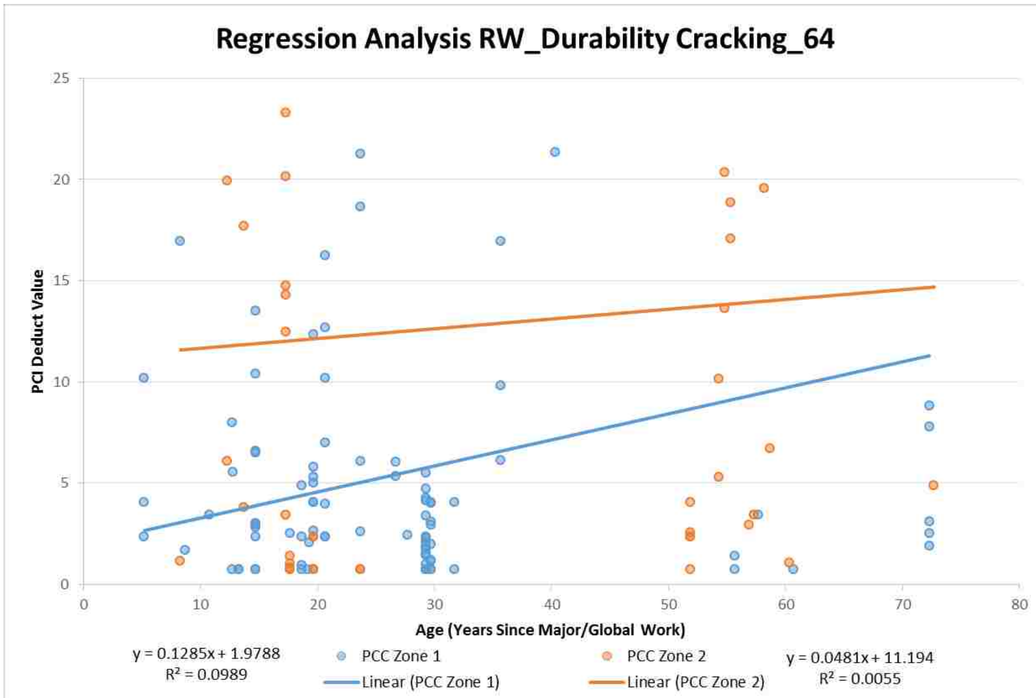
Another area of additional research is to consider the correlation between specific weather phenomenon and distress occurrence (for example wind and joint seal damage or solar radiance and weathering, etc.). Or if a certain distress usually accompanies another distress; such as joint seal damage and corner spalling. There is an endless amount of analysis that can be conducted on the data contained within the AF Roll-up Database and because the pavement behavior model presented in this research was created from the actual distress data, which is a numerical representation of the five pavement deterioration factors, it should be used as a starting point to conduct the additional analysis.

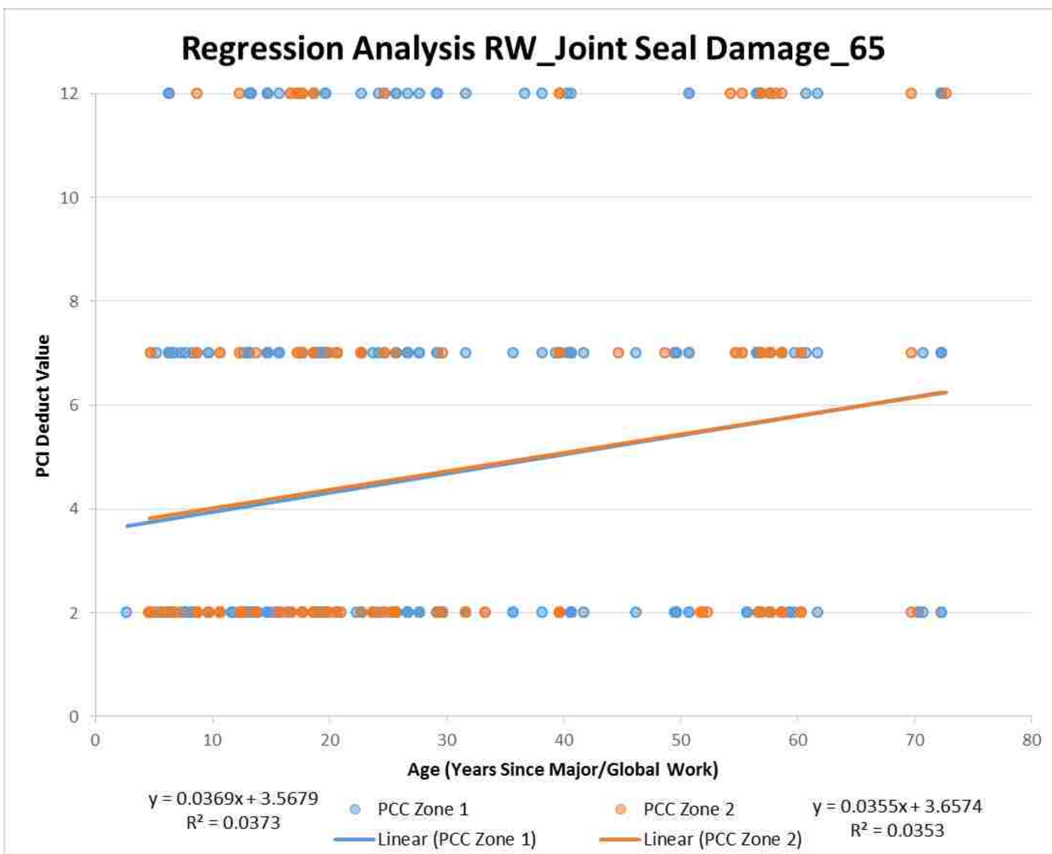

Regression Analysis RW_AC_Raveling_52
PCI Deduct Value
30
25
20
15
10
5
0
0
10
20
30
40
50
60
70
Age (Years Since Major/Global Work)
y = 0.5461x + 2.4237
R² = 0.2128
AC Zone 1
Linear (AC Zone 1)
AC Zone 2
Linear (AC Zone 2)
y = -0.294x + 23.962
R² = 0.0968

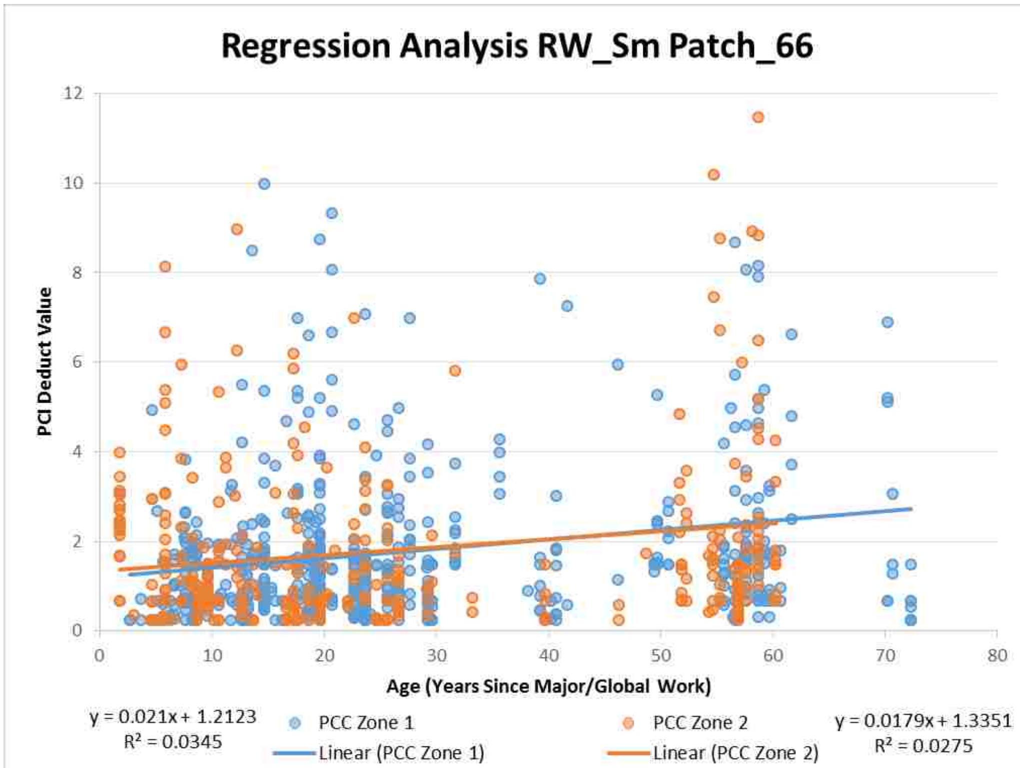

Regression Analysis RW_AC_Weathering_57
PCI Deduct Value
20
15
10
5
0
0
5
10
15
20
25
30
35
Age (Years Since Major/Global Work)
y = 0.0547x + 7.292
R² = 0.0046
AC Zone 1
Linear (AC Zone 1)
AC Zone 2
Linear (AC Zone 2)
y = 0.1928x + 4.3787
R² = 0.0583


Regression Analysis RW_Corner Break_62
PCI Deduct Value
Age (Years Since Major/Global Work)
y = 0.0049x + 2.076
R² = 0.0008
PCC Zone 1
Linear (PCC Zone 1)
PCC Zone 2
Linear (PCC Zone 2)
y = 0.3141x - 5.3314
R² = 0.247

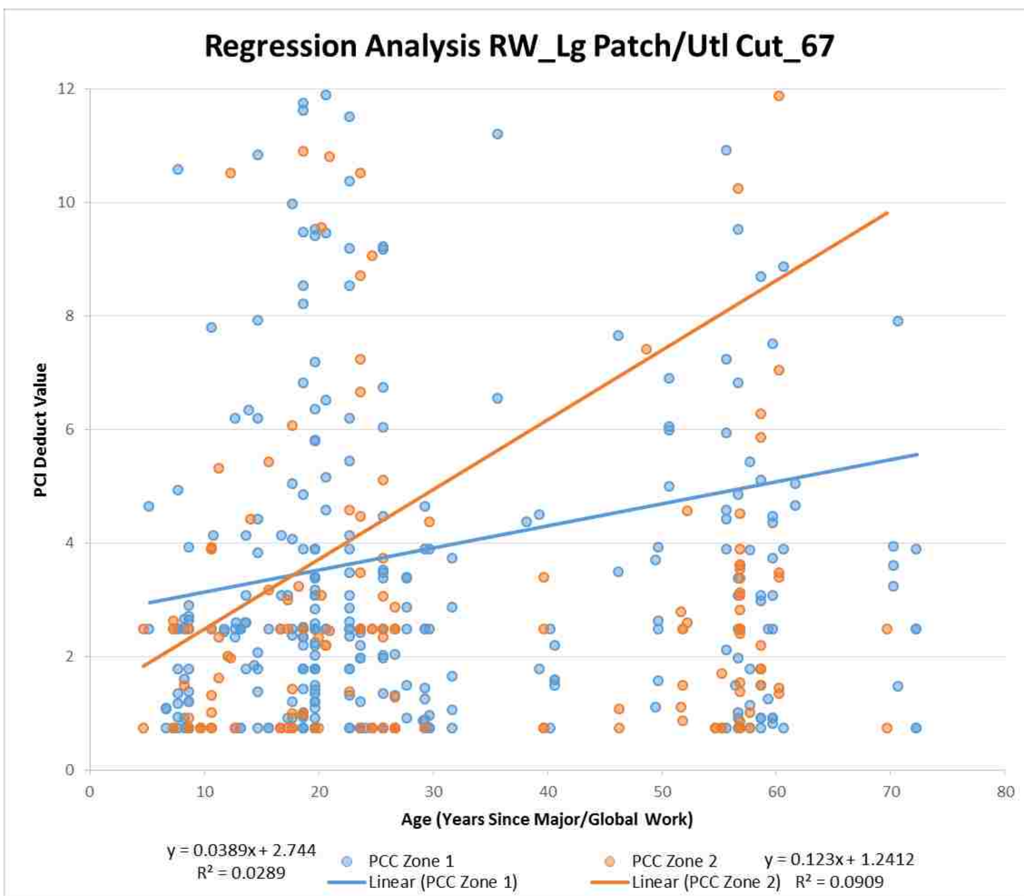

Regression Analysis RW_Linear Cracking_63
PCI Deduct Value
Age (Years Since Major/Global Work)
y = 0.1647x + 3.7562
R² = 0.105
PCC Zone 1
Linear (PCC Zone 1)
PCC Zone 2
Linear (PCC Zone 2)
y = 0.1191x + 2.259
R² = 0.0756


Regression Analysis RW_Durability Cracking_64
PCI Deduct Value
Age (Years Since Major/Global Work)
y = 0.1285x + 1.9788
R² = 0.0989
PCC Zone 1
Linear (PCC Zone 1)
PCC Zone 2
Linear (PCC Zone 2)
y = 0.0481x + 11.194
R² = 0.0055

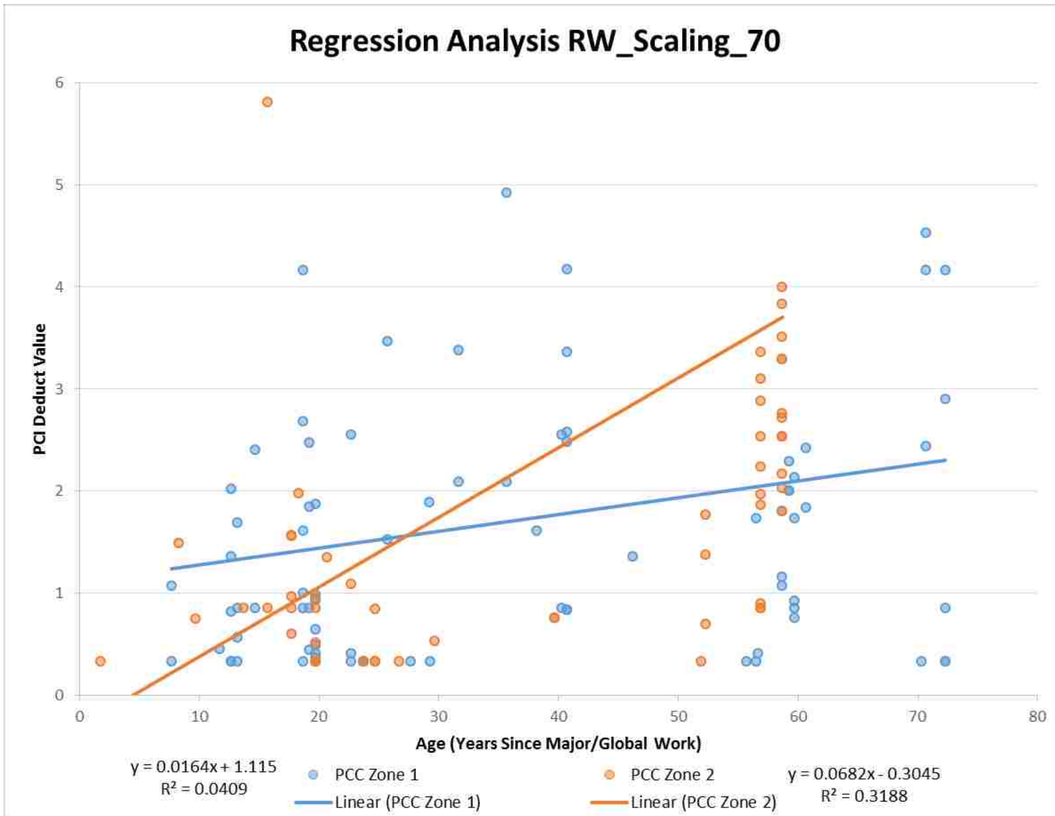

Regression Analysis RW_Joint Seal Damage_65
PCI Deduct Value
Age (Years Since Major/Global Work)
y = 0.0369x + 3.5679
R² = 0.0373
PCC Zone 1
Linear (PCC Zone 1)
PCC Zone 2
Linear (PCC Zone 2)
y = 0.0355x + 3.6574
R² = 0.0353



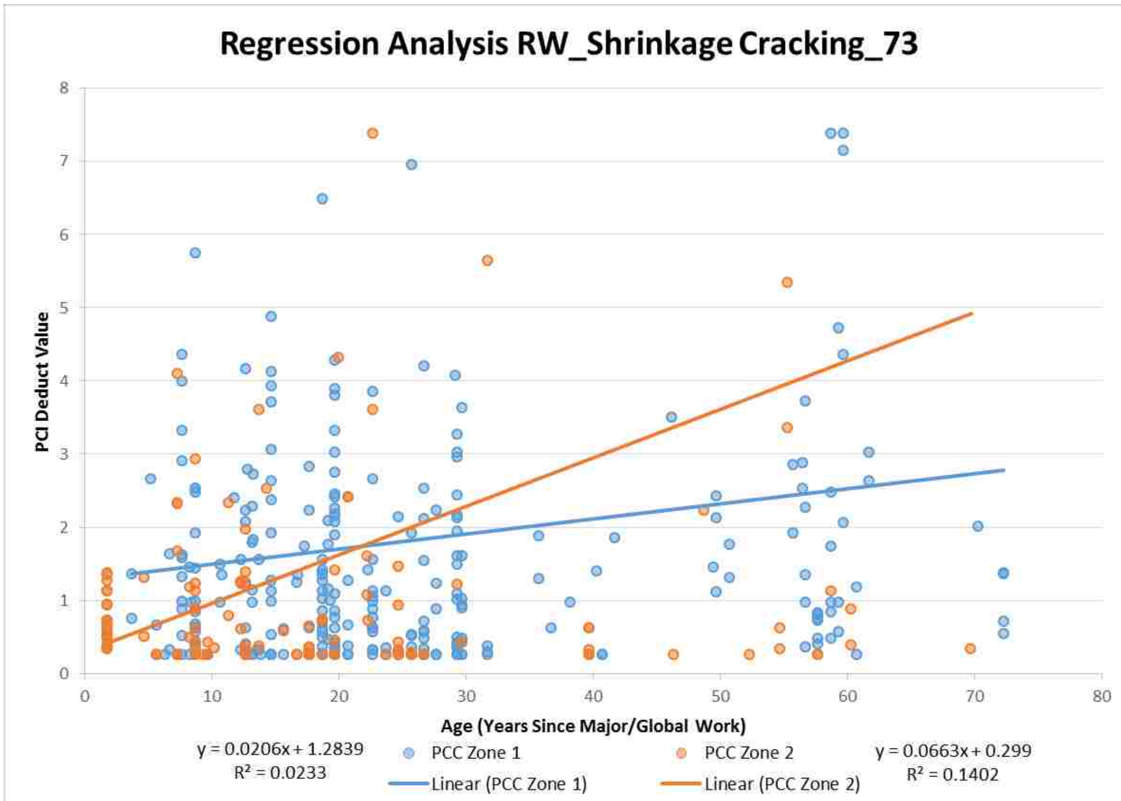
Regression Analysis RW_Sm Patch_66
PCI Deduct Value
Age (Years Since Major/Global Work)
y = 0.021x + 1.2123
R² = 0.0345
PCC Zone 1
Linear (PCC Zone 1)
PCC Zone 2
Linear (PCC Zone 2)
y = 0.0179x + 1.3351
R² = 0.0275

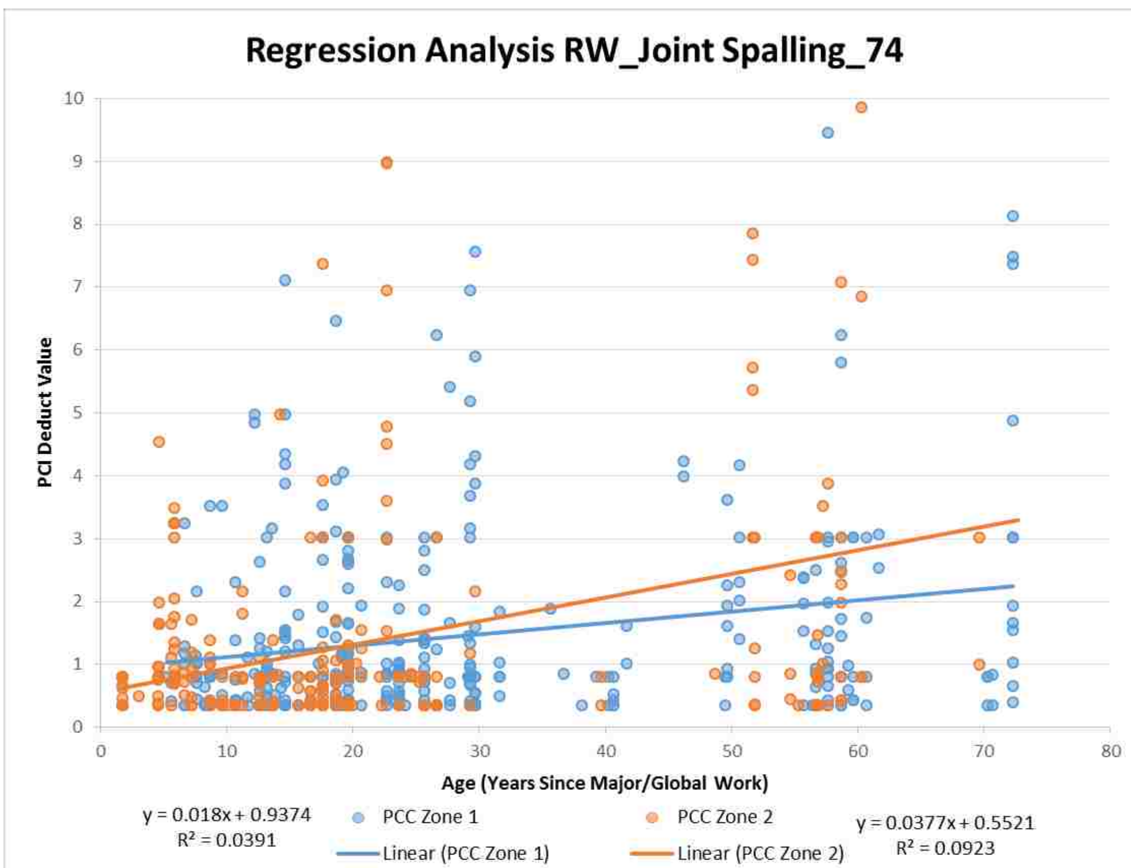


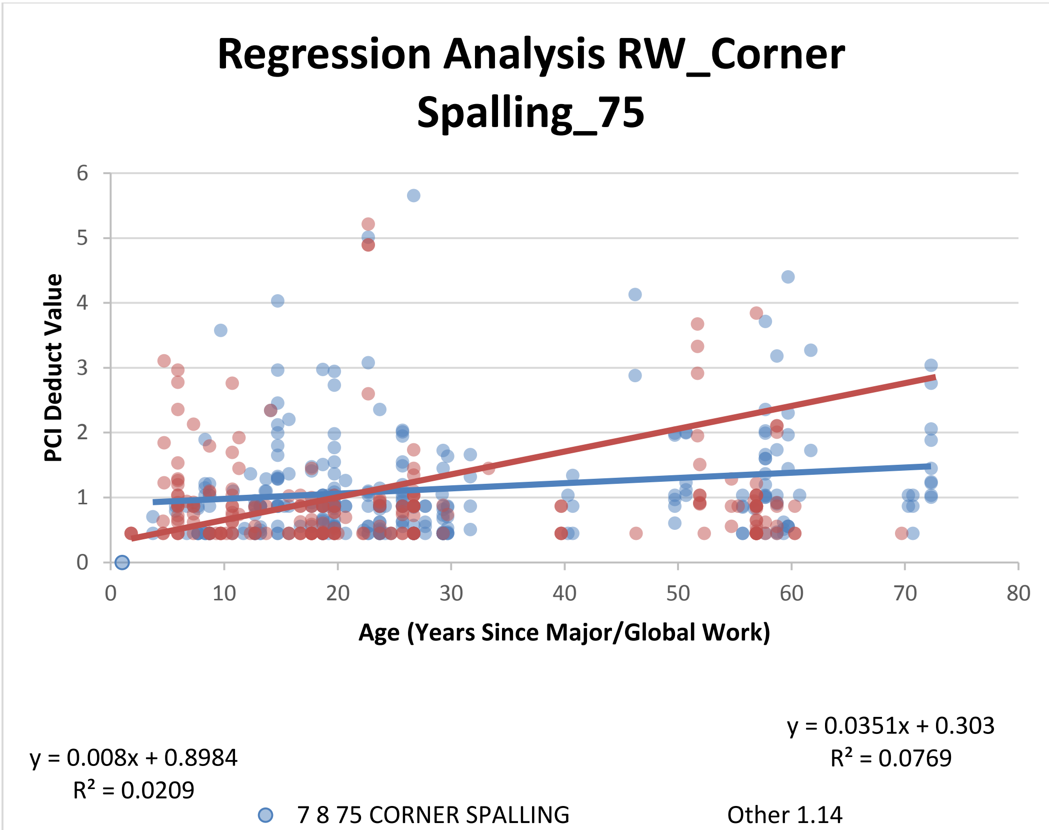
Regression Analysis RW_Lg Patch/Utl Cut_67
PCI Deduct Value
Age (Years Since Major/Global Work)
y = 0.0389x + 2.744
R² = 0.0289
PCC Zone 1
Linear (PCC Zone 1)
PCC Zone 2
Linear (PCC Zone 2)
y = 0.123x + 1.2412
R² = 0.0909


Regression Analysis RW_Scaling_70
PCI Deduct Value
Age (Years Since Major/Global Work)
y = 0.0164x + 1.115
R² = 0.0409
PCC Zone 1
Linear (PCC Zone 1)
PCC Zone 2
Linear (PCC Zone 2)
y = 0.0682x - 0.3045
R² = 0.3188


Regression Analysis RW_Shattered Slab_72
PCI Deduct Value
Age (Years Since Major/Global Work)
y = 0.2773x + 1.0072
R² = 0.1759
PCC Zone 1
Linear (PCC Zone 1)
PCC Zone 2
Linear (PCC Zone 2)
y = 0.0491x + 10.393
R² = 0.0041

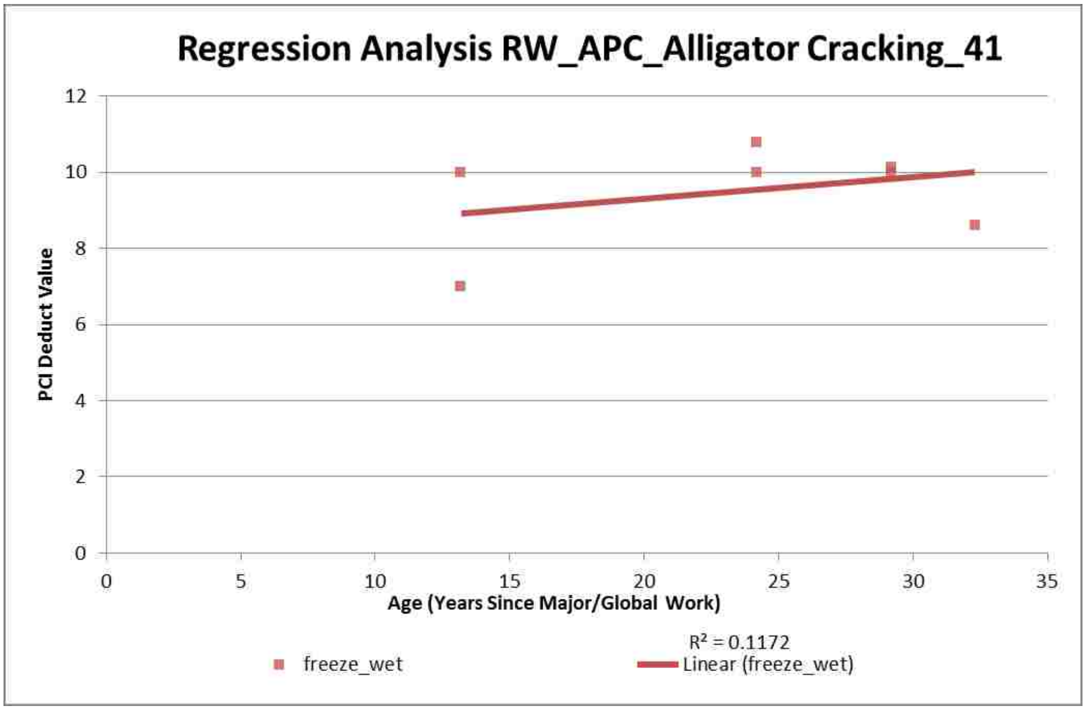

Regression Analysis RW_Shrinkage Cracking_73
PCI Deduct Value
Age (Years Since Major/Global Work)
y = 0.0206x + 1.2839
R² = 0.0233
PCC Zone 1
PCC Zone 2
y = 0.0663x + 0.299
R² = 0.1402
Linear (PCC Zone 1)
Linear (PCC Zone 2)

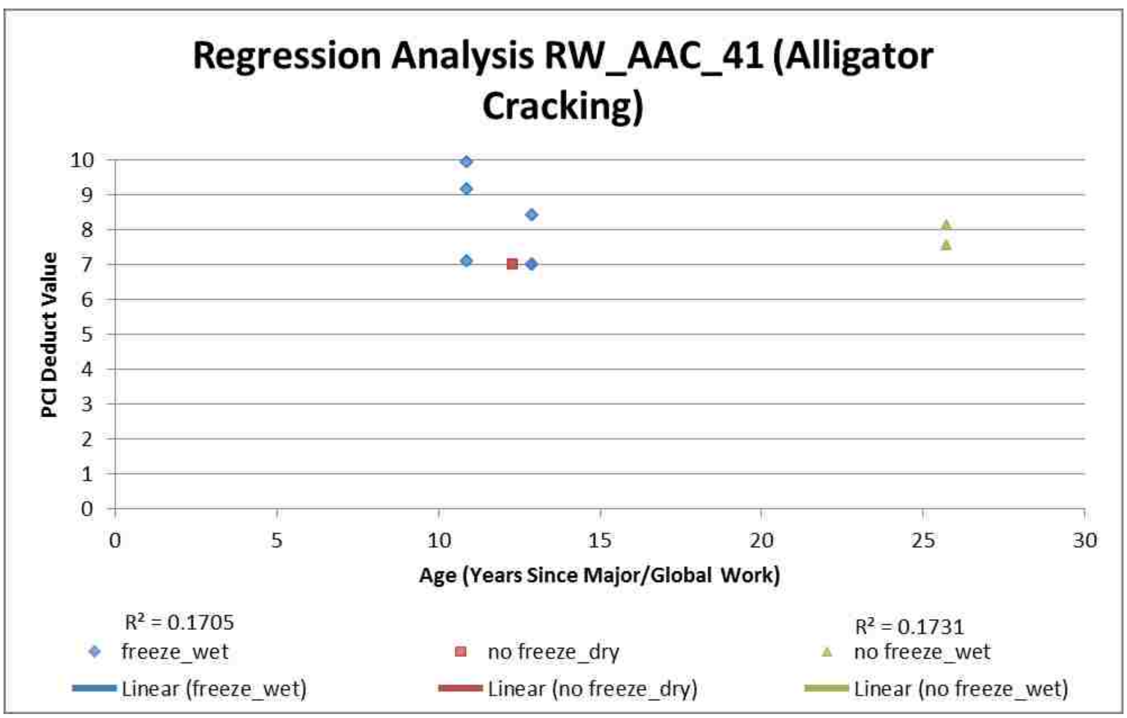

Regression Analysis RW_Joint Spalling_74
PCI Deduct Value
Age (Years Since Major/Global Work)
y = 0.018x + 0.9374
R² = 0.0391
PCC Zone 1
PCC Zone 2
y = 0.0377x + 0.5521
R² = 0.0923
Linear (PCC Zone 1)
Linear (PCC Zone 2)

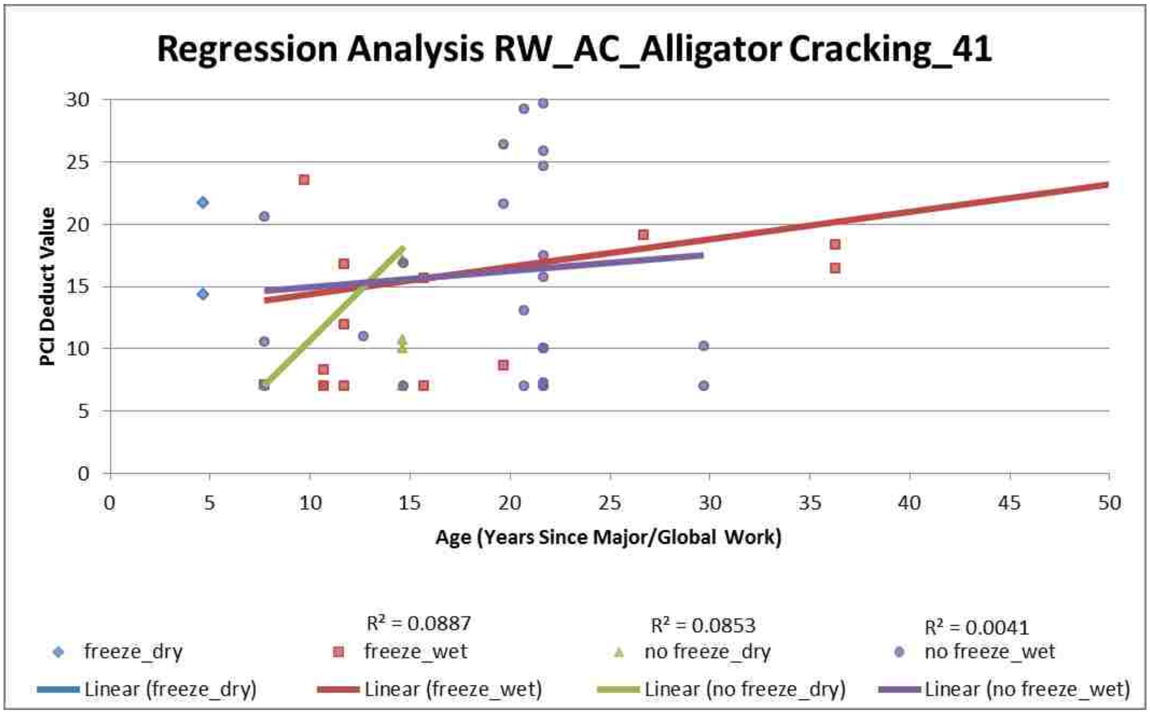


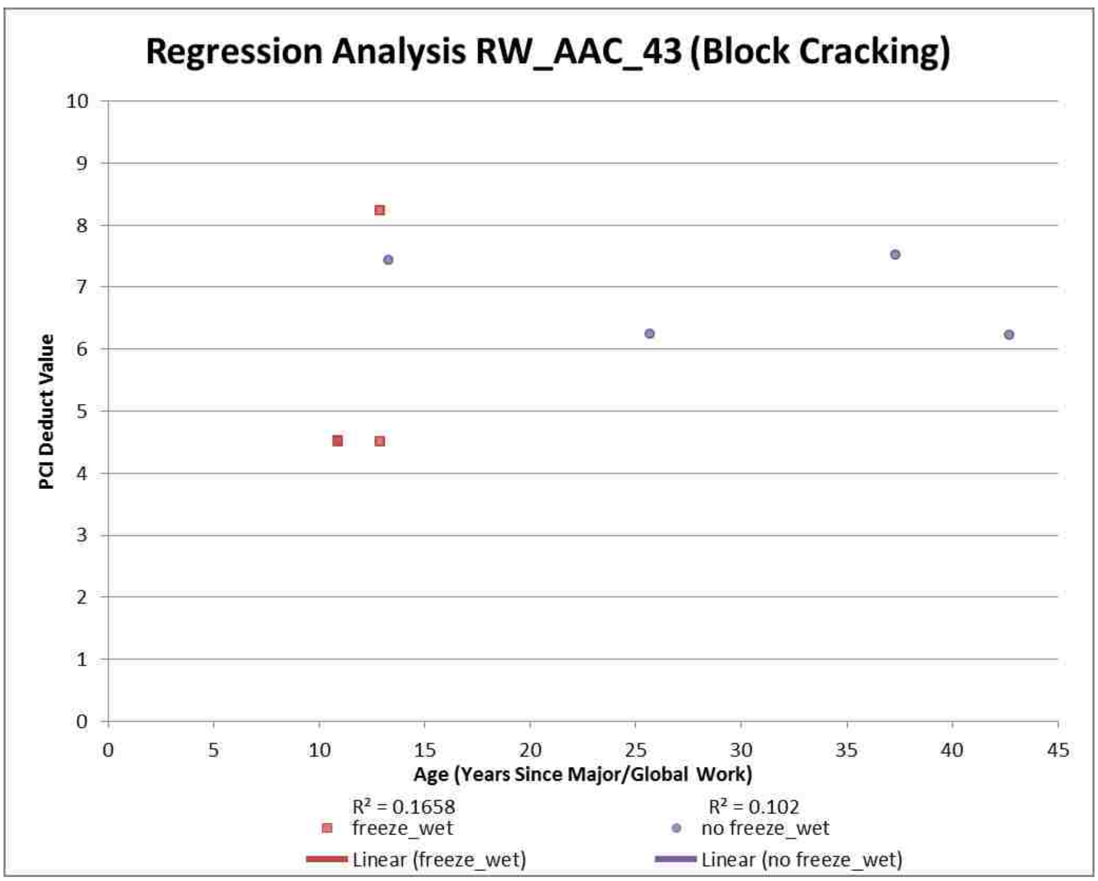
Regression Analysis RW_Corner Spalling_75
PCI Deduct Value
Age (Years Since Major/Global Work)
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80
y = 0.0351x + 0.303
R² = 0.0769
y = 0.008x + 0.8984
R² = 0.0209
7 8 75 CORNER SPALLING
Other 1.14

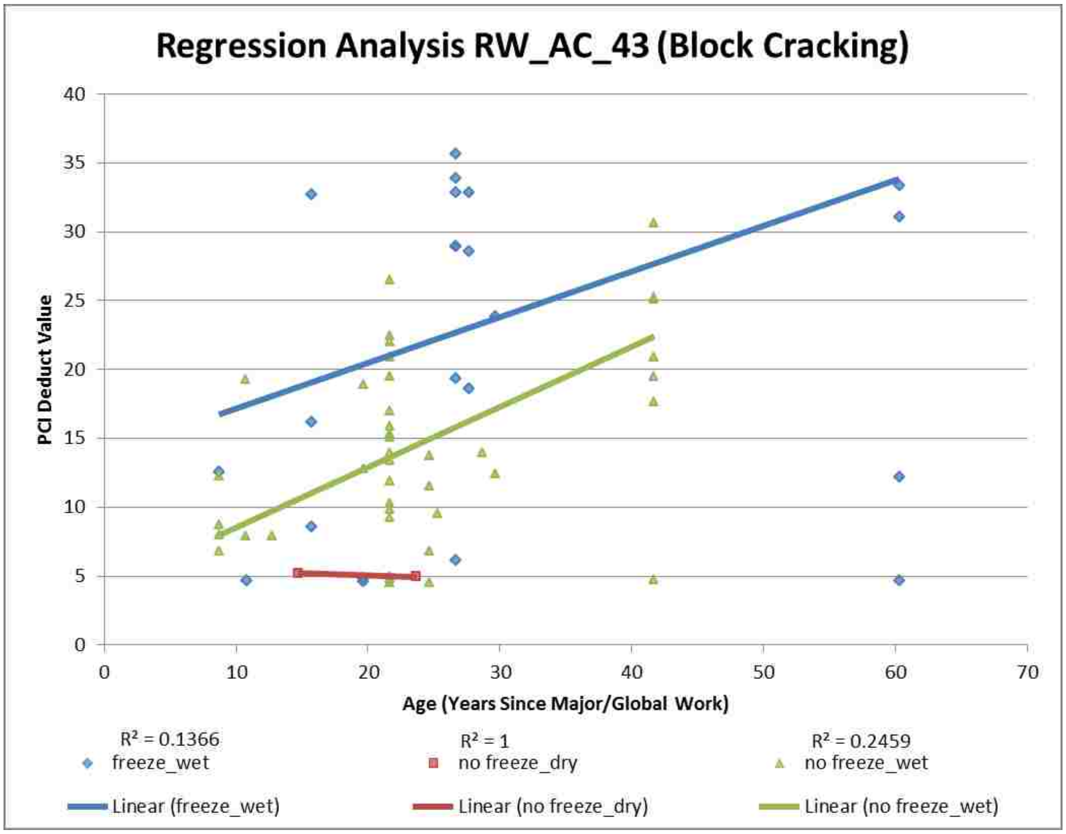
Appendix B- AFIT Climate Model Regression Analysis

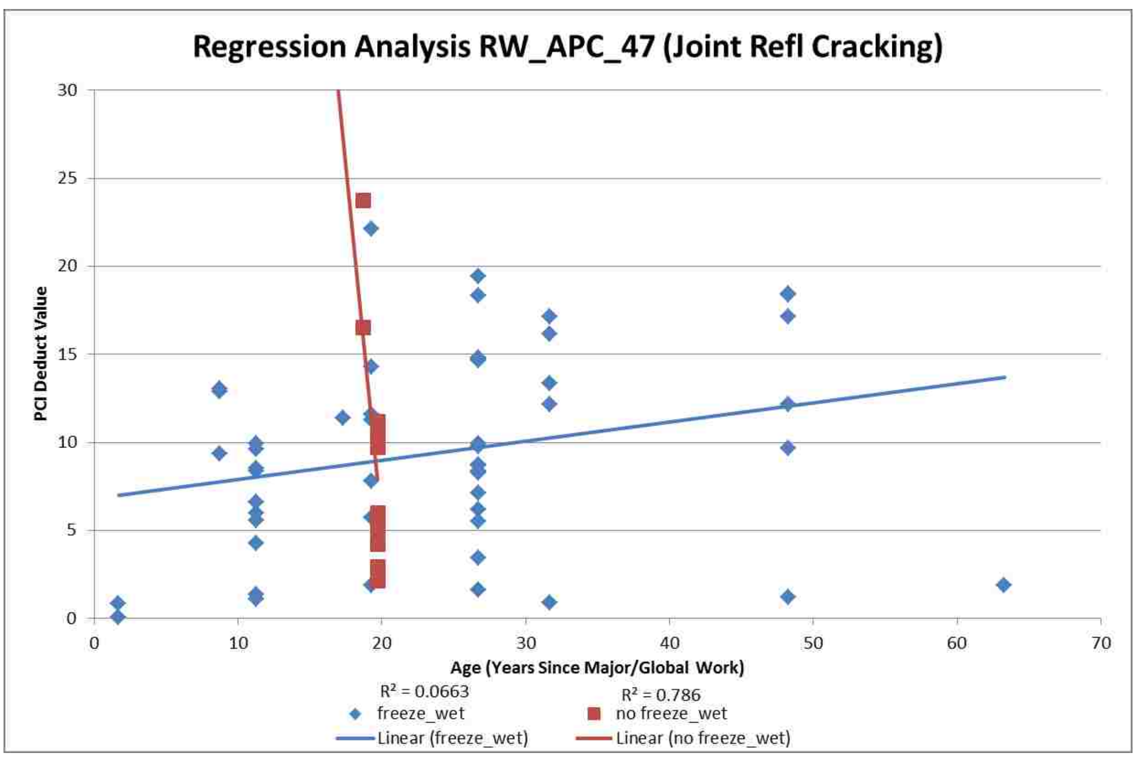


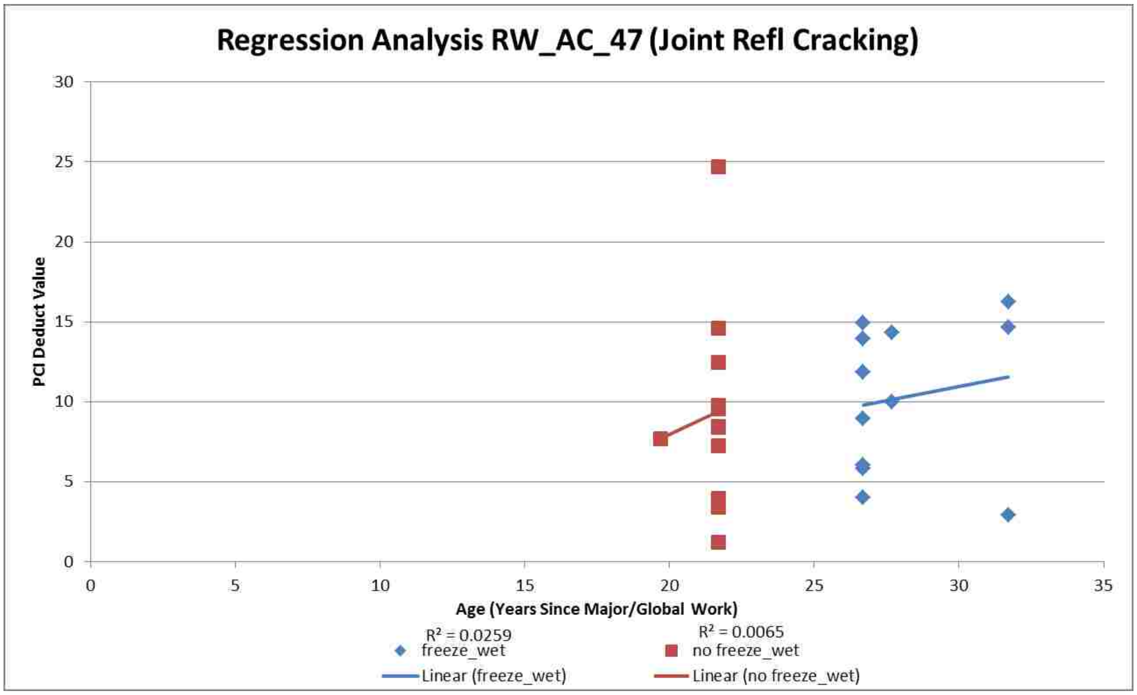


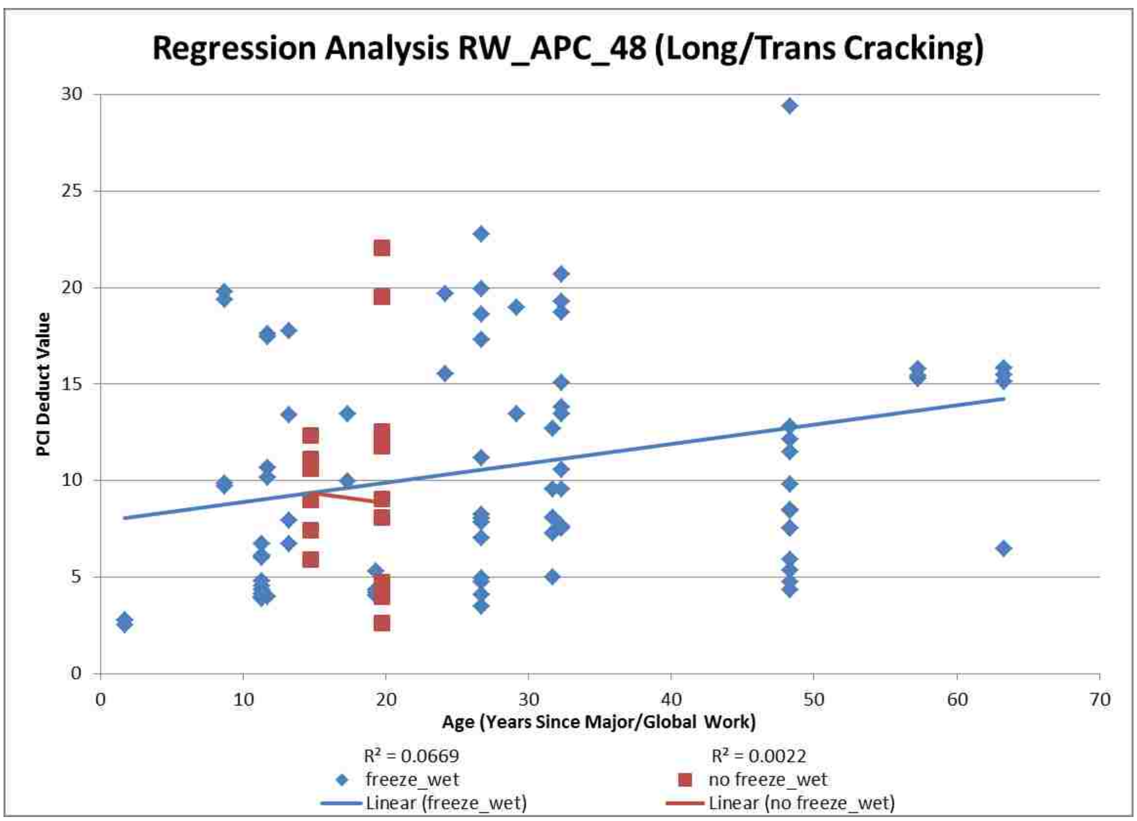

Regression Analysis RW_AC_Alligator Cracking_41
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.0887
R² = 0.0853
R² = 0.0041
freeze_dry
freeze_wet
no freeze_dry
no freeze_wet
Linear (freeze_dry)
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)

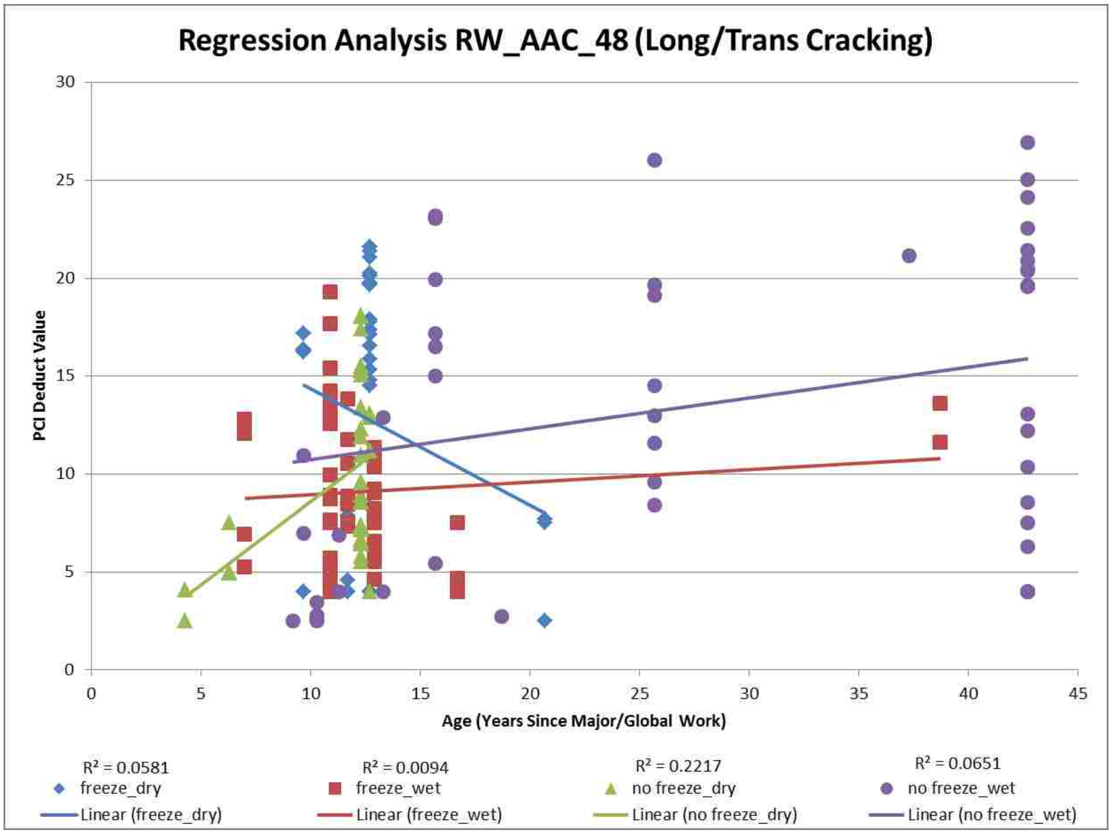

Regression Analysis RW_AAC_43 (Block Cracking)
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.1658
R² = 0.102
freeze_wet
no freeze_wet
Linear (freeze_wet)
Linear (no freeze_wet)

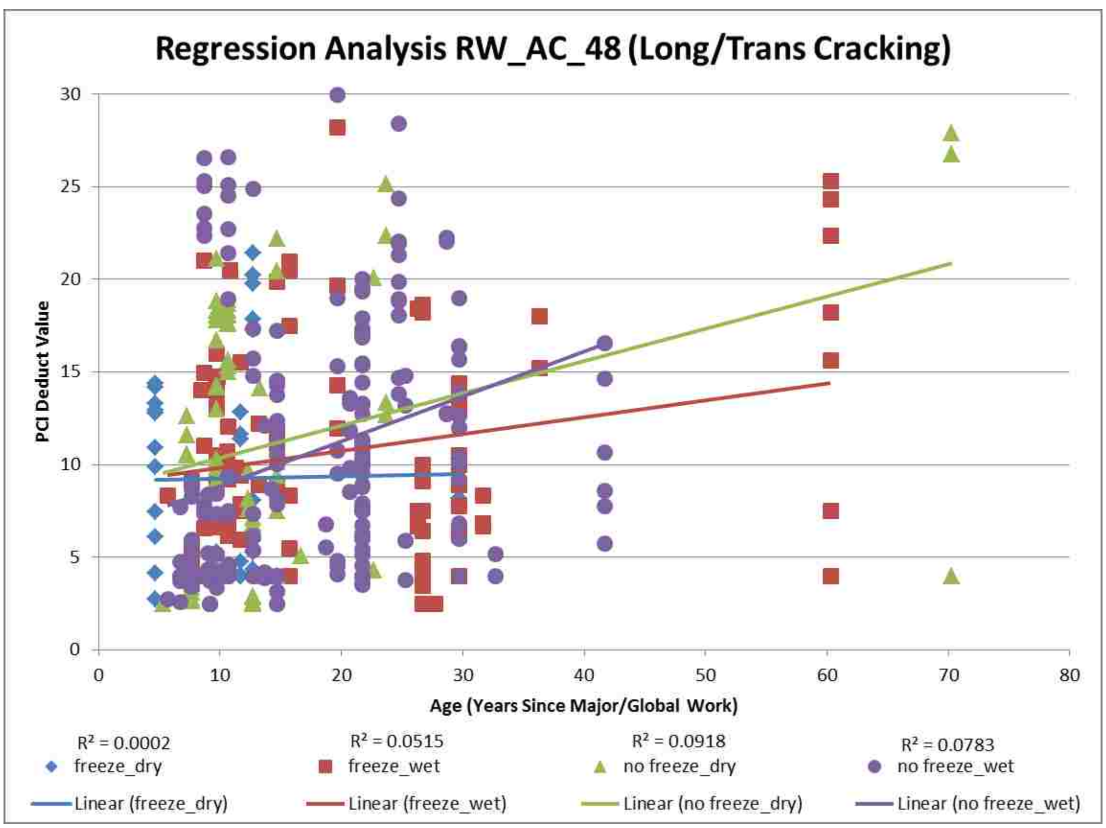

Regression Analysis RW_AC_43 (Block Cracking)
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.1366
freeze_wet
R² = 1
no freeze_dry
R² = 0.2459
no freeze_wet
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)

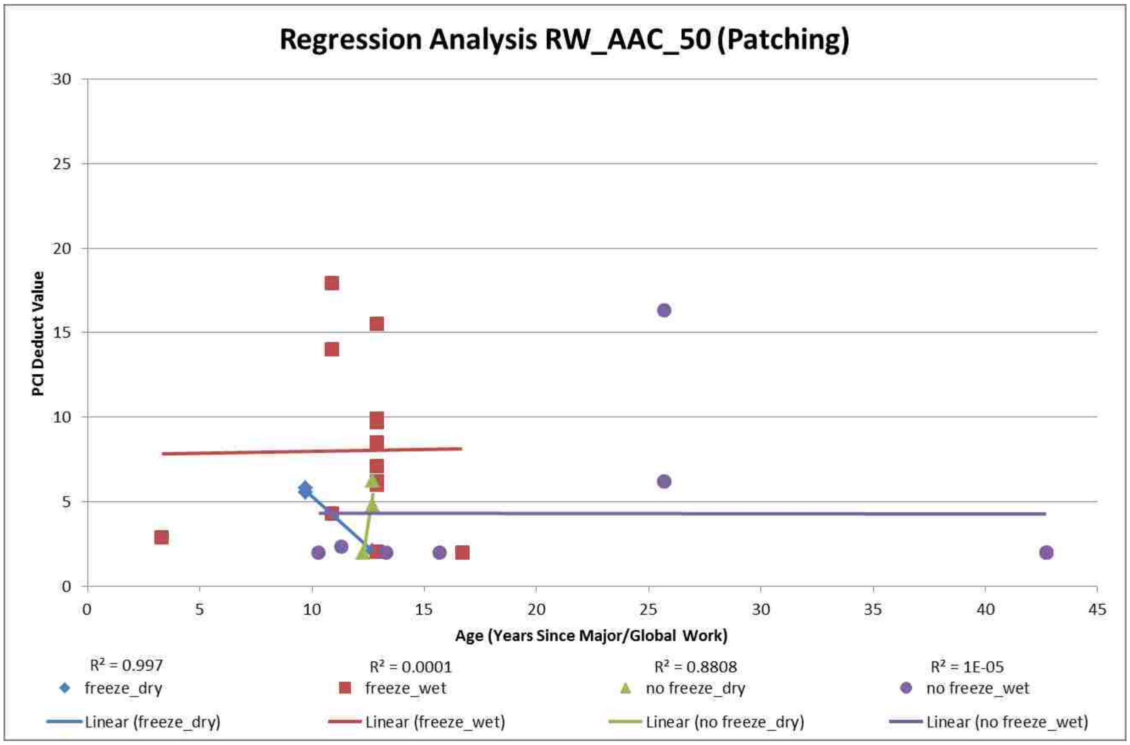

Regression Analysis RW_APC_47 (Joint Refl Cracking)
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.0663
freeze_wet
R² = 0.786
no freeze_wet
Linear (freeze_wet)
Linear (no freeze_wet)

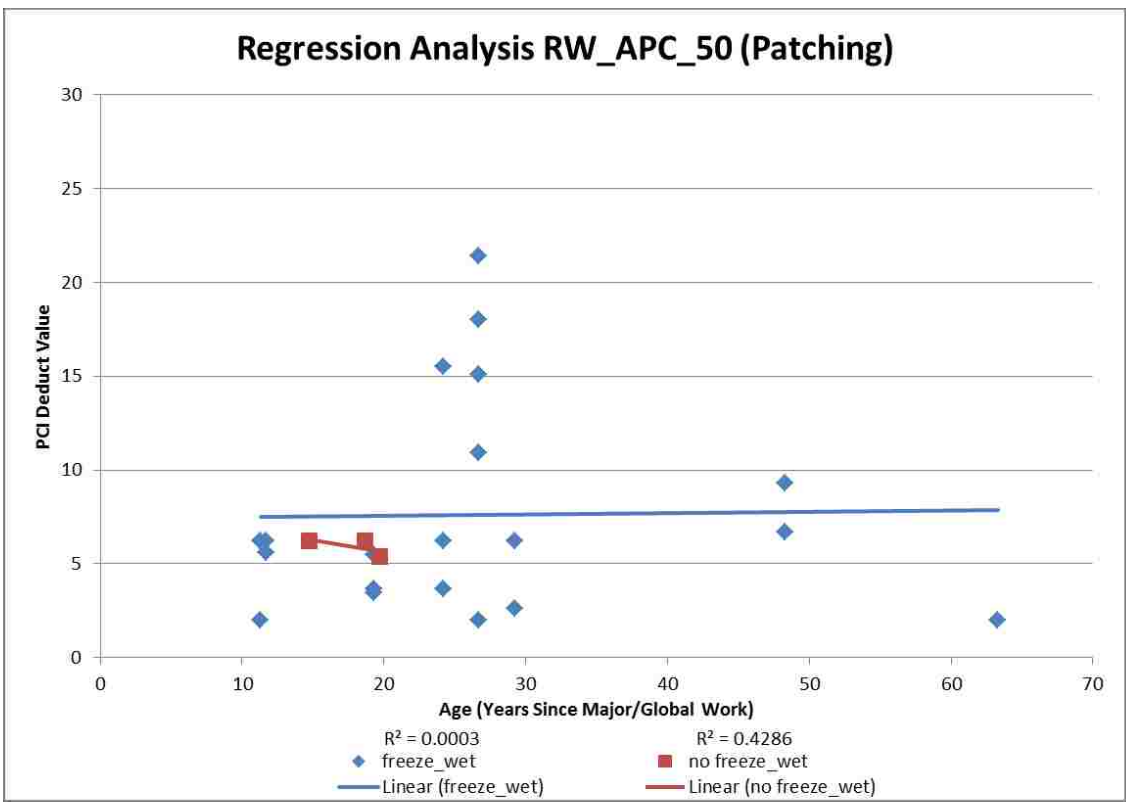

Regression Analysis RW_AC_47 (Joint Refl Cracking)
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.0259
R² = 0.0065
freeze_wet
no freeze_wet
Linear (freeze_wet)
Linear (no freeze_wet)

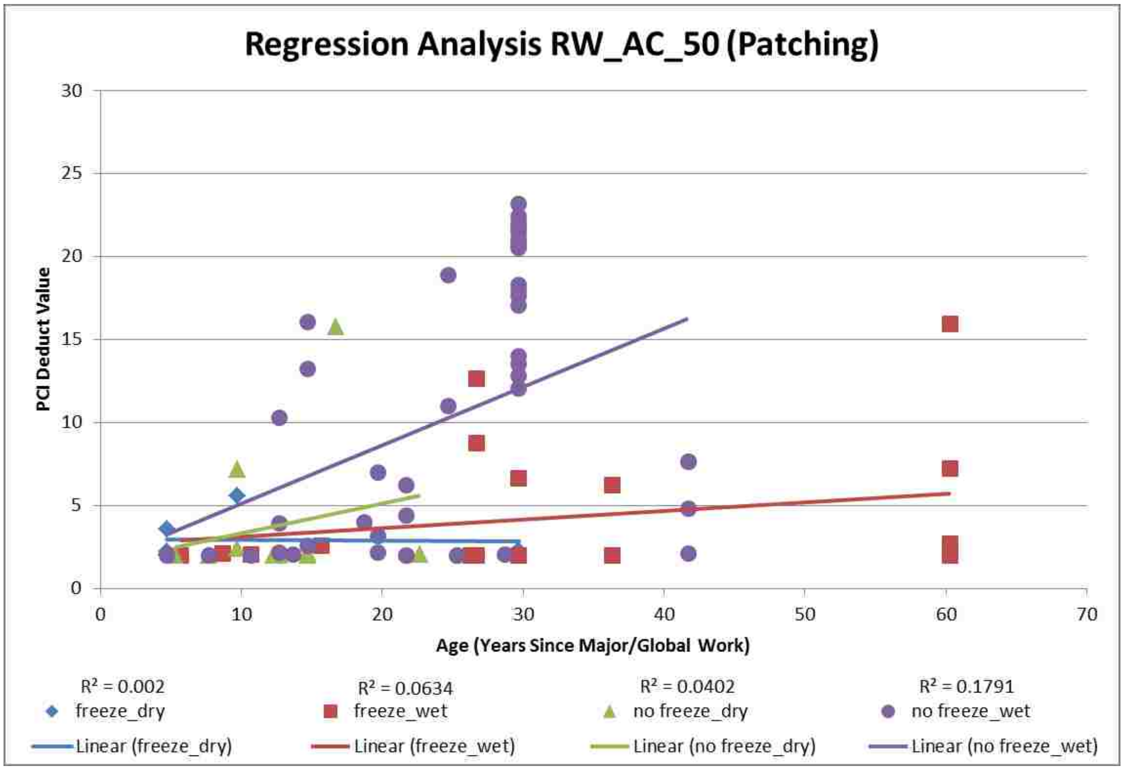

Regression Analysis RW_APC_48 (Long/Trans Cracking)
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.0669
R² = 0.0022
freeze_wet
no freeze_wet
Linear (freeze_wet)
Linear (no freeze_wet)

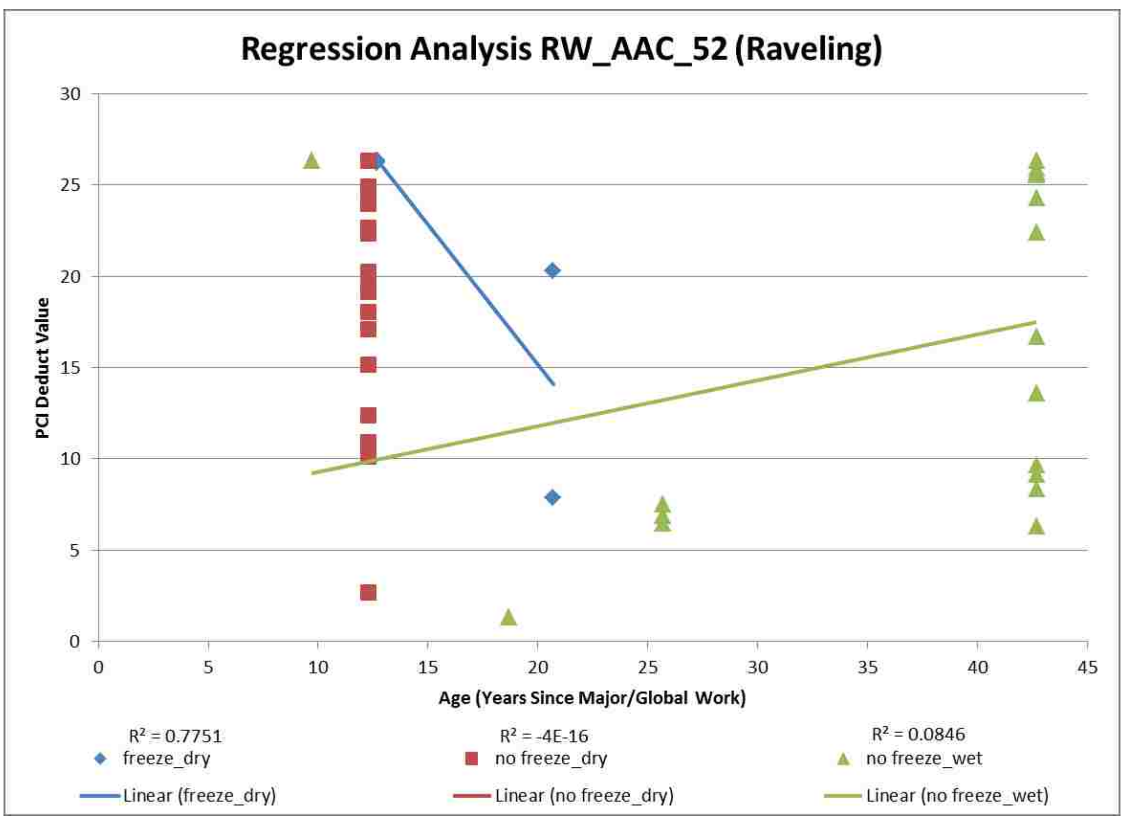

Regression Analysis RW_AAC_48 (Long/Trans Cracking)
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.0581
freeze_dry
R² = 0.0094
freeze_wet
R² = 0.2217
no freeze_dry
R² = 0.0651
no freeze_wet
Linear (freeze_dry)
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)

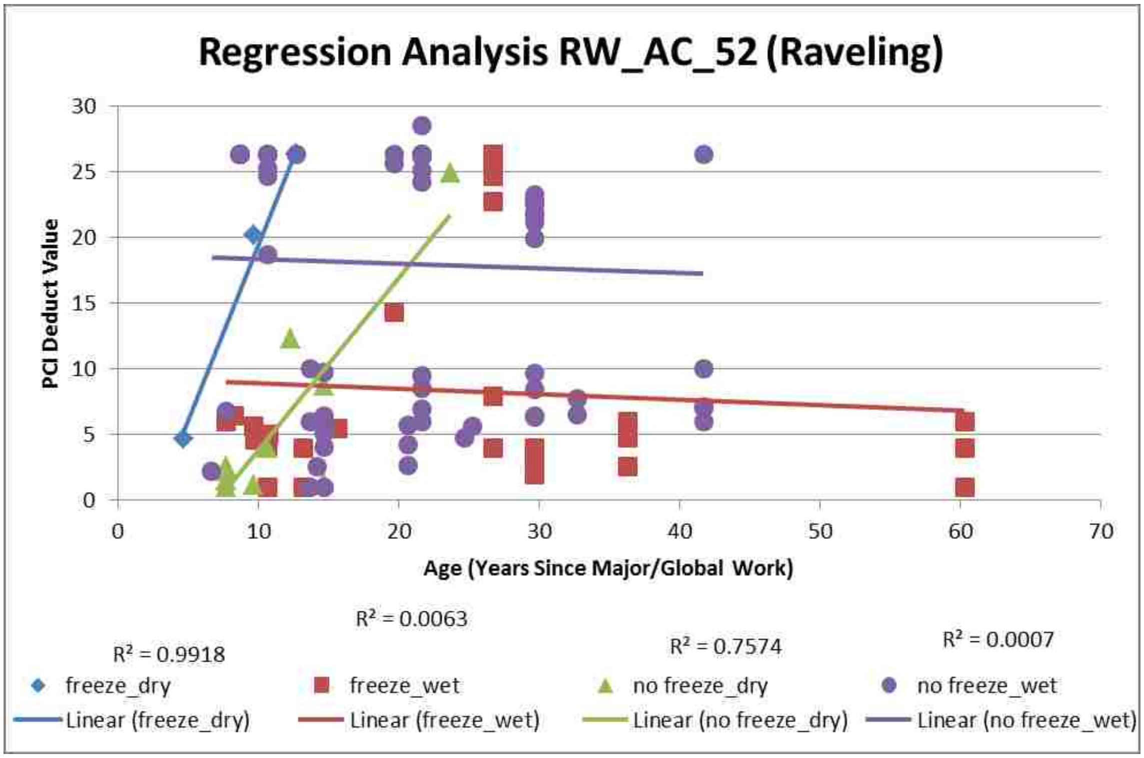

Regression Analysis RW_AC_48 (Long/Trans Cracking)
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.0002
freeze_dry
R² = 0.0515
freeze_wet
R² = 0.0918
no freeze_dry
R² = 0.0783
no freeze_wet
Linear (freeze_dry)
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)

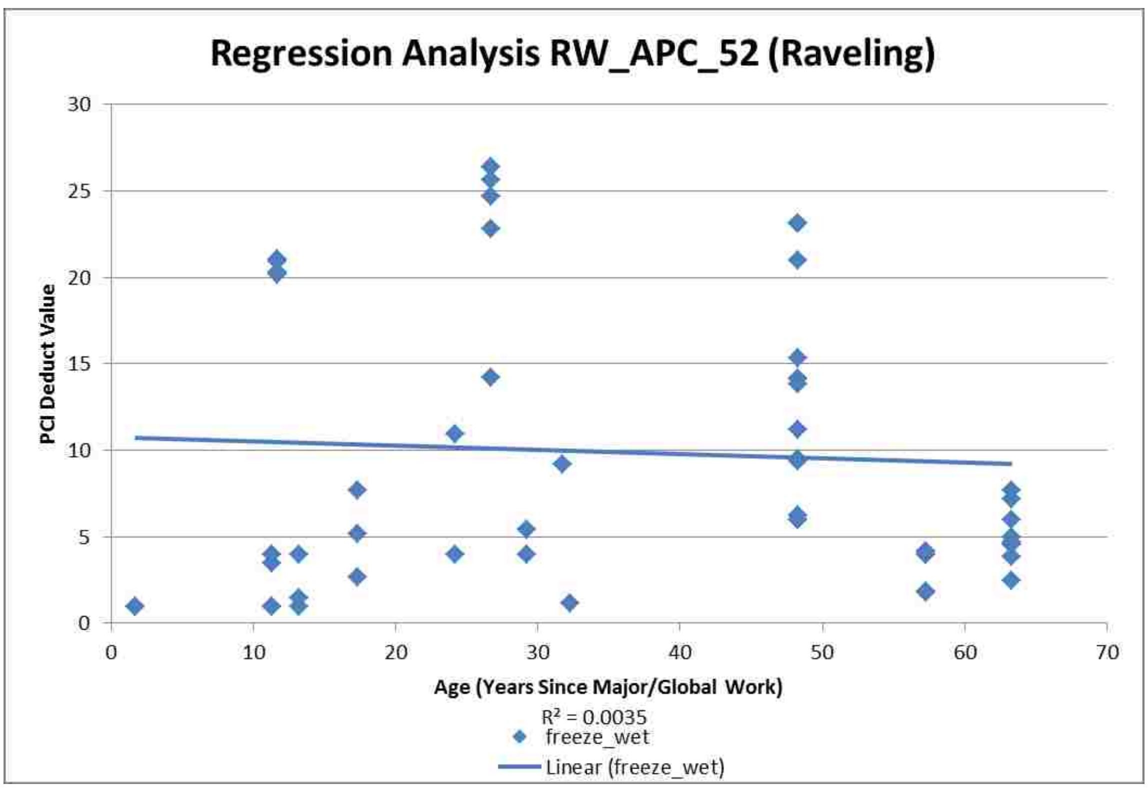

Regression Analysis RW_AAC_50 (Patching)
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.997
freeze_dry
R² = 0.0001
freeze_wet
R² = 0.8808
no freeze_dry
R² = 1E-05
no freeze_wet
Linear (freeze_dry)
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)

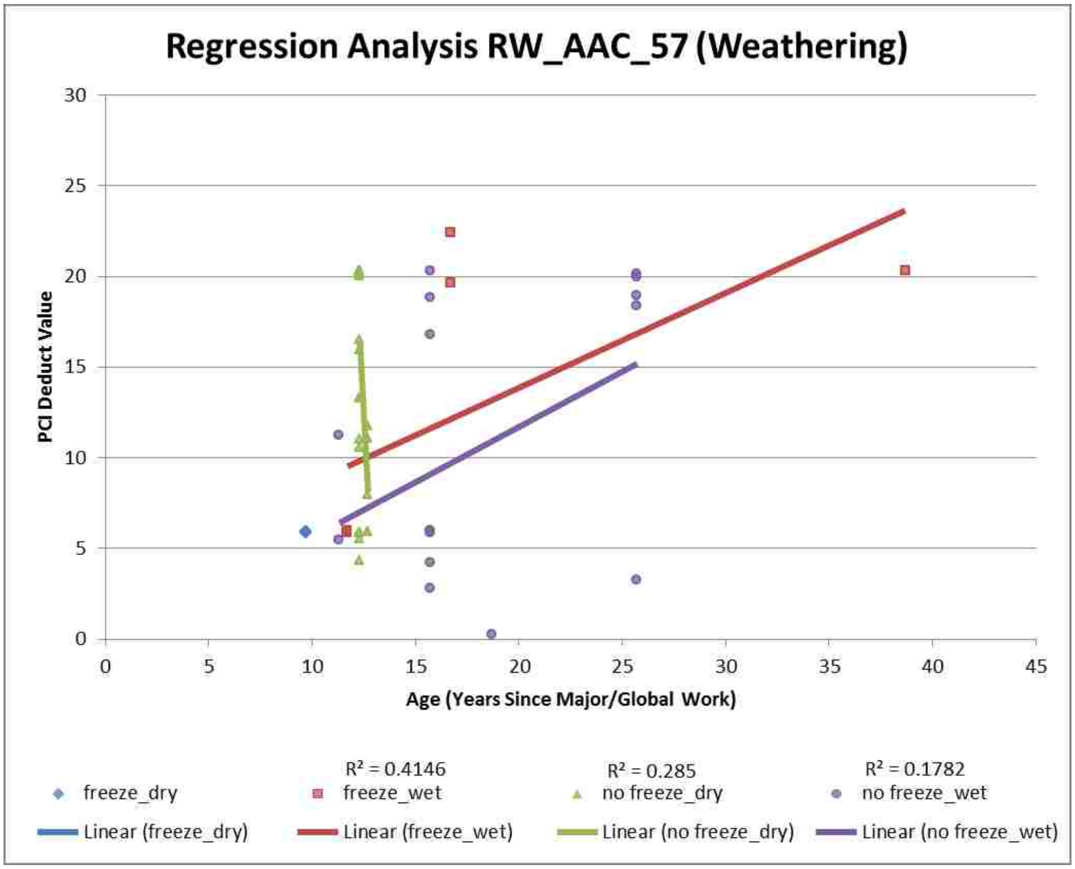

Regression Analysis RW_APC_50 (Patching)
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.0003
freeze_wet
R² = 0.4286
no freeze_wet
Linear (freeze_wet)
Linear (no freeze_wet)

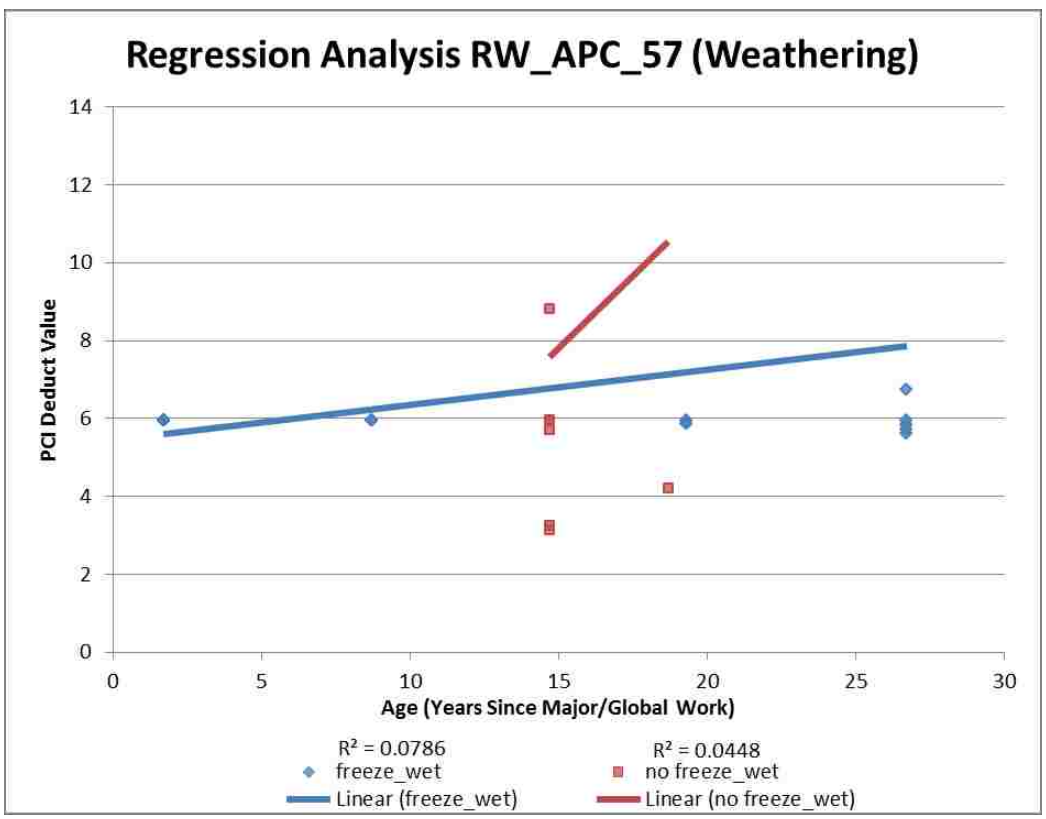

Regression Analysis RW_AC_50 (Patching)
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.002
freeze_dry
R² = 0.0634
freeze_wet
R² = 0.0402
no freeze_dry
R² = 0.1791
no freeze_wet
Linear (freeze_dry)
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)

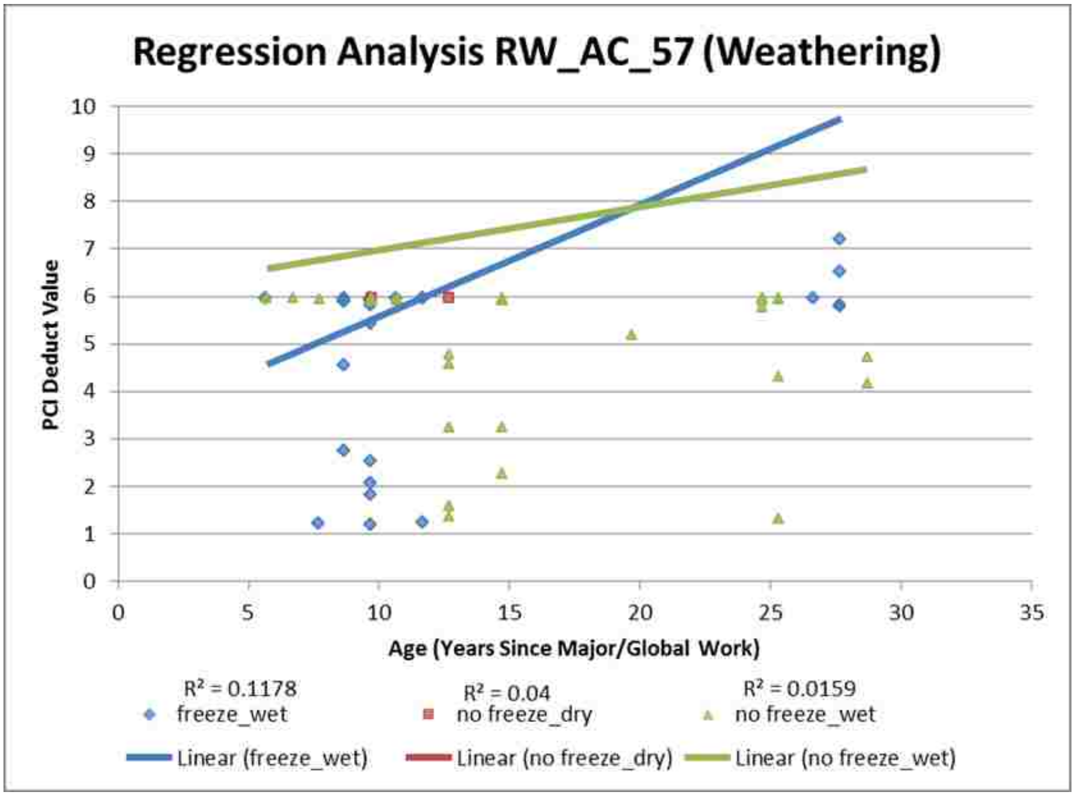

Regression Analysis RW_AAC_52 (Raveling)
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.7751
freeze_dry
R² = -4E-16
no freeze_dry
R² = 0.0846
no freeze_wet
Linear (freeze_dry)
Linear (no freeze_dry)
Linear (no freeze_wet)

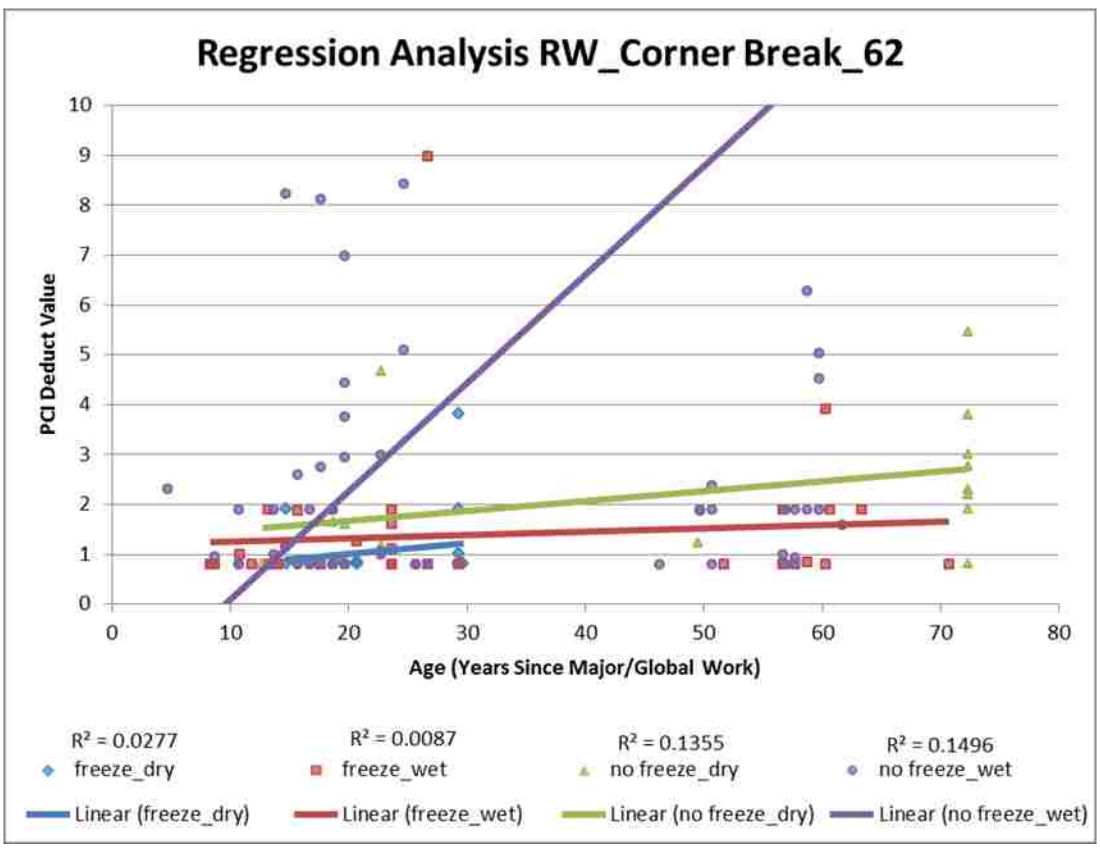

Regression Analysis RW_AC_52 (Raveling)
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.0063
R² = 0.9918
R² = 0.7574
R² = 0.0007
freeze_dry
freeze_wet
no freeze_dry
no freeze_wet
Linear (freeze_dry)
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)

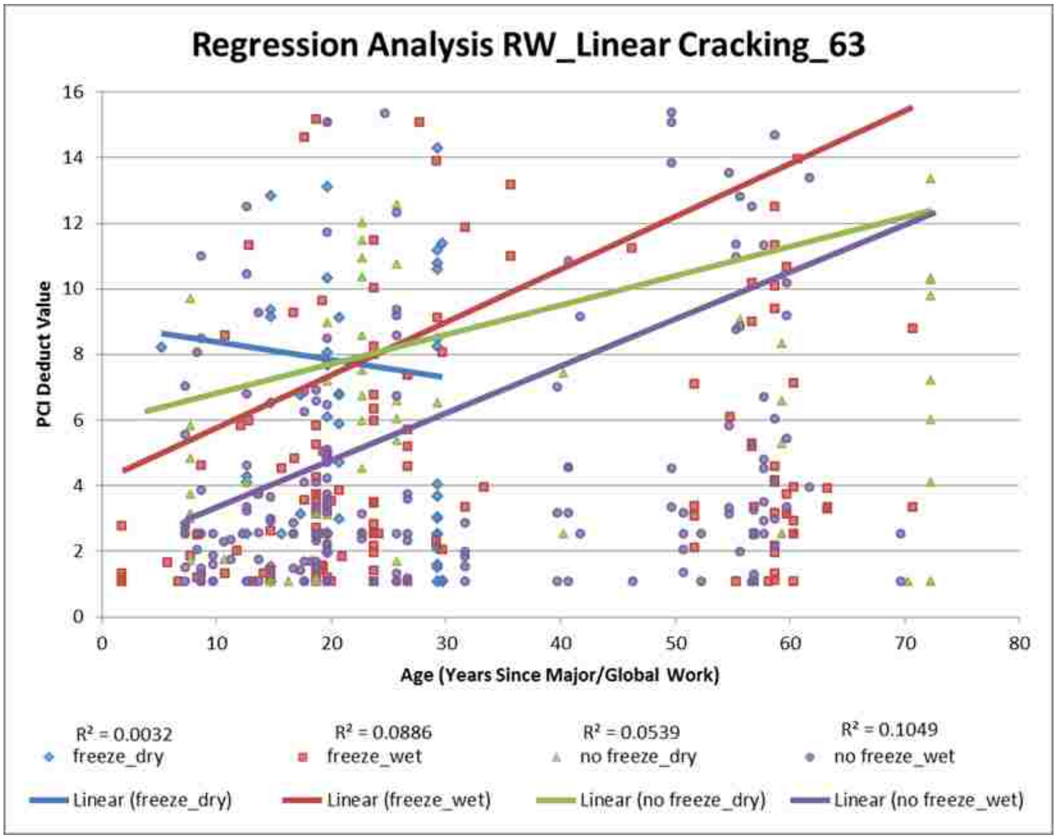

Regression Analysis RW_APC_52 (Raveling)
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.0035
freeze_wet
Linear (freeze_wet)

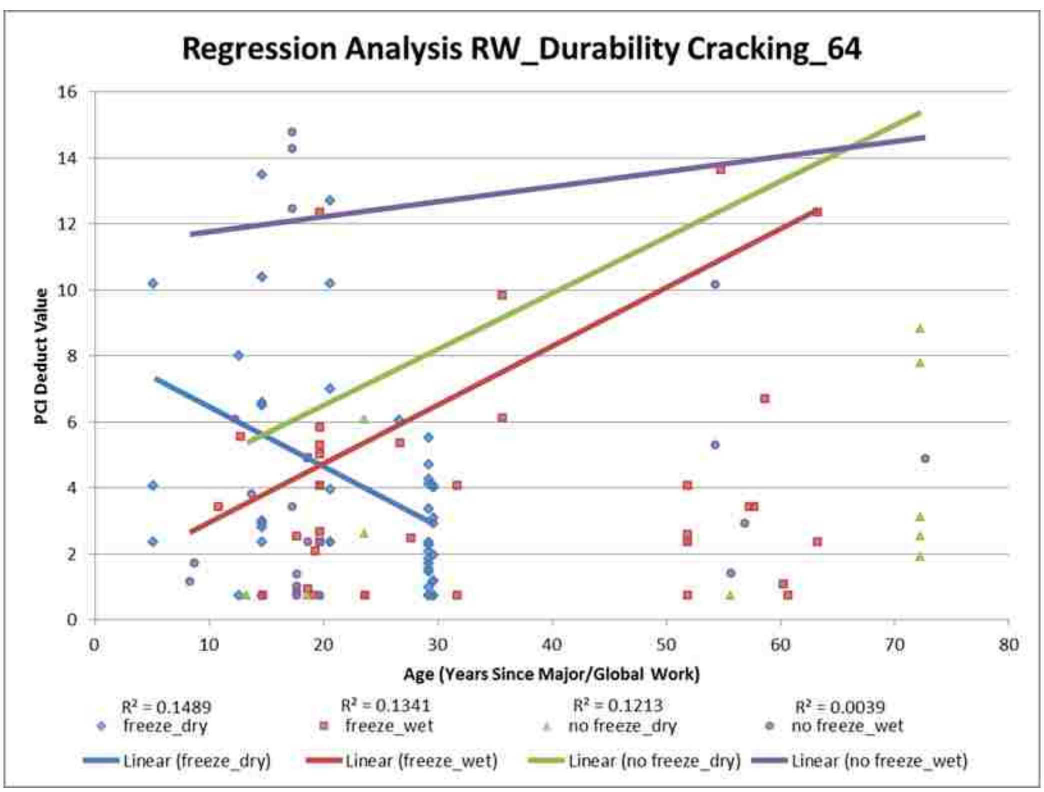

Regression Analysis RW_AAC_57 (Weathering)
PCI Deduct Value
Age (Years Since Major/Global Work)
0
5
10
15
20
25
30
35
40
45
R² = 0.4146
R² = 0.285
R² = 0.1782
freeze_dry
freeze_wet
no freeze_dry
no freeze_wet
Linear (freeze_dry)
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)

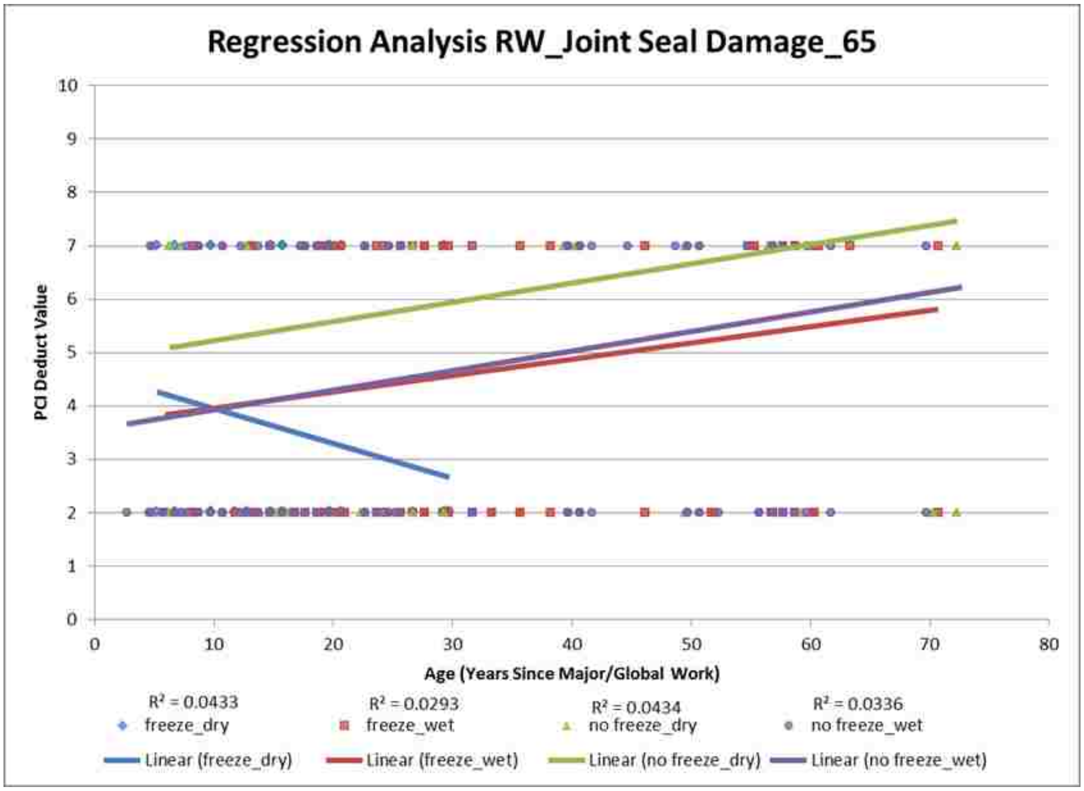

Regression Analysis RW_APC_57 (Weathering)
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.0786
R² = 0.0448
freeze_wet
no freeze_wet
Linear (freeze_wet)
Linear (no freeze_wet)

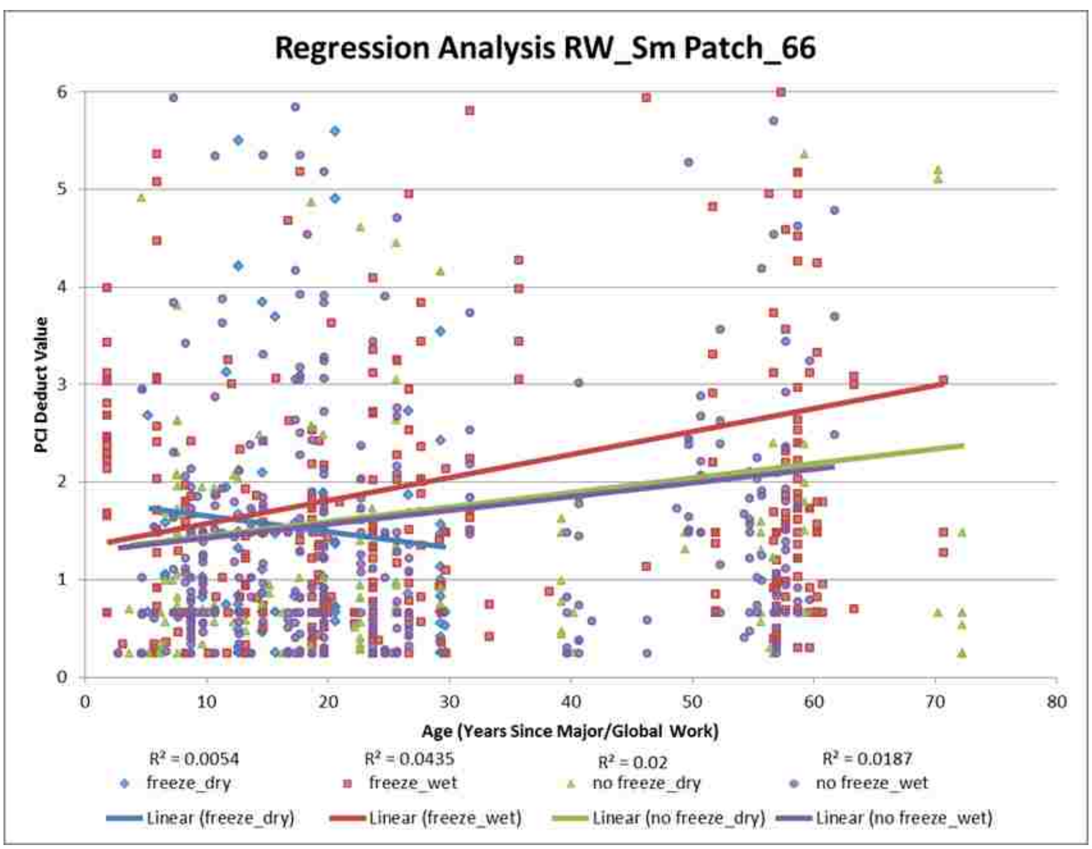

Regression Analysis RW_AC_57 (Weathering)
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.1178
freeze_wet
R² = 0.04
no freeze_dry
R² = 0.0159
no freeze_wet
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)

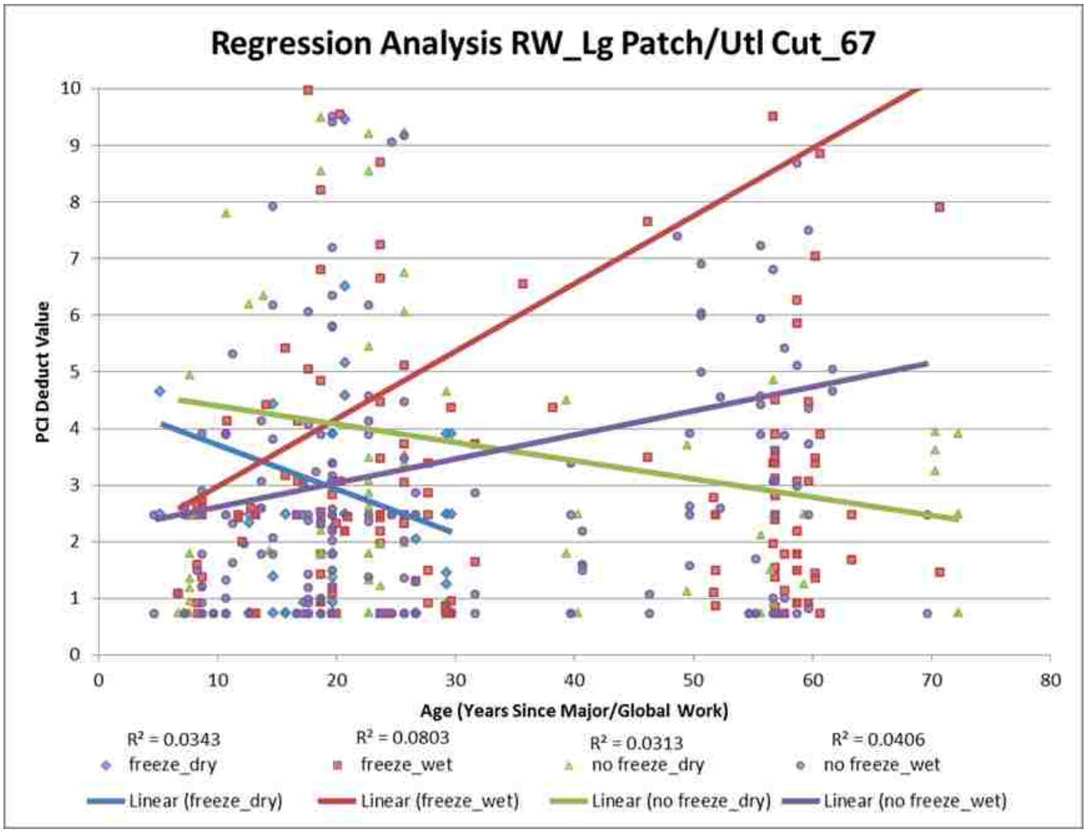

Regression Analysis RW_Corner Break_62
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.0277
freeze_dry
R² = 0.0087
freeze_wet
R² = 0.1355
no freeze_dry
R² = 0.1496
no freeze_wet
Linear (freeze_dry)
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)

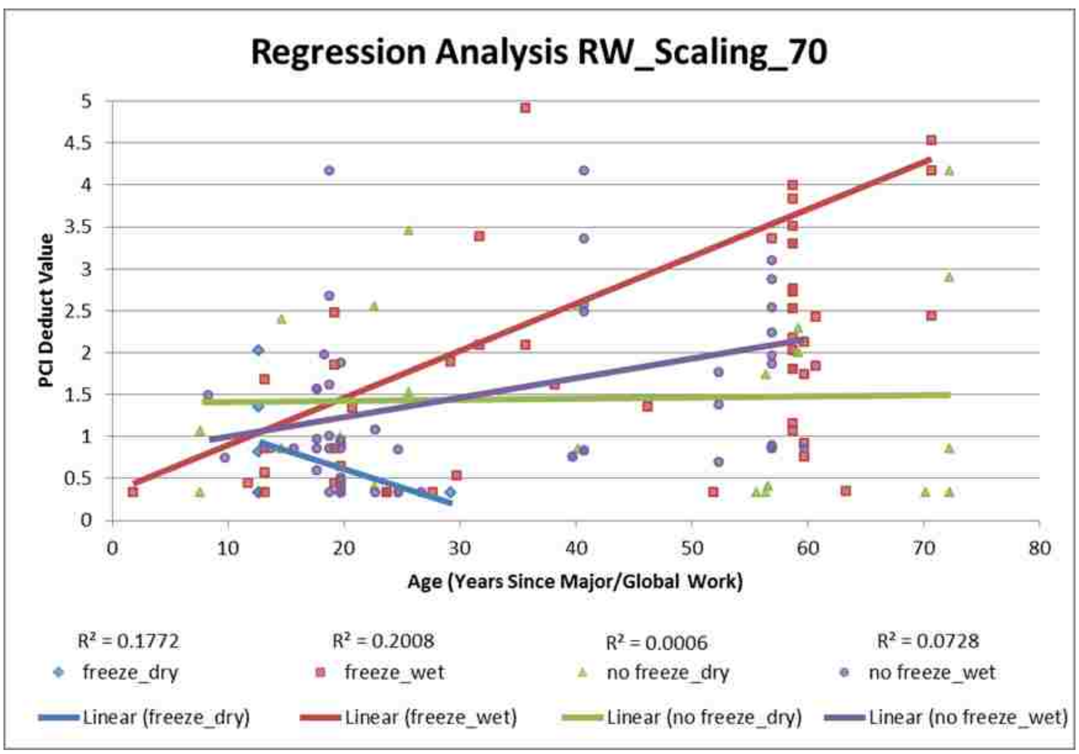

Regression Analysis RW_Linear Cracking_63
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.0032
freeze_dry
R² = 0.0886
freeze_wet
R² = 0.0539
no freeze_dry
R² = 0.1049
no freeze_wet
Linear (freeze_dry)
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)

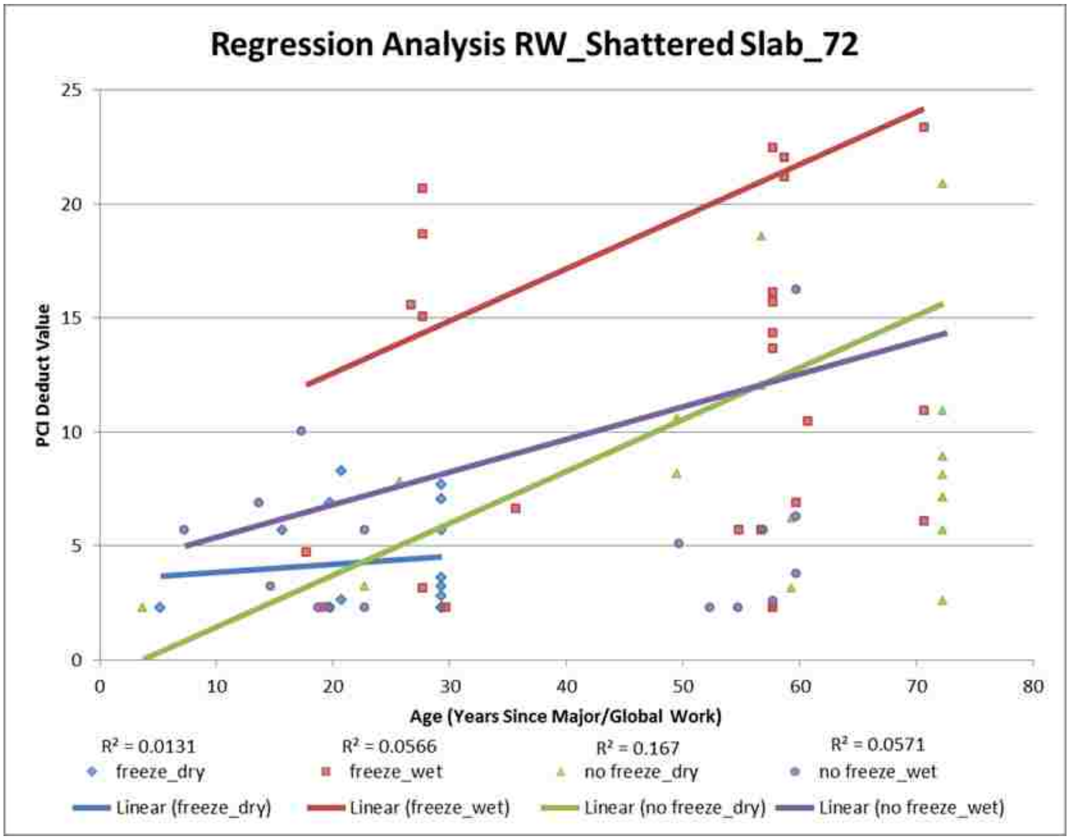

Regression Analysis RW_Durability Cracking_64
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.1489
freeze_dry
R² = 0.1341
freeze_wet
R² = 0.1213
no freeze_dry
R² = 0.0039
no freeze_wet
Linear (freeze_dry)
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)

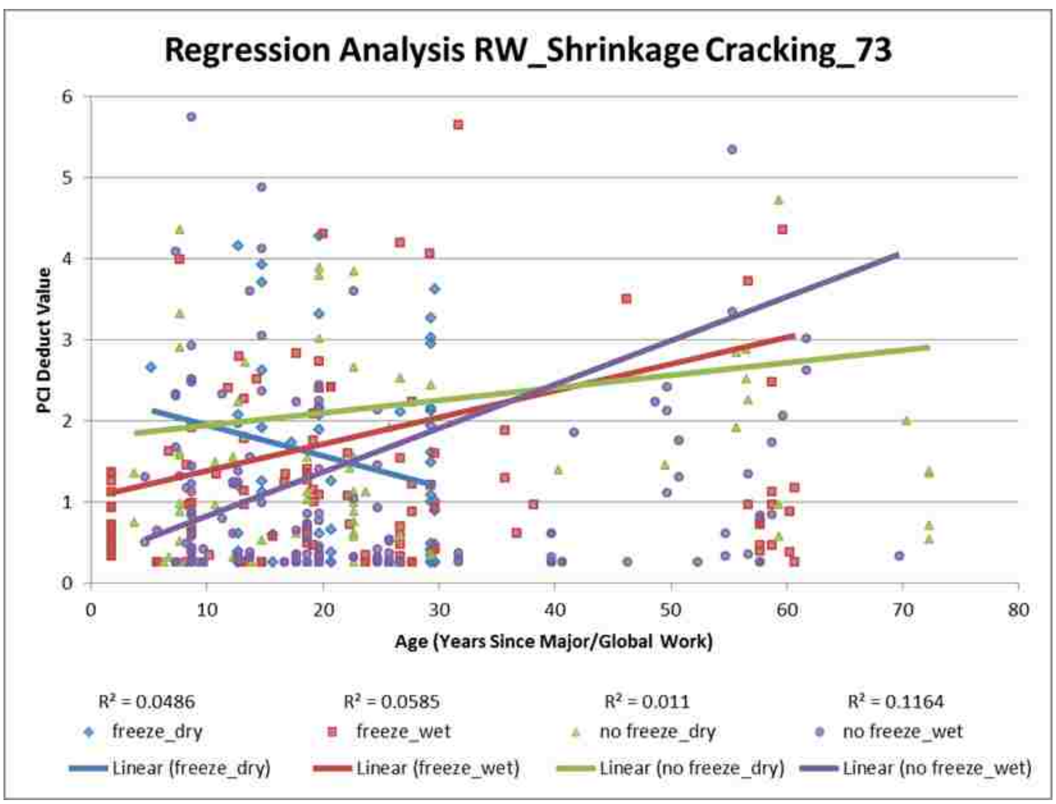

Regression Analysis RW_Joint Seal Damage_65
PCI Deduct Value
Age (Years Since Major/Global Work)
R^2 = 0.0433
freeze_dry
R^2 = 0.0293
freeze_wet
R^2 = 0.0434
no freeze_dry
R^2 = 0.0336
no freeze_wet
Linear (freeze_dry)
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)

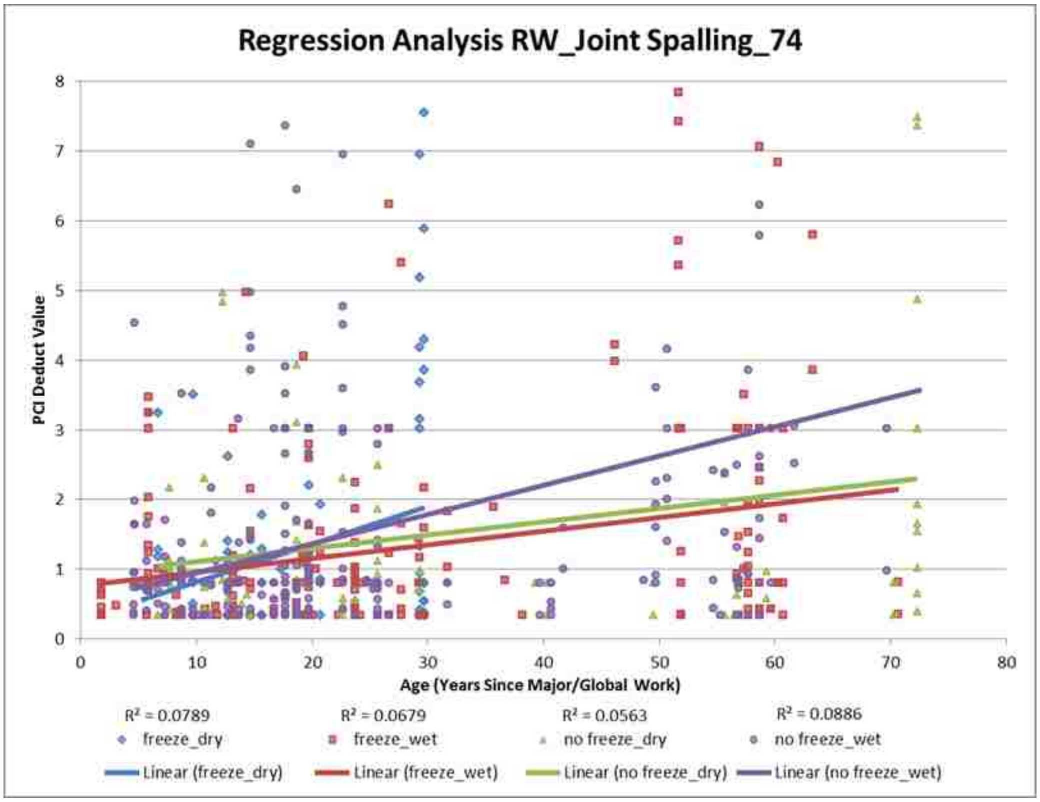

Regression Analysis RW_Sm Patch_66
PCI Deduct Value
Age (Years Since Major/Global Work)
R^2 = 0.0054
freeze_dry
R^2 = 0.0435
freeze_wet
R^2 = 0.02
no freeze_dry
R^2 = 0.0187
no freeze_wet
Linear (freeze_dry)
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)

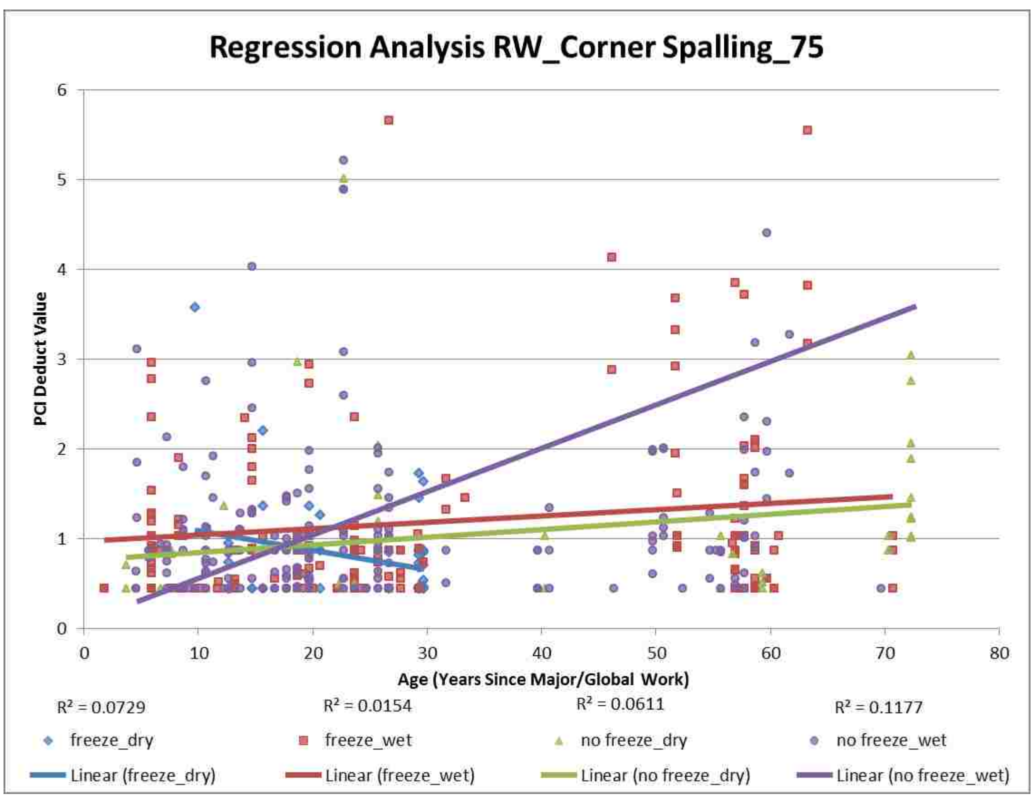

Regression Analysis RW_Lg Patch/Utl Cut_67
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.0343
R² = 0.0803
R² = 0.0313
R² = 0.0406
freeze_dry
freeze_wet
no freeze_dry
no freeze_wet
Linear (freeze_dry)
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)


Regression Analysis RW_Scaling_70
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.1772
R² = 0.2008
R² = 0.0006
R² = 0.0728
freeze_dry
freeze_wet
no freeze_dry
no freeze_wet
Linear (freeze_dry)
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)


Regression Analysis RW_Shattered Slab_72
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.0131
freeze_dry
R² = 0.0566
freeze_wet
R² = 0.167
no freeze_dry
R² = 0.0571
no freeze_wet
Linear (freeze_dry)
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)


Regression Analysis RW_Shrinkage Cracking_73
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.0486
freeze_dry
R² = 0.0585
freeze_wet
R² = 0.011
no freeze_dry
R² = 0.1164
no freeze_wet
Linear (freeze_dry)
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)


Regression Analysis RW_Joint Spalling_74
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.0789
R² = 0.0679
R² = 0.0563
R² = 0.0886
freeze_dry
freeze_wet
no freeze_dry
no freeze_wet
Linear (freeze_dry)
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)


Regression Analysis RW_Corner Spalling_75
PCI Deduct Value
Age (Years Since Major/Global Work)
R² = 0.0729
R² = 0.0154
R² = 0.0611
R² = 0.1177
freeze_dry
freeze_wet
no freeze_dry
no freeze_wet
Linear (freeze_dry)
Linear (freeze_wet)
Linear (no freeze_dry)
Linear (no freeze_wet)

Appendix C- Consolidated Regression and Krig Analysis for AC and PCC Pavement Distresses (*note: distress behavior was not analyzed for sample sizes smaller than 30)

AC Model				
Distress	AC Zone 1	AC Zone 2	Additional Remarks	Ref Table
41 Alligator Cracking	linear regression slope=-0.0822x	dominant deterioration behavior, linear regression slope=.26x	The regression analysis shows a negative regression in the PCI deduct value with age for AC Zone 1. Nellis AFB, Dyess AFB and Travis AFB (AC Zone 1) have relatively young runway pavements (compared with the age of other pavement sections considered in this regression analysis) with very large PCI deduct values. The krig analysis does not illustrate the negative regression seen in the regression analysis because these large PCI deduct values are diluted after normalizing for pavement size. The runways at these bases are very large 2 million, 4 million and 3 million square feet respectively. Although, the individual section PCI deduct values may be quite	8

			large compared to other section PCI deduct values, when the size of the branch is considered a better representation of the average pavement behavior is made. Consideration should be made on how traffic load correlates with this distress. These three bases have very large runways that facilitate many sorties by cargo, bomber and fighter type aircraft. The krig analysis does show the same dominant pavement behavior as the regression analysis in AC Zone 2.	
42 Bleeding	Not Enough Data*			
43 Block Cracking	Not Enough Data			
44 Corrugation	Not Enough Data			
45 Depression	Not Enough Data			
46 Jet Blast	Not Enough Data			
47 Joint Reflection Cracking	Not Enough Data			

48 Long/Trans Cracking	dominant distress zone, linear regression slope=.173x	linear regression slope=.143x	Regression analysis shows that the distress is wide spread across both zones and that the deterioration behavior is similar between zones. The krig analysis shows that the normalized PCI deduct values are larger in Zone 2 than in Zone 1. This could be the result of the pavement age being smaller in the Eastern U.S. or more likely the typical branch size being smaller in Zone 2 airfields. The PCI deduct values tend to be larger than those of other distress types.	9
49 Oil Spillage	Not Enough Data			
50 Patching	dominant distress zone, linear regression slope=.607x	linear regression slope=.05x	This data analysis is skewed by many instances of patching at Randolph AFB. Before conducting further analysis an investigation into what is causing the patching at Randolph AFB should be conducted.	10
51 Polished Aggregate	Not Enough Data			

52 Raveling	linear regression slope=.546x	dominant deterioration behavior, linear regression slope=-.294x	This distress shows the strongest geographic/climate relationship of all investigated distresses. The krig analysis shows a strong trend centered at Columbus AFB and extending through the bases in the Southeastern U.S. Bases that include high deterioration behavior are Columbus AFB, Shuqualak Auxiliary Field, Avon Field, Patrick AFB and Keesler AFB. The missions between these bases vary from pilot training to space shuttle support.	11
53 Rutting	Not Enough Data			
54 Shoving	Not Enough Data			
55 Slippage Cracking	Not Enough Data			
56 Swell	Not Enough Data			
57 Weathering	linear regression slope=.054x	linear regression slope=.19x	There is a slight bias toward AC Zone 2 in the deterioration behavior of this distress. The krig analysis shows a few hot spots centered at Vance AFB and MacDill/Avon Park. The PCI deduct values associated with each are comparable to PCI deducts at other	12

			airfields; however, the size of the runways at Vance, MacDill and Avon Park are small compared to others.	
PCC Model				
Distress	PCC Zone 1	PCC Zone 2	Additional Remarks	Ref Table
61 Blow UP	Not Enough Data*			
62 Corner Break	Propagation rate very flat, linear regression slope=0.0049x	dominant deterioration zone, linear regression slope=0.3141x	Regression analysis shows very aggressive linear regression line caused by PCI deduct values at Avon Park. Pavement has not been renovated in 72.7 years and PCI deduct value are very large (30, 39, 72). Maintenance strategy is an obvious factor in this distress behavior. This regression analysis is corroborated by the krig analysis performed on the normalized PCI deduct value for this distress. The krig image shows a strong trend in the Southeastern quadrant of the U.S.	13

63 Linear Cracking	dominant deterioration zone, linear regression slope=0.1647x	linear regression slope=0.1191x	Regression analysis shows similar propagation rates for both zones; however, the magnitudes of PCI deducts are higher in Western airfields. This is corroborated in the krig analysis. PCC Zone 1 clearly shows a more severe deterioration behavior than PCC Zone 2.	14
64 Durability Cracking	linear regression slope=0.1285x	linear regression slope=.0481x	The data for this distress type is highly variable. Clear vertical bands are discernable within the PCC Zone 2 data presented in the regression analysis. These bands suggest that age of the pavement does not seem to have an effect on the PCI deduct value. The krig analysis does not present any strong trends either. The bases that have high PCI deduct values are Edwards, Holloman, Wright-Patterson, and Seymour Johnson where the main traffic loads range from fighters to cargo and tankers to unmanned aerial vehicles. Additional investigation should be conducted before a trend can be suggested.	15

65 Joint Seal Damage	linear regression slope=0.0369x	linear regression slope=0.0355x	The regression analysis shows no discernable difference in the pavement behavior between the two zones and both have low propagation rates compared to the propagation rates of other pavement distresses. The krig analysis suggests that the normalized PCI deduct values are larger in PCC Zone 1 than they are in PCC Zone 2. Considering the suggestions made by the regression analysis and the krig analysis provides a more complete picture of the pavement behavior. The regression analysis shows that PCI deduct values are only reported at three values (2, 7, 12) which correspond to severity levels (L, M, H). The striations in the regression data mask any difference in the linear regression. The krig analysis shows that the distresses tend to be more severe in PCC Zone 1, driving the normalized PCI deduct value up.	16

66 Small Patch	linear regression slope=.021x	linear regression slope=.017x	The regression analysis shows no discernable difference between the distress behaviors of the pavements in these two zones. The distress propagation rates are also very small. What the regression analysis does show is that this distress is very prevalent in all PCC runways although the PCI deducts tend to be small. The krig analysis suggests that there is atypical pavement behavior in the Northeastern U.S. The data shows that these pavements have not been renovated in upwards of 50 years.	17
67 Large Patch/Utl Cut	linear regression slope=.038x	dominant deterioration zone, linear regression slope=0.123x	The regression analysis shows that the distress propagation rate for pavements in PCC Zone 2 is much faster than of those in PCC Zone 1. The krig analysis suggests that the normalized PCI deduct values are pretty consistent across the U.S. Combining the two analyses facilitates the conclusion that while PCI deduct values tend to be similar in both zones, the	18

			propagation of the distress is faster in Zone 2.	
68 Popouts	Not Enough Data			
69 Pumping	Not Enough Data			
70 Scaling	linear regression slope=.0164x	dominant deterioration zone, linear regression slope=.068x	The regression analysis shows that the propagation rate for both zones is very gradual and that JBMDL and Dover make up most of the data. There is not a strong geographic pattern presented in the Krig analysis.	19
71 Faulting	Not Enough Data			
72 Shattered Slab	dominant deterioration zone, linear regression slope=.277x	linear regression slope=.0491x, not enough data for this zone to draw strong conclusions	This distress is strongly biased to the Western U.S. With many distress occurrences at Vance AFB and Ellsworth AFB. The propagation rate is also very steep compared to other distresses.	20
73 Shrinkage Cracking	linear regression slope=.021x	dominant deterioration zone, linear regression slope=.066x	This distress is wide spread; however, the distress propagation rate is faster in PCC Zone 2.	21

74 Joint Spalling	linear regression slope=.018x	linear regression slope=.037x	This distress is wide spread and occurs frequently in both zones. PCI deduct values tend to be small. The krig analysis shows high deterioration behavior in the Northeastern U.S. This is caused by a few sections of very old pavement at Westover ARB.	22
75 Corner Spalling	linear regression slope=.008x	linear regression slope=.0351x	This distress is widespread and causes small PCI deduct values. There are a few larger occurrences of this distress in OK, MO, LA.	23
76 Alkali Silica Reaction	Not Enough Data			

Appendix D- List of Acronyms Used

asphalt concrete (AC)

asphalt-over-asphalt concrete (AAC)

Air Force Base (AFB)

Air Force Civil Engineer Center (AFCEC)

Air Force Institute of Technology (AFIT)

Air Force Pavement Evaluation Program (AFPEP)

asphalt-over-portland cement concrete (APC)

corrected deduct value (CDV)

Department of Defense (DoD)

maintenance and repair (M&R)

portland cement concrete (PCC)

Pavement Condition Index (PCI)

Pavement Management System (PMS)

rate of deterioration (ROD)

runway (RW)

total deduct value (TDV)

taxiway (TW)

References

ASTM D5340-11, Standard Test Method for Airport Pavment Condition Index Surverys, ASTM International, West Conshohocken, PA, 2011

ASTM D5922-96(2010), Standard Guide for Analysis of Spatial Variation in Geostatistical Site Investigation, ASTM International, West Conshohocken, PA, 2010

Byers, T. (2012). *Air Force Civil Engineer 2012 Almanac*. USAF.

Chief Financial Officer. (2012). *Defense Budget Priorities and Choices.* Washington, D.C.: Department of Denfense.

Colorado State University (2014). *PAVERTM*. Retrieved September 2014

Davit, A. (2002). U.S. Air Force Airfield Pavement Evaluation Program. *Federal Aviation Administration Airport Technology Transfer Conference.*

Department of the Air Force. (2013). *Pavement Evaluation Program.* AFCEC/COAP: AFI 32-1041. 10 September 2013

Haas, R. (2001). Reinventing the (Pavement Mangement) Wheel. *Distinguished Lecture at Fifth International Conference on Managing Pavments.* Seattle.

Hayter, A. (2007). *Probability and Statistics for Engineers and Scientists.* Belmont, CA: Thomson Higher Education.

Johnston, J. M. (2002). *Using ArcGIS Spatial Analyst.* Redlands, CA: ESRI.

Markieta, M. (2014, September). *Geographic Information Systems*. Retrieved from StackExchange: http://gis.stackexchange.com/questions/18814/how-to-change-symbology-of-multiple-layers-at-once

Mayer, V. A. (2009). Volume 04.09 Soil and Rock (II) D5877. In A. International, *Annual Book of ASTM Standards.* West Conshohocken, PA: American Society for Testing and Materials.

Meihaus, J. (2013). *Understanding the Effects of Climate on Airfield Pavment Deterioration Rates.* Wright-Patterson AFB, OH: Air Force Institute of Technology.

Mitchell, B. B. (2001). *Getting Started with ArcGIS.* Redlands, CA: ESRI.

Shahin, M.Y. (2005). *Pavement Management for Airports, Roads, and Parking Lots* (2nd Edition). New York: Springer.

U.S. Air Force Base Locator. (2014, August). Retrieved from airforce.com: http://www.airforce.com/contact-us/base-locator/

VITA

Lauren Sahagun

sahagl1@unlv.nevada.edu
Mobile: (860)301-4501 Office: (702)895-1638

Education

University of Nevada - Las Vegas, NV
MSE in Civil Engineering, December 2014
Core Courses included:
Advanced Soil Mechanics, Advanced Foundation Engineering, Geology Engineering, Contract Law,
Asphalt testing, Statistics
Research Experience:
Project: Nevada Department of Transportation Rubberized Asphalt Testing

- Test set up and execution
- Result analysis and trouble shooting

Cumulative GPA- 3.98

United States Air Force Academy – Colorado Springs, CO
BS in Civil Engineering, May 2010
Core Courses included:
Calculus I-III, Differential Equations, Physics I-II, Chemistry I-II, Hydraulics, Structural Analysis, Electrical Engineering, Power Systems, Steel, Concrete and Pavement Design, Soil Mechanics
Cumulative GPA- 3.24
Superintendent's List 3 times, Dean's List 6 times, Commandant's List 7 times, Athletic List 4 times
Awarded Dept. Civil Engineering Most Honorable Cadet for the graduating class of 2010
Passed National Exam for Fundamentals of Engineering, 2010

Professional Experience

Altus AFB, 2011-Present

- Base Energy Manager

Responsibilities Include:

Promote sustainable environmental practices across base and in new construction or major renovation, manage base meter plan, conduct facility energy audits, utility billing, oversight on utility contracts, brief Wing Commander weekly on base energy consumption

Accomplishments Include:

Developed and received funding for 3 energy projects worth $1.65 Million/projects save $337K and 23K MBTUs per year, enabled Altus AFB to win $100K from AETC Energy Competition, rewrote potable, raw and sewer utility contracts unaltered since 1970

- Project Programmer

  Responsibilities Included:

  Program sustainment, restoration and modernization of real property assets worth $1.2 Billion, Develop long-range plans for mission and base sustainment, prioritized $189 Million project program by managing facilities board process

  Accomplishments Included:

  Authored and received funding for: $1.2 Million Base Network Control Center P-341 project, $900K Emergency Management and Controls Shop upgrade, $500K Club HVAC repair, $190K Chapel repair. 120 projects programmed worth $50 Million, designed Entomology shop from ground up saving AF $397K

Skills

Computer: ArcGIS, PAVER™, Microsoft Office

References:

Dr. Moses Karakouzian, PhD, PE
Professor of Civil Engineering, University of Nevada Las Vegas
Department of Civil and Environmental Engineering
4505 Maryland Parkway, Box 454015
Las Vegas, NV 89154
Tel: (702)895-0959
Email: mkar@unlv.edu

Dr. Mehdi Khalili, PhD, PE
Postdoctoral Scholar, University of Nevada Las Vegas
Department of Civil and Environmental Engineering
4505 Maryland Parkway, Box 454015
Las Vegas, NV 89154-4015
Tel: 702-895-1638