RELATIONSHIP BETWEEN JOINT SPACING AND DISTRESSES PRESENT

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INTRODUCTION

Purpose and Scope

Previous research by Parsons and Hall has shown that joint spacing in Portland cement concrete (PCC) airfield pavements has an effect on pavement deterioration rates [1] and life cycle costs [2]. The purpose of this study was to investigate the how the differences in pavement performance for various joint spacing lengths (slab sizes) are manifested in the individual distresses used to measure pavement condition. Specifically, this study investigates if the poorer performance in pavements with larger joint spacing is related to a difference in the types, amounts, or severities of distresses present as compared to pavements with smaller joint spacing. The hypotheses investigated in this study were:

- Smaller slabs perform better because they have fewer overall distresses.
- Smaller slabs perform better because they have lower overall severities.
- Smaller slabs perform better because they have fewer "high-deduct" distresses

HISTORY OF JOINT SPACING DESIGN

Concrete Pavement Design

The first concrete runway in the world was constructed in 1906 on the island of Lindholm, Denmark [3] to support experimental aircraft. Since then, concrete pavements have been widely used for constructing runways, taxiways, and apron areas on airfields. Kohn et al. reported the first concrete pavement for airport use in the United States (U.S.) was constructed during 1927 and 1928 at the Ford Terminal in Dearborn, Michigan [4]. Joint spacing design for airfield pavement is rooted in early highway research in the U.S. Until 1922, many pavements were constructed with no joints and a thickened center section in attempt to prevent the formation of "an erratic longitudinal crack" that developed in many 16 foot to 18 foot wide pavements [5]. Center joints were adopted to relieve stresses and eliminate cracking caused by expansion, contraction, and warping of the concrete based on results of the Bates Road Tests conducted in Illinois between 1912 and 1923 [6].

Since then, most airfield pavement design in the U.S. has been predicated on Westergaard's response model, first published in 1926 [7]. The model includes calculations for stresses and deflections in rigid pavements based upon the theory of elasticity. The model was validated in 1936 by Teller and Sutherland [8]. The arrival of heavy bomber aircraft during World War II presented designers with loadings three to five times greater than any previous highway or airfield loading [9]. In a series of tests during the Second World War, Corps of Engineers investigators established the framework for military airfield rigid pavement design that adapted the Westergaard models to reasonably predict strains and stresses in airfield pavements. The military funded Westergaard to help develop his 1948 free-edge equations, which considered critical stresses developed by edge-loading adjacent to the joints rather than the center-of-slab loading condition in his early models [10]. The Federal Aviation Administration (FAA) used the same edge-loaded model design criteria implemented by the military from the 1940s up until

2009, when the FAA adopted thickness design procedures based on three-dimensional finite element theory [11].

Joint Spacing Design

Experience suggests that a concrete slab has an ideal joint spacing, and if the designer does not provide for appropriate joints, the slab will crack at approximately even intervals. In general, joint spacing is designed to be smaller than the interval at which the cracks that would develop. Joint spacing affects internal slab stresses, which determine how and where a slab cracks, as well as how much a slab will shrink or expand with temperature changes [5]. According to Byrum, there are two primary theories that are used to describe the need for joints [12]:

1. Subgrade drag theory estimates the tensions that build-up in a slab due to friction present at the bottom of the slab acting to resist thermal shrinkage of the slab. In general, if the slab is long enough, the friction buildup from thermal contraction can crack the slab.

2. Thermal and shrinkage gradient theory is used to describe bending moment and associated curling that forms in slabs as they cure and are exposed to changing ambient temperatures and humidity.

An investigation of joint spacing on airfield pavement was conducted by the Corps of Engineers shortly after adoption of the Westergaard models for pavement design. This was part of an effort to develop empirical supplements to treat factors not treated directly by the mechanistic Westergaard models. A 1956 report, "Investigation of Joint Construction in Airfield Pavements," established the first criteria for designing joint spacing as a function of slab thickness; this guidance was based on a of study of joints in airfield pavements for the period of 1951 through 1955. A design table was provided for selecting transverse contraction joint spacing, recommending a maximum joint spacing of 25 feet for pavements 10 inches thick or greater [9]. Maximum 25-foot joint spacings were recommended in design tables for military pavements until 2001, when the maximum spacing was reduced to 20 feet.

The now superseded FAA Advisory Circular (AC) 150/5320-6D published in 1995 restricted joint spacing to a maximum 25 feet and recommended the longest dimension of a slab over stabilized base be less than 4 to 6 times the radius of relative stiffness, a term defined by Westergaard as the stiffness of the slab relative to the stiffness of the foundation, based on the equation [13]:

$$l = \left[\frac{Eh^3}{12(1-u^2)k}\right]^{\frac{1}{4}} \tag{1}$$

where:

l = radius of relative stiffness, in.
E = modulus of elasticity of the concrete, psi
h = slab thickness, in.
u = Poisson's ratio for concrete

k = modulus of subgrade reaction, pci

The current FAA AC for airfield pavement design, FAA AC 150/5320-6E, published in 2009, also restricts joint spacing to a maximum 20 feet and provides two joint spacing tables: spacings for pavements over stabilized bases shown in Table 1 and spacings for pavements over unstabilized bases shown in Table 2 [11]. Smaller joint spacing is specified for pavements over stiffer stabilized bases, as stresses in pavements increase with a greater modulus of subgrade reaction.

Table 1.
FAA Recommended Maximum Joint Spacings for Rigid Pavement with Stabilized Base[a]

Pavement Thickness (in.)	Spacing (ft)
8-10	12.5
10.5-13	15
13.5-16	17.5
>16	20

[a]based on FAA Advisory Circular 150/5320-6E, Table 3-16

Table 2.
FAA Recommended Maximum Joint Spacings for Rigid Pavement without Stabilized Base[b]

Pavement Thickness (in.)	Spacing (ft)
6	12.5
6.5-9	15
>9	20

[b]based on FAA Advisory Circular 150/5320-6E, Table 3-16

PREVIOUS RESEARCH

The FAA investigated the effects of slab size on airport pavement performance in 2000 by examining Pavement Condition Index (PCI) data collected from 174 airports in six FAA regions [14]. This study considered the effects of joint spacings with finite element analyses and statistical analyses of 288 million square feet of PCC airfield pavement distress data. This research found that slabs with 20-foot joint spacing exhibited better performance than slabs with 25-foot joint spacing for all pavement functional areas (runway, taxiway, and apron), as shown in Figure 1. This study also found that larger slabs on apron sections performed the worst, and the authors recommend constructing smaller slabs on aprons.

A 2003 study by Parsons and Hall examined PCI data from 48 inspections of military and civil airfields in the continental U.S to identify potential relationships between joint spacing and PCC performance [1]. The authors found that slab thickness had the greatest effect on the relationship between pavement performance and slab size. Other reported findings were that climate has some influence on the relationship between slab size and pavement performance, and "the trends clearly show that larger slab sizes have a faster rate of deterioration. For example, a typical pavement with a slab size of less than 15 feet has a PCI of approximately 86 at age 30. The typical pavement with a slab size of more than 25 feet has a PCI of approximately 70 at age 30." This study also supported the conclusion that smaller joint spacing performed better for all pavement functional areas. This study included 4,211 data points representing PCC pavements aging from new to 60 years old.

Parsons and Hall investigated the effects of slab size and cost in 2005 [2]. A probabilistic life cycle cost analysis was performed on the dataset from their 2003 study to determine if the effect of slab size on pavement performance would affect the total cost of ownership of PCC pavements. Life cycle costs were calculated by estimating construction costs, maintenance costs, reconstruction costs, and salvage value of a hypothetical 100,000 ft^2 PCC pavement section for a period of 50 years. This study found that smaller slabs cost more to maintain on a per-unit basis; however, their slow deterioration rate results in a lower total cost of ownership over time.

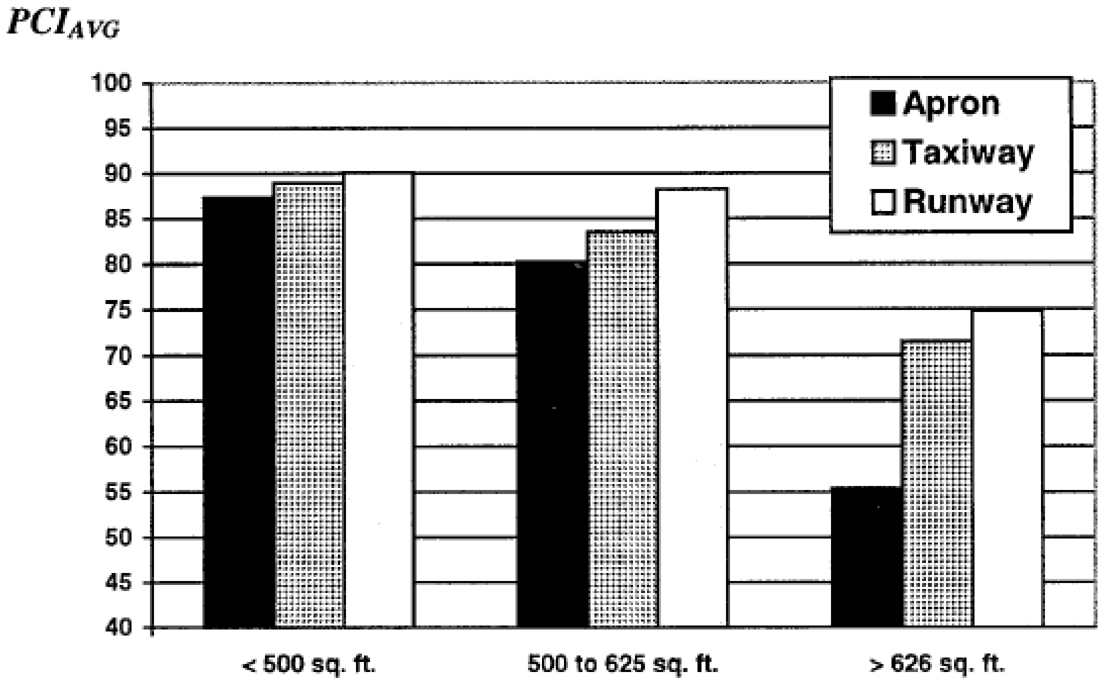

Figure 1. PCI vs Slab Size vs Function [14]

Research by Jia, et al, in 2011 indicated that [15] runway pavements perform similarly regardless of joint spacing. Behavior of apron pavements followed the trends described in the previous research. The different conclusions may be due to different uses for the airfields. The Parsons-Hall data was primarily military in nature, and the Jia, et al, data was primarily from civilian airfields, including airfields with heavy commercial utilization.

A more recent 2013 Air Force Institute of Technology study further examined the effect of climatic conditions on the deterioration rate of USAF airfield pavements from PCI data [16]. The author divided the U.S. into climatic regions and performed several analyses to identify trends. The author suggests efforts should be made to accurately identify and record the nature of the mechanism driving pavement deterioration in pavement management models.

One theory is the poor performance of larger is slabs is somewhat enhanced by changes in industry. Byrum postulates, “Older curing and placement methods allowed the use of longer joint spacing with less premature cracking issues... The use of slipform pavers, cements that generate more heat, and light membrane curing methods” may lead to increased deterioration [12].

PAVEMENT DATA AND ANALYSIS

Pavement Performance Data

For the purposes of this study, pavement condition is measured using PCI as defined by the American Society for Testing and Materials (ASTM) [17]. PCI is a visual inspection procedure 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.

Approximately 7,800 inspections of pavement sections representing nearly twenty years of world-wide airfield pavement evaluations were analyzed to determine the prevalence of the various distresses on each section and the average density of each distress when it does occur. The data were obtained from the United States Air Force (USAF). 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. The inspected sections contained over 39,000 distresses.

Analysis

Data were divided according to the joint spacing of each section. Slabs having different joint spacing in the length and width directions (non-square slabs) were categorized based on the largest dimension. The joint spacing categories in this investigation were selected to match the categories from previous research [1][2] and are shown in

Table 3. Oversize slabs were not considered during the analysis due to the relatively small sample size.

Table 3.
Joint Spacing Categories.

Category	Joint Spacing, s (ft)	Typical Joint Spacing in Category (ft)	N (section inspections)
Small-slab	$s \leq 15$	12.5x12.5 15x15	1485
Medium-slab	$15 < s \leq 20$	18.75x18.75 18.75x20 20x20	2815
Large-slab	$20 < s \leq 25$	25x25	3330
Oversize	$s > 25$	25x30 30x30	140
Total			7770

Two items were calculated for each joint spacing category using the data: the average rate of occurrence by distress, and the average distress density for each distress. Data were first normalized to account for the different ages of the pavement sections dividing the data elements of interest by the age of the pavement at the time of inspection. The average rate of occurrence was calculated as the normalized number of sections exhibiting a given distress divided by the total number of sections. This provides an estimate of how likely a pavement section is to develop any given distress per year. Distress density is the number of slabs in a section that exhibit a distress divided by the total number of slabs in that section. The average distress density for a given distress was calculated based on the normalized distress density of sections that exhibit that distress (as opposed to calculating the average for all sections, with some sections having a distress density of 0). This provides an estimate of the quantity of a particular distress within a pavement section that will develop, given that the pavement section has developed that distress. It can also be conceptualized as the percentage of slabs within a section that will develop a particular distress per year.

ANALYSIS RESULTS

Percentage of Sections Containing Distress

An analysis of the number of sections containing each distress was conducted to determine if a pavement section had a greater or smaller probability of developing the various distresses based on joint spacing. If large-slab sections had a higher overall probability of distress than small-slab sections, or a higher probability for certain distresses, it would be reasonable to assume this is a contributing factor to the poorer performance of pavements with large slabs. Figure 2 is a plot of the percentage of sections containing each distress, normalized by the age of the pavement section at the time of inspection. This is an approximation of the probability that a pavement section will exhibit a given distress in a given year. As shown in the plot, there appears to be a weak or negative correlation between joint spacing and probability of distress occurrence for most distresses. The negative correlation is most pronounced in joint spalls (74) and corner spalls (75). A negative correlation may be inferred from the corner break (62) and linear cracking (63) data, or this data may be interpreted that small slabs have more of these distresses than either medium or large slabs. Large-slab sections have a significantly higher probability of patching (66 and 67) than either small- or medium-slab sections. Small patching in particular occurs nearly twice as much in large slabs than in small slabs. The three most common of the structural distresses as defined by ASTM, corner breaks, linear cracks, and shattered slabs, do not appear to have a strong correlation between probability of distress and joint spacing. The material related distresses, durability cracking (64), popouts (68), pumping (69), and scaling (70) do not appear to have a significant difference in the rate of occurrence in the various slab size categories.

These results indicate that sections with larger joint spacing are not more likely to develop a given distress than sections with smaller joint spacing, with the exception of patches. The decreased performance of large-slab sections cannot be accounted for by a greater percentage of large-slab sections having distresses than small-slab sections. Large-slab sections have a significantly higher probability of patching, indicating that patching may be a contributing factor to pavements with larger joint spacings having poorer performance.

Severity of Distresses

An analysis of distress severity was conducted to determine if a pavement section had a greater or smaller probability of developing high-severity distresses based on joint spacing. If large-slab sections had a higher probability of containing medium- or high-severity distresses, it would be reasonable to assume this is a contributing factor to the poorer performance of large-slab sections. Figure 3 shows the rate of occurrence of each severity of distress for each slab size and indicates the probability of a section containing a high, medium, or low severity distress. The data do not appear to indicate a correlation between joint spacing and the percentage of sections containing low- and high-severity distresses, either positive or negative.

These results indicate that sections with larger joint spacing are not more likely to develop more severe distresses than sections with smaller joint spacing. The decreased performance of large-slab sections cannot be accounted for by a greater percentage of large-slab sections having more severe distresses than small-slab sections.

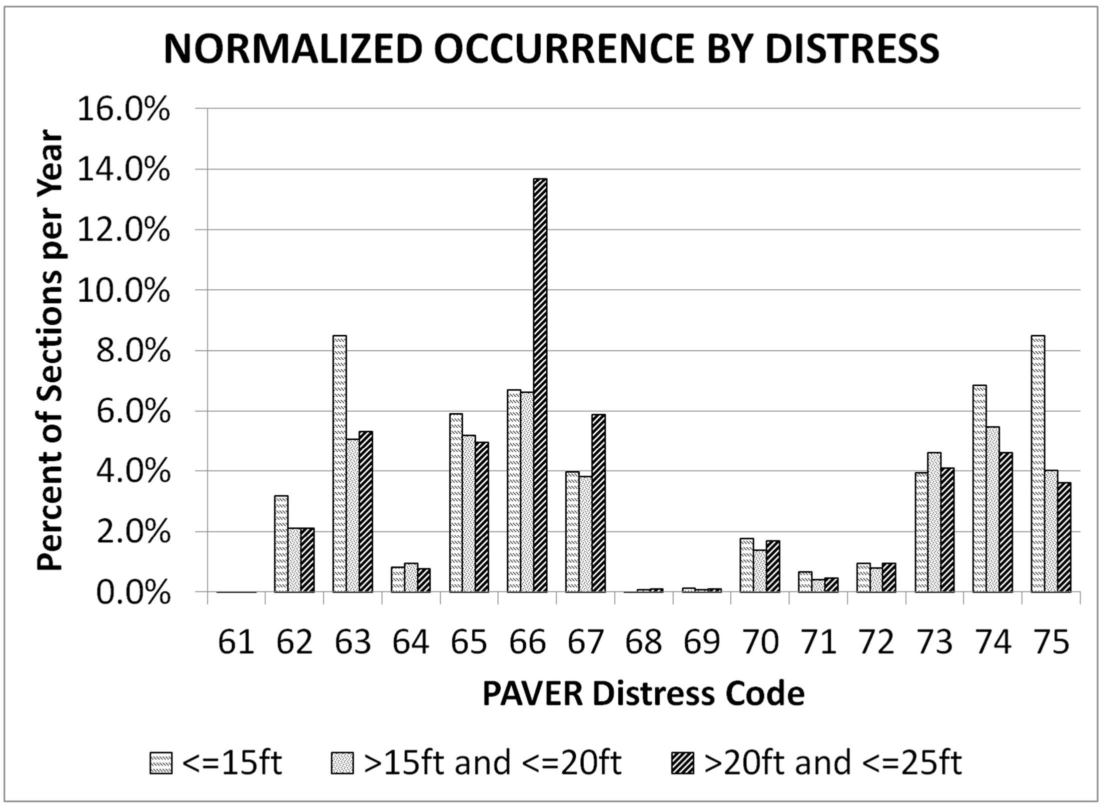

Figure 2. Normalized Rate of Occurrence of Each Distress.

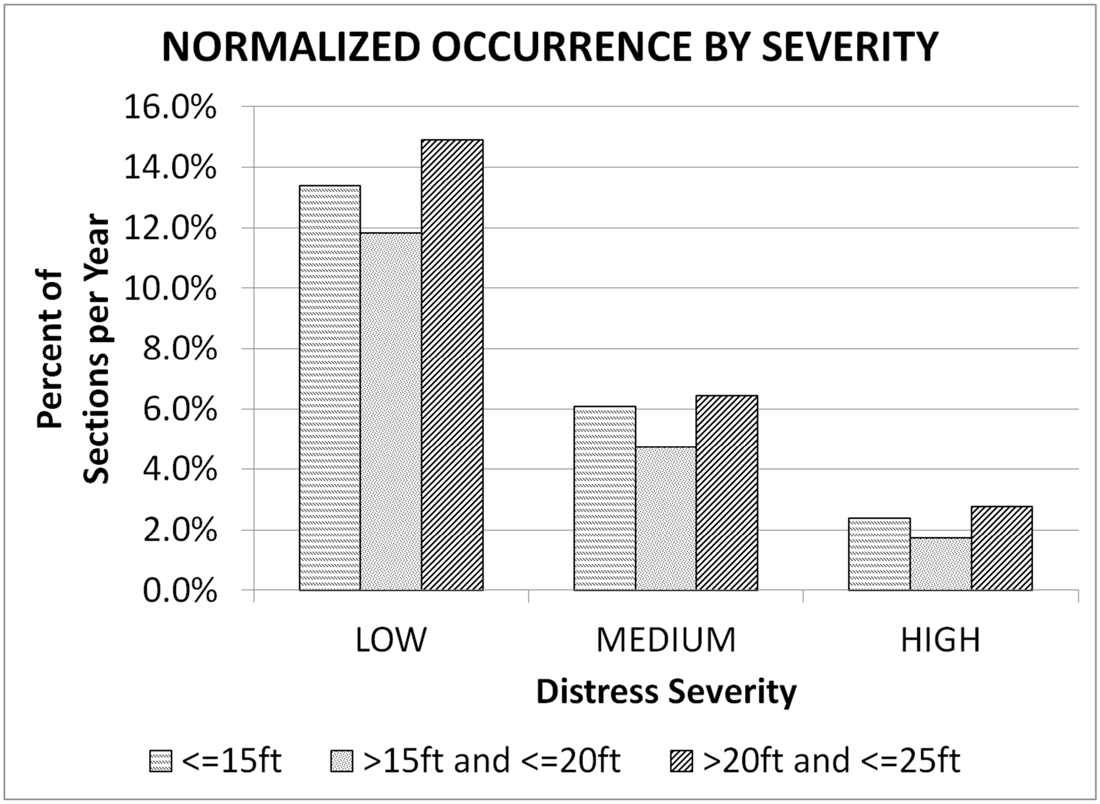

Figure 3. Normalized Rate of Occurrence of Distresses by Severity.

Density of Distress

An analysis of the density of distress within a section was conducted to determine if pavement sections had more or less distress in them based on joint spacing. If large-slab sections exhibited more distress than small-slab sections, it would be reasonable to assume this is a contributing factor to the poorer performance of pavements with large slabs. Figure 4 is a plot of the average distress density for each distress, normalized by pavement age. The data indicate that linear cracking and patching have a positive correlation between joint spacing and distress density, as do popouts and settlement/faulting. Corner spalls, scaling, and blow-ups appear to have a negative correlation. Other distresses do not appear to have a correlation with joint spacing. To determine if the increased patching could counteract the decreased spalling on large slabs, the deduct value of each of the patching and spalling distresses was calculated from the average normalized density then multiplied by the normalized probability. The results are provided in Table 4 through

Table 8. As shown, larger slabs have higher deducts than small slabs, but small-size slabs have higher deducts than medium-size slabs.

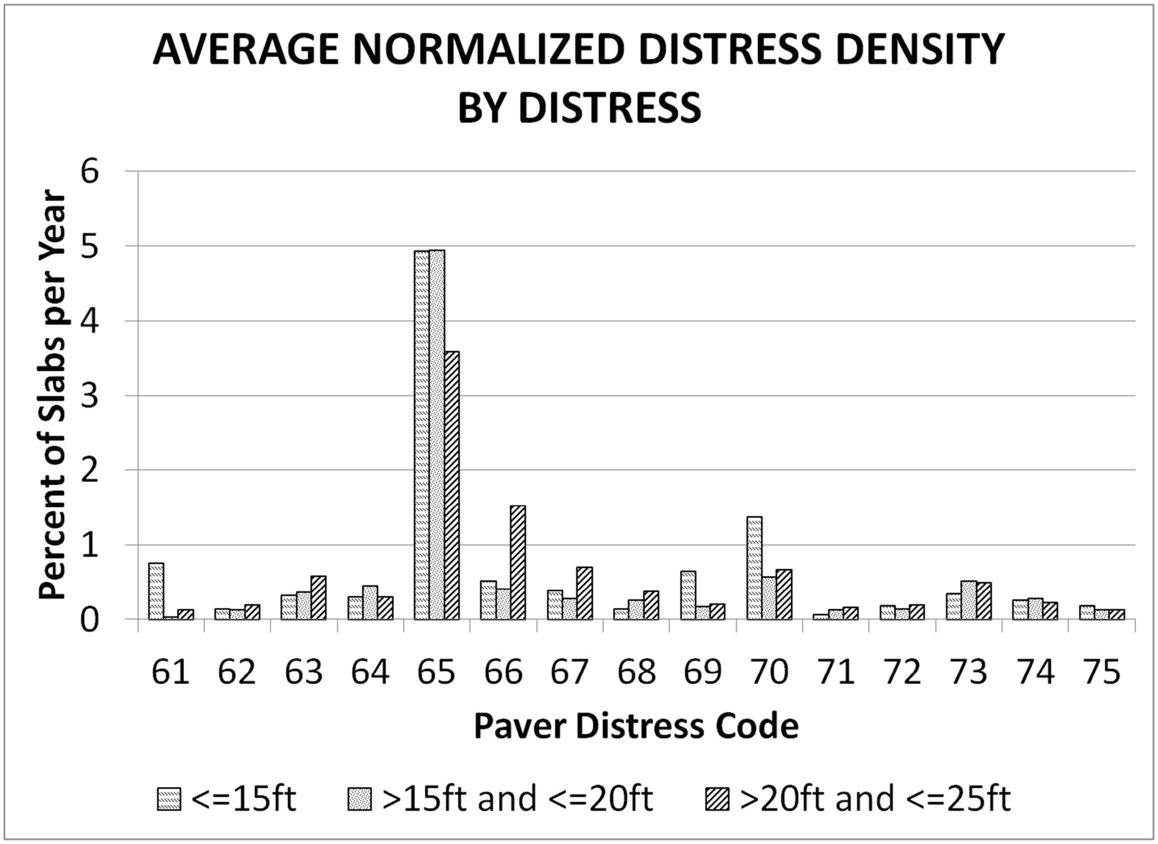

Figure 4. Normalized Density of Distresses by Distress.

These results indicate that as joint spacing increases, pavement sections are more likely to exhibit higher densities of linear cracking, patching, popouts, and faulting. Large slabs are also more likely to have high densities of patching. These distresses could be contributing factors to the decreased performance of large-slab sections, but are not enough by themselves to explain the observed trend in pavement performance.

Table 4.
Deduct Values Due to Small Patching.

	Severity			
Joint Spacing (ft)	Low	Medium	High	Total
s<=15	0.0068	0.0018	0.0002	0.0089
15<s<=20	0.0048	0.0014	0.0003	0.0065
20<s<=25	0.0340	0.0034	0.0003	0.0378

Table 5.
Deduct Values Due to Large Patching.

	Severity			
Joint Spacing (ft)	Low	Medium	High	Total
s<=15	0.0115	0.0035	0.0008	0.0158
15<s<=20	0.0074	0.0028	0.0010	0.0112
20<s<=25	0.0224	0.0285	0.0011	0.0520

Table 6.
Deduct Values Due to Joint Spalling.

Joint Spacing (ft)	Severity Low	Medium	High	Total
s<=15	0.0052	0.0032	0.0019	0.0103
15<s<=20	0.0046	0.0018	0.0009	0.0073
20<s<=25	0.0031	0.0021	0.0015	0.0066

Table 7.
Deduct Values Due to Corner Spalling.

Joint Spacing (ft)	Severity Low	Medium	High	Total
s<=15	0.0063	0.0016	0.0004	0.0083
15<s<=20	0.0017	0.0007	0.0004	0.0027
20<s<=25	0.0013	0.0008	0.0003	0.0024

Table 8.
Summary of Spalling and Patching Deduct Values.

Joint Spacing (ft)	Small Patching	Large Patching	Joint Spalling	Corner Spalling	Total
s<=15	0.0089	0.0158	0.0103	0.0083	0.0433
15<s<=20	0.0065	0.0112	0.0073	0.0027	0.0277
20<s<=25	0.0378	0.0520	0.0066	0.0024	0.0988

Density of Distress Severity

An analysis of the probability of distress severity was conducted to determine if a pavement section had a greater or smaller quantity of high-severity distresses within the section based on joint spacing. If large-slab sections exhibited a higher density of medium- or high-severity distress than small-slab sections, it would be reasonable to assume this is a contributing factor to the poorer performance of pavements with large slabs. Figure 5 is a plot of the average density of each distress severity, normalized by pavement age at the time of inspection. As shown, there is no correlation between the density of distress severity and joint spacing.

These results indicate that sections with larger joint spacing are not more likely to develop greater quantities of medium- and high-severity distresses than sections with smaller joint spacing. The decreased performance of large-slab sections cannot be accounted for by a greater percentage of large-slab sections having more severe distresses than small-slab sections.

VERIFICATION OF PREVIOUS RESULTS

The results of the analysis did not indicate an obvious reason for small slabs to perform better than large slabs and could possibly be interpreted that large slabs perform better because they exhibit fewer distresses and lower densities of distresses. A regression analysis of pavement condition versus age was conducted to verify that the dataset used for this research yielded the same results as the previous research. As shown in Figure 6, the findings are substantially the same, with a general trend of larger joint spacing resulting in lower performance as reported by

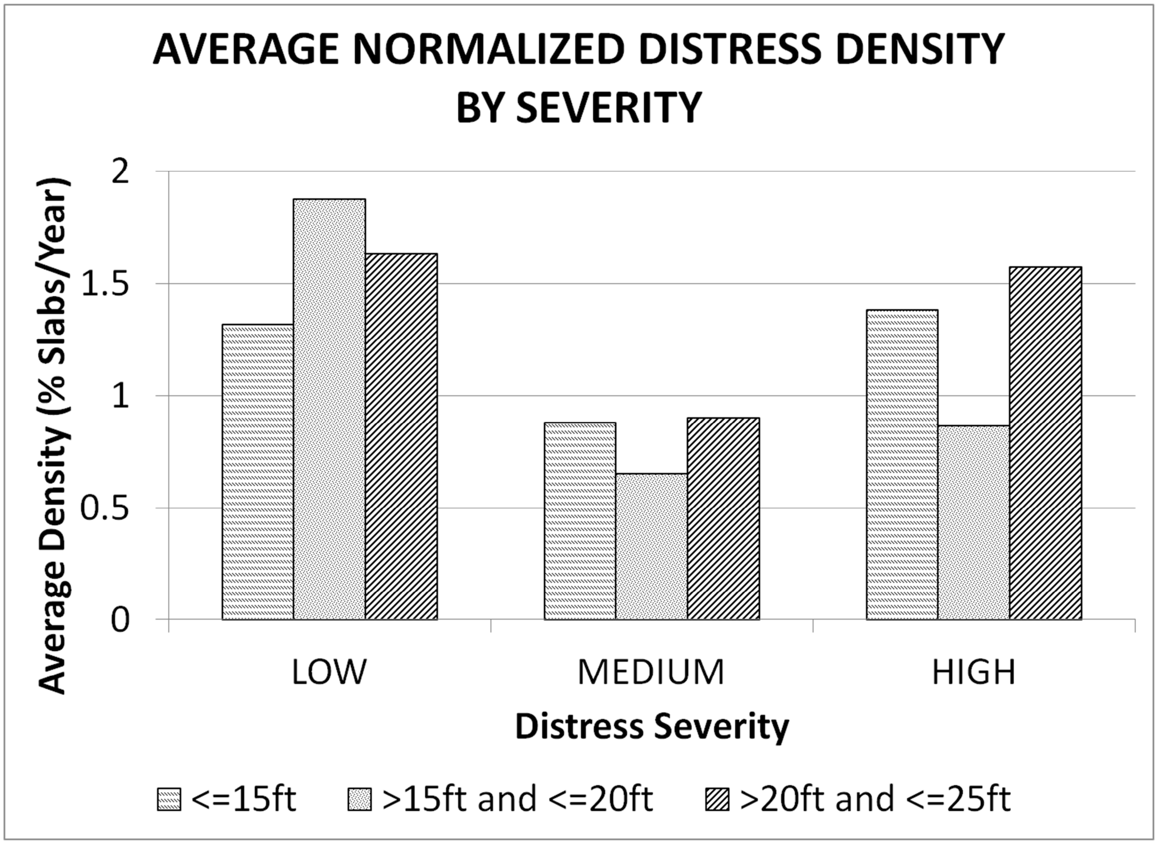

Figure 5. Normalized Density of Distresses by Severity.

Parsons and Hall. The data support the findings of the previous research that small slabs perform better than large slabs, even though inspection of the data on a distress-by-distress basis is inconclusive.

RELATIONSHIP BETWEEN AGE AND JOINT SPACING

A plot showing the percent of slabs in each size category grouped by age is shown in Figure 7. As shown, there appears to be a trend away from 25-foot joint spacing. If there is a correlation between joint spacing and when the pavement was constructed, there could be another variable related to the time of construction (such as a particular construction practice) that may explain the lack of correlation between individual distresses and joint spacing. Over 60% of the pavements over 30 years in age have a 25-foot joint spacing, however, over one quarter of the pavements in each age category have a 25-foot joint spacing. Also, the data represents multiple inspections through time, and age is the age at the time of inspection, which does not directly correlate to a specific date of construction. Further research is needed to determine if a date-of-construction-related variable is present.

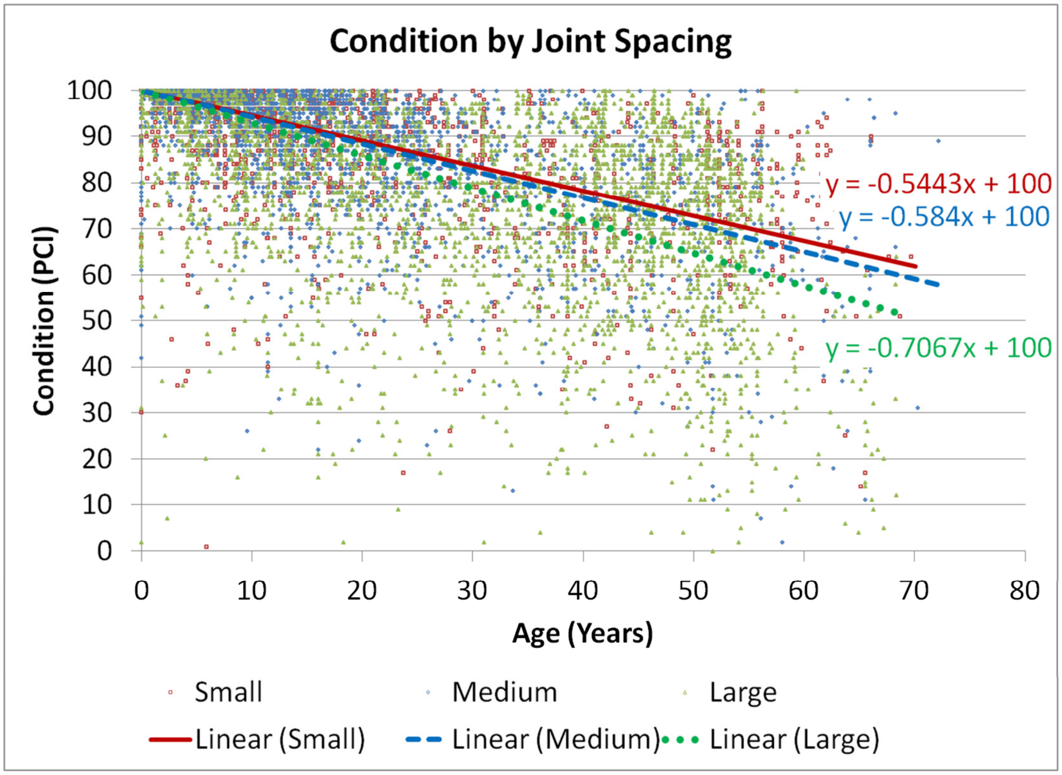

Figure 6. Verification of previous research using a larger dataset.

CONCLUSIONS

This investigation verified the results of earlier research concerning the relationship between joint spacing and PCC pavement performance. Analysis using a larger data set confirmed that pavements with larger joint spacing generally deteriorate faster than pavements with smaller joint spacing.

Pavement sections with larger joint spacing do not appear to develop distress in general at a greater rate than smaller slabs, and do not appear to develop distresses at a generally greater density than smaller slabs. Many distresses have either no correlation or a negative correlation between the distress and joint spacing. The hypothesis that smaller slabs perform better than larger slabs because they have fewer distresses overall is not supported by this data. There appears to be no correlation between joint spacing and distress severity. The hypothesis that smaller slabs perform better because they have lower overall severities is not supported by this data.

Patching appears to have the strongest positive correlation to joint spacing, both in terms of probability and density. Further research to determine the cause of patching (which cannot be determined using the PCI data) may be appropriate. Another contributing factor may be linear cracking, which generally occurs at a greater density in large-slab sections than small-slab sections. Popouts also have a strong positive correlation to larger joint spacing, though the cause of a relationship between the two is not immediately apparent.

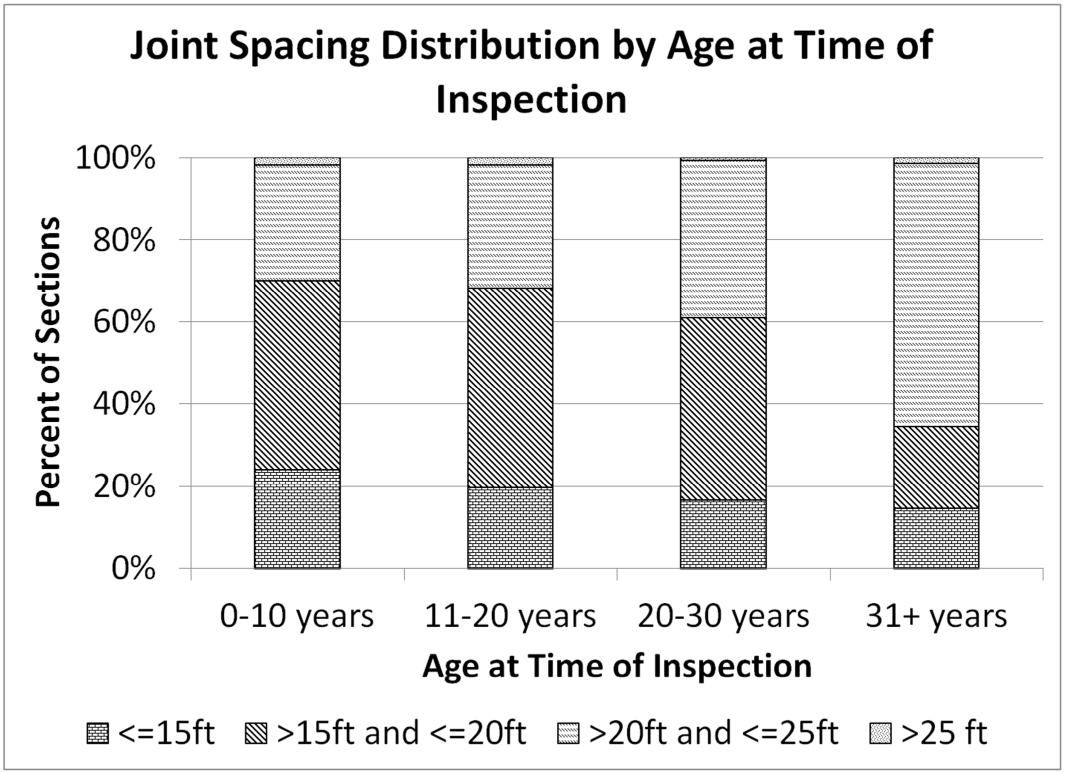

Figure 7. Pavement Age at Time of Inspection versus Joint Spacing.

The hypothesis that smaller slabs perform better than larger slabs because they have fewer "high-deduct" distresses is inconclusive. Although there are distresses with strong positive correlation to slab size, there are other distresses such as spalling that have a strong negative correlation. Comparison of the deduct values for the distresses with the strongest positive and negative correlations is inconclusive, because although the data support the performance trend between small and large joint spacing, the trend between small and medium joint spacing is not supported. The hypothesis that smaller slabs perform better because they have fewer "high-deduct" distresses is most likely to be correct based on this analysis, but the specific "high-deduct" distresses have not been identified. Further research to investigate which distresses cause the highest deduct values is necessary.

The data show that sections with larger joint spacing tend to be older. Age at time of inspection does not directly correlate to the date of construction, but there may be a variable related to the date of construction affecting the observed correlation between joint spacing and performance. Further research into this possibility is recommended.

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