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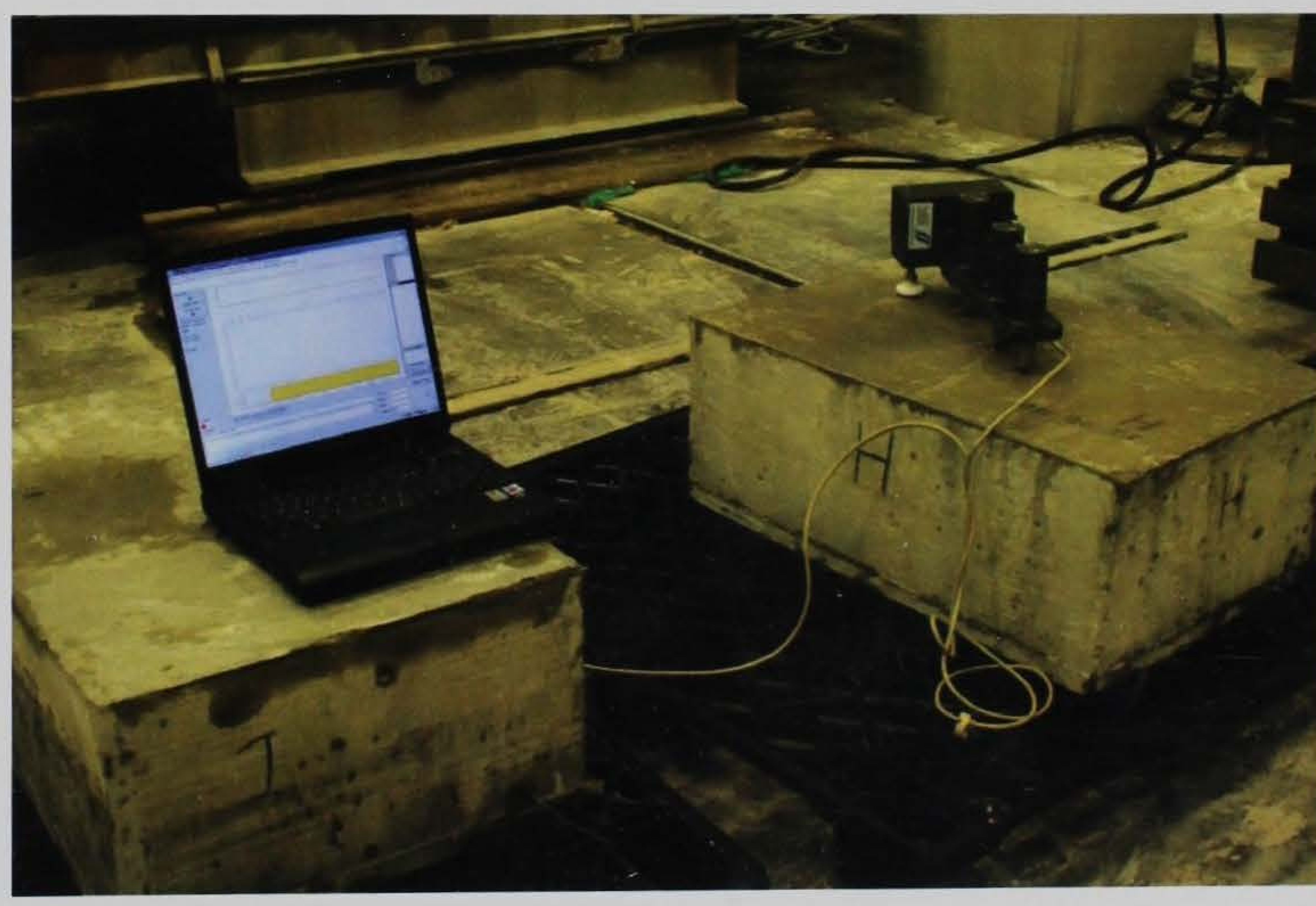
In Situ Determination of Flexural Strength Using Seismic Testing

Haley P. Bell

June 2009



Geotechnical and Structures Laboratory

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In Situ Determination of Flexural Strength Using Seismic Testing

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Final report

Prepared for Headquarters, Air Force Civil Engineer Support Agency
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Abstract: Personnel of the U.S. Army Engineer Research and Development Center were tasked by Headquarters, Air Force Civil Engineer Support Agency, to update an existing relationship between the in situ pavement modulus as measured by the portable seismic pavement analyzer (PSPA) and the concrete flexural strength as determined in the laboratory. The PSPA is a nondestructive testing device that measures the Young's modulus of surface pavements using ultrasonic surface waves. An existing mathematical model between the PSPA-measured modulus and concrete flexural strength was developed based on previous research involving seismic testing and concrete strength properties (Bell 2006). The existing model provided a correlation coefficient (R) of 0.73. Results from the current seismic testing research determined a slightly improved regression between the PSPA-measured modulus and flexural strength. The regression model developed and reported in this publication has a correlation coefficient (R) of 0.74. This report provides information about existing methods for predicting flexural strength in the field, procedures used for casting various small-scale concrete slabs using different aggregates in the laboratory, test procedures and results, data analysis, and recommendations for the use of the updated flexural strength prediction model.

Contents

Figures and Tables

Figures

Tables

Preface

The project described in this report was sponsored by Headquarters, Air Force Civil Engineer Support Agency, Tyndall Air Force Base, FL.

Personnel of the U.S. Army Engineer Research and Development Center (ERDC), Geotechnical and Structures Laboratory (GSL), Vicksburg, MS, prepared this publication. The findings and recommendations presented in this report are based upon the results of a series of laboratory and seismic tests involving small-scale concrete slabs constructed using various coarse aggregate types. Testing was conducted during February–May 2008. The ERDC research team consisted of Haley Bell, Airfields and Pavements Branch (APB), GSL, and Billy Neeley, Joe Tom, Brian Green, Rudy Andreatta, Kirk Walker, Byron Sherwin, and Dan Wilson, Concrete and Materials Branch, GSL. Bell prepared this publication under the supervision of Dr. Gary L. Anderton, Chief, APB; Dr. Larry N. Lynch, Chief, Engineering Systems and Materials Division; Dr. William P. Grogan, Deputy Director, GSL; and Dr. David W. Pittman, Director, GSL.

COL Gary E. Johnston was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

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Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
inches	0.0254	meters
kips (force) per square inch	6.894757	megapascals
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms
square feet	0.09290304	square meters

1 Introduction

Background

The U.S. Air Force Civil Engineer Support Agency (AFCESA) airfield pavement evaluation teams are tasked with providing accurate field assessments of rigid pavement load-carrying capability. Pavement evaluation results provide critical information needed by major command engineers for operations planning and optimization of rehabilitation strategies. The flexural strength, or bending strength, has been identified as an adequate measurement of concrete because it characterizes the strength under the state of stress that the concrete experiences under typical field loading conditions (Yuan et al. 2006).

Currently, the AFCESA airfield pavement evaluation teams remove core samples from rigid pavement for use in determining flexural strength. The concrete core samples are broken using splitting tensile tests (ASTM C 496/C 496M-04), and flexural strength is determined using a correlation between splitting tensile strength and flexural strength. This process of obtaining flexural strength is costly, time-consuming, destructive, and may not be representative of the entire pavement feature.

The portable seismic pavement analyzer (PSPA) has been used as a means of nondestructively determining Portland cement concrete (PCC) strength parameters. The PSPA measures the in situ pavement modulus of PCC or asphalt concrete (Figure 1). AFCESA airfield pavement evaluation teams currently utilize the PSPA on rigid pavements in addition to taking core samples.

This research was a continuation of a 2005 PSPA study. A mathematical model for estimating the flexural strength of in situ PCC using the PSPA-measured modulus was developed from the study (Bell 2006). The model was developed with laboratory data of past PSPA studies using only four aggregate types. The results from the 2005 project supported the need to update the existing relationship by incorporating additional data of cast concrete slabs constructed using various aggregates with the existing data.

Figure 1. Operating the PSPA on an asphalt concrete test section.

Objective and scope

The focus of this project was to utilize results from field and laboratory testing to develop a stronger mathematical relationship between the PSPA-measured modulus and flexural strength of PCC. Cast PCC slabs constructed of various aggregates were formed and cured in the concrete materials laboratory at the U.S. Army Engineer Research and Development Center (ERDC). After curing, laboratory testing, including PSPA, flexural strength, and splitting tensile strength tests, was conducted on each slab. The test results were combined with existing PSPA data to develop an updated relationship between the PSPA-measured modulus and flexural strength. The objectives for this project are as follows:

- Update the correlation between seismic modulus measurements and concrete flexural strength.
- Determine the influence of the PSPA-measured modulus on concrete aggregates.
- Evaluate the variation of flexural strength obtained from the PSPA-measured modulus correlation and the splitting tensile strength correlation.

This report presents background information on the existing flexural strength prediction models, various properties of the aggregates used for the rigid pavement slabs, test procedures and results, data analysis, conclusions, and recommendations for future use of the updated PSPA-measured modulus and flexural strength correlation.

2 Research Approach

The following paragraphs present the general approach for improving the existing correlation between the PSPA-measured modulus and laboratory-determined flexural strength. The test procedures are presented in more detail in Chapter 4. Figure 2 presents a flowchart of the procedure.

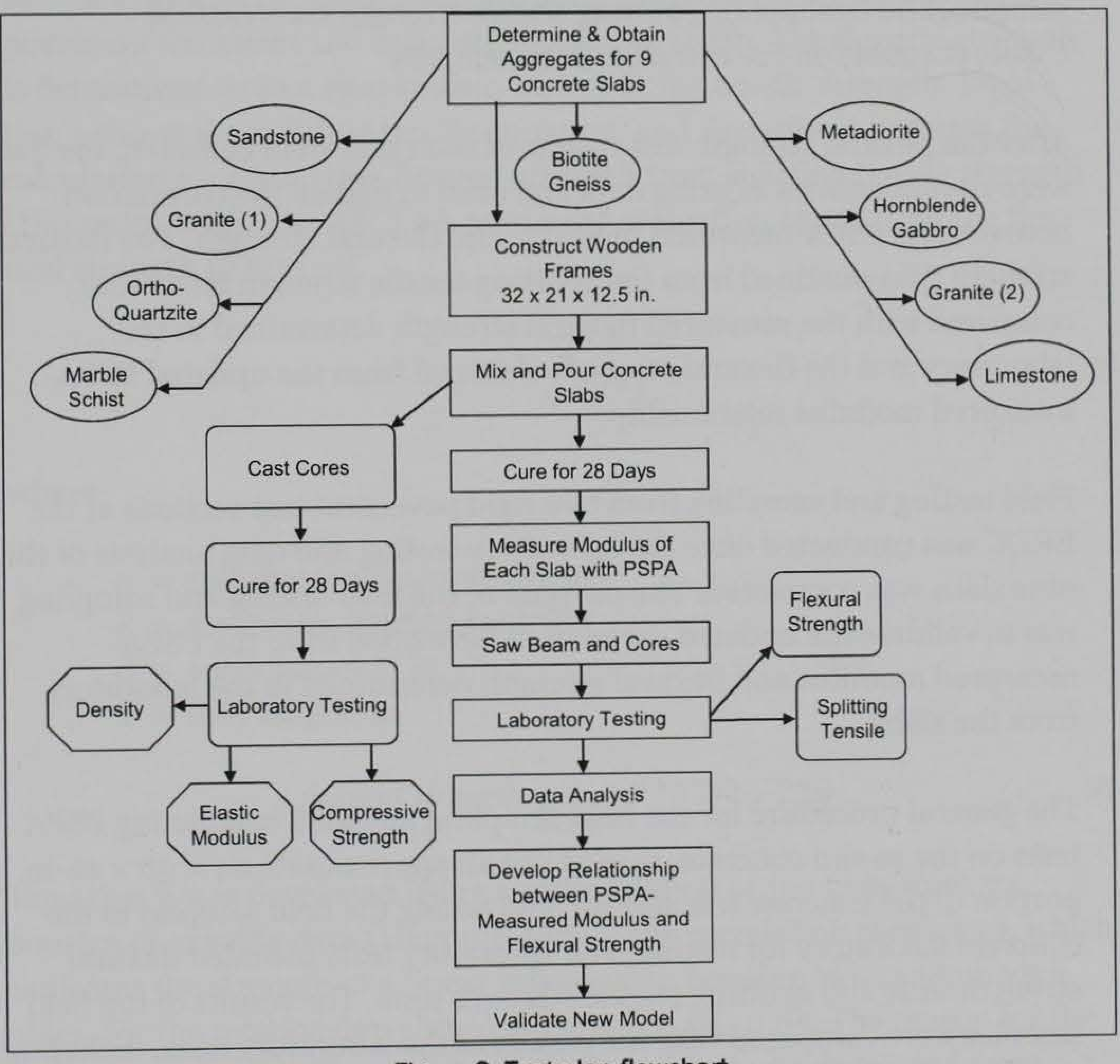

Figure 2. Test plan flowchart.

The general approach to this project was to evaluate the PSPA-measured modulus of representative PCC slabs using small-scale laboratory testing. Nine 32 × 21 × 12.5-in. concrete slabs were constructed using various-strength aggregate mixtures. The PCC was mixed in a rotating barrel and formed in wooden frames lined with spray oil. Additionally, three core specimens of each mixture were cast separately for laboratory testing. The slabs and cast cores were cured for 28 days. The procedures outlined in ASTM C 192/C 192M were followed for the mixing and curing of the concrete test specimens. The moduli of the rigid pavement slabs were then determined using the PSPA. Next, four beams and three cores were extracted from each slab for laboratory testing. The laboratory testing included determining the compressive strength (ASTM C 39/C 39M), density (ASTM C 127), and elastic modulus (ASTM E 1876) of the cast cores, conducting flexural strength tests (ASTM C 78) on the extracted beam samples, and conducting splitting tensile strength tests (ASTM C 496/C 496M) on the extracted core samples.

After the flexural strength test results of each slab were collected, the data were combined with existing data and used to update the correlation between the PSPA-measured modulus and flexural strength. The flexural strength data obtained from the splitting tensile strength tests were compared with the measured flexural strength determined in the laboratory and the flexural strength obtained from the updated PSPA-measured modulus relationship.

Field testing and sampling from two rigid pavement test sections at the ERDC was conducted once the laboratory testing and data analysis of the nine slabs was completed. The purpose of the field testing and sampling was to validate the updated correlation developed from the PSPA-measured modulus and flexural strength determined in the laboratory from the slabs.

The general procedure for the field sampling included conducting PSPA tests on the in situ concrete, sawing out an approximate 24 × 36 × 12-in. portion of the concrete test section, and taking the field samples to the concrete laboratory for testing. The laboratory tests included flexural strength tests and splitting tensile strength tests. The results of the field samples were compared with the results of the laboratory tests, including the newly developed model.

3 Existing Flexural Strength Prediction Models

Splitting tensile strength

The AFCESA airfield pavement evaluation teams obtain concrete core samples from airfield pavements to determine and/or verify the surface pavement thickness and calculate flexural strength. The flexural strength is determined from a relationship with splitting tensile strength. Equation 1 shows the splitting tensile equation, and Equation 2 presents the calculation for estimating flexural strength from splitting tensile strength (Hammitt 1974). The AFCESA pavement evaluation teams limit the flexural strength to 800 psi.

$$\sigma = \frac{2 * P}{\pi * d * l} \quad (1)$$

where

σ = splitting tensile strength, psi
P = maximum applied load, lb_f
d = core diameter, in.
l = core length, in.

$$\mathit{flexural\ strength,\ psi} = \sigma * 1.02 + 210 \quad (2)$$

Equation 2 was developed using a consolidation of 199 tests from six sources of existing data (Hammitt 1974). The correlation coefficient, which indicates the strength of a linear relationship between two random variables, for the relationship shown in Equation 2 is 0.85. The reason for the high correlation coefficient is because Equation 2 was developed from rigid pavement samples that were constructed of similar concrete properties using similar procedures (Hammitt 1974). The similar properties of the concrete mixtures used to develop the model are unknown. Based on the information contained in Hammitt's report, it is appropriate to say that the relationship shown in Equation 2 may not accurately represent all pavement types. It is important to note that there are several factors (i.e., pavement age, air entrainment, curing, aggregate grading, etc.) that affect the relationship of concrete strengths (Hammitt 1974). This makes it difficult to develop and apply a simple relationship between two concrete strength tests.

Figure 3 shows the plot used to develop the regression shown in Equation 2. Again, Figure 3 was developed from data of concrete with similar properties. Figure 4 is a revised plot of Figure 3. The data in Figure 4 include the nine data points from the laboratory-prepared slabs and two data points from the field samples used for the current PSPA study. Although there were only eleven data points added to the existing 199 data points, the margin of error was increased (the R value decreased). The margin of error increased because data of differing concrete properties were added to existing data that had similar concrete properties. This demonstrates how difficult it is to develop a relationship between varying types of concrete. Furthermore, this reiterates the fact that Equation 2 may not be accurate for all pavement types.

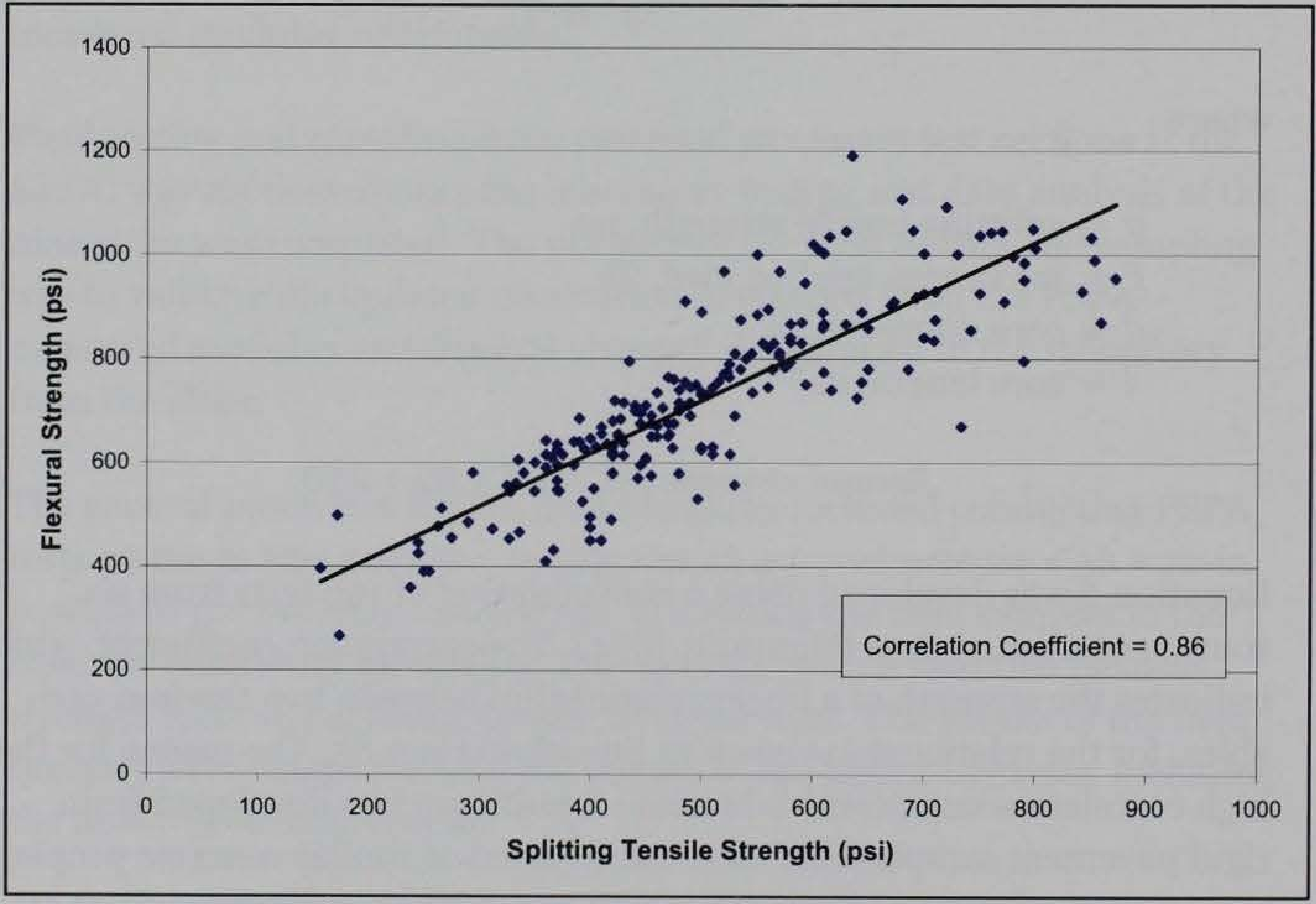

Figure 3. Relationship between splitting tensile strength and flexural strength developed by Hammitt.

Generally, the AFCESA airfield pavement evaluation teams remove one or two concrete core specimens per airfield feature; however, as many as 10 or 15 samples have been extracted (per feature) during specific

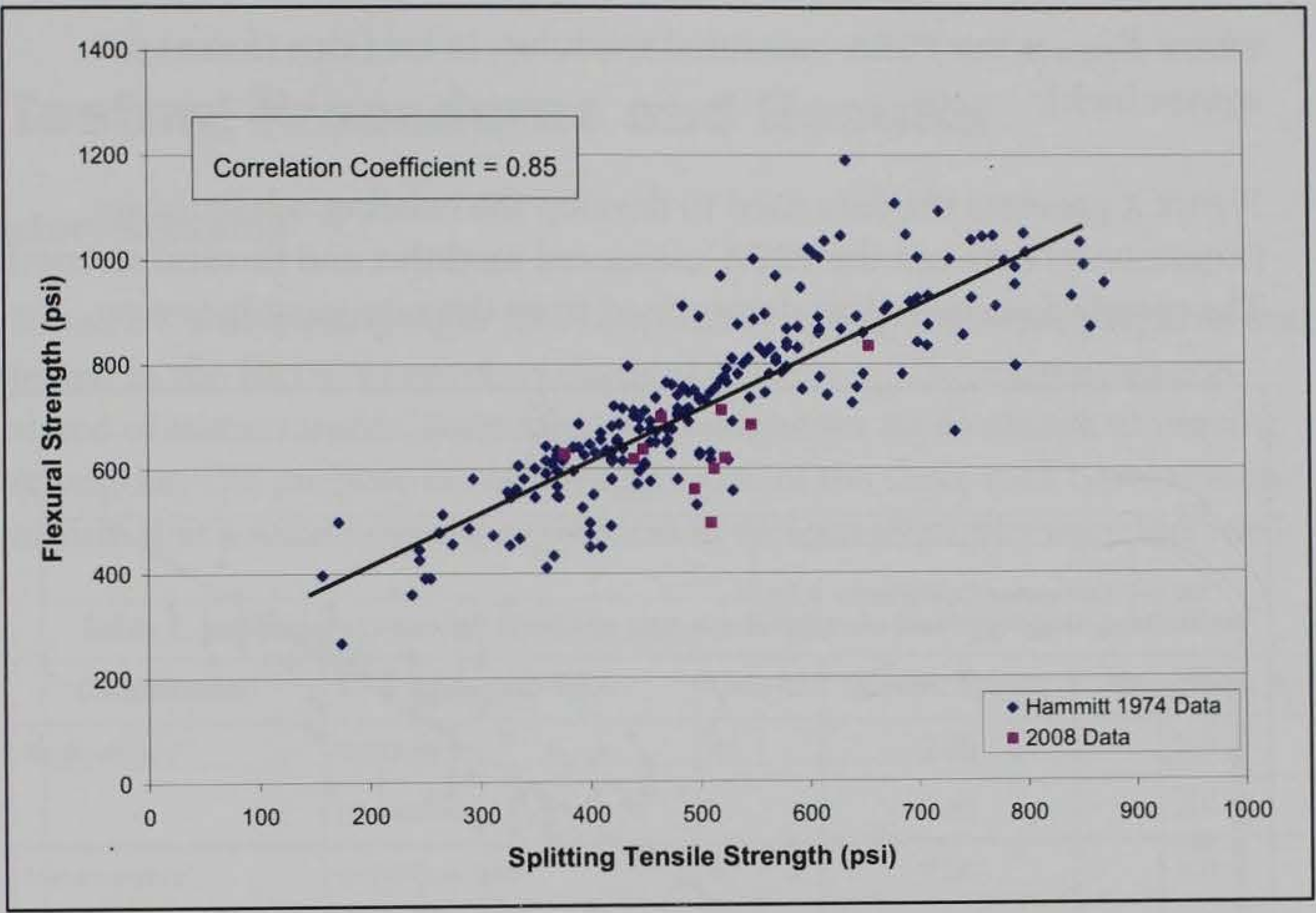

Figure 4. Current data added to existing correlation between splitting tensile strength and flexural strength.

instances. The number of core samples extracted per feature depends on the feature size and preexisting airfield pavement evaluation data. The few samples are used to represent an entire pavement feature, which can easily be 600,000 ft^2 or more. If only one concrete specimen is obtained per feature, then there are generally no test repeats to use for averaging the splitting tensile strengths. There really is no means for verifying the accuracy of the data. Nonetheless, the test result is used to estimate the flexural strength of the pavement feature.

PSPA-measured modulus

The U.S. Army Corps of Engineers' airfield pavement evaluation program presently uses the PSPA to estimate and/or validate the flexural strength of rigid airfield pavements. This flexural strength is currently computed from a relationship with the PSPA-measured modulus (Equation 3). The model was developed in 2006 from laboratory data of four aggregates at varying strengths of past PSPA studies (Bell 2006). The flexural strength is measured in units of psi [pounds (force) per square inch].

$$flexural\ strength = 0.12 * E_{PSPA} \qquad (3)$$

where E_{PSPA} is the PSPA-measured modulus, in ksi [kips (force) per square inch].

Figure 5 presents the data used to develop the existing relationship (Equation 3) between the PSPA-measured modulus and flexural strength. The correlation coefficient determined from the relationship is 0.73.

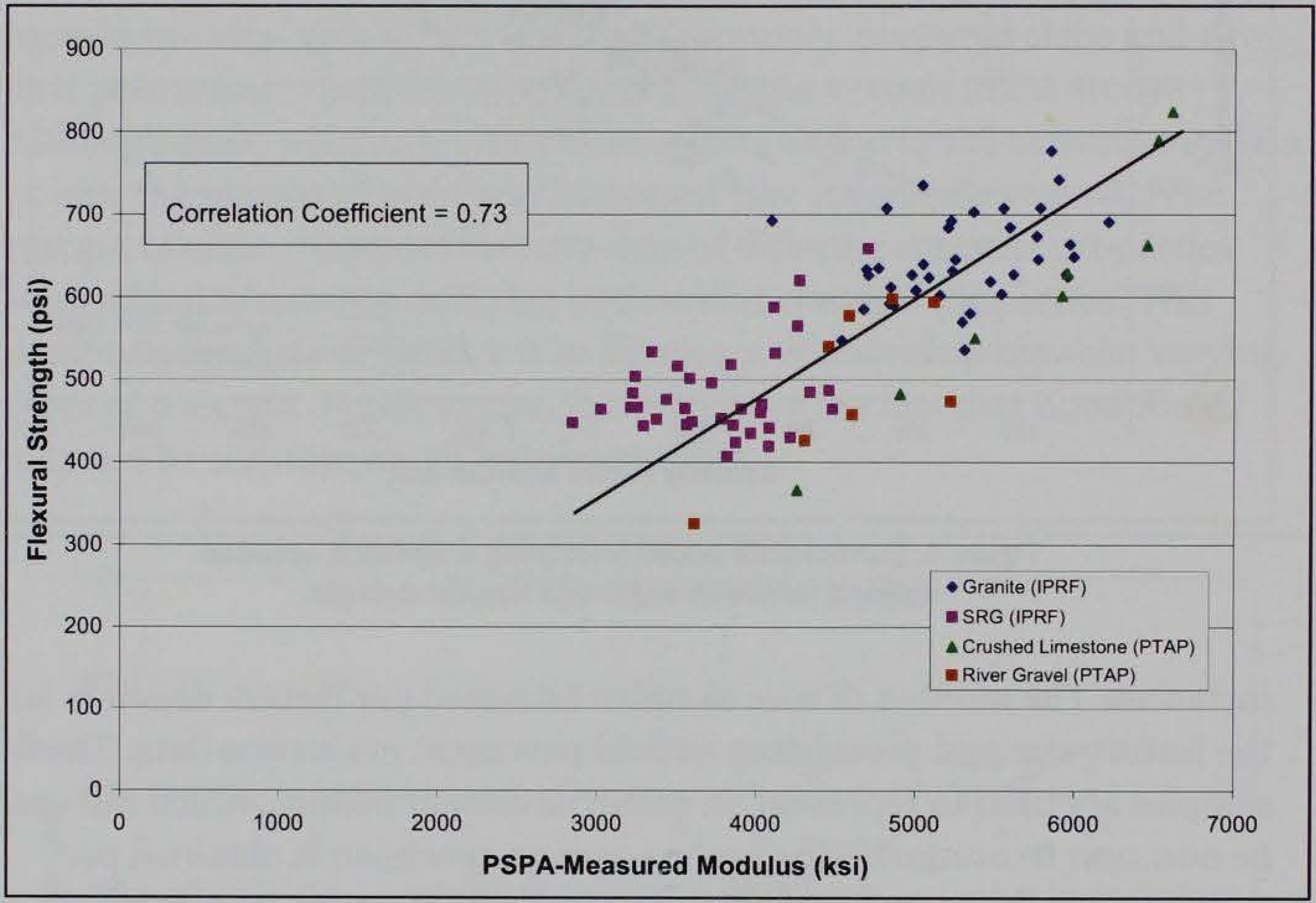

Figure 5. Existing correlation between PSPA-measured modulus and flexural strength.

The data used to develop the relationship shown in Figure 5 come from the 1996 Pavement Technical Assistance Program (PTAP) and the 2005 Innovative Pavement Research Program (IPRF) PSPA-related projects. The PTAP study was a combined field and laboratory study conducted to evaluate the capabilities of the PSPA and to develop test procedures and relationships for the determination of PCC flexural strength for use in pavement evaluations. The IPRF study was a laboratory study conducted to implement seismic testing as an acceptance criterion for concrete airfield pavement construction (Yuan et al. 2006). More information about the previous PSPA studies can be found in (Bell 2006). The PSPA-measured data for both studies can be found in Chapter 5.

4 Testing Procedures and Results

Laboratory samples

Nine PCC slabs, using eight different coarse aggregates, were prepared and tested in the ERDC's concrete laboratory (Table 1). The aggregates consisted of metamorphic, sedimentary, and igneous types of rock at varying strengths. The purpose of testing aggregate of the three rock types was to ensure that a wide range of aggregates of various strengths were included.

Table 1. Laboratory-prepared concrete slab nomenclature and aggregate properties.

Classification	Aggregate Type	Slab ID	Specific Gravity	Absorption, %
Sedimentary	Sandstone	A	2.60	1.3
	Limestone	I	2.33	3.6
Metamorphic	Ortho-Quartzite	B	2.50	2.0
	Marble Schist	C	2.86	0.3
	Biotite Gneiss	E	2.72	0.4
Igneous	Granite	D	2.61	0.6
	Metadiorite	F	2.93	0.4
	Hornblende Gabbro	G	2.94	0.5
	Granite	H	3.08	0.4

Sedimentary rocks are the most common of the three rock types. They are formed from sediments such as gravel, sand, silt, and clay that become compacted by the process of lithification. Metamorphic rocks are formed from existing rocks through excessive heat and pressure. Igneous rocks are formed from the solidification of cooled molten rock, or magma, from beneath the Earth's surface. The magma is typically ejected by volcanic eruption (Das 2002).

The specific gravities listed in Table 1 are the ratio of the aggregate's unit weight to the unit weight of water, or a comparison of its density to that of water. Absorption is defined as the percentage increase in mass of an aggregate after being submerged in water for a given amount of time (American Society for Testing and Materials 2007).

Table 2 presents the properties measured during construction of the concrete slabs. The water-cement ratio was 0.42, and the batch size was approximately 6.3 ft^3 for each slab.

Figures 6 through 17 show the general procedure for preparing and testing each concrete slab. Each aggregate, admixtures, water, etc. were poured into a rotating barrel where they were mixed for 3 min, at rest for 2 min, and mixed again for 2 min (ASTM C 192/C 192M). Once the mixing was complete, a slump test was performed to indirectly measure the concrete's quality and workability. The samples were cured for 28 days in a fog room set at 73°F.

On day 29, each sample was tested with the PSPA where the in situ modulus was estimated. The PSPA was tested three times in each direction (longitudinal, lateral, and diagonal) on each slab for a total of nine measurements. This ensured that an accurate estimate was achieved. The PSPA was set to the following properties: 12 in. thick, Good PCC, Cured, Poisson's Ratio = 0.18, and Density = 150 pcf. Table 3 presents the average PSPA-measured modulus results.

After PSPA testing, the slabs were covered with burlap and moistened with water until the extraction of the beam and core specimens. Four beam specimens and three core specimens were extracted from each cured slab sample. The beams, 21 × 6 × 6 in., were used for flexural strength testing (ASTM C 78). The 6-in.-diam cylindrical specimens were used for splitting tensile strength testing (ASTM C 496/C 496M). The results are presented in Table 3. The splitting tensile strength results were used to predict the flexural strength determined from Equation 2. The flexural strength results from Equation 2 were compared with the flexural strength results determined from the beams tests and to the flexural strength results determined from the newly developed regression using the PSPA-measured modulus.

The elastic modulus (ASTM E 1876), density (ASTM C 127), and compressive strength (ASTM C 39/39M) were then determined from the three cast concrete specimens of each mixture. The elastic moduli for each mixture were determined in compression. The average results (two to three repeats per test) of each slab mixture are presented in Table 4.

Table 2. Concrete slab mixture properties.

Slab ID	Aggregate Type	Portland Cement lb/ft³	Fine Aggregate lb/ft³	Coarse Aggregate lb/ft³	Water lb/ft³	Sand to Total Aggregate Ratio, %	Water-Reducing Admixture fl oz/ft³	Air-Entraining Admixture fl oz/ft³	Mortar Content ft³	Air Content %	Slump in.	Unit Weight lb/ft³	Yield ft³
A	Sandstone	22	44	66	9	40.0	0.87	0.16	15.95	6.0	1.75	142.0	6.3
B	Ortho-Quartzite	25	38	65	10	36.0	0.98	0.29	15.76	5.3	2.00	140.0	6.4
C	Marble Schist	22	41	73	10	38.0	0.87	0.16	16.00	4.3	2.00	149.2	6.2
D	Granite	25	39	65	11	38.0	0.98	0.29	16.35	5.5	2.25	140.4	6.3
E	Biotite Gneiss	22	39	67	11	38.0	0.87	0.16	16.35	5.8	2.50	141.2	6.4
F	Metadiorite	25	39	72	11	38.0	0.98	0.29	16.35	5.1	2.00	148.8	6.3
G	Hornblende Gabbro	22	40	73	10	38.0	0.87	0.16	16.23	5.9	2.75	148.4	6.3
H	Granite	25	34	81	11	33.4	0.98	0.29	15.60	5.6	2.75	150.8	6.4
I	Limestone	22	38	59	11	36.3	0.87	0.16	15.97	6.1	3.00	130.6	6.4

Figure 6. Pouring aggregate into the mixing barrel.

Figure 7. Performing a slump test on a concrete mixture.

Figure 8. Pouring a concrete mixture into a wooden frame.

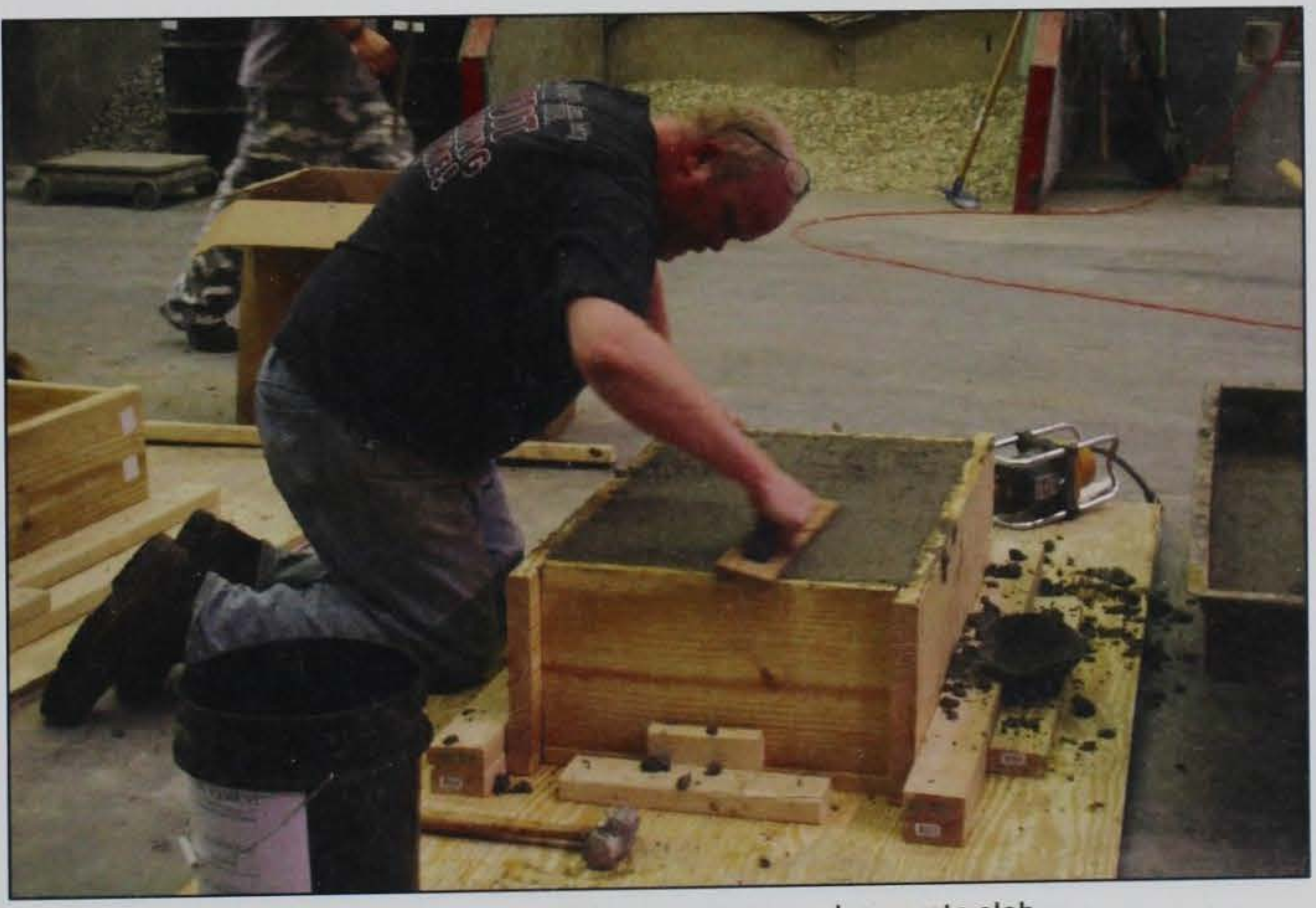

Figure 9. Finishing a laboratory-prepared concrete slab.

Figure 10. Keeping slabs moist before transporting to the fog room.

Figure 11. Samples curing in fog room.

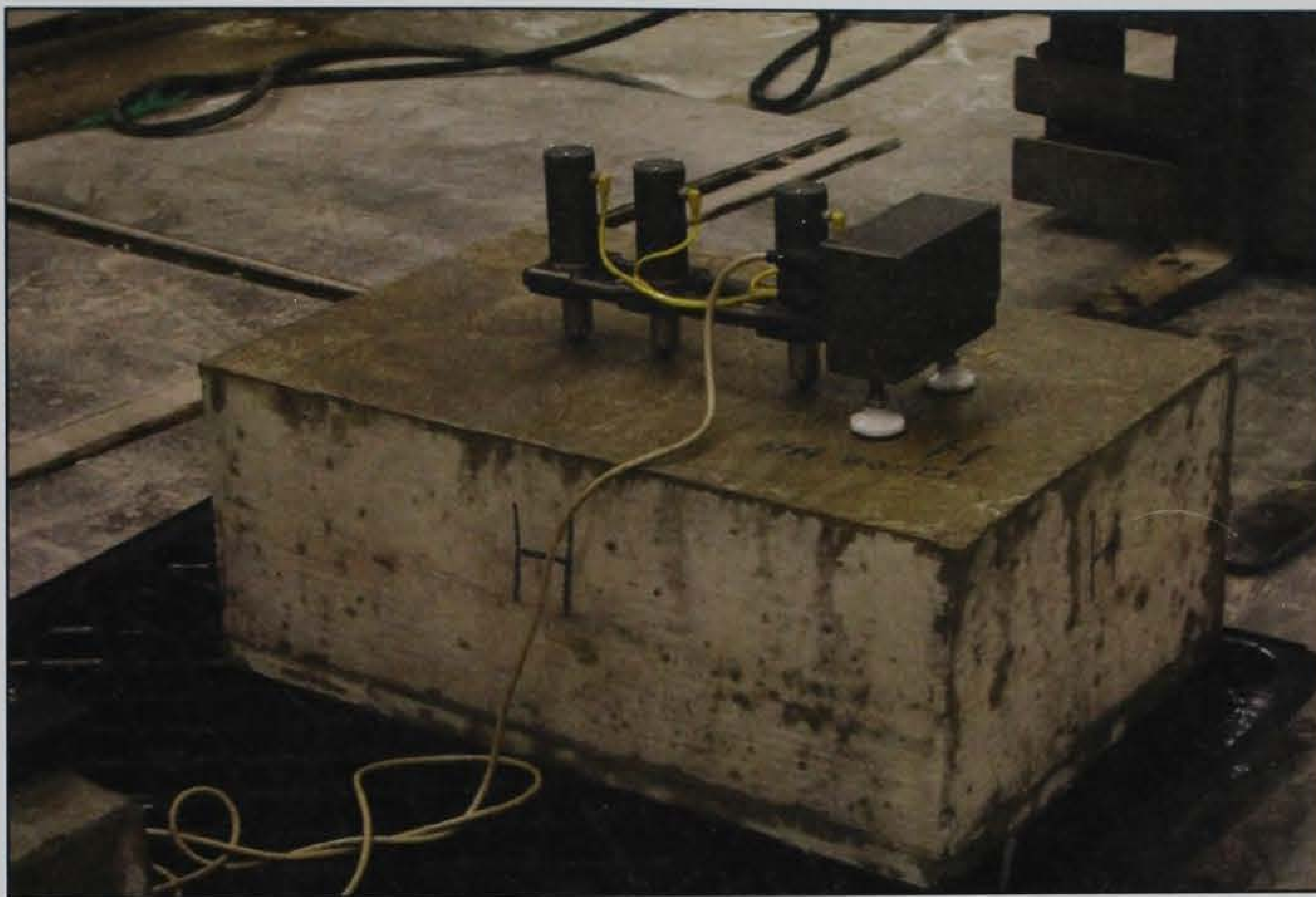

Figure 12. PSPA testing on a cured PCC slab.

Figure 13. Sawing cylindrical specimens for splitting tensile strength testing.

Figure 14. Sawing beam specimens for flexural strength testing.

Figure 15. Keeping beam specimens moist before flexural strength testing.

Figure 16. Measuring a core sample before splitting tensile strength testing.

Figure 17. Core sample after splitting tensile strength testing.

Table 3. Laboratory test results.

Slab ID	Aggregate Type	Average PSPA-Measured Modulus, ksi	Splitting Tensile Strength, psi			Flexural Strength, psi			
A	Sandstone	2567	555	500	485	470	710	625	590
B	Ortho-Quartzite	3560	470	550	510	470	700[a]	420	595
C	Marble Schist	4560	445	395	480	580	580	600	710
D	Granite	2699[1]	435	485	475	660	645	685	800
E	Biotite Gneiss	5553	405	470	470	595	660	645	645
F	Metadiorite	5519	530	550	490	545	665	620	650
G	Hornblende Gabbro	5096	470	560	530	695	695	705	750
H	Granite	4558	480	545	460	595	745[a]	525	560
I	Limestone	3524	365	355	410	655	635	615	605

[1] Statistically identified as an outlier according to the procedure outlined in ASTM E 178-02; removed from data set.

Table 4. Average cast specimen test results.

Slab ID	Aggregate Type	Elastic Modulus ksi	Compressive Strength, psi	Density, lb/ft³
A	Sandstone	4200	6183	145.4
B	Ortho-Quartzite	4030	6350	141.5
C	Marble Schist	n/a[1]	5905	149.5
D	Granite	n/a[1]	6783	145.5
E	Biotite Gneiss	n/a[1]	6087	147.3
F	Metadiorite	6660	4530	153.5
G	Hornblende Gabbro	6207	4950	153.0
H	Granite	4300	5870	156.6
I	Limestone	2700	5837	138.3

[1] Test not completed due to failure of testing apparatus.

Field samples

After the laboratory testing was completed, two additional samples were extracted from two full-scale concrete test sections at the ERDC. The purpose of the field samples was to validate the updated model (PSPA-measured modulus to predict flexural strength) developed from the laboratory data. Also, the field samples were extracted so that the field test results could be compared with the laboratory test results.

One field sample (Slab K) was constructed of 12 in. of 5,000-psi (compressive strength) concrete in 2006. The second field sample (Slab J) was also constructed of 12 in. of 5,000-psi concrete in 2007. Both were constructed by the same commercially available vendor and were intended to be the same mixture. For these field samples, the PSPA was tested on the in situ concrete using three test repeats at the same location. After the PSPA testing, the samples (approximately 2 × 3 ft) were extracted and delivered to the concrete laboratory for additional testing. Splitting tensile strength tests were completed on three 6-in.-diam core specimens, and flexural strength tests were completed on four beam specimens for each field sample (Table 5).

Table 5. Field samples test results.

Slab ID	Average PSPA-Measured Modulus, ksi	Splitting Tensile Strength, psi			Flexural Strength, psi			
J	5270	575	555	510	650	680	640	760
K	5423	660	490[1]	650	875	885	790	785

[1] Statistically identified as an outlier according to the procedure outlined in ASTM E 178-02; removed from data set.

Slabs J and K were constructed of the same type of concrete; however, they were not constructed at the same time. Slab K is 1 year older than Slab J. After 29 days of curing, the average flexural strength of Slab K was determined to be about 619 psi based on laboratory data provided by the project manager of the field site. Two years later, the flexural strength is averaging 834 psi. The average flexural strength after 1 year for Slab J is 683 psi; no early-age flexural strength data are available. The flexural strengths were determined in the same laboratory following the same procedures. Because the field samples were constructed of the same mixture by the same vendor but at different times, one would assume that Slab J and Slab K would have similar flexural strengths, with Slab K having a slightly higher strength.

5 Data Analysis

General

The first step for the data analysis was to combine the existing laboratory data that were used to develop the model shown in Equation 3 with the current laboratory data (Table 6). The data from the field samples (Barksdale AFB slab and Hangar 4 slab) of the 2006 PSPA study were also added to the existing data. The PSPA-measured modulus values (Table 6) for the current study were an average of six to nine PSPA tests on each slab. The high number of PSPA test repeats was not necessary; however, it was important to be sure the estimated modulus was consistent. Typically, three PSPA test repeats are the norm (Bell 2006). The laboratory-measured flexural strength values shown in Table 6 were an average of three to four flexural strength tests per slab. Some of the PSPA studies tested three samples, while the others tested four samples.

Table 6. Data from past and current PSPA studies.

PSPA Study	Aggregate Type	PSPA-Measured Modulus, ksi	Laboratory-Measured Flexural Strength, psi
1996 Pavement Technical Assistance Program	River Gravel (Low)	3610	325
	River Gravel (Low)	4304	426
	River Gravel (Low)	4602	458
	River Gravel (Low)	5220	474
	River Gravel (High)	4453	540
	River Gravel (High)	4582	578
	River Gravel (High)	4853	598
	River Gravel (High)	5115	594
	Cr Limestone (Low)	4258	366
	Cr Limestone (Low)	4904	483
	Cr Limestone (Low)	5373	550
	Cr Limestone (Low)	5920	601
	Cr Limestone (High)	5953	629
	Cr Limestone (High)	6456	663
	Cr Limestone (High)	6522	789
	Cr Limestone (High)	6610	824

PSPA Study	Aggregate Type	PSPA-Measured Modulus, ksi	Laboratory-Measured Flexural Strength, psi
2005 Innovative Pavement Research Program	Granite	4504	693
	Granite	5772	645
	Granite	5754	632
	Granite	5743	692
	Granite	6832	691
	Granite	5899	703
	Granite	6149	684
	Granite	6432	777
	Granite	5821	570
	Granite	5590	623
	Granite	6106	707
	Granite	5546	735
	Granite	5319	592
	Granite	5667	602
	Granite	6174	627
	Granite	6334	673
	Granite	4989	547
	Granite	5326	612
	Granite	5159	633
	Granite	5296	707
	Granite	5242	635
	Granite	5723	684
	Granite	6359	708
	Granite	6486	742
	Granite	5345	590
	Granite	6092	603
	Granite	5500	608
	Granite	6549	625
	Granite	6014	619
	Granite	6538	627
	Granite	6345	645
	Granite	6592	648
	Granite	5837	536

PSPA Study	Aggregate Type	PSPA-Measured Modulus, ksi	Laboratory-Measured Flexural Strength, psi
	Granite	5875	580
	Granite	6565	663
	Granite	5473	627
	Granite	5171	627
	Granite	5139	585
	Granite	5551	640
	SRG	3906	465
	SRG	4090	496
	SRG	3709	452
	SRG	4683	565
	SRG	4696	620
	SRG	4519	588
	SRG	3532	466
	SRG	3563	504
	SRG	3621	444
	SRG	3576	466
	SRG	3545	484
	SRG	3675	534
	SRG	3852	516
	SRG	3918	446
	SRG	3956	449
	SRG	3326	464
	SRG	3131	448
	SRG	3778	476
	SRG	4239	445
	SRG	4256	424
	SRG	4488	442
	SRG	4294	465
	SRG	4435	470
	SRG	4769	485
	SRG	3940	502
	SRG	4359	435
	SRG	4924	465

PSPA Study	Aggregate Type	PSPA-Measured Modulus, ksi	Laboratory-Measured Flexural Strength, psi
	SRG ·	4430	460
	SRG	4528	532
	SRG	5169	659
	SRG	4156	453
	SRG	4222	518
	SRG	4633	430
	SRG	4197	407
	SRG	4484	419
	SRG	4902	487
Field data from the 2006 PSPA study	Hangar 4 Slab	5441	547
	Barksdale Slab	6046	814
Laboratory data from the 2008 PSPA study	Sandstone	2567	599
	Ortho-Quartzite	3560	495
	Marble Schist	4560	618
	Granite (Slab D)	2699	698
	Biotite Gneiss	5553	636
	Metadiorite	5519	620
	Hornblende Gabbro	5096	711
	Granite (Slab H)	4558	560
	Limestone	3524	628

Identifying outliers

The data in Table 6 were used to develop the plot shown in Figure 18. Figure 18 is the flexural strength determined in the laboratory versus the PSPA-measured modulus. The data points, except for the two circled in red, generally hover near each other. The two data points circled in red were identified as possible outliers based on visual inspection of all the data points. Looking at the x-axis of Figure 18, the upper circled data point is from one of the granite slabs (Slab D), and the lower circled data point is from the sandstone slab (Slab A). Both data points were from the current study. These possible outliers were analyzed further using a statistical method for identifying outliers.

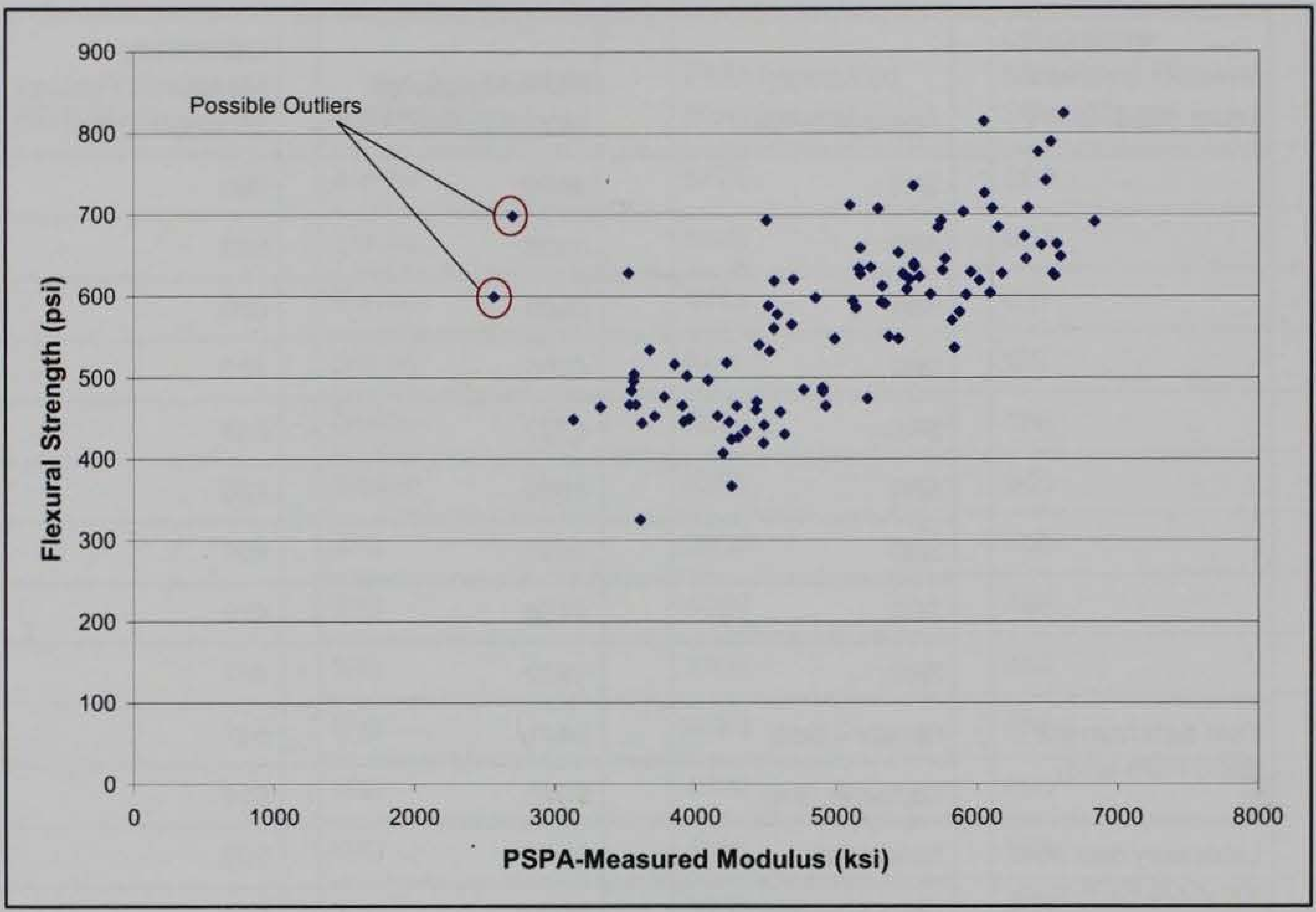

Figure 18. Flexural strength versus PSPA-measured modulus of all data points.

The statistical method used for validating the two possible outliers and identifying any additional outliers within the data set was the computations behind drawing box plots. Box plots are a means of showing several elements of a data set and visualizing outliers. Box plots show the smallest observation (minimum value), lower quartile (Q1), median, upper quartile (Q3), and the largest observation (maximum value) of the data set. Table 7 presents the computational test results of the PSPA-measured modulus values for identifying the outliers of the data presented in Table 6. The minimum and maximum values are compared with the minimum and maximum valid values, respectively. If the minimum value is lower than

Table 7. Test results for outlier verification.

Statistic	Limestone	Granite	River Gravel	All Data
Q1	4904	5326	3834	3834
Min	3524	2699	3131	3131
Median	5920	5754	4275	5115
Max	6610	6832	5220	6832
Q3	6456	6174	4587	5797
Min Valid	2576	4054	2704	1995
Max Valid	8783	7446	5717	8078

the minimum valid value, then the data point is deemed an outlier. The same holds true if the maximum value is higher than the maximum valid value.

There were several data points from slabs constructed with limestone, granite, or river gravel coarse aggregates. The PSPA-measured modulus data from each of the three aggregate types were combined to determine if there were any unnoticeable outliers in the data set and to validate one of the two possible outliers (upper circled data point – Slab D) shown in Figure 18. There were no additional sandstone data to compare with Slab A; therefore, the sandstone data point was computed with the entire data set.

Based on the minimum value (Min) and the minimum valid value (Min Valid), the only outlier noted was a slab constructed with the granite aggregate. This data point is from Slab D of the current study. The data associated with Slab D were removed from the data set.

After the outlier within the granite data was identified and removed, all of the existing data were combined to determine if there were any outliers within the entire data set. Based on the Min Valid and Max Valid values shown in Table 7, it was determined that there were no outliers when observing the entire data set. Therefore, the sandstone slab (Slab A) was not deemed an outlier and remained in the data set.

Newly developed regression

Once the outlier from the granite slab was removed, the data were plotted as shown in Figure 19, and a new mathematical model for predicting flexural strength from the PSPA test was developed (Equation 4). Flexural strength is measured in units of psi, and the PSPA-measured modulus, E_{PSPA}, is in units of ksi.

$$\textit{Flexural Strength} = 0.08 * E_{PSPA} + 173 \quad (4)$$

Table 8 presents the statistical results of the linear regression analysis (Table 6 data minus the outlier). Significance is judged by the P-value, which is the probability of being incorrect if the independent variable (in this case, the PSPA-measured modulus) is identified as contributing significantly to the prediction of the dependent variable (flexural strength). Generally, independent variables with P-values less than 0.05 (5%) are

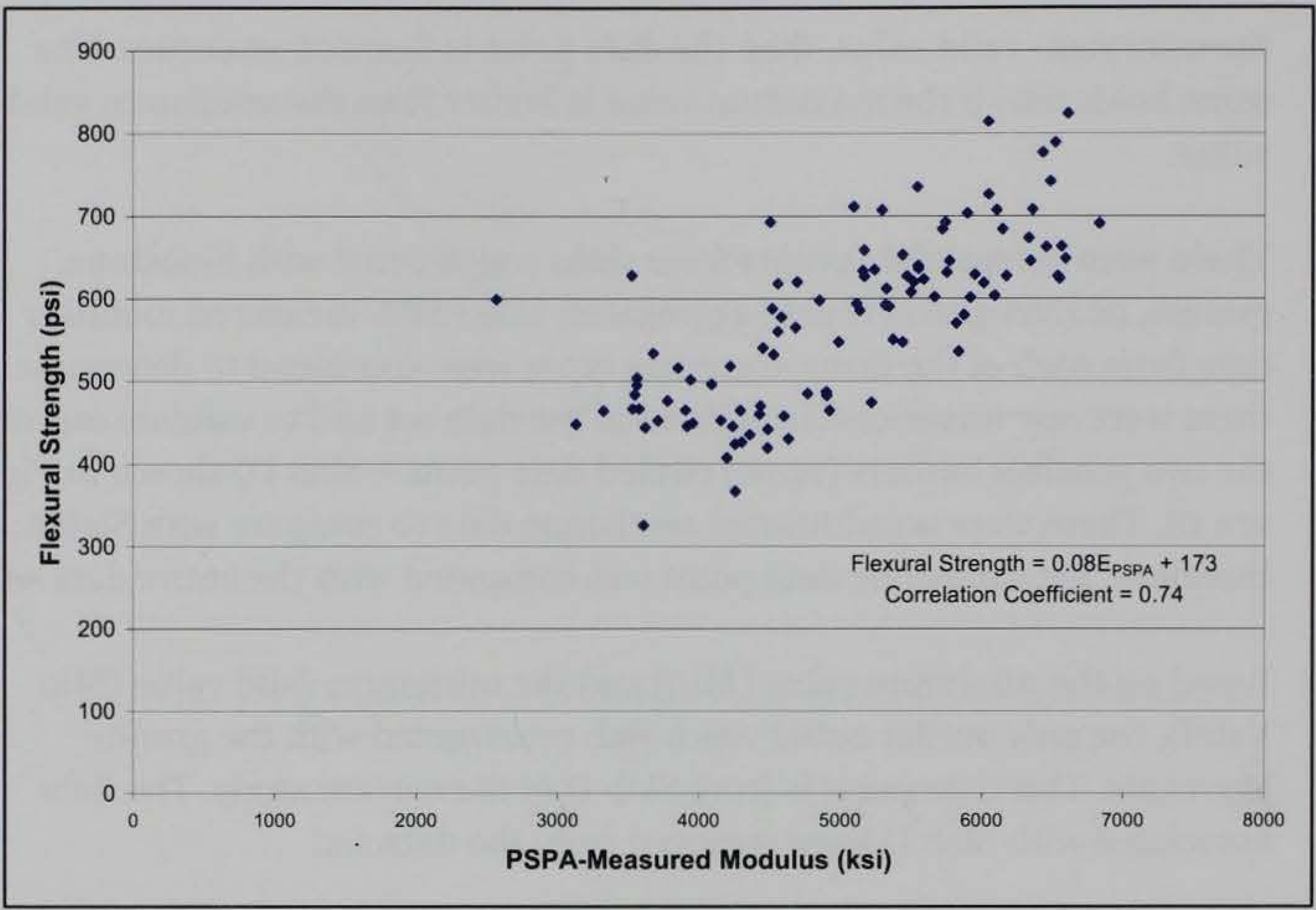

Figure 19. Regression plot for predicting flexural strength from PSPA-measured modulus.

Table 8. Summary output of regression analysis.

Regression Statistics	
Multiple R	0.744
R Square	0.553
Adjusted R Square	0.549
Standard Error	70.340
Observations	103.000

ANOVA

	df	SS	MS	F	Sig. F
Regression	1	618077	618077.1	124.923	2.329E-19
Residual	101	499713	4947.7		
Total	102	1117790			

	Coefficients	Std. Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	173.045	36.4443	4.748	6.790E-06	100.749	245.341
X Variable 1	0.080	0.0071	11.177	2.329E-19	0.066	0.094

considered worthy of including in the regression model. The regression analysis showed that the PSPA-measured modulus (X Variable 1) was significant in predicting flexural strength.

The regression analysis also shows that the R^2 value is 0.55, and the Multiple R (correlation coefficient) is 0.74. The R^2 value is the coefficient of determination, which provides a measure of the amount of response variability explained by the model (Younger 1979). An R^2 of 0.55 is acceptable considering the variability of the concrete properties of the data set.

There was a slight improvement with the newly developed relationship. The correlation coefficient for the current relationship (Equation 3) was 0.73, and the correlation coefficient for the newly developed relationship (Equation 4) is 0.74; the R^2 value increased from 0.53 to 0.55. It was not surprising that there was only a slight improvement over the existing relationship considering the variation of the laboratory-prepared PCC slab mixtures and the small number of additional data points. Again, the model shown by Equation 3 was developed from four aggregates at varying strengths. The model shown in Equation 4 was developed from 10 aggregates at various strengths.

Influence of PSPA testing with aggregate type

One of the objectives of this study was to determine the influence of the PSPA-measured modulus on the type of coarse aggregate used in a rigid concrete pavement. The data of the PCC slabs mixed with limestone, granite, and river gravel were individually examined to determine if the aggregate type had a direct influence on the PSPA-measured modulus. The other types of aggregate included in this study could not be examined individually because there were not multiple data points of each.

Figure 20 shows a plot of the PSPA-measured modulus ranges for the PCC slabs constructed using limestone, granite, and river gravel aggregates. Each box depicts the normal range of PSPA-measured modulus values for the respective aggregate type. The red horizontal lines within each box are the data median values, and the black horizontal lines above and below each box represent the extreme values.

Figure 20 shows that the rigid pavement slabs constructed with limestone have the largest range of PSPA-measured modulus values when compared with the granite and river gravel slabs. The slabs constructed with river

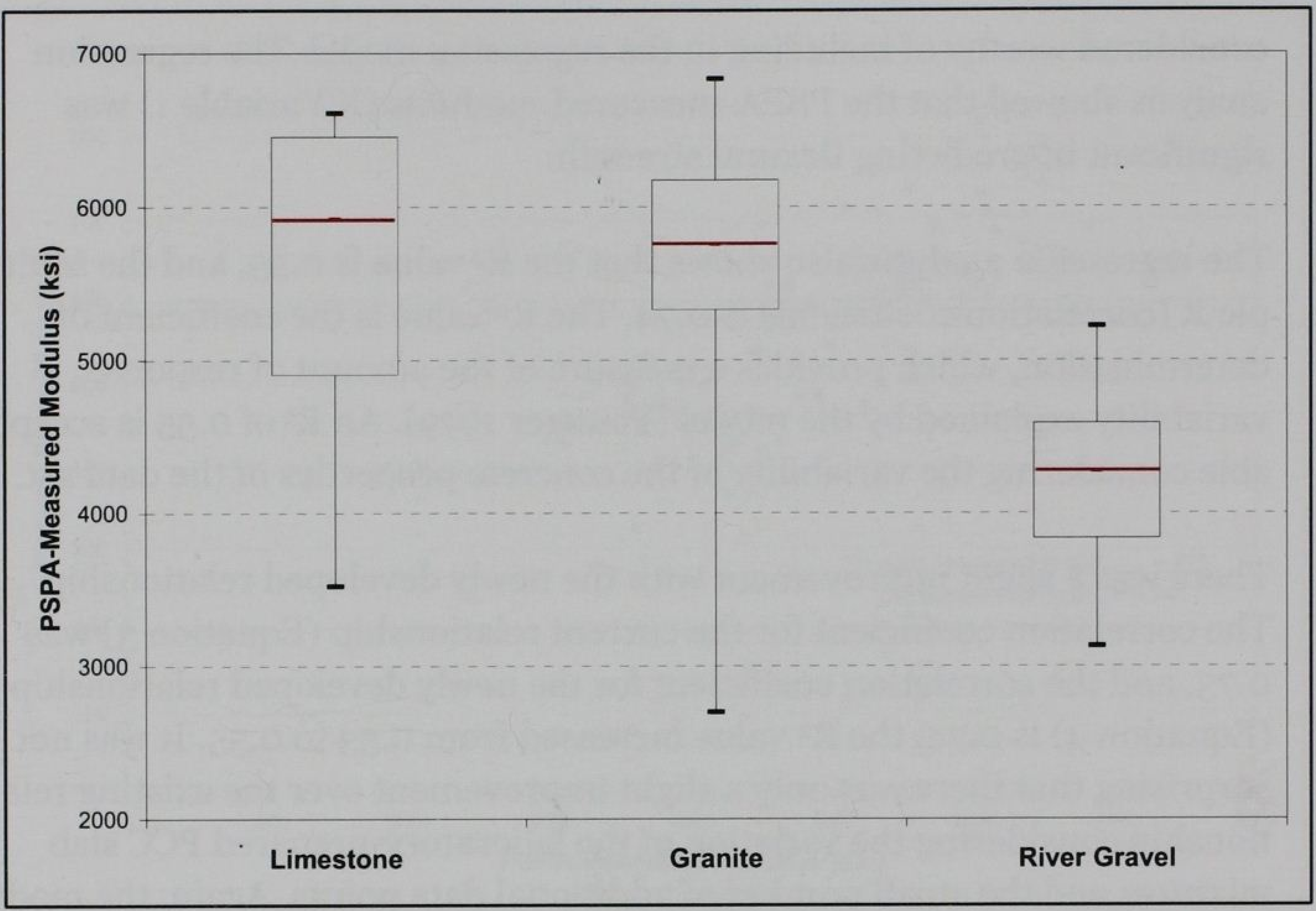

Figure 20. Box plot showing PSPA-measured modulus ranges of three aggregate types.

gravel have a smaller range of normal PSPA-measured modulus values, and the slabs are not as stiff as those constructed using limestone or granite aggregate.

Figures 21, 22, and 23 were completed to determine if an individual regression for predicting flexural strength based on each aggregate type used for a concrete pavement were stronger than the model shown in Equation 4. The correlation coefficients associated with each coarse aggregate type were relatively low, especially when compared with the correlation coefficient of the newly developed regression (Equation 4).

Figures 21, 22, and 23 show that the aggregate type alone does not have a direct influence on the PSPA-measured modulus of a rigid pavement. According to the results, individual regressions based on the aggregate type used in a rigid pavement will not predict a more accurate flexural strength than the regression shown in Equation 4. Limestone aggregate is the most promising, however (Figure 21). If the data point at a modulus of 3,500 psi and a flexural strength of 625 psi was removed, the regression would be much stronger. However, there was no reason to remove the data point; it was not considered an outlier.

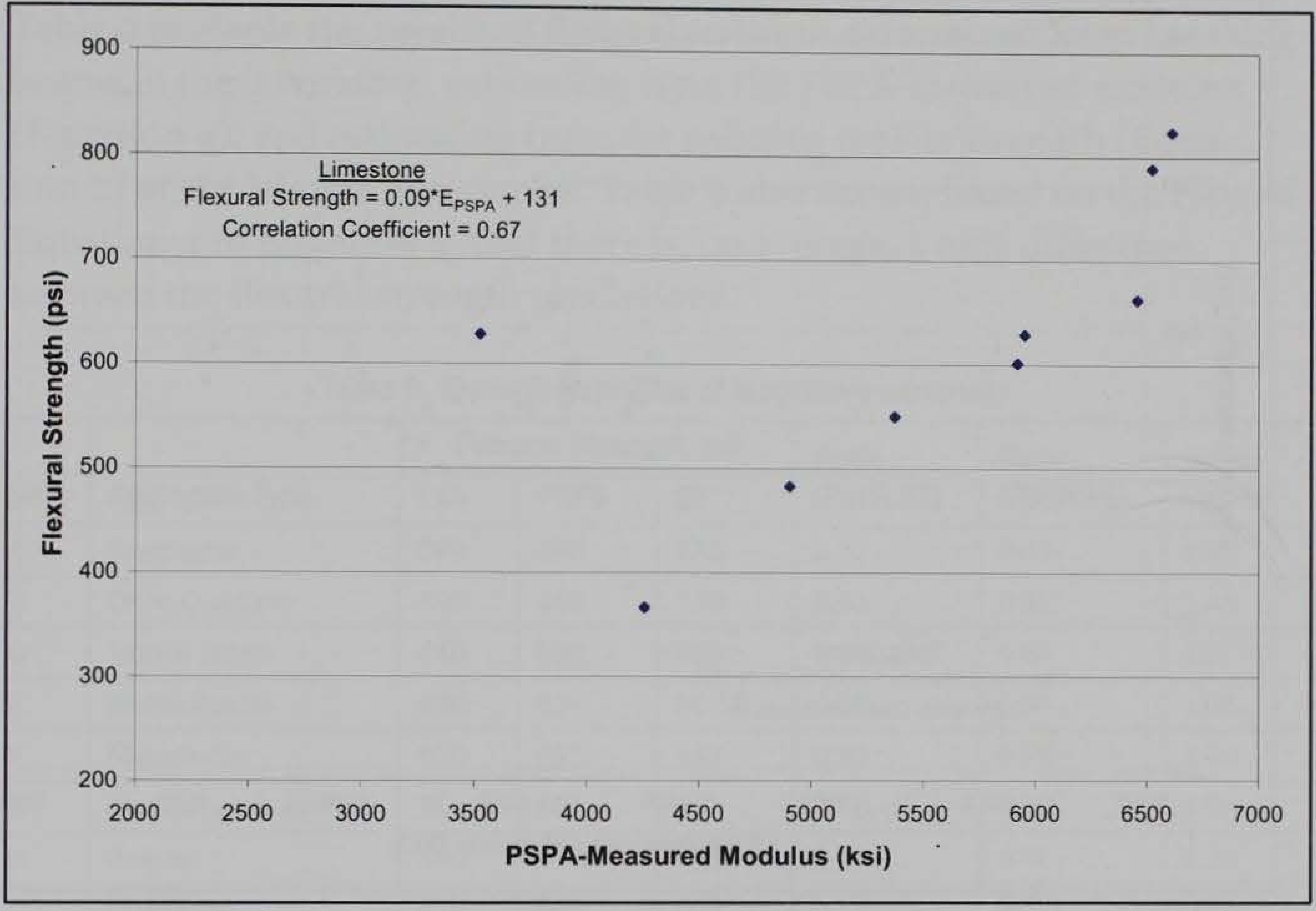

Figure 21. Laboratory-determined flexural strength versus PSPA-measured modulus of limestone slabs.

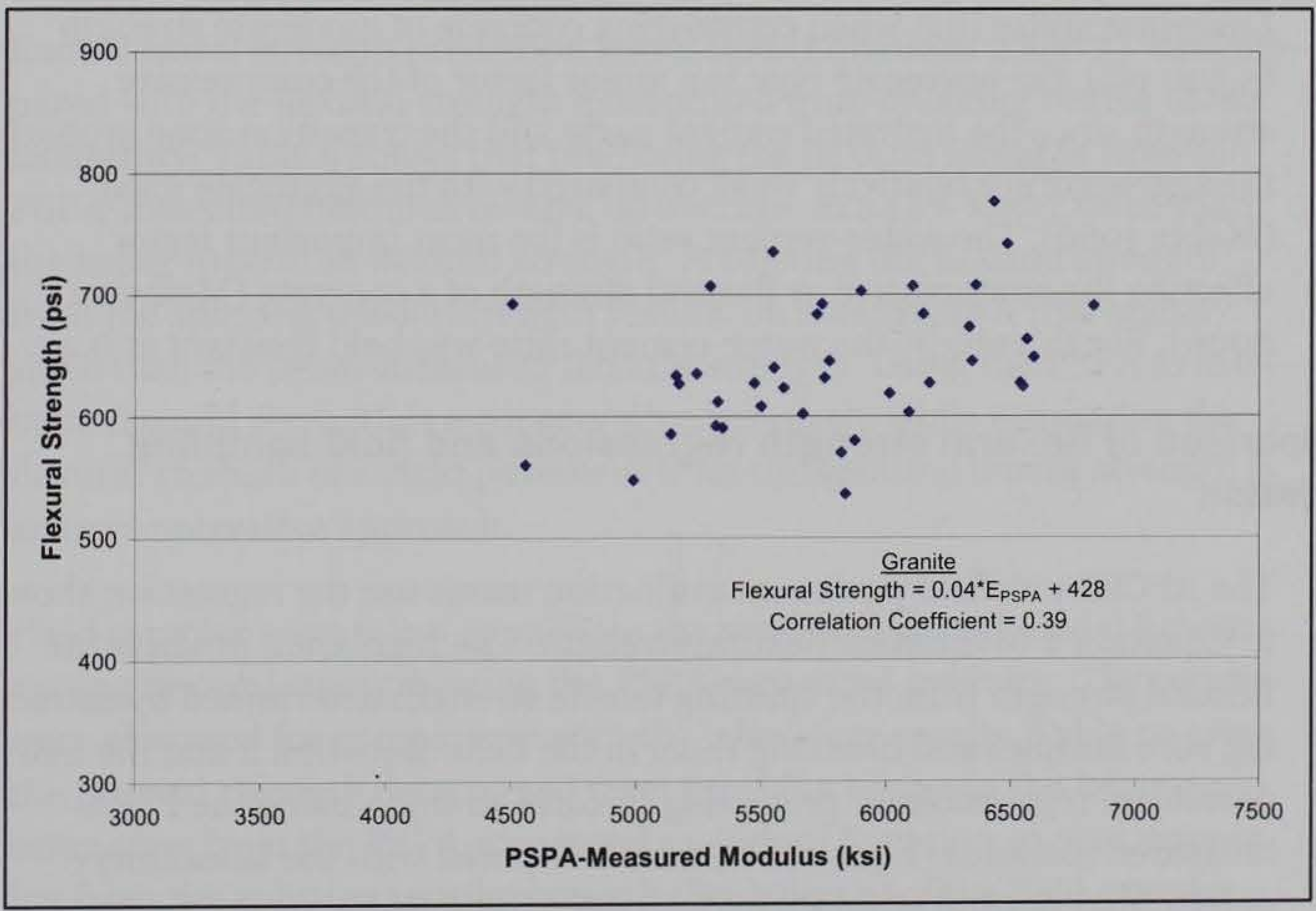

Figure 22. Laboratory-determined flexural strength versus PSPA-measured modulus of granite slabs.

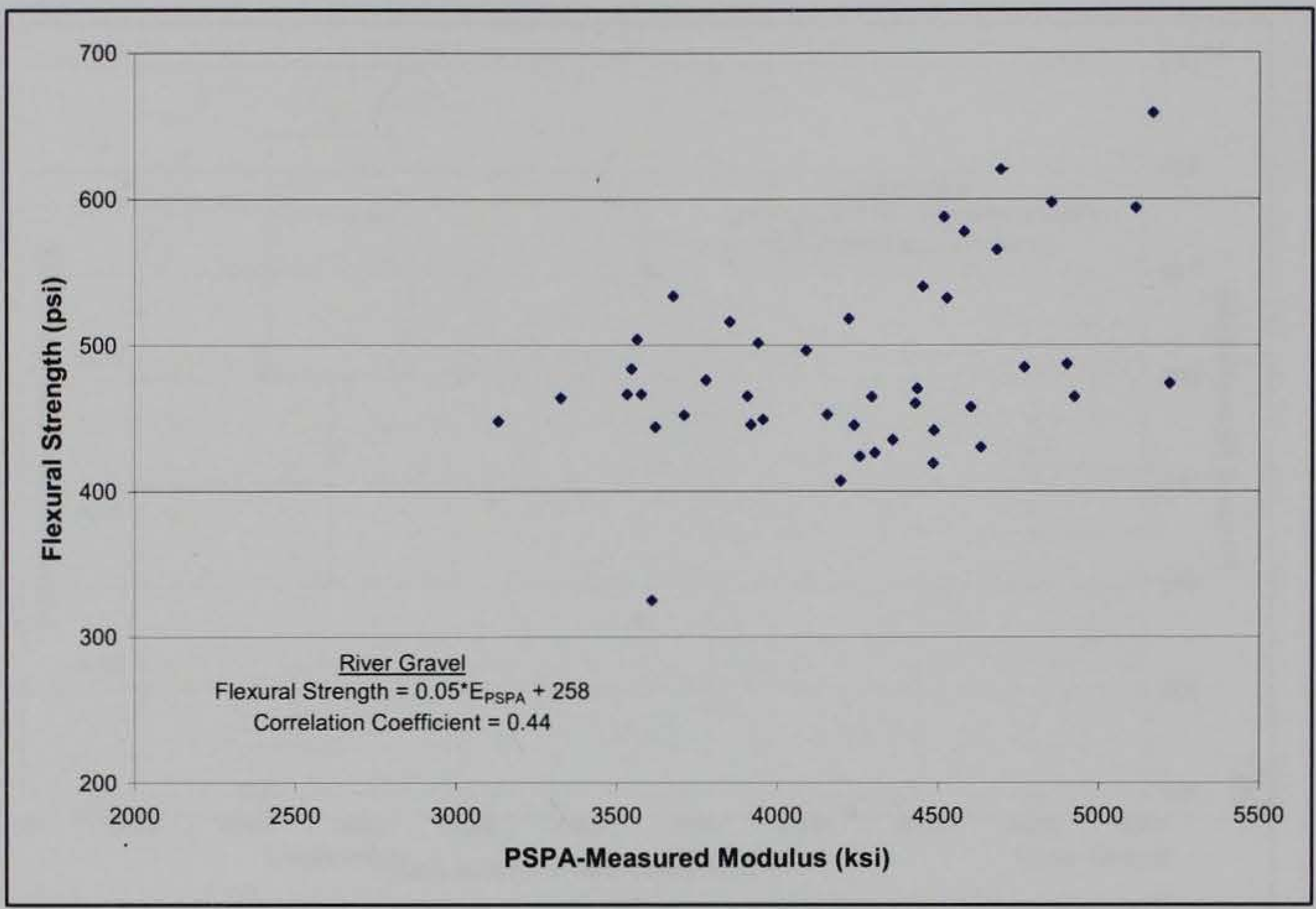

Figure 23. Laboratory-determined flexural strength versus PSPA-measured modulus of river gravel slabs.

Literature states that when considering concrete of moderate strength (5,500 psi), the aggregate type is a minor factor of the compressive strength since the hydrated cement paste and the transition zone around the aggregate are relatively weak compared with the aggregate itself (Mehta 1986). The water-cement ratio is the most important factor affecting the compressive or flexural strength of a concrete (Malhotra 2006). For this study, the water-cement ratio was held constant at 0.42.

Comparison of flexural strength regressions and field sampling validation

The AFCESA airfield pavement evaluation teams use the regression shown in Equation 2 to estimate flexural strength. The regression predicts the flexural strength from the splitting tensile strength determined by extracting core samples and breaking them in the field. Equation 2 and the newly developed regression for predicting flexural strength using the PSPA-measured modulus (Equation 4) were compared with the laboratory-determined flexural strength to determine the consequences of each prediction.

Table 9 presents the results of flexural strength determined from breaking beams in the laboratory, estimating from the PSPA-measured modulus (Equation 4), and estimating from the splitting tensile strength (Equation 2) of the laboratory samples. Table 9 also shows, based on the ratio of Equation 4 to Equation 2, that there is, on average, a 25% difference between the flexural strength predictions.

Table 9. Flexural strengths of laboratory samples.

Slab	Aggregate Type	Flexural Strength, psi			Ratio (PSPA:ST)	Ratio (PSPA:FS)	Ratio (ST:FS)
		Lab	PSPA	ST			
A	Sandstone	599	378	733	0.52	0.63	1.22
B	Ortho-Quartzite	495	458	730	0.63	0.92	1.48
C	Marble Schist	618	538	659	0.82	0.87	1.07
E	Biotite Gneiss	636	617	667	0.93	0.97	1.05
F	Metadiorite	620	615	743	0.83	0.99	1.20
G	Hornblende Gabbro	711	581	740	0.78	0.82	1.04
H	Granite	560	538	715	0.75	0.96	1.28
I	Limestone	628	455	595	0.77	0.72	0.95
				Average:	0.75	0.86	1.16

Each flexural strength prediction regression (Equations 2 and 4) was compared with the flexural strength determined from breaking beams in the laboratory. Table 9 shows that predicting the flexural strength from the PSPA-measured modulus results, on average, in a 14% lower value than the beam-measured flexural strength. Predicting the flexural strength from the splitting tensile strength results, on average, in a 16% higher value than the beam-measured flexural strength. Using the PSPA to estimate flexural strength is a conservative approach, while estimating the flexural strength of a rigid pavement from the splitting tensile strength is an unconservative approach.

Field samples were taken to validate the newly developed model for estimating flexural strength using the PSPA-measured modulus. The results were also used for comparison with the laboratory results. Table 10 gives the flexural strength determined from breaking beams in the laboratory, estimating from the PSPA-measured modulus (Equation 4), and estimating from the splitting tensile strength (Equation 2) of the field samples.

Table 10 shows, based on the ratio of Equation 4 to Equation 2, that there is, on average, a 27% difference in the results of the flexural strength

Table 10. Flexural strengths of field samples.

Slab	Flexural Strength, psi			Ratio (PSPA:ST)	Ratio (PSPA:FS)	Ratio (ST:FS)
	Lab	PSPA	ST			
J	683	595	768	0.77	0.87	1.12
K	834	607	878	0.69	0.73	1.05
Hangar 4	547	608	788	0.77	1.11	1.44
Barksdale AFB	814	657	936	0.70	0.81	1.15
			Average:	0.73	0.88	1.19

predictions in the field. When the field samples (Table 10) are combined with the laboratory-prepared samples (Table 9), the difference in the flexural strength predictions is averaged to be 25%.

Similar to the laboratory results, using the PSPA to predict flexural strength in the field results in an approximate 12% decrease from the laboratory-determined flexural strength. Using the splitting tensile strength to predict flexural strength results in an approximate 19% increase over the laboratory-determined flexural strength. Again, estimating beam-measured flexural strength from the PSPA-measured modulus tends to underpredict flexural strength, and estimating beam-measured flexural strength from the spitting tensile strength tends to overpredict flexural strength.

Figure 24 is a plot of the newly developed PSPA regression (Equation 4) versus the currently used PSPA regression (Equation 3). According to the plot, there is no difference in the predictive equations (R^2 = 1). They are essentially the same, so one regression is just as accurate as the other. Knowing this, it may be better to utilize Equation 3 for estimating flexural strength with the PSPA. Equation 3 is a simpler regression than Equation 4.

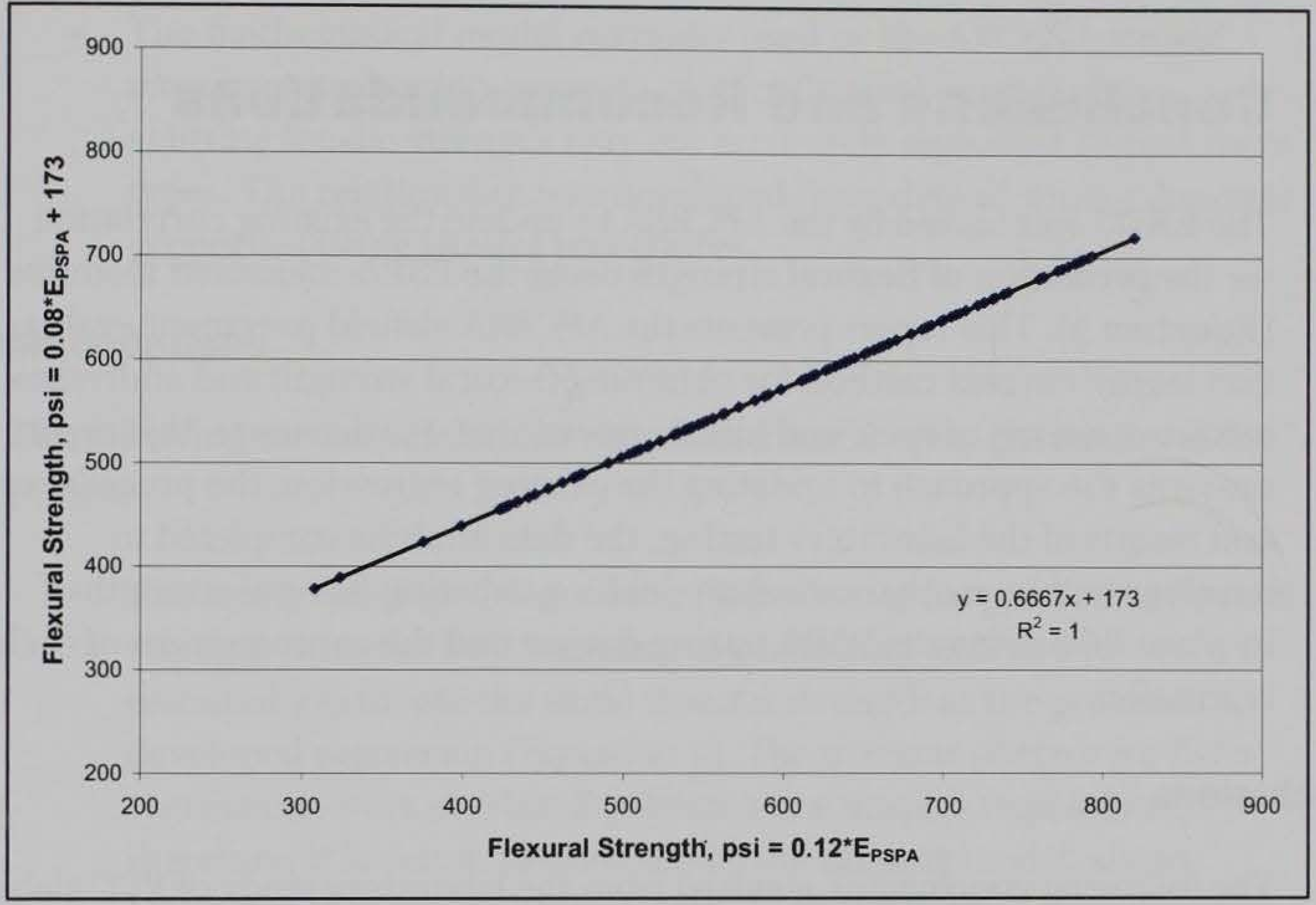

Figure 24. Currently used PSPA regression versus newly developed PSPA regression.

6 Conclusions and Recommendations

The ERDC was tasked by the AFCESA to update the existing correlation for the prediction of flexural strength using the PSPA-measured modulus (Equation 3). This report presents the AFCESA airfield pavement evaluation teams' current method for obtaining flexural strength and addresses certain concerns of their evaluation procedures. Furthermore, this report presents the approach to updating the existing regression, the procedures and results of the laboratory testing, the data analysis completed to develop the new mathematical model for predicting flexural strength of in-place PCC using the PSPA testing device, and the consequences of each regression.

Conclusions

The following conclusions resulted from the laboratory study of PCC slabs:

- A slightly improved mathematical model over the existing model for predicting flexural strength from the PSPA-measured modulus was developed using data from four PSPA studies of various concrete mixtures at varying strengths.

$$flexural\ strength, psi = 0.08 * E_{PSPA}, ksi + 173$$

- The PSPA-measured modulus is not dependent on limestone, granite, and river gravel concrete aggregate types alone.
- In general, the newly developed relationship to be used for predicting beam-measured flexural strength from the PSPA-measured modulus is conservative; it tends to underpredict flexural strength. According to the 2008 PSPA data, the relationship predicts a result approximately 13% lower than the flexural strength measured in the laboratory.
- In general, the existing relationship used by the AFCESA airfield pavement evaluation teams to predict flexural strength based on splitting tensile strength tests is unconservative; it tends to overpredict flexural strength. According to the 2008 PSPA data, the relationship predicts a result approximately 18% higher than the flexural strength measured in the laboratory.

- The mathematical model currently used by the AFCESA airfield pavement evaluation teams to predict flexural strength from splitting tensile strength may not accurately represent all pavement types. The relationship was developed from data of similar concrete properties using similar procedures.

Recommendations

The following recommendations are offered based upon the results of the project:

- The newly developed regression (Equation 4) for predicting flexural strength from the PSPA-measured modulus was found to essentially estimate the same flexural strength as the previously developed regression (Equation 3). The margins of error for both regressions were similar. Equation 3 is a simpler regression; therefore, it is recommended to use the existing model, shown below, for predicting flexural strength in the field.

$$\textit{flexural strength, psi} = 0.12 * E_{PSPA}, \textit{ksi}$$

- The AFCESA airfield pavement evaluation teams estimate flexural strength from the splitting tensile strength. This method is time-consuming and does not accurately represent all pavement types. It is recommended to use the PSPA device rather than the splitting tensile strength for estimating flexural strength in the field.
- When using the PSPA to estimate flexural strength in the field, the device should be tested, depending on the size of the feature, between four and ten times per feature. Each test should include at least three repeats.
- This study looked at the effects of the PSPA-measured modulus on ten coarse aggregate types. Of the ten, only three aggregate types (limestone, granite, and river gravel) had multiple data points. An extensive laboratory study should be conducted on multiple rigid pavements constructed with the same coarse aggregates at varying strengths and concrete properties. Additional data points should refine the accuracy of the predicted flexural strength.

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14. ABSTRACT

Personnel of the U.S. Army Engineer Research and Development Center were tasked by Headquarters, Air Force Civil Engineer Support Agency, to update an existing relationship between the in situ pavement modulus as measured by the portable seismic pavement analyzer (PSPA) and flexural strength as determined in the laboratory. The PSPA is a nondestructive testing device that measures the Young's modulus of surface pavements using ultrasonic surface waves. An existing mathematical model between the PSPA-measured modulus and flexural strength was developed based on previous research involving seismic testing and concrete strength properties (Bell 2006). The existing correlation provided a correlation coefficient (R) of 0.73. Results from the current seismic testing research determined a slightly improved regression between the PSPA-measured modulus and flexural strength. The regression model developed and reported in this publication has a correlation coefficient (R) of 0.74. This report provides information about existing methods for predicting flexural strength in the field, procedures used for casting various small-scale concrete slabs using different aggregates in the laboratory, test procedures and results, data analysis, and recommendations for the use of the updated flexural strength prediction model.

15. SUBJECT TERMS

Concrete aggregate	Flexural strength	PSPA
Concrete properties	Linear regression	Seismic testing
	Modulus	Splitting tensile strength

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