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Analyses of Structural Capacity of Rigid Airfield Pavement Using Portable Seismic Technology

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Abstract: Airfield pavement evaluations were performed at four military installations. Several rigid airfield pavement features at each installation underwent structural testing using the heavy weight deflectometer (HWD) and the portable seismic pavement analyzer (PSPA). The HWD data were used to backcalculate layer moduli for each pavement structure based on the composition of the underlying layers and layer thickness from historical construction records. The PSPA data were used to calculate the in-situ properties for the pavement layers in terms of Young's modulus. PSPA-estimated moduli were used to calculate in-situ flexural strengths of the rigid pavements based on a predetermined relationship between the PSPA-measured modulus and flexural strength. Structural analyses were performed using the flexural strengths obtained from as-built construction records and the flexural strengths estimated from PSPA moduli. Results indicated that the structural capacity of rigid pavements was slightly more conservative when the PSPA moduli were used to calculate the flexural strength than when historical construction data were used. As a result, structural capacity decreased, and overlay requirements increased when the PSPA data were used in lieu of the historical data. The PSPA provides a useful tool for analyses of structural capacity, particularly when historical data is not available.

Key words: *Flexural strength; HWD; Modulus seismic; PSPA.*

Introduction

Background

Since 1982, the U.S. Army Engineer Research and Development Center (ERDC) has been charged with evaluating pavement properties, load-carrying capacity, and general pavement condition at major U.S. Army airfields (AAFs). These evaluations provide airfield managers with a measure of the structural adequacy of the pavements relative to the mission aircraft and projected operations during the 20-year period following the inspection.

Current structural evaluation procedures include performing a condition survey [1] and a series of non-destructive heavy weight deflectometer (HWD) tests on the existing airfield pavements. The HWD is an impact-load device that applies a single-impulse dynamic load to the pavement surface. The results of the HWD tests are used in a linear elastic analysis program to determine the in-situ properties of the pavement layers. Additional pavement properties are required to determine structural capacity including the thickness of the pavement layers and the flexural strength of the portland cement concrete (PCC) layer.

The pavement properties may be obtained from as-built construction records, generally available as a part of the installation's construction history. Historical data from these records provide typical strength values for all facilities constructed at that time. Alternatively, concrete core samples provide an opportunity to characterize the in-situ concrete properties rather than base a pavement evaluation on construction records that may be more than 50 years old. The core samples are used to determine the pavement's flexural strength and validate the surface thickness. The cores may also undergo splitting tensile strength tests in accordance with ASTM C 496-04 to estimate the flexural strength by using a relationship developed by Hammit [2, 3].

The portable seismic pavement analyzer (PSPA) has been used as a means of non-destructively determining PCC strength parameters. The PSPA measures the in-situ pavement modulus via ultrasonic surface waves. Recently, the U.S. Army and Air Force airfield pavement evaluation programs have adopted the use of the PSPA to estimate and/or validate the flexural strength of rigid airfield pavements.

Objective and Scope

The objective of this paper is to describe an improved method for obtaining the in-situ strength properties of the PCC layer in a rigid pavement system, which is required to conduct the engineering analysis of structural capacity. The use of the PSPA provides a means of rapidly and non-destructively measuring pavement properties. Four military airfields underwent testing using the PSPA alongside the HWD. Subsequent analyses of structural capacity were performed at the ERDC to validate the use of the PSPA in pavement evaluations.

PSPA (Portable Seismic Pavement Analyzer)

The PSPA, which is operated using a laptop computer, is used in rigid pavement evaluations to estimate the in-situ flexural strength of the PCC layer. The laptop interfaces with the electronics box, which transmits power to the receivers and the source (Fig. 1). The source impacts the pavement surface, generating surface waves that

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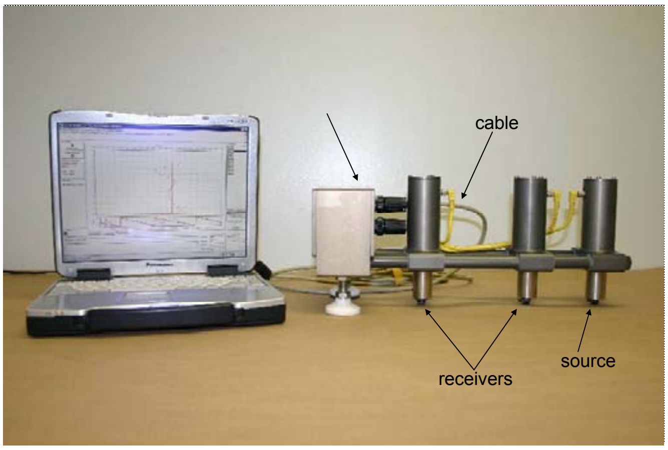

Fig. 1. PSPA Equipment.

are detected by the receivers. The measured signals are returned to the data acquisition board in the computer. The velocity at which the surface waves propagate is determined and Young's modulus is computed. Tests can be completed within a few seconds.

Historical PSPA Studies

A number of studies involving the use of the PSPA on rigid pavements have been performed in recent years [4-7]. Several studies have directly compared the Young's modulus obtained with the PSPA to various measures of pavement strength.

A series of PCC slabs were cast in the laboratory as a part of a 1996 study for the Pavement Technical Assistance Program (PTAP) [4]. Variables in the PTAP study included concrete strength (high and low) and aggregate type (river gravel and limestone). After curing, the slabs underwent PSPA testing to estimate Young's modulus (E_{PSPA}). The flexural strength of each slab was determined by saw-cutting beams from the slab and testing in accordance with ASTM C 78-07 [5]. Alexander [4] proposed a linear relationship between the *flexural strength* and the E_{PSPA} shown in Eq. (1).

$$\text{flexural strength} = 0.000133997 \cdot E_{PSPA} - 136.94 \tag{1}$$

In this relationship, E_{PSPA} is input in terms of ksi (1 MPa = 0.145 ksi), the reported value output from the PSPA. The *flexural strength* is in terms of psi (1 MPa = 145 psi). Eq. (1) has empirical components, so the input must be entered in English units as noted, resulting in an output in English units.

In a study sponsored by the Innovative Pavement Research Foundation (IPRF), a series of cured small-scale laboratory slabs underwent PSPA testing prior to the removal of beam and core samples [5]. Beams were tested for flexure, while cylinders underwent splitting tensile strength testing. Variables in this study included three aggregate types (river gravel, granite, and limestone) used in a series of different mixture designs. The authors developed a sizeable data set based on concrete testing periodically throughout the curing process. The conclusion of this study was presented as a relationship between the free-free resonant column test and the flexural strength.

Bell directly compared in-situ PSPA measurements to flexural strengths obtained from splitting tensile strength testing of concrete cores at three military airfield locations [6]. For this study, the PSPA was utilized on in-situ airfield pavements. Samples were saw cut from the PCC slabs tested in the field. After field testing, these samples were taken to the laboratory, and beams were extracted. Flexural strength tests were conducted on these beams according to the procedure outlined in ASTM C 78 [8]. The historical data reported in the PTAP and IPRF studies were combined with Bell's field data to develop a relationship between the PSPA-measured modulus and the flexural strength for PCC pavements. The correlation between E_{PSPA} and *flexural strength* is presented in Eq. (2). Note that the units for the terms are the same as for Eq. (1).

$$\text{flexural strength} = 0.12 \cdot E_{PSPA} \tag{2}$$

Bell conducted a follow-on study that utilized the results of field and laboratory testing to update the relationship between the PSPA-measured modulus and the flexural strength of PCC shown in Eq. (2) [7]. This study evaluated small-scale laboratory PCC slabs constructed of various aggregates. After curing, laboratory testing, including PSPA, flexural strength, and splitting tensile strength tests, was conducted on samples obtained from each slab. The purpose of the splitting tensile strength testing was to compare Hammit's relationship of splitting tensile strength and flexural strength to the relationship between PSPA-measured modulus and flexural strength. The PSPA and beam-measured flexural strength test results were combined with historical data to develop an updated relationship between the PSPA-measured modulus and the laboratory-measured flexural strength. The inclusion of data from previous PSPA studies produced an extensive data set, which included concrete aggregates of various strengths and mineralogies. The results of the project produced an updated relationship between the PSPA-measured modulus, E_{PSPA}, and beam-measured *flexural strength,* which is shown in Eq. (3). Note that the units for the terms are the same as for Eqs. (1) and (2).

$$\text{flexural strength} = 0.08 \cdot E_{PSPA} + 173 \tag{3}$$

The correlation coefficients of Eqs. (2) and (3) (0.73 and 0.74, respectively) were compared, and the results indicated that the flexural strength values determined from the two relationships were essentially the same. As a result, Bell recommended continuing the use of Eq. (2) for estimating in-situ flexural strength with the PSPA. Eq. (2) is a less complex relationship when compared to Eq. (3) [7].

During Bell's follow-on study [7], individual regression equations were developed for three different aggregate types used to cast slabs (limestone, granite, and river gravel) to develop a method of estimating the influence of the coarse aggregate mineralogy on the PSPA-measured modulus. The correlation coefficients for each individual regression were relatively low compared to the correlation coefficient for the general regression previously developed [Eq. (2)]. It was determined that additional studies with a more extensive data set are required to develop a useful regression for estimation of flexural strength using the PSPA-measured modulus for a specific mineralogy. Bell recommended using the general regression in lieu of an aggregate specific relationship [7].

Bell's 2009 PSPA study revealed the differences between flexural strength values obtained from beam testing, splitting tensile tests,

Table 1. Flexural Strength Values from Laboratory Tests [7].

Aggregate Type	Flexural Strength (MPa) Lab	Flexural Strength (MPa) PSPA	Flexural Strength (MPa) ST	Ratio (PSPA:ST)	Ratio (PSPA:Lab)	Ratio (ST:Lab)
Sandstone	4.13	2.61	5.05	0.52	0.63	1.22
Ortho-Quartzite	3.41	3.16	5.03	0.63	0.92	1.48
Marble Schist	4.26	3.71	4.54	0.82	0.87	1.07
Biotite Gneiss	4.39	4.25	4.60	0.93	0.97	1.05
Metadiorite	4.27	4.24	5.12	0.83	0.99	1.20
Hornblende Gabbro	4.90	4.01	5.10	0.78	0.82	1.04
Granite	3.86	3.71	4.93	0.75	0.96	1.28
Limestone	4.33	3.14	4.10	0.77	0.72	0.95
			Average:	0.75	0.86	1.16

and predictions made using the PSPA (Table 1). In Table 1, “Lab” refers to the concrete flexural strength measured in beam testing, “PSPA” refers to flexural strength estimated using Eq. (2), and “ST” refers to flexural strength estimated using Hammit’s relationship. The results indicated that there is a difference of approximately 25% between the flexural strength predictions using Hammit’s and Bell’s relationships. More importantly, the relationship shown in Eq. (2) tends to underpredict the beam-measured flexural strength by approximately 14%; however, Hammit’s relationship tends to overpredict the beam-measured flexural strength by approximately 16% [7].

Testing and Evaluation

Airfield Pavement Evaluation Testing Procedures

HWD Testing Procedure

Non-destructive tests were performed on a series of airfield pavements with the Dynatest Model 8081 HWD, an impact load device that applies a single-impulse transient load of approximately 25- to 30-millisecond durations. With this trailer-mounted device, a dynamic force is applied to the pavement surface by dropping a weight onto a set of rubber cushions. This action results in an impulse loading on an underlying 30-cm-diameter circular plate that is in contact with the pavement. The applied force and the pavement deflections are measured with a load cell and velocity transducers, respectively. The drop height of the weights can be varied within the range of 0 to 102 cm, producing a force in the range of 0 to 27,216 kg. The system is controlled with a laptop computer that also records the output data. Velocities are measured and deflections are computed at the center of the load plate (D1) and at distances of 30.5, 61, 91.5, 122, 152.4, and 183 cm (D2-D7) from the center of the load plate to obtain deflection basin measurements.

For the airfield pavement evaluations conducted as part of this study, deflection basin measurements were made at 30.5-m intervals within the main gear wheel path on runways and taxiways. The tests were performed on 3- to 3.7-m offsets in the center of the slab corresponding to this station, alternating left and right of the centerline. The parking aprons were tested in a grid pattern of approximately 30.5-m intervals or at locations selected to ensure that adequate non-destructive tests were performed for evaluation purposes. At all test locations, testing was performed in the center of the slab. Pavement deflection measurements were recorded at various force levels. Applied forces corresponded to levels of approximately 7257 and 13,608 kg.

PSPA Testing Procedure

In 2008, PSPA testing was incorporated into the AAF pavement evaluation procedure for PCC features, including runways, taxiways, and aprons. Each airfield was broken up into features based on pavement type, profile, and age. The number of test locations per feature was a function of the feature size. At least three locations were tested per feature, with a minimum of three test replicates per location. Features larger than 41,800 m^2 required at least five test locations. Additional test locations were added when the variability of individual test results exceeded 20% from the average modulus.

Field Testing

Testing reported in this paper was performed at four military installations: Campbell Army Airfield (CAAF), Hunter Army Airfield (HAAF), Simmons Army Airfield (SAAF), and Wright Army Airfield (WAAF) [9-12]. Structural evaluations, condition surveys, and seismic testing were performed concurrently at each airfield. HWD and PSPA testing was performed within a one week period at each site. Tests incorporated a matrix of pavement conditions, summarized in Table 2.

At each test site, ERDC personnel obtained a representative traffic mixture of the airfield’s operations from the installation. The critical aircraft, which was determined as the aircraft producing the greatest structural damage to the rigid pavement, was used in the subsequent analyses. The number of equivalent passes of the design aircraft represented an equivalent damage level for the design aircraft and the damages associated with the traffic pattern provided by the installation.

Analysis Procedures

HWD test results were analyzed using the Pavement-Transportation Computer Assisted Structural Engineering (PCASE) software program [13]. This program uses the WESLEA routine to backcalculate layer moduli. The number of deflection basins obtained per pavement feature varied based on the size of the feature. Between 3 and 55 sets of deflection basins were obtained on

Table 2. Summary of Pavement Conditions during Field Testing.

	Campbell Army Airfield (CAAF)	Hunter Army Airfield (HAAF)	Simmons Army Airfield (SAAF)	Wright Army Airfield (WAAF)
Location	Kentucky	Georgia	North Carolina	Georgia
Subgrade Classification	CL	SM	SP, SP-SM	SM
PCC Thickness	17.8 – 38.1 cm	15.2 – 55.9 cm	20.3 cm	15.2 – 25.4 cm
Traffic Type	Fixed- and Rotary-Wing	Fixed-Wing	Fixed-Wing	Fixed- and Rotary-Wing
Design Aircraft	C-17 (263,083 kg) CH-47 (6,803 kg)	MD-11 (287,124 kg)	C-27 (28,000 kg)	C-12 (7,530 kg) UH-60 (7,394 kg)
Features Tested	18	34	30	4
Test Window	March 2008	October 2007	July 2007	October 2007

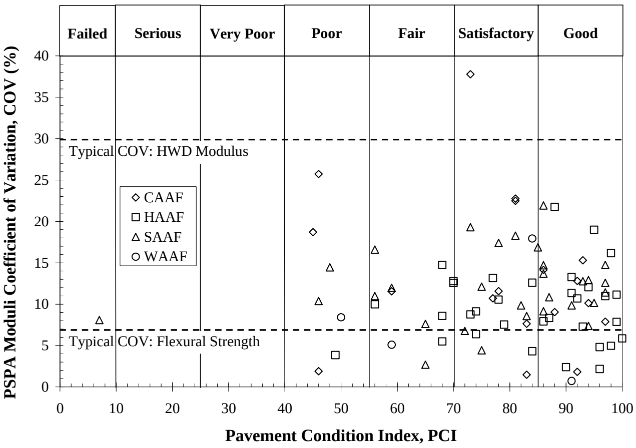

Fig. 2. Variation in Measured Pavement Moduli of Airfield Features.

the features used in this study. The quantity of tests was determined based upon the feature size. A representative deflection basin was selected for each pavement feature. This basin was selected as a typical basin for backcalculation purposes to prevent using a basin with anomalous results. These basins and the pavement layer thicknesses from construction drawings were analyzed using the linear-elastic backcalculation module of PCASE. The modulus values for the PCC surface and subgrade layers were backcalculated for each feature. Pavement thicknesses used in this analysis were obtained from construction records provided by the installation.

A subsequent analysis was performed to evaluate the structural capacity of each pavement feature. The analysis was performed using the PCASE software program [13]. The features were evaluated using a PCC surface layer modulus value of 34,475 MPa and the backcalculated subgrade modulus values, as required by UFC 3-260-03 [14]. These values were used to calculate the critical pavement stresses under the critical load. The published flexural strength from the historical construction data was used to calculate the allowable stresses in the pavement. The PCASE analysis follows the procedure outlined in UFC 3-260-03 [14]. In these analyses, a structural condition index (SCI) of 50 was assumed. The SCI is used to calculate the Design Factor (*DF*) using Eq. (4).

$$DF = A + B \cdot Log(C) \tag{4}$$

where,

$$A = 0.2967 + 0.002267 \cdot SCI$$
$$B = 0.3881 + 0.000039 \cdot SCI$$
$$C = Coverage\ Level$$

The allowable stress was then calculated as the ratio of the design factor to the flexural strength. The allowable stress is an output of the analysis in terms of the pavement classification number (PCN), an index expressing the load-carrying capacity of the pavement in terms of the pavement life, for each feature. The PCN was then compared to the aircraft classification number (ACN), which represented the structural effect of the design aircraft at a specific level of subgrade strength.

A secondary analysis was performed using the PSPA data. Eq. (2) was used to calculate an in-situ flexural strength for each rigid pavement feature. The evaluation was performed in the manner described previously; however, the structural capacity was evaluated using the flexural strength estimated from the PSPA for calculation of the allowable pavement stresses and the resulting PCN value.

Results and Discussion

Effect of Pavement Condition

As noted previously, a condition survey was performed on each feature during the pavement evaluation. The pavement condition index, or PCI, indicates the relative condition of the pavement surface on a scale of 0-100 with 100 indicating a distress-free pavement [1]. Measured PCI values from the four military installations ranged from 7 to 100.

Fig. 2 pairs the coefficient of variation (COV) from the PSPA moduli of a feature with its respective PCI. Due to the linear relationship between the PSPA-measured modulus and the flexural strength, these COVs are also representative of the flexural strength. One feature at CAAF showed significant variability of the modulus across the feature. The remaining features tended to exhibit COVs less than 25%, with an average COV of 11%. While independent historical data are not available specifically for the PSPA, typical COVs of 7% and 30% have been reported for flexural strength and PCC moduli backcalculated from HWD data, respectively [15]. The COVs reported in this study tended to match these levels. Fig. 2 indicates that the variability of PCC moduli and the resulting flexural strength of a rigid pavement feature were not affected by the PCI when using the PSPA.

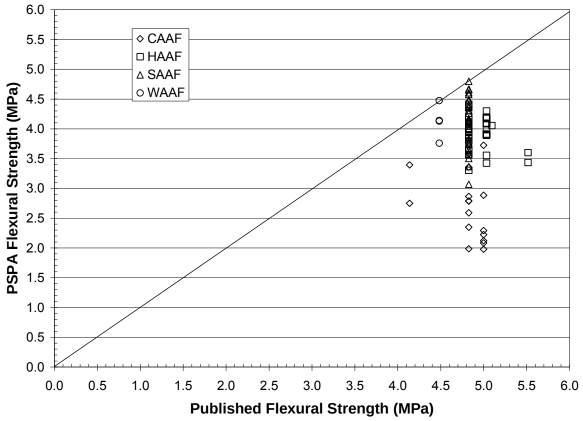

Fig. 3. Comparison of Reported and Measured Flexural Strengths.

Flexural Strength

The flexural strength of the rigid airfield pavements was calculated using Eq. (2). Fig. 3 presents the flexural strengths measured in the field with the PSPA relative to the flexural strength values reported in the construction history. Each point represents an individual feature at an airfield. The data indicate significant variation from the published values.

A statistical description of the flexural strength data used in this study is summarized in Table 3. The flexural strengths measured in the field with the PSPA indicate a reduction from the original constructed values. In no case did the predicted value exceed the “as-constructed” value. The predicted flexural strength values reflect the in-service, deteriorating pavement strength, while the as-constructed values represent the design strength at construction. Thus, it is expected that decreases in flexural strength occur during the 10- to 45-year period between pavement construction and the PSPA testing of the pavement surface. This reinforces Bell’s observations of reduced flexural strengths from the PSPA correlation due to the differences between splitting tensile strength tests and beam flexure tests.

As indicated in Fig. 3 and Table 3, selected flexural strengths reported at CAAF were significantly reduced relative to the published strengths. Alkali-silica reaction (ASR) problems have been reported on PCC pavements at CAAF. It is suggested that the ASR may have reduced PCC strengths from their as-constructed levels at CAAF. The measured PSPA moduli tend to support this observation.

ACN/PCN Values

The ratio of the ACN and PCN values were compared for the two analysis methods. This ratio relates the stresses imparted by an aircraft to the pavement’s allowable stresses. The aircrafts used to determine the ACN in this analysis were the design aircrafts obtained from the installation’s traffic mixture. The ACN/PCN ratio determined using the PSPA measurements was higher than that determined using the “as-built” data for each feature inspected (Fig. 4).

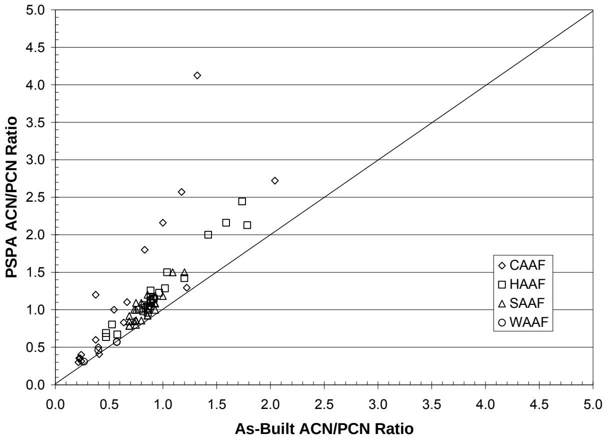

Fig. 4. Comparison of ACN/PCN Ratios using As-Built and PSPA-Measured Strengths for Structural Analysis.

The frequency distribution for the number of observations of various levels of the ACN/PCN ratio is shown for both analysis methods in the histogram presented in Fig. 5. A cursory inspection of this figure shows that the distribution of observations in the bins representing ACN/PCN ratios between 0.70 and 1.30 changed significantly. Due to the presence of several structurally inadequate pavements, the frequency distributions were skewed to the right for both analysis methods. Since the ACN/PCN ratios were not normally distributed, the Wilcoxon Ranked Sum Test was used to analyze the two data sets [16]. Under the null hypothesis, H_0, the two samples were considered identical. At a 95% confidence level, a P value of 2.5E-15 was obtained, leading to rejection of the null hypothesis. The two analysis methods led to a statistically significant difference in the ACN/PCN ratio.

Impact of Installation Status Report Rating Conditions on Pavement Rehabilitation

The ratio of the ACN of the design aircraft to the PCN is denoted as the Installation Status Report (ISR) rating. The ISR rating represents the allowable traffic level for a given aircraft-pavement feature pairing. The three ISR rating conditions are defined in Table 4. A green ISR rating indicates that the pavement will sustain minimal damage under the aircraft loading. The amber condition indicates

Table 3. Summary of Flexural Strength Data.

Airfield	As-Constructed Strength (MPa)			PSPA-Measured Strength (MPa)		
	Maximum	Minimum	Median	Maximum	Minimum	Median
CAAF	5.0	4.1	4.8	3.7	2.0	2.8
HAAF	5.5	4.8	4.8	4.4	3.3	3.9
SAAF	4.8	4.8	4.8	4.8	3.1	4.2
WAAF	4.5	4.5	4.5	4.5	3.8	4.1

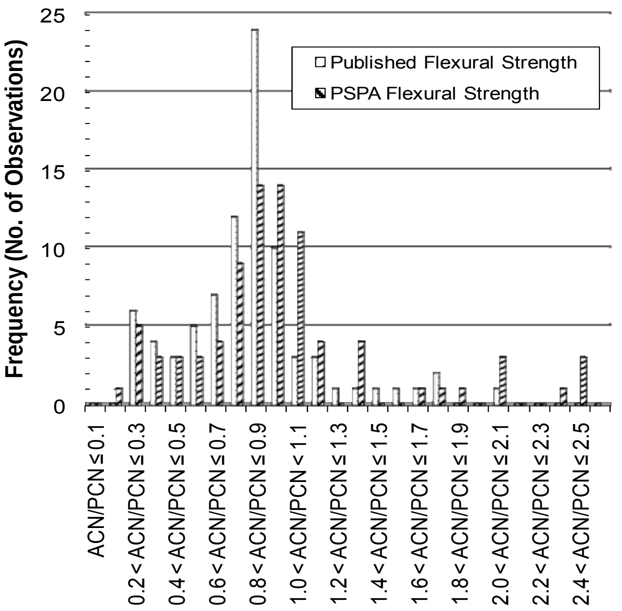

Fig. 5. Frequency Distribution of ACN/PCN Ratios.

Table 4. ISR Condition Levels.

ACN/PCN	ISR Condition
< 1.0	Green
1.10 - 1.40	Amber
> 1.40	Red

Table 5. Change in ISR Values due to PSPA Implementation.

ISR Rating	Number of Features using Published Flex Strength	Number of Features using PSPA Flex Strength
Green	74	57
Amber	5	15
Red	6	14

that moderate damage will occur and that pavements should be inspected after each operation. A red rating indicates that the proposed operation will overload the pavement. In this case, the aircraft should not be allowed to operate on the pavement except under emergency conditions.

Table 5 summarizes the ISR values calculated based on the design aircraft for each feature. This table indicates an increase in amber and red ratings when the analysis was performed using the flexural strength from Eq. (2). Those features rated as red require structural overlays to withstand the projected 20-year aircraft traffic. The use of the PSPA-predicted strength values reduced the potential for overloading the pavement structure.

Conclusions and Recommendations

Eighty-six rigid airfield pavement features were tested using the HWD and the PSPA. The PSPA moduli were used to estimate the flexural strength of the rigid pavements. The data sets obtained in the field were used to perform structural analyses of the individual features. Flexural strengths obtained from PSPA measurements were lower than those obtained from the installations' construction histories. Subsequent structural analyses produced reduced structural capacity for the pavement features.

The PSPA was shown to produce repeatable estimates of in-situ flexural strength, reducing the logistical constraints associated with removing core samples in the field for testing in the laboratory when pavement thicknesses were available from construction records. This method also provided a reduction in the time required to perform a structural evaluation in the field. The resulting changes in structural ratings for pavements tended to be conservative.

It is recommended that the PSPA be incorporated into future analyses of rigid pavements on AAFs. The PSPA is a useful tool for obtaining flexural strengths when they are not available in the construction history. PSPA results may also be used in lieu of the as-built strengths as pavements age and begin to deviate from previously published design strengths. This may be particularly relevant for pavements such as those at CAAF, where post-construction deterioration has led to reduced PCC strength.

Further studies to increase the dataset are recommended to provide improved guidance for the mineralogical makeup of the coarse aggregate portion of the concrete. A more extensive dataset will provide improved estimates of the flexural strength as well as the ACN/PCN ratio of the various pavements.

Acknowledgements

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