Title: Comparison of United States Air Force PCI Standard Deviation Values to Default Values in ASTM D5340

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ABSTRACT

This paper presents the results of an analysis of nearly 20 years of Pavement Condition Index (PCI) inspection data from the United States Air Force (USAF), comprised of over 10,000 inspected pavement sections, and compares the standard deviation of the PCI of individual sample units within pavement sections to the published defaults in ASTM D5340 (Standard Test Method for Airport Pavement Condition Index (PCI) Surveys), which is 10 points for asphalt pavements and 15 for Portland cement pavements. The USAF is committed to proactively maintaining and rehabilitating its airfields, in part through performing routine PCI surveys to identify and document distresses present in its airfield pavements. Pavements are divided into sections for inspection based on the pavement design, construction history, and traffic area. Because of the time and effort involved, surveys of entire sections are often beyond available manpower, funding, or time. A statistical sampling routine is defined in ASTM D5340 to reduce the effort required to determine the PCI of a given section of pavement. The sampling rate calculation is based on surveying enough samples to achieve a 95% confidence interval of ±5 PCI points and is calculated using the number of sample units and the standard deviation of PCI values of sample units in the section. The standard deviation is not known until after the survey has been accomplished; therefore, default values are provided. This study calculates the standard deviation for each inspected section and compares the results to the defaults. The paper also investigates the effect of other factors such as pavement use, pavement rank, age at time of inspection, and slab size on PCI standard deviation. Results indicate that the default values provided in the standard are generally not conservative for all pavements.

INTRODUCTION

Purpose and Scope

The United States Air Force (USAF) is committed to proactively maintaining and rehabilitating its airfields, in part through performing routine Pavement Condition Index (PCI) surveys to identify and document distresses present in its airfield pavements. Pavements are divided into sections for inspection based on the pavement design, construction history, and traffic area. Because of the time and effort involved, surveys of entire sections are often beyond available manpower, funding, or time. A statistical sampling routine is defined in *ASTM D5340 Standard Test Method for Airport Pavement Condition Index Surveys* to reduce the effort required to determine the PCI of a given section of pavement (1). The sampling rate calculation is based on surveying enough samples to achieve a 95% confidence interval of ±5 PCI points and is calculated using the number of sample units and the standard deviation of PCI values of sample units in the section. The standard deviation is not known until after the survey has been accomplished; therefore, default values are provided. The purpose of this study was to compare the default standard deviation values to calculated values from over 10,000 inspected pavement sections collected from nearly 20 years of USAF PCI inspection data. Furthermore, this study examines the effect of factors such as pavement use, pavement rank, age at time of inspection, and slab size on PCI standard deviation.

Pavement Condition Index

PCI is a visual inspection procedure defined by the American Society for Testing and Materials (ASTM) (1) to determine the current condition of a pavement. The PCI process consists of inspecting the pavement surfaces for specific types of distresses, determining the severity level of each distress, and measuring the quantity of each distress. These data are combined to determine the PCI value of the pavement, a number between zero (failed) and 100 (no distresses) that reflects the current condition. Pavement performance is defined as the change in PCI over time for a given section of pavement. A pavement section is a piece of pavement with a unique construction and traffic history.

Origin of PCI Sampling

The sampling routine prescribed in ASTM D 5340 was first developed and published by Shahin, Darter, and Kohn at the US Army Construction Engineering Research Laboratory (CERL) in 1977 during early development of PCI as a method for the USAF to determine the condition of airfield pavements and plan maintenance strategies (2). The authors recognized that inspecting entire pavement sections may require considerable effort; therefore, a method to inspect only a portion of the pavement by dividing it into smaller pieces (sample units) was developed. Their sampling method required:

- dividing jointed portland cement concrete (PCC) pavement sections into sample units of approximately 20 slabs for inspection
- dividing asphalt concrete (AC) and tar-surfaced pavement sections into sample units of approximately 5,000 square feet (ft^2) [464.52 square meters (m^2)]

Figure 1 provides an example of sample unit division for a PCC surface, and Figure 2 shows the same for an AC surface.

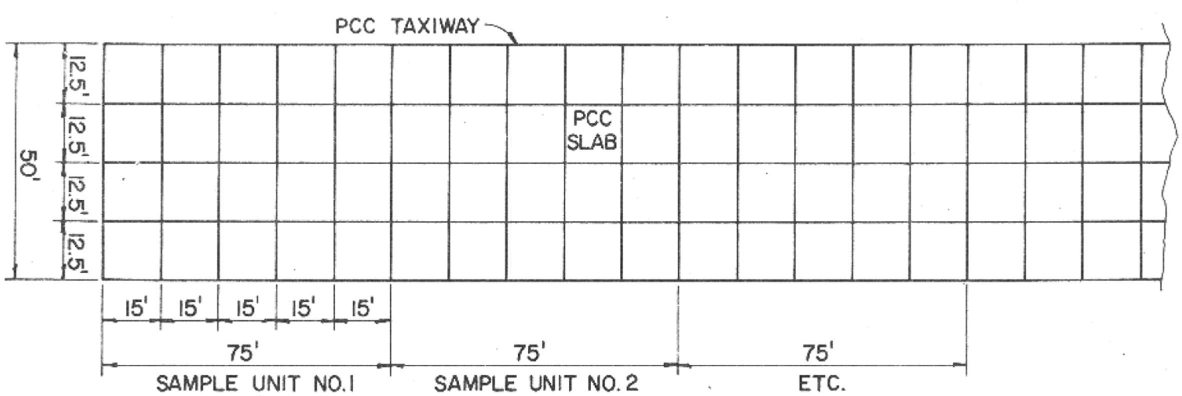

FIGURE 1 Example of a jointed concrete pavement section divided into sample units of 20 slabs (2).

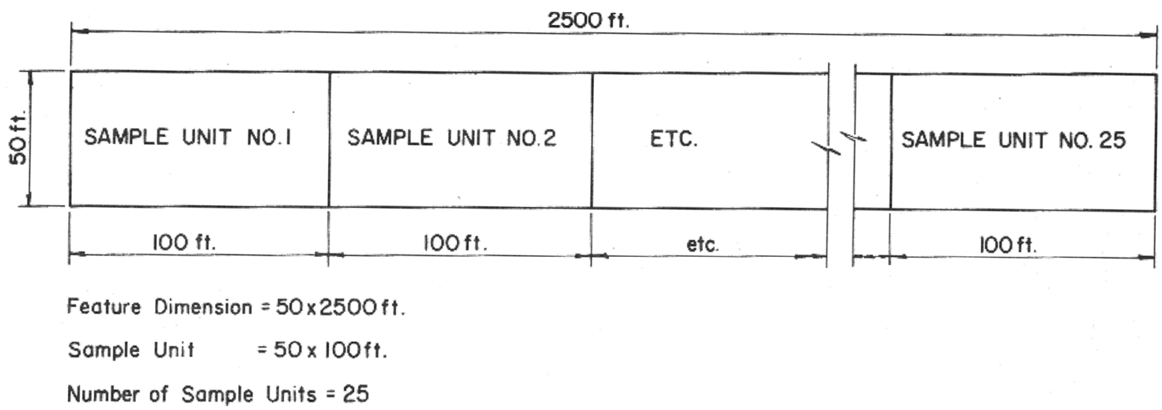

FIGURE 2 Example of an asphalt- or tar-surfaced pavement section divided into sample units (2)**.**

Shahin, Darter, and Kohn reported that heterogeneity of pavements and traffic loadings would contribute to variability of the PCI within a pavement section. They designed the sampling procedure to mitigate the effects of this variability on inspection results by requiring that enough samples be inspected to be "reasonably certain" the results are reflective of the true condition of the pavement. "Reasonably certain" was defined as a 95% confidence interval of ±5 PCI points assuming sample unit conditions are "approximately normally distributed". In this paper, confidence intervals will be presented as 95%±5. From this, the authors of the PCI method developed Eq. 1 to determine how many samples in a pavement section must be inspected to be "reasonably certain" the reported condition is correct. This equation appears to be based on sample standard deviation instead of population standard deviation to allow reduced inspection effort on sections containing less than about 20 sample units.

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

where:

- n = number of sample units to inspect
- e = acceptable error in estimating the section PCI. Commonly, e = ±5 PCI points
- s = standard deviation of the PCI from one sample unit to another within the section
- N = total number of sample units in the section

Issues with Sample Unit Selection

Eq. 1 is currently provided in ASTM D5340 as the method by which the number of sample units to be inspected is calculated. The issue with Eq. 1 is that the inspector must have an estimate of the variability of pavement condition, in the form of the standard deviation *s*, prior to beginning the inspection. Recognizing this, Shahin, Darter, and Kohn provided default values for *s*. The default values of 10 points for AC pavements and 15 points for PCC pavements were "tentatively selected" based on inspection data from 6 military airfields. These default values are provided in the ASTM, and the authors were unable to locate any further studies validating them. The ASTM implicitly recognizes that the values may not be correct by providing the equations to calculate *s* after inspection to confirm that an adequate number of sample units has been inspected.

If the actual value of *s* is less than the default value selected, the certainty of the results has increased above what has been defined as "reasonably certain", i.e., the confidence interval has improved. Since a confidence interval has two parts, the confidence and the interval, this can be interpreted numerically according to the needs of the user. If the confidence is important, the user can conclude there is a greater than 95% probability that the reported PCI value is within ±5 points of the true condition, for example, 98%±5 points. If the interval is important, the inspector can conclude that there is a 95% probability that the reported value of the PCI is within ±*e*, where *e* is some number less than the default (5), for example, 95%±2 points. Conversely, if the actual value of *s* is greater than the defaults, the confidence interval is worse than what has been accepted as "reasonably certain".

The practical implications of inaccurately determining the confidence interval are twofold. If the *s* is smaller than the default values, the inspectors have inspected more samples than necessary, wasting time and effort. If *s* is greater than the default values, the probability that the reported condition is correct is less than what has been defined as acceptable.

RESULTS AND ANALYSIS

Pavement Data

Approximately 10,000 inspections of pavement sections were analyzed to determine the typical standard deviation of sample unit conditions within a pavement section. The data were obtained primarily from the United States Air Force (USAF) and represent military installations in North America, Europe, and Asia. Many of the pavement sections included in this study have been inspected multiple times, with each inspection represented by a separate data point in the data set. At least two data points are required to calculate a standard deviation; therefore, pavement sections consisting of a single sample unit were removed from the dataset, leaving approximately 8,300 data points for analysis. The pavement section data set contained other information including pavement use, rank, and surface type for each pavement section. It did not contain surveyor information for each sample unit; therefore, the authors were unable to investigate if differences between surveyors contribute to the standard deviation of a pavement section. The type of standard deviation, sample or population, was also determined by comparing the number of surveyed sample units to the total number of sample units.

A histogram of the pavement data is provided in Figure 3, showing that the standard deviations of the pavement sections are not normally distributed. Non-normality was confirmed using an Anderson-Darling test, which resulted in A-squared values of at least 6, with some A-squared values over 100. Non-normality had significant implications for this analysis, most importantly that statistical methods assuming normality could not be used to determine if the standard deviation of two categories of pavement are different from each other. However, non-normality of *s* does not imply non-normality of the distribution of PCI within a pavement section and does not invalidate any assumptions in the original research.

Approximately 6% of pavement sections (532) had a standard deviation of exactly zero. These sections were typically sections that were recorded as having either no distresses or the same distress in every sample unit (e.g., 100% low raveling). Another 572 sections had an *s* of less than one, indicating that approximately 13% of all pavement sections have little internal variability in condition.

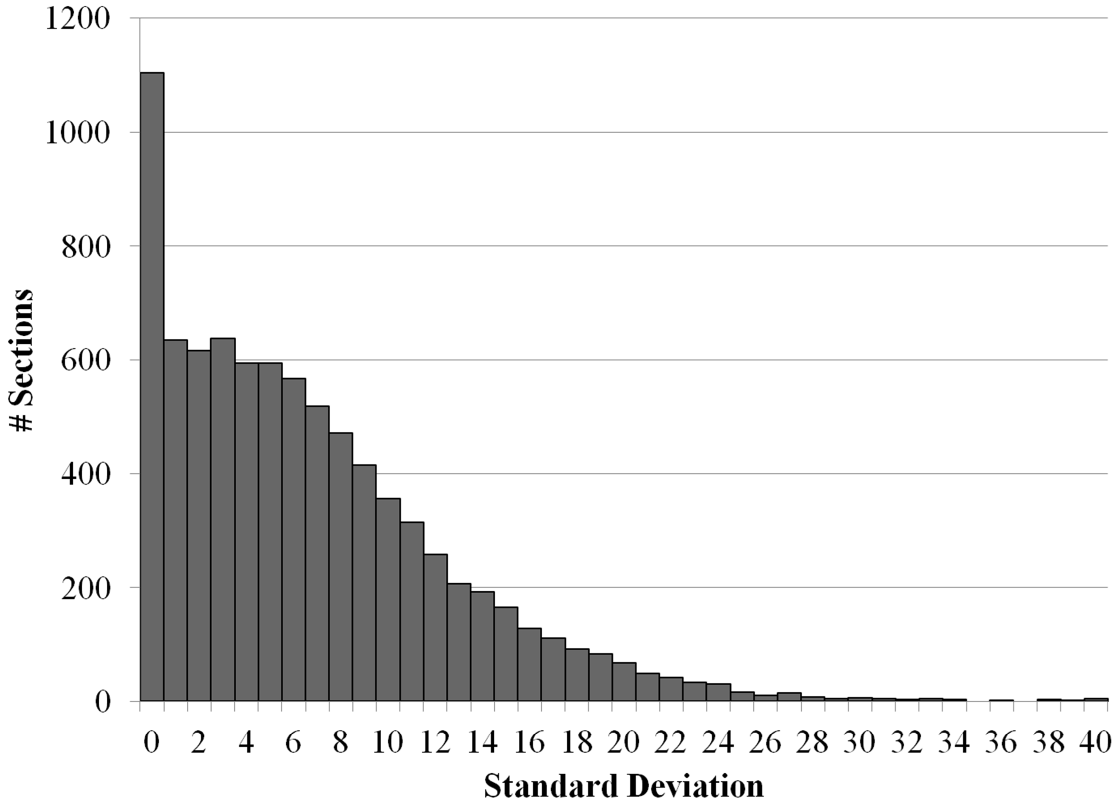

FIGURE 3 Histogram of standard deviation for all data points.

Descriptive Statistics

The data were divided into categories based on attributes, and descriptive statistics were calculated for each category. Results of these calculations are provided in Table 1. As shown, the mean and median for all categories is well below the default values suggested in the ASTM standard. The maximum values are well above the default values. The 95th percentile is above 15 for all categories. This indicates that there is a less than 95% probability that a given pavement section has a standard deviation less than the default values given for calculating sampling rates. A standard deviation of ten ranks at approximately the 70th percentile in the data set, indicating that only 70% of pavement sections have a standard deviation less than the default for asphalt pavements. When only non-PCC pavement sections are considered, just 77% of sections have a standard deviation less than the default. A standard deviation of 15 is approximately the 90th percentile, indicating that only 90% of pavement sections have a standard deviation less than the default for PCC pavements. This implies that nearly 25% of asphalt pavement sections and over 10% of PCC pavement sections had too few sample units inspected to achieve the accuracy specified in ASTM D5340. The 95th percentile *s* for PCC and non-PCC are both between 18 and 19. Because the data are non-normal, this research does not consider if these values are different or can be considered the same for purposes of analysis.

TABLE 1. Descriptive Statistics for *s* (PCI Points).

Category	Count	Mean	Median	Maximum	95th %-ile	% Rank 10	% Rank 15
All data	8364	7.17	6.01	45.15	18.74	0.73	0.89
Non-PCC Surface	1712	6.10	4.37	41.10	18.12	0.77	0.90
PCC Surface	6652	7.45	6.30	45.15	18.85	0.73	0.89
Aprons	3380	8.22	7.13	43.76	20.40	0.67	0.85
Runways	1871	5.59	4.43	31.94	15.24	0.83	0.95
Taxiways	2856	7.18	6.13	45.15	18.19	0.74	0.90
Primary	5411	6.94	5.91	38.64	17.82	0.75	0.91
Secondary	2579	7.52	6.06	45.15	20.31	0.71	0.88
Tertiary	374	8.23	6.94	42.51	20.73	0.67	0.83
Population *s*	3891	6.96	5.53	45.15	18.85	0.74	0.89
Sample *s*	4473	7.36	6.34	41.10	18.55	0.73	0.90
Slab Size ≤ 15 ft	1306	6.78	5.58	39.95	17.81	0.76	0.91
15 ft< Slab Size ≤ 20 ft	2380	6.21	4.99	45.15	16.37	0.80	0.93
15 ft< Slab Size ≤ 20 ft	2859	8.87	7.93	43.76	20.43	0.64	0.85
Slab Size > 25 ft	120	5.62	4.20	25.44	17.42	0.86	0.91

Implications of results on accuracy of PCI results

The effect on the confidence interval when the standard deviation increases but the number of surveyed samples is not increased can be calculated using Eq. 2

$$n = \frac{(z_{(1-\alpha)})^2 s^2}{e^2} \qquad \text{Eq. 2}$$

where $z_{(1-\alpha)}$ is the quantile function of the standard normal distribution. Simplistically, the quantile function can be conceptualized as "there is a (*1-α*) percent chance that the real value is within *z* standard deviations of the mean value". Shahin, Darter, and Kohn selected a (*1-α*) value of 0.95, or 95%, yielding $z_{(0.95)}$=1.96, which was rounded to 2. The number of samples surveyed *n* is held constant, resulting in Eq. 3:

$$\left(\frac{\left(z_{(1-\alpha)}\right)^2 s^2}{e^2}\right)_{default} = \left(\frac{(z_{(1-\alpha)})^2 s^2}{e^2}\right)_{measured} \qquad \text{Eq. 3}$$

Substituting known values results in Eq. 4 and Eq. 5 for asphalt pavements. The same type substitution can be made for PCC pavements. Results of the calculations for both PCC and asphalt pavements are provided in Table 2.

Calculate *e*:
$$\frac{2^2 10^2}{5^2} = 16 = \frac{2^2 18^2}{e^2} \qquad \text{Eq. 4}$$

Calculate *α*:
$$\frac{2^2 10^2}{5^2} = 16 = \frac{(z'_{(1-\alpha')})^2 18^2}{5^2} \qquad \text{Eq. 5}$$

TABLE 2. Effect of Increased *s* on Confidence Interval

Surface	*e* for 95% Confidence Interval	Confidence Interval for *e*=5
Asphalt (non-PCC)	95%±9.0	86.7%±5
PCC	95%±6.3	94.3%±5

Comparisons

Figure 4 compares the standard deviation of pavements by surface type using box plots. As shown, PCC pavement has a generally higher standard deviation than non-PCC pavement. PCC pavement appears to have more outliers than non-PCC pavement, but as shown above, the 95th percentile is approximately the same for both PCC and non-PCC pavements.

Figure 5 compares the standard deviation of pavements by use. As shown, runways have the lowest median standard deviation and a smaller interquartile range than taxiways or aprons. Interquartile range is a measure of spread in the data. A larger interquartile range indicates more variation. This may be indicative of increased maintenance or different deterioration patterns for runways versus other pavements.

Figure 6 compares the standard deviation of pavements by rank as assigned by the pavement manager. By policy, secondary pavements receive less maintenance than primary pavements, and tertiary pavements receive even less than secondary pavements. This likely explains the increasing median standard deviation and interquartile range from primary to secondary to tertiary pavements.

Figure 7 compares the population and sample standard deviations. Population standard deviations are calculated when 100% percent of the sample units in a section were inspected. There does not appear to be a significant difference between surveying 100% of sample units and not surveying 100% of sample units.

Figure 8 compares the standard deviation of PCC pavements by slab size. The mean and median *s* of the nominal 25-ft slabs are noticeably higher than the other slab sizes. The interquartile range and other indicators of variability all point to nominal 25-ft slabs having a less uniform intra-section condition than other slab sizes.

Figure 9 is a scatter plot of section standard deviation versus the age at the time of inspection. The researchers expected the mean standard deviation to increase with age, meaning that older pavements should be sampled at a higher rate. As shown by the trend line, there is a slight positive correlation between age and standard deviation, but with an R-squared value of just 0.139, the correlation is not strong. Based on this, there would not be a reason to increase the amount of sampling on older pavements.

CONCLUSIONS

The default standard deviation values given in ASTM D5340 to calculate sample rates appear to result in under-sampling approximately 25% of non-PCC pavement sections and approximately 10% of PCC pavement sections. Based on this analysis, more appropriate default standard deviation values, consistent with the 95th percentile of this data, would be 18 for non-PCC and 19 for PCC pavements.

Using these data, the actual confidence intervals for non-PCC and PCC pavements are 95%±9.0 and 95%±6.3, respectively.

Although PCI was designed to be an objective process, surveyor skill and subjectivity may contribute to variability of reported condition within a pavement section. The dataset does not identify the surveyor for each sample unit, so there is not enough information to investigate this possibility at this time.

The data show that standard deviation increases as maintenance priority decreases. Runways, which are usually well maintained, also appear to have a lower standard deviation than other pavements. This indicates that there is a relationship between maintenance and variability of condition, but the data did not include maintenance activities or costs to test this hypothesis.

There is a slight positive correlation between pavement age and standard deviation, but there does not appear to be a need to increase the sampling rate on older pavements.

There does not appear to be a difference between population and sample standard deviations. This implies that inspecting more than the recommended number of samples does not significantly decrease the confidence interval of the pavement condition data, and that the sampling process is generally valid.

Large slabs (those with a nominal size of 25 feet) appear to have greater variability in pavement condition, but there is no immediately obvious cause for this.

REFERENCES

1. American Society for Testing and Materials, "Standard Test Method for Airport Pavement Condition Index Surveys," D5340, West Conshohocken, Pennsylvania, 2011.
2. Shahin, M. Y., M. I. Dater, and S. D. Kohn, *Development of a Pavement Maintenance Management System*, Vol. 1, CEEDO-TR-77-44, CERL, Tyndall AFB, FL, 1977, pp. 83-100.

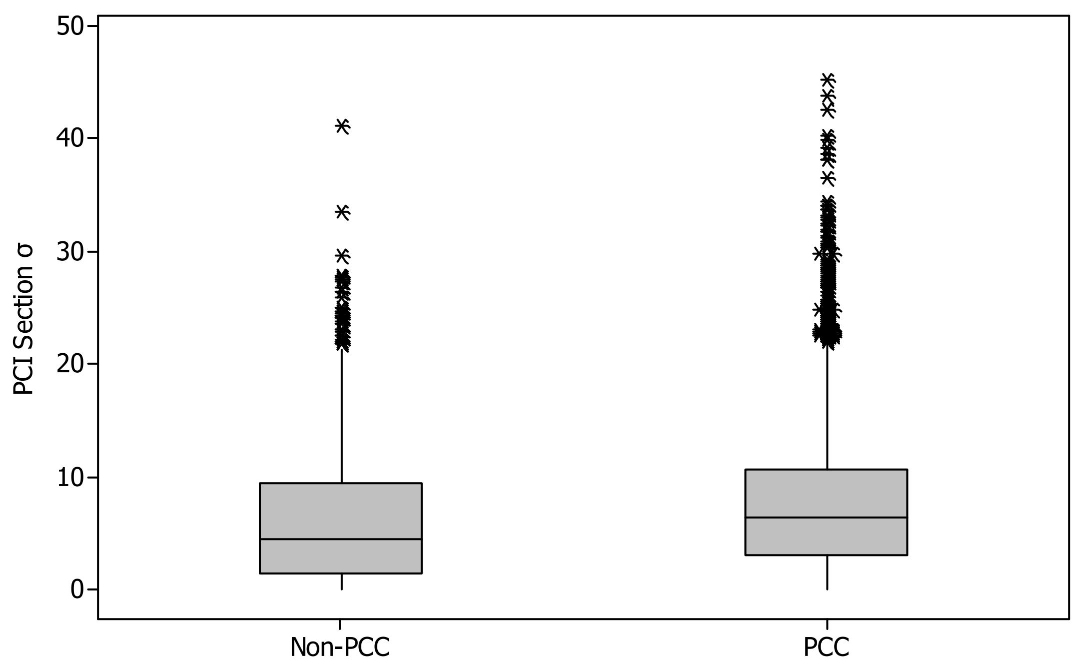

FIGURE 4 Comparison standard deviation of PCC and non-PCC pavement.

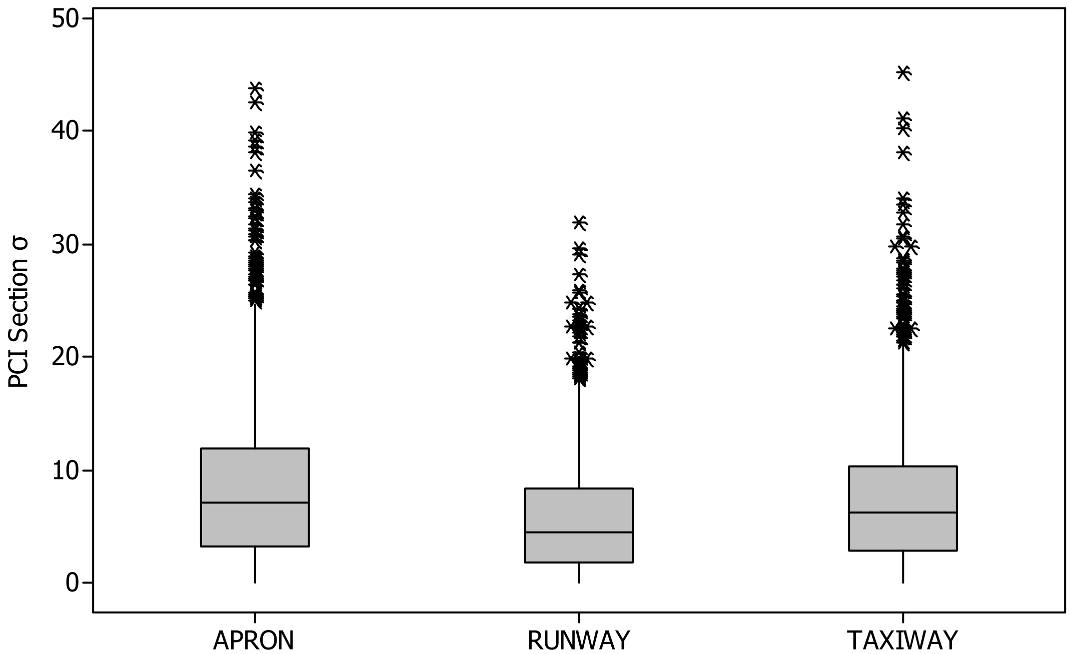

FIGURE 5 Comparison of standard deviation by pavement use.

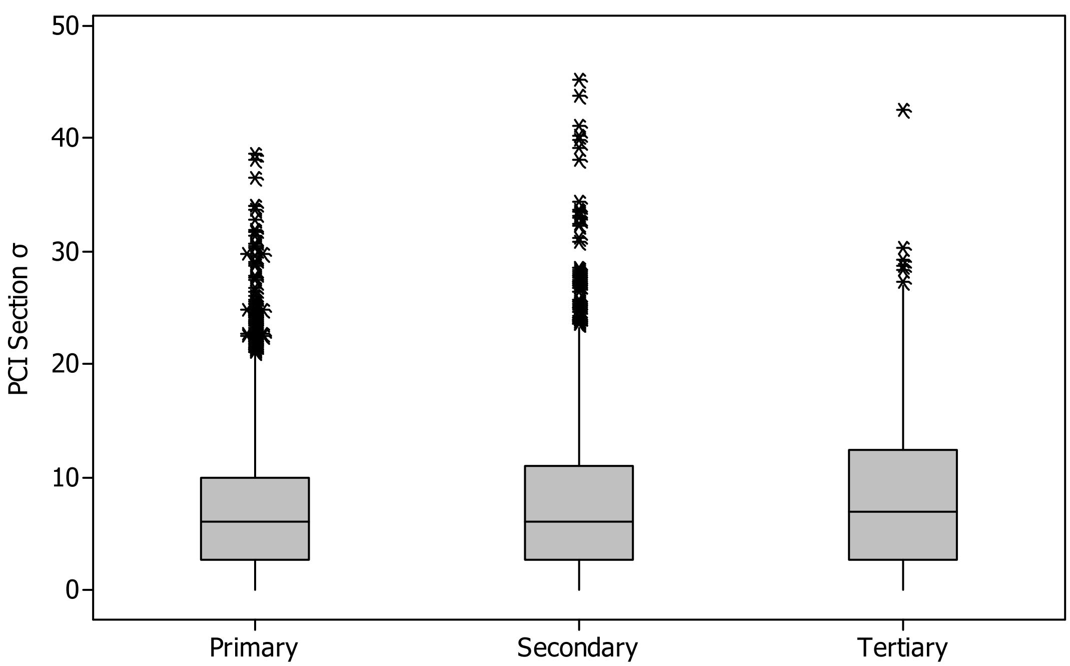

FIGURE 6 Comparison of standard deviation by pavement rank.

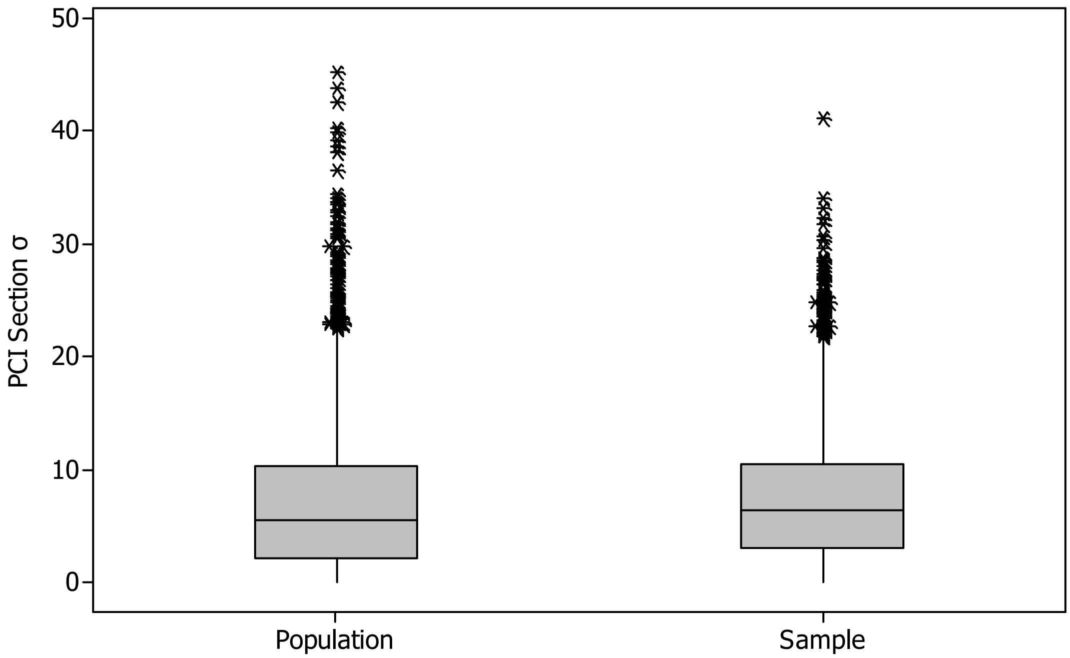

FIGURE 7 Comparison of population and sample standard deviations.

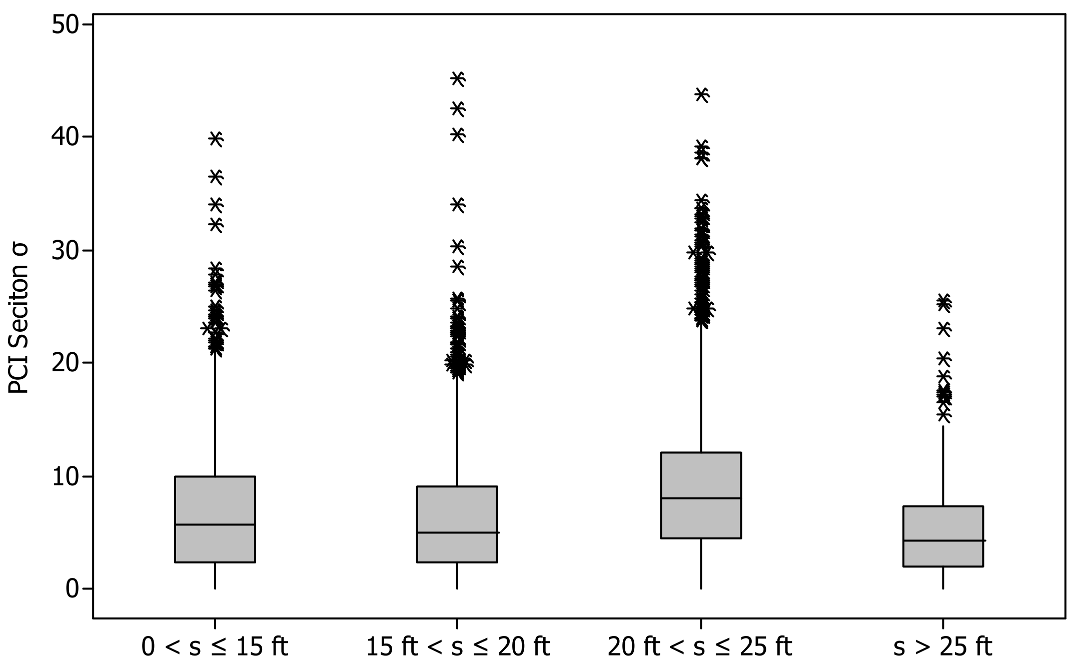

FIGURE 8 Comparison of standard deviation by slab size.

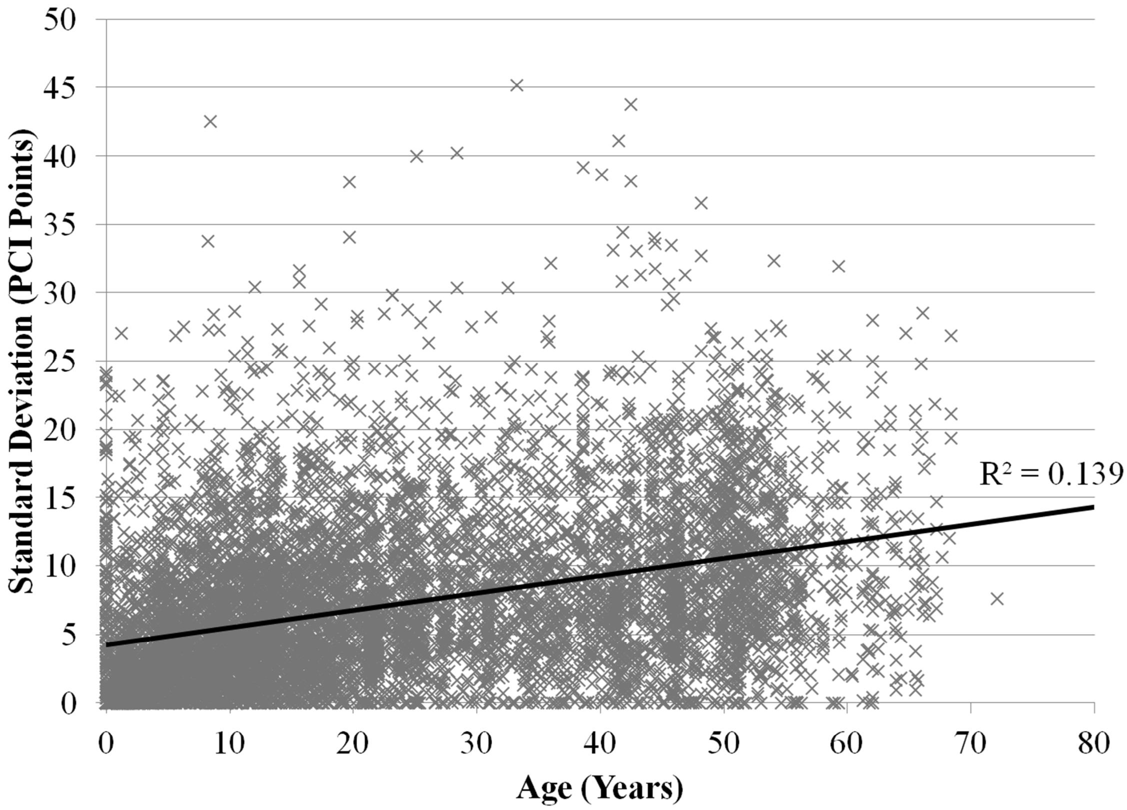

FIGURE 9 Age versus standard deviation.