An *IPRF* Research Report

Innovative Pavement Research Foundation

Airport Concrete Pavement Technology Program

Report IPRF-01-G-002-02-2

Acceptance Criteria of Airfield Concrete Pavement Using Seismic and Maturity Concepts

Programs Management Office
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Acceptance Criteria of Airfield Concrete Pavement Using Seismic and Maturity Concepts

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EXECUTIVE SUMMARY

The acceptance of newly constructed concrete pavement by the Federal Aviation Administration (FAA) depends on the concrete strength and the pavement thickness. The current strength acceptance criteria have several limitations. First, the results from strength tests on lab-cured specimens are often different from those conducted on the in-place concrete. It is almost impossible to ensure identical bleeding, compaction, and curing conditions between the cast specimens and the pavement. In addition, the lack of repeatability and precision of strength testing, especially flexural strength testing, usually requires that the contractors produce stronger concrete than the design value to ensure full pay.

Coring is a straightforward way to measure the pavement thickness, and the cores retrieved can be used for compressive strength testing to represent the strength of in-place concrete. However, coring is time-consuming, expensive, destructive, and representative of only a small portion of the pavement structure. In particular, there are extra constraints that limit access to and closure of airfield pavements, especially on fast-track paving projects.

Under this project, maturity and seismic nondestructive testing technologies were evaluated as a basis for developing new acceptance criteria for concrete airfield pavement construction. The study included extensive experimental work on concrete specimens and small slabs of different mixes that were cured under different conditions as well as on two airfield pavement construction projects. Seismic tests were performed with the free-free resonant column (FFRC) devices in the laboratory and with a nondestructive device called the portable seismic pavement analyzer (PSPA) in the field. This study shows that concrete strength can be estimated from either seismic modulus or maturity or both with appropriate calibrations. The pavement thickness measurement is a by-product of the seismic test conducted for the strength estimate.

The main goals of this report are to provide the rationale behind the selection of promising technologies for further consideration, to develop a process to evaluate their technical merits, and to develop protocols for the practical implementation of the new technologies. Resource requirements for the recommended methods and a proposed percent within limits (PWL) specification for the new acceptance criteria are also presented.

Based on the outcome of this study, the following observations can be made:

- The strengths measured on standard lab-cured specimens are different than those measured from specimens extracted from pavement, especially when the pavement is exposed to the natural environmental conditions at construction sites.
- Flexural (or compressive) strength maturity calibration curve can be developed with confidence in the laboratory. However, the laboratory strength-maturity calibration curves are affected by the change in the mix proportions, especially by the cement content and water-cement ratio. If the maturity method is used alone, rigorous process control procedures are needed to ensure that the lab-developed calibration curve can be used with confidence in the field.
- Laboratory calibration between the strength and seismic modulus can also be developed with confidence. In this case, the strength-seismic modulus relationships are less

sensitive to the mix proportions than the maturity relationships. Again, process control during mixing is desirable.

- The seismic moduli measured on a pavement with a PSPA generally correspond well with the seismic moduli measured with an FFRC device on specimens extracted from the same pavement.
- The predicted strengths for the in-place concrete from the seismic and maturity methods in most cases agree well with strengths measured on cores and beams extracted from the pavement. For the cases where the curing conditions are inadequate or the mix proportions deviate from the designed values, the maturity method tended to over-estimate, whereas the seismic method tended to under-estimate the in-place concrete strength.
- The thickness of a pavement can be determined with the impact-echo method with an accuracy of about 3% to 4%. This accuracy exceeds the current thickness tolerances within FAA's P-501 specification. Consequently, the impact-echo method cannot be used for acceptance.
- The seismic method is more precise than conventional concrete strength tests, and tests can be carried out at a larger number of locations on a pavement. Thus, a PWL analysis based on this method may be more favorable to both the owner and contractor.

The seismic and maturity methods can complement one another in acceptance testing of airfield PCC paving. Based on the favorable results obtained from laboratory testing performed on a wide range of concrete mixes, it is recommended that the combined maturity-seismic methods be implemented on several future construction projects to more broadly assess its feasibility.

1. INTRODUCTION.

Concrete strength and pavement thickness are the primary factors considered by the FAA and most other agencies for the acceptance of newly-constructed rigid pavements. The current strength acceptance criterion is based on testing molded specimens (beams or cylinders) that are cured under ideal conditions. The strength of lab-cured specimens can be significantly different from that of the in-place concrete due to the differences in bleeding, compaction, and curing conditions between the cast specimens and the in-place pavement. The lack of repeatability and precision of flexural strength testing usually results in a stronger concrete mix than the design requires to ensure full payment.

Coring is a straightforward way to measure the pavement thickness, and the cores retrieved can be used for strength testing to represent the strength of in-place concrete. However, coring is time-consuming, expensive, destructive, and the cores retrieved are representative of only a small portion of the pavement structure. In many projects on active airfields, there are extra constraints that limit access to and closure of airfield pavements, especially on fast-track paving projects.

Current design methodologies and performance models utilized by the FAA have been based on the flexural strength of the PCC. A suitable rapid quality acceptance test to replace the flexural strength method has not been accepted by the FAA.

1.1 OBJECTIVES.

New and innovative technologies are evaluated under this project as a basis for developing new acceptance criteria for airfield concrete pavement construction. The focus of the study is primarily on implementing maturity and seismic technologies. Several agencies have found that maturity concept can contribute to a reasonable estimate of the in-place concrete strength. Since temperature monitoring devices are placed in discrete points in the pavement, any variability in the strength of concrete caused by batching errors, construction, equipment-related problems, or the curing process might not be identified. Seismic nondestructive testing technology has shown promise in overcoming some of these limitations in estimating the strength of the in-place concrete.

The main goals of this report are to provide the rationale behind the selection of promising technologies for further consideration, to evaluate their technical merits, and to develop protocols for the practical implementation of the technologies.

1.2 ORGANIZATION.

The parameters that are important to the acceptance of PCC pavements are defined in Section 2. The limitations of current methods of measuring those parameters are discussed in that section. The newer methodologies that can potentially address these limitations are also introduced.

Section 3 is dedicated to a concise description of the theoretical background and the practical implementation of the maturity and seismic methods. The resource requirements for implementing these methods are also provided in that section.

Protocols for implementing the maturity and seismic methods for strength and pavement thickness estimates are proposed in Section 4. The protocols are illustrated by using an example of the results from laboratory and field tests on an actual airfield pavement construction project. A PWL-based pay schedule for seismic/maturity methods consistent with the acceptance criteria in FAA P-501 specification is also described.

Extensive tests were conducted to evaluate the maturity and seismic methods. The rationale behind the test program is included in Section 5. The material-related, construction-related, and environmental-related parameters that may impact these methods are identified. A specific step-by-step procedure is proposed for each important parameter.

The results from side-by-site testing at two airfield construction projects are included in Section 6.

Summary and conclusions of this research project are included in Section 7.

A number of appendices are provided to support the information presented in these sections.

2. ASSESSING PARAMETERS IMPORTANT TO ACCEPTANCE OF PCC.

This section reviews the two most critical components of the construction quality control and acceptance of PCC pavements: thickness and concrete strength. Current methods for measuring the strength and thickness are reviewed. A more detailed summary of these methods is presented in Appendix A.

2.1 IMPORTANT STRUCTURAL DESIGN PARAMETERS.

A number of materials and construction parameters may significantly affect the performance of a PCC pavement. Adequate pavement thickness, effective concrete strength, proper curing, and proper timing and location of the joint saw cuts all contribute to achieving maximum performance. The importance of these parameters according to the FAA rigid pavement design procedure (FAA, 1995) is illustrated in Figure 2.1. Even small deviations in the as-constructed values of these parameters (from their design specifications) result in significant differences in pavement life (expressed in terms of departures). For example, a reduction of 5% from the design pavement thickness produces an estimated 60% reduction in life. Similarly, a 5% reduction in flexural strength produces a 40% life reduction. Because of the sensitivity of performance to these parameters, attention must be given to their control during construction.

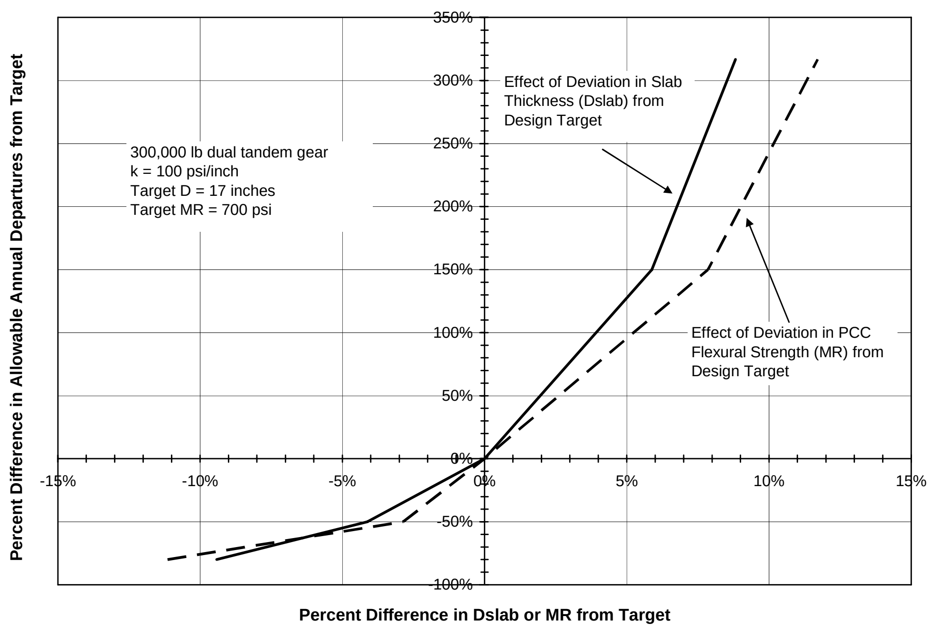


Figure 2.1 - Sensitivity of Pavement Performance to Key Design Parameters

2.1.1 Pavement Thickness.

For PCC airport pavements, the pavement thickness is selected as part of the design process to provide the structural requirements needed to sustain the anticipated aircraft loadings over the design life. Thickness control during construction is typically achieved through the use of a string-line to maintain the target surface elevation of the pavement.

2.1.2 Concrete Strength.

A concrete mix design is developed to satisfy a specified strength requirement corresponding to an accepted standard or specification. In construction, the adequate strength is achieved through close control of the mixing and placement operations.

Flexural strength is the desirable measure of strength because it characterizes the strength under the state of stress that the concrete experiences in typical field loading conditions. The disadvantages of flexural strength include the preparation of relatively large beams in the field as test specimens and the high variability associated with the test results. The strength of concrete used in the paving operation is usually greater than the design strength because of the current payment provisions and the variability in the acceptance test results. The use of concrete with higher than intended strength is not economical and may compromise the durability of the pavement.

Compressive strength is determined from smaller and more easily handled cylindrical concrete specimens that exhibit less variable test results. However, the state of stress induced in compressive strength testing is not representative of the conditions under which pavements typically deteriorate. For these cases, engineers usually rely on correlations between compressive and flexural strengths.

2.2 PARAMETERS IMPACTING CONCRETE STRENGTH.

Mixture characteristics are selected based on the intended use of the concrete. Other characteristics such as environmental conditions affect the mix design. The water-cement ratio is the primary parameter in a mix design. Differences in concrete strength related to mix design for a given water-cement ratio then result from changes in:

1. Amount of cement
2. Types and sources of cementing materials
3. Curing regime and length of curing time
4. Aggregate size, grading, surface texture and shape
5. Entrained-air content
6. Presence of admixtures

Tables 2.1 and 2.2 demonstrate typical batch-to-batch variations in the above parameters under acceptable construction practices. The variations in these mix design parameters can affect concrete strength, as well as other important properties. Their specification and control during construction is important, but it is believed that their use as acceptance criteria is not appropriate. Although general relationships between the parameters and concrete strength exist, there are many instances where environmental factors and mix interactions may produce unexpected results.

Table 2.1 - Summary of Historical Information Related to Variability in Portland Cement Concrete (Freeman and Grogan, 1997)

Material Property	Batch-to-Batch Coefficient of Variation (%)	
	Range	Median
% passing max. aggregate size	5 to 20	10
Air content	15 to 20	15
Slump	30	30
Unit weight	1 to 2	1
28-day compressive strength	5 to 20	15
Chord modulus	25 to 35	30
Flexural strength	5 to 10	7
Thickness	1 to 10	3

Table 2.2 - Summary of Historical Bureau of Reclamation Data Related to Variability in Portland Cement Concrete (Freeman and Grogan, 1997)

Material Property	Batch-to-Batch Coefficient of Variation (%)	
	Range	Median
28-day compressive strength	10 to 35	20
Water cement ratio	0 to 15	5
Slump	5 to 55	30
Water content	0 to 15	5
Cement content	0 to 20	5
Air content	5 to 70	30
Unit weight	0 to 5	1

Zollinger et al. (1998) also studied the use of mix-design parameters for quality acceptance. They concluded that the most benefit is gained by controlling the water-cement ratio and water content. They also indicated that while these two parameters—as well as a number of other parameters—may be quite useful in terms of quality control, they do not seem reliable enough to be used for quality acceptance.

Traditionally, the quality of in-place concrete is judged based on the strength of specimens that are cured under ideal conditions. As such, the quality of construction practices and the effectiveness of the curing method under the field environmental conditions are ignored. For decisions on the opening of airfield to traffic these parameters play critical roles. Therefore, a more direct measurement of the in-place concrete strength is necessary for acceptance.

2.3 METHODS OF MEASURING IMPORTANT PARAMETERS.

The accurate measurement of the as-constructed pavement thickness and PCC strength under a valid quality control program provides essential information to the contractor that can be used to adjust materials and/or address construction needs, improve process control, and maximize the production of a quality pavement. At the same time, the accurate measurement of the parameters as part of a valid quality assurance program provides the owner/agency with a basis for acceptance and, if necessary, pay adjustments.

Table 2.3 provides a list of feasible methods available for measuring pavement thickness and PCC strength. The direct methods refer to tests in which the thickness or strength are measured *directly* according to a standard test method (e.g., ASTM). The indirect methods refer to those tests that rely on the measurement of one or two other properties that are either theoretically or statistically correlated with either the pavement thickness or concrete strength. The current "standard" for assessing the pavement thickness is the measurement of the length of drilled cores, whereas the current "standard" for accepting the strength is through flexural strength testing of fabricated beams.

Table 2.3 - Test Methods for Pavement Thickness and Concrete Strength

Method	Pavement Thickness	Concrete Strength
Direct	Measurement of Drilled Cores *(standard)* Thickness Probing	Compressive Strength Test Flexural Strength Test *(standard)* Splitting Strength Test
Indirect	Ground Penetrating Radar (GPR) Seismic Test (Impact Echo Method)	Maturity Test Seismic Tests (FFRC and USW) Integrated Maturity/Seismic Method

A detailed description of these test methods is provided in Appendix A. Table A.1 in that appendix provides a summary of each method, including a listing of the advantages and disadvantages.

2.4 LIMITATIONS OF CURRENT METHODS.

The limitations associated with the current test methods for determining pavement thickness and strength are discussed in Appendix A. The samples for conventional concrete strength testing are fabricated in the field, are relatively heavy and bulky to transport, and are cured under a different set of conditions than the in-place concrete. Even though the quality of the concrete may be determined as early as 12 hours after placement, the pavement is normally not accepted and the contractor is not compensated until the 28-day strength results are obtained.

The samples for conventional thickness measurement must be obtained through a destructive coring process that is performed after the concrete has hardened. This process also requires the repair of the core holes.

The level of effort required for these tests is significant and the time lag between pavement construction and getting the test results is sometimes problematic. Moreover, these conventional tests represent a limited sampling upon which major decisions are made regarding the acceptability and payment for the as-constructed pavement. Clearly, improvements to these methods of assessing in-place PCC pavement properties would benefit both contractors and owner agencies.

Flexural strength (ASTM C78) is an example of a test method that could benefit from some improvements. Flexural strength is evaluated based on the assumption that the fracture initiates in the tension surface within the middle third of the span length. The fracture occurs at the weakest point preceded by local micro-cracking. The micro-cracked zone redistributes the elastic stress distribution, which may compromise the accuracy of the flexural strength test results. ASTM C78 allows the use of an alternative relationship if the fracture occurs outside of the middle third of the span length by less than 5% of the span length. Large scatter has been reported even for those tests that the fracture occur within the middle third.

2.5 RECOMMENDED TECHNOLOGIES FOR FURTHER EVALUATION.

In the last 20 years, new and innovative technologies have evolved to address the limitations of conventional test methods. The maturity method (ASTM C1074) essentially eliminates the need for field sampling and testing to monitor concrete strength gain. The maturity method is being employed on highway projects by at least one agency (Iowa DOT). An evaluation of the applicability of maturity method to one airfield project was recently studied under an IPRF project (Rasmussen et al., 2003).

Seismic nondestructive testing (NDT) methods represent a recent major innovation in concrete pavement testing. Although the analytical processes associated with seismic technology have been around for a long time, the recent evolution of computer technology has made it possible to develop equipment and software that can process the complex information in seconds. Equipment for estimating pavement thickness is commercially available that can measure the velocity of stress waves reflected off the bottom of the pavement using the impact-echo test. Equipment is also commercially available that can measure the speed of waves that are generated and travel within the pavement and use them to estimate both the dynamic modulus and associated strength of the in-situ concrete.

The ground penetrating radar (GPR) has several distinct advantages since it can provide rapid and continuous measurements. These advantages are discussed in Appendix A. Unfortunately, experience has shown that GPR has certain limitations in its ability to assess PCC pavement thickness (Maser et al., 2003). As such, further evaluation of GPR was not carried out under this project.

The maturity and seismic based approaches were further evaluated under this project to assess their applicability for use in airfield rigid pavement construction for the following reasons:

- The maturity method provides a basis for monitoring the strength gain of concrete after it is placed without having to prepare and test any specimens during pavement construction.
- Seismic methods can be used to estimate pavement thickness and the concrete strength.
- The combined maturity-seismic method makes it possible to determine the key properties of the as-constructed concrete nondestructively and in a statistically reliable fashion with little interruption to the construction process. The method provides timely information as to whether the as-constructed pavement satisfies key design requirements and specifications.

3. MATURITY AND SEISMIC CONCEPTS.

Since the maturity and seismic methods are referenced extensively in this report, a background of the two methods is provided in this section.

3.1 MATURITY METHOD.

The strength of a concrete mixture, which has been properly placed, consolidated and cured, is a function of its age and temperature history (Saul, 1951). At an early age, temperature has a dramatic effect on strength development. The maturity method accounts for the combined effects of time and temperature on the strength development of concrete.

The strength gain of a concrete pavement can be estimated by simply monitoring the in situ concrete temperature with time after construction using a calibration curve. The calibration curve is developed by using the results of laboratory strength tests and maturity measurements to establish a maturity-strength relationship before construction. A separate calibration curve must be established whenever the mix design is changed.

A device that can measure the temperature of the concrete at regular time intervals is used in the maturity method. This measurement is achieved either by using thermocouples attached to a maturity meter or a data logger, or by using i-buttons (small, self-powered and self-contained microprocessors). Both maturity meters and i-buttons (see figure 3.1) were used in this study to measure and record the temperature history of concrete specimens and pavement.

Saul (1951) gave the following expression to calculate the maturity with respect to a "datum temperature, T_o," which is defined as the lowest temperature at which the gain in strength of concrete is observed:

$$M(t)=\Sigma(T_a-T_o)\Delta t \tag{3.1}$$

where M(t) = time-temperature factor (TTF) at age t, Δt = time interval between consecutive measurements, and T_a = average concrete temperature during time interval, Δt. Saul

a) I-button and Accessories

b) Humboldt M-3056 Maturity Meter

Figure 3.1 - Maturity Measurement Tools

recommended a datum temperature of 10.5°C, while Plowman (1956) recommended a temperature of -12°C. ASTM C1074 does not mandate a datum temperature. In this study, a temperature of -10°C was adopted. However, it is more desirable to obtain the datum temperature using the mortar cube tests at several temperatures below and above the field climate.

3.2 SEISMIC METHODS FOR STRENGTH ESTIMATE.

Seismic methods of measuring strength rely on generation, detection and measurement of the velocity of propagation of elastic waves within a medium. The measured velocity can be converted to the modulus of elasticity (also called the seismic modulus) based on the theory of elasticity. Three types of waves (i.e., compression wave, shear wave, or surface wave) are typically used in civil engineering applications. Seismic tests can be carried out in the laboratory and the field.

3.2.1 Laboratory Seismic Tests.

The free-free resonant column (FFRC) test (ASTM C215) is particularly suitable for measuring the seismic (dynamic) modulus of concrete in the laboratory. When a concrete cylinder or beam is subjected to an impulse load at one end, seismic energy over a large range of frequencies will propagate within the specimen (see Figure 3.2). Depending on the dimensions and the stiffness of the specimen, energy associated with one or more frequencies are trapped and resonate as they propagate within the specimen.

Results from a typical test are shown in Figure 3.3. Resonant frequencies appear as peaks in a so-called amplitude spectrum. Two peaks are evident, one corresponding to the longitudinal propagation of waves in the specimen, and the other corresponding to the shear mode of vibration. It is simple to distinguish the two peaks, because for typical concrete specimens, the longitudinal resonance occurs at a higher frequency than the shear resonance.

Figure 3.2 - Setup of Free-Free Resonant Column (FFRC) Test

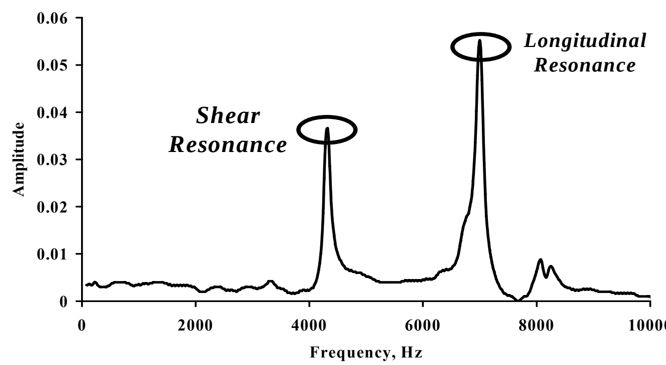


Figure 3.3 - Typical Response from FFRC Test on a Concrete Cylinder

Once the longitudinal resonant frequency, f_L, the length and the mass density of the specimen, L and ρ, are known, laboratory modulus, E_{lab}, can be found from the following relation:

$$E_{lab} = \rho \ (2 f_L L)^2 \quad (3.2)$$

The test with the setup shown in Figure 3.2 can be performed in less than 30 seconds. One of the advantages of this method is that it provides properties that can also be directly measured in the field.

3.2.2 Field Seismic Tests.

Field seismic tests consist of impacting the surface of the pavement with a source and monitoring the propagation of waves with two or more receivers (see Figure 3.4). The analysis recommended here can be conducted via the Ultrasonic Surface Waves (USW) method and the field seismic modulus (E_{field}) can be obtained from surface wave velocity, V_R, through the following relationship:

$$E_{field} = 2 \rho (1 + \nu) [V_R (1.13 - 0.16 \nu)]^2 \quad (3.3)$$

The most dominant arrivals are related to the surface (Rayleigh) waves since they contain about two-thirds of the seismic energy. At wavelengths less than or equal to the thickness of the uppermost layer, the velocity of propagation of surface waves is independent of wavelength. Therefore, if one simply generates high-frequency (short-wavelength) waves, and if one assumes that the properties of the uppermost layer are uniform, the seismic modulus of the upper layer, E_{field}, can be determined from Equation 3.3.

The laboratory and field seismic moduli, E_{lab} and E_{field}, are theoretically related through Poisson's ratio, ν, (Richart et al., 1970). The relationship is in the form of:

$$E_{field} / E_{lab} = (1 + \nu) (1 - 2\nu) / (1 - \nu) \quad (3.4)$$

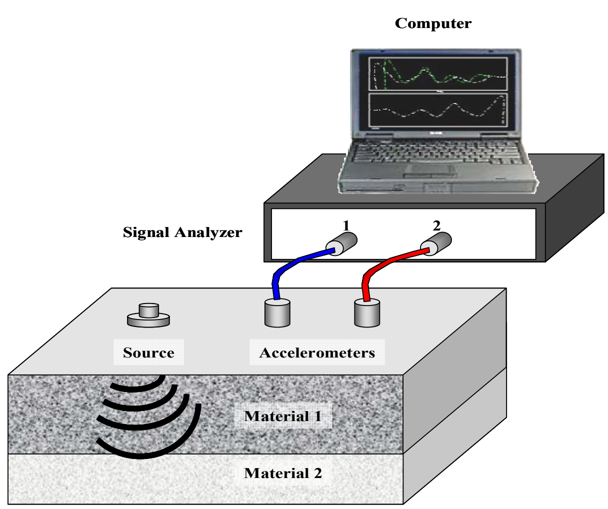


Figure 3.4 - Schematic of Set up for Seismic Field Testing

The Poisson's ratio for a typical concrete varies between 0.15 and 0.20. The modulus from the USW method has to be divided by 0.90 to 0.95 (for Poisson's ratios of 0.20 and 0.15, respectively) to obtain the modulus of the identical material tested with an FFRC device.

The portable seismic pavement analyzer (PSPA) is a device that employs an impact load and measures the velocity of surface waves to estimate concrete seismic modulus as per Equation 3.3. The PSPA (see Figure 3.5) consists of two transducers and a source packaged into a hand-portable unit, and is operable from a computer. The major mechanical components of the PSPA sensor unit are near and far accelerometers and an electric-magnetic source. The data collected with the PSPA can be processed using signal processing and spectral analysis to determine the modulus of a concrete pavement using the USW method.

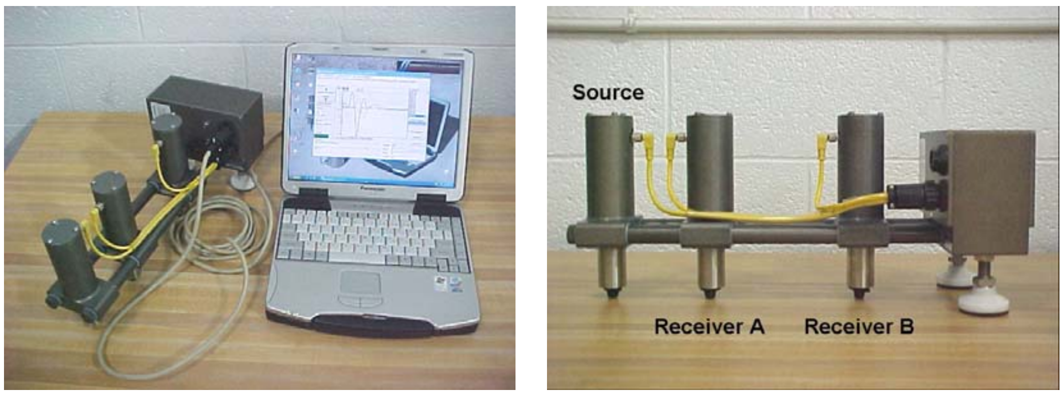


Figure 3.5 - Portable Seismic Pavement Analyzer (left) and Its Sensor Unit (right)

<u>3.3 SEISMIC METHOD FOR THICKNESS MEASUREMENT.</u>

The Impact Echo (IE) method primarily provides information about the thickness of a layer. The method, as sketched in Figure 3.6, is based on detecting the frequency of the standing wave reflecting from the bottom and the top surfaces of the top pavement layer. Some of the energy due to an impact is reflected from the bottom of the layer, and some is transmitted into the base and subgrade. Since the top of the layer is in contact with air, almost all of the energy is reflected from that interface. The receiver senses the reflected energy at periodic time intervals, where the period depends on the thickness and compression wave velocity of the layer. To conveniently determine the frequency associated with the periodic arrival of the signal, one can utilize a fast Fourier transform algorithm. The frequency associated with the reflected wave appears as a peak in the amplitude spectrum. Using the compression wave velocity of the layer, V_p, the depth-to-reflector, h, can be determined from (Sansalone and Streett, 1997):

$$h = 0.96\ V_p / 2f \tag{3.5}$$

where f is the resonant frequency obtained by transforming the time record into the frequency domain.

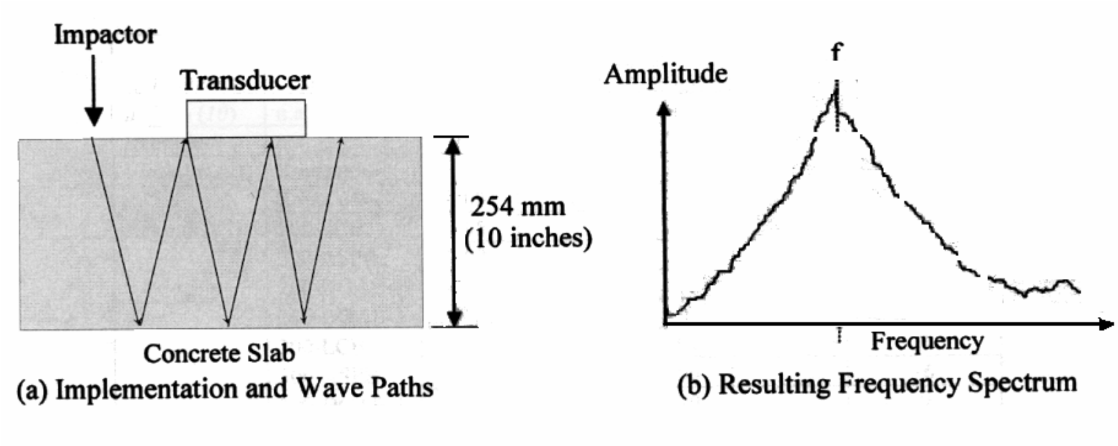


Figure 3.6 - Schematic of Impact Echo Method (Infrasense 2003)

The method is not applicable to layers less than 4 in. thick and layers where the difference in moduli of adjacent layers is small. The impact-echo tests can be carried out with commercially available equipment, such as the PSPA described above.

3.4 RESOURCE REQUIREMENTS.

The resource requirements for the technologies recommended above are discussed in Appendix A. The highlights are summarized in Table 3.1. Maturity tests are quite straightforward. The major field task is to place the temperature probes properly. The initial cost of acquiring a basic recording/downloading system is about $1,000 (for a thermocouple based system) to $2,500 (for an i-button type system). For each test point, either about 10 ft to 15 ft of thermocouple wire (at a cost of about $1/ft) or a disposable sensor (at a cost of about $35) is needed. It is prudent to periodically verify the calibration of any thermocouple-based maturity systems.

Before a maturity system can be used for acceptance, a strength-maturity calibration curve has to be developed. This task requires about a dozen beams or cylinders. However, the calibration can be carried out in conjunction with the mix design verification. This calibration is sensitive to changes in the mixture and has to be periodically validated. For more accurate calibration, ASTM C1074 requires the determination of datum temperature for a given mix. This task requires additional lab testing.

Table 3.1 - Operational Aspects of Proposed Technologies

Parameter	Device	
	Maturity	**Seismic**
Initial Cost	$1,000-$2,500	$20,000-$30,000
Material Cost (per point)	$10-$35	None
Measurement Speed	Continuous	2 minutes
Skill Level of Operator	Conscientious Technician or Engineer	
Skill Level for Interpretation	Conscientious Technician or Engineer	
Training Requirement	One day	One day for operation, one additional day for interpretation

The seismic technology is the newest and least known to the paving industry. Real-time analysis is available on current devices, for which the initial cost is currently about $20,000 to $30,000. However, with the acceptance of the technology, the initial cost should decrease. Under production mode, up to 200 points can be tested daily.

About one day of training is needed to operate such equipment, with a second, follow-up training to fine-tune the details of the equipment's use. Seismic devices work based on the determination of the travel time of waves; as such, the calibration of the device is infrequent. However, it is prudent to periodically test the device on a cured concrete pavement to ensure that it is working properly.

A laboratory strength-modulus calibration curve has to be developed for each mix. This task requires about a dozen beams or cylinders that can be coordinated with the mix design verification. The strength-modulus calibration curve is less sensitive to changes in the mixture as compared to the strength-maturity calibration curve. Therefore, the validation of the relationship can be carried out less frequently. The main parameter that impacts the strength-modulus calibration curve is the type of coarse aggregate.

4. IMPLEMENTATION OF MATURITY AND SEISMIC CONCEPTS.

The maturity and seismic methods, and especially the combination of the two, are viable alternatives to the traditional acceptance testing of concrete pavement construction. The maturity probes, placed at discrete points in the pavement during paving, provide information about the quality of the concrete at a given point. The seismic device can provide any variability in the strength of concrete due to batching errors, construction, or equipment-related problems between the maturity probes. The combination of the seismic and maturity is quite attractive as a comprehensive acceptance test.

Test protocols for estimating the in situ concrete strength and pavement thickness with seismic and maturity methods are discussed in this section.

4.1 PROTOCOL FOR ESTIMATING STRENGTH.

The test protocol for estimating the strength of in situ PCC consists of the following six phases:

I. Specimen preparation,
II. Maturity measurements,
III. Seismic modulus tests,
IV. Strength tests (either flexural or compressive),
V. Correlation development, and
VI. Estimation of in situ strength.

Each item is discussed below. Appendices B and E provide the procedures and guide specification for implementing the maturity and seismic tests for this purpose.

I. Specimen Preparation

The specimen preparation requirements are identical to those recommended by the FAA P-501 specification. At least 15 standard (6 in. by 12 in.) cylinders or (6 in. by 6 in. by 21 in.) beams are cast as per ASTM C192/C192M. At least two of the cylinders or beams should be equipped with maturity sensors (e.g., thermocouples or i-buttons) as per ASTM C1074. All specimens are cured as per ASTM C192/C192M.

II. Maturity Tests

The specimens equipped with thermocouples are either connected to a maturity-meter or a temperature data-logger as soon as practical. If i-buttons are used, they are reset to start monitoring temperature as soon as feasible. The temperature should be continuously monitored for 28 days. The temperature-time history is converted to the time-temperature factor (TTF) using ASTM C1074. The average TTF at the nominal ages of 1, 3, 7, 14 and 28 days are required.

III. Seismic Tests

At least three cylinders or beams are randomly selected at ages of 1, 3, 7, 14 and 28 days. The free-free resonant column (FFRC) tests are carried out on the specimens in accordance with

ASTM C215. The seismic modulus of each specimen is determined from Equation 3.2. The average modulus is used for each age.

IV. Strength Tests

Compression tests as per ASTM C39/C39M or flexural tests as per ASTM C78 are performed on the cylinders or beams subjected to FFRC tests at ages of 1, 3, 7, 14 and 28 days. The average compressive strength or the flexural strength from the tests is obtained for each age.

V. Development of Correlations

Several correlations are developed to estimate the in situ strength. These relationships include:

- *Strength vs. Maturity*: A plot between the average strengths and average maturity parameters at corresponding times is made and a best-fit curve is drawn through the plot. The most general form for this relationship is:

  $$F = \alpha \text{ LOG } (TTF)^{\beta} \tag{4.1}$$

  where f can be either the compressive or flexural strength, and α and β are the best-fit parameters.

- *Strength vs. Seismic Modulus*: Similarly, a plot between the average strengths and average seismic moduli is developed. A best-fit curve is drawn through these data, using the general relationship:

  $$F = \gamma \, (E_{SEISMIC})^{\delta} \tag{4.2}$$

  where $E_{seismic}$ is the seismic modulus from either cylinders or beams, and γ and δ are the best-fit parameters.

- *Strength vs. Maturity and Seismic Modulus*: Finally, a relationship between the strength and both the maturity parameter and seismic modulus can be developed. The following general relationship is used:

  $$F = \alpha \, (E_{SEISMIC})^{\beta} + \gamma \text{ LOG } (TTF) + \delta \tag{4.3}$$

  where α, β, γ and δ are the best-fit parameters.

VI. Estimation of In-Situ Strength

The strength can be predicted in several ways. These alternatives include:

- *Maturity-Based*: The strength-maturity curve developed in Item V is used for estimating the strength of in-place concrete based on maturity parameters measured in the field as per ASTM C918.
- *Seismic Modulus-Based*: The strength-seismic modulus curve developed in Item V is used with the seismic moduli measured with the PSPA in the field for estimating the in-place strength of the pavement.
- *Maturity and Seismic Modulus Based:* In this alternative, both the field maturity parameter and the seismic modulus with the PSPA are used to estimate the strength of the in-place concrete.

4.2 PROTOCOL FOR ESTIMATING THICKNESS.

The test method for estimating thickness is described in ASTM C1383. Appendix C contains a step-by-step procedure for implementing the IE test. The test protocol includes two steps: calibration and actual measurement. The calibration step consists of conducting impact-echo (IE) tests at several locations and coring those locations. A representative compression wave velocity (P-wave speed) is determined by relating the return frequency of the IE measurements to the actual thickness (see Equation 3.5). Once the calibrated velocity is obtained, IE tests can be carried out at other locations.

If cores are not available, the P-wave velocity can be determined from the result of the USW test at each test point. The time records obtained from the PSPA can be used to estimate both the strength and thickness.

4.3 ILLUSTRATIVE EXAMPLE.

The typical results from a construction project are used in this example. The laboratory relationships between the compressive strength and flexural strength and the time-temperature factor (TTF) are shown in Figure 4.1. A good correlation is observed between the two strength parameters and TTF as judged by a coefficient of determination (R^2 value) of greater than 0.98.

An R^2 of 0.99 or 0.98 between the seismic modulus and TTF is also observed as shown in Figure 4.1c. Such relationships can be readily used to project the modulus of concrete as a function of maturity. The seismic modulus is practically independent of the cross section of the specimen being tested. Similar results were reported by Ramaiah et al. (2001).

The compressive and flexural strengths are also highly correlated to the seismic modulus as shown in Figure 4.2. The R^2 values are greater than 0.97. The combined TTF and seismic modulus are also successfully correlated to the two strength parameters with R^2 values of 0.99 (see Figure 4.3).

In the next step, the laboratory-calibrated strength-maturity and strength-seismic modulus relationships are applied to the results from the field maturity and PSPA measurements to estimate the in-situ strengths. Compressive strength tests were carried out on cores retrieved from the pavement at the ages of 4, 7, and 28 days. The strengths estimated from field measurements are similar to the measured ones as shown in Figure 4.4.

Representative IE amplitude spectra measured with the PSPA along the project at different ages are shown in Figure 4.5. The return frequency increases with age, because the pavement becomes stiffer (i.e. P-wave velocity increases) with time. In this case, four cores were used for calibration. The variation in estimated pavement thickness at 7 days is shown in Figure 4.6. The estimated thickness varies by 0.3 in. from the average length of cores, with a coefficient of variation of about 3% as shown in Table 4.1.

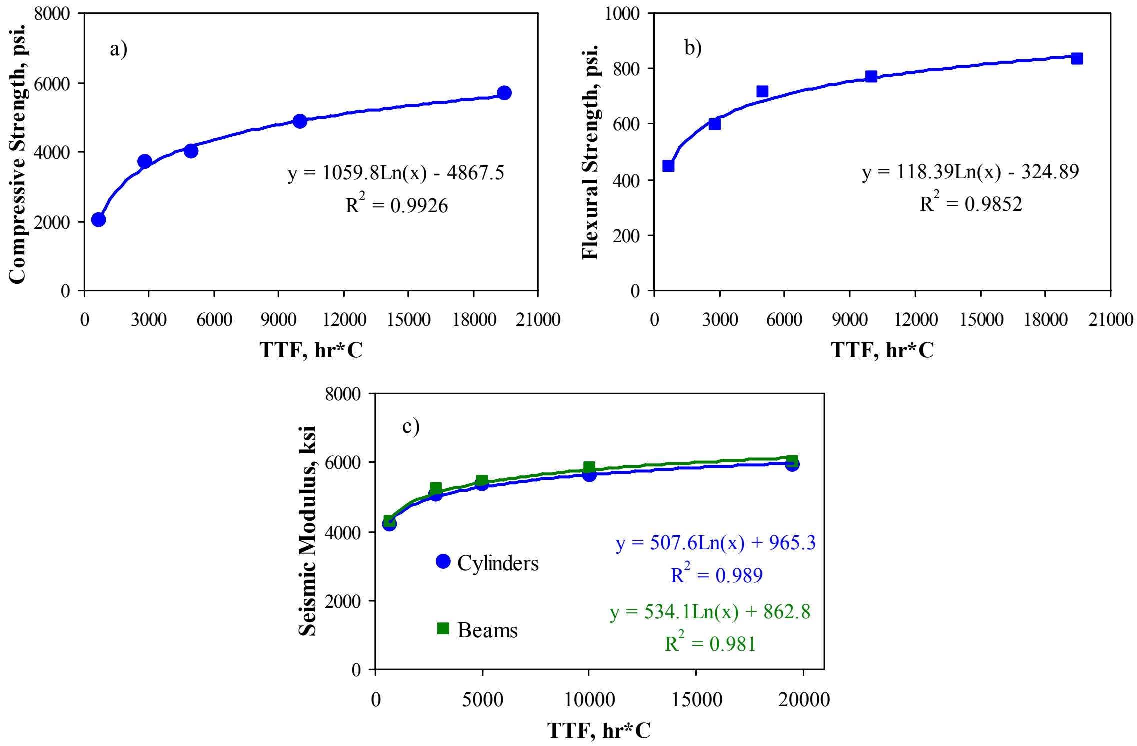


Figure 4.1 - Variations in Strength Parameters and Seismic Modulus with Maturity

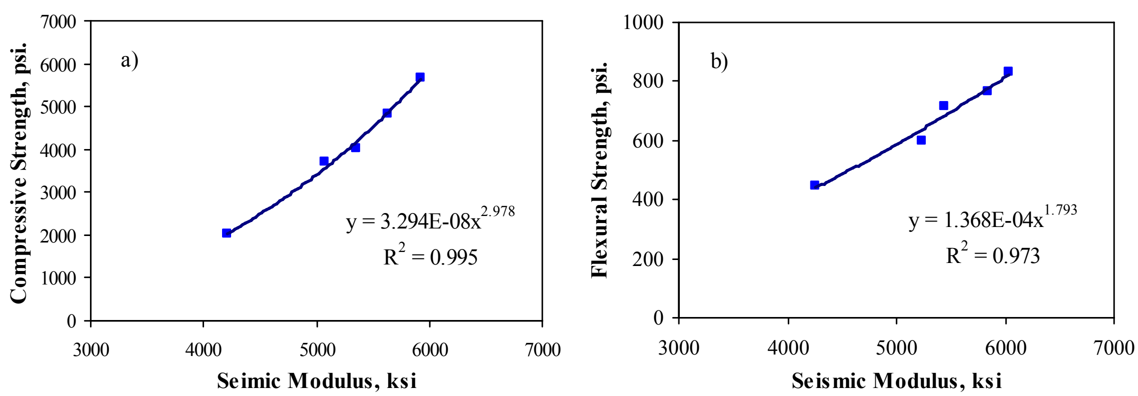


Figure 4.2 - Variations in Strength Parameters with Seismic Modulus

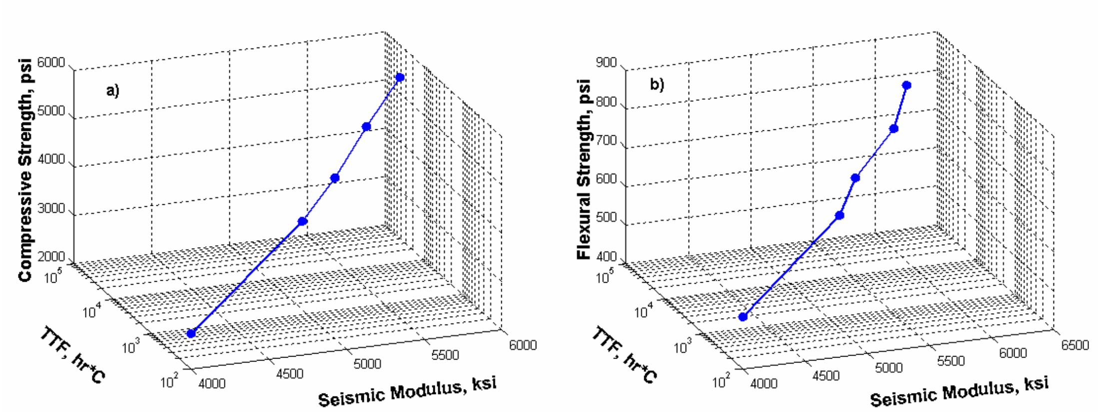


Figure 4.3 - Variations in Strength Parameters with Combined TTF and Seismic Modulus

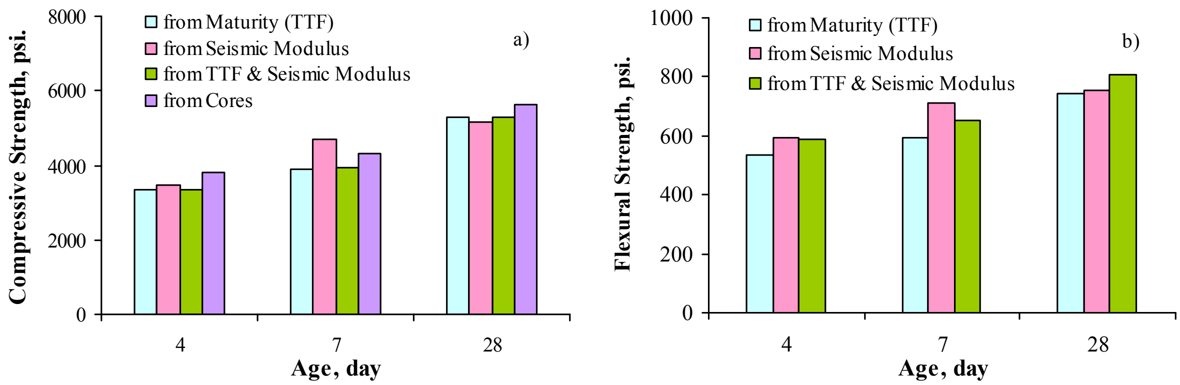


Figure 4.4 - Comparison of Strength Parameters Obtained from Different Sources

Table 4.1 - Average Estimates of Pavement Thickness with PSPA

Pavement Age, day	Average Estimate, in.	C.V., %	Difference, in.*
1	9.5	2.3	0.2
4	9.4	2.5	0.1
7	9.4	2.9	0.1
28	9.4	3.3	0.1

* Average core thickness = 9.3 in.

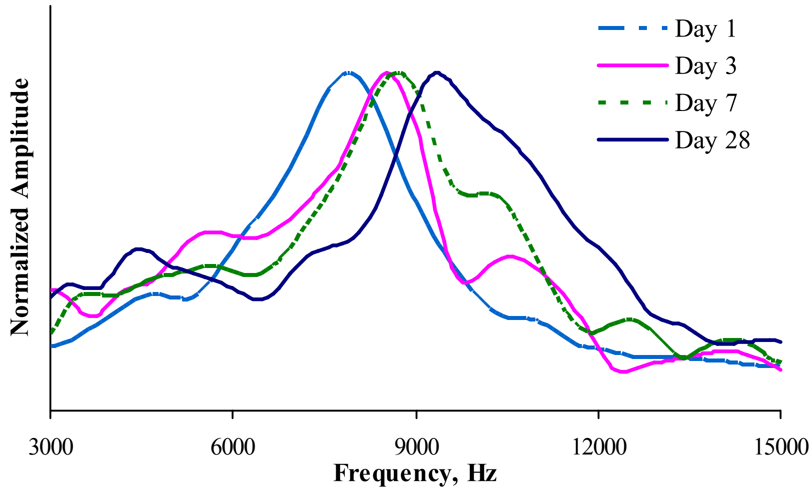


Figure 4.5 - Variation in Representative Return Frequency with Pavement Age

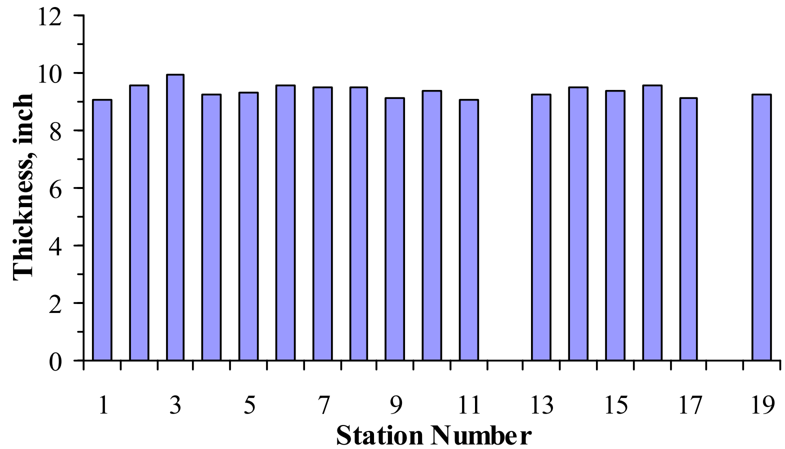


Figure 4.6 - Individual Pavement Thickness Measurements at Age of 7 Days

4.4 PWL-BASED PAY SCHEDULE FOR SEISMIC/MATURITY CRITERIA.

To be applicable to the current FAA P-501 specification, appropriate equivalent PWL-based pay schedules were developed for the proposed methods. Appendix D contains an extensive background on this subject.

The strengths of specimens prepared using the plastic concrete delivered to the job site are used in the FAA P-501 specifications. The lot size for a project is specified by the Engineer based on the total quantity and the expected production rate. Each lot is typically divided into four equal sublots and one sample is taken from each sublot. Two specimens are typically prepared from each sample. Sampling locations are typically determined by the Engineer using random sampling procedures (e.g. ASTM D3665). The representative strength for each sublot is computed by averaging the results of the two test specimens.

For pavement thickness, one core is extracted by the contractor from each sublot from a location determined by the Engineer in accordance with random sampling procedures contained in ASTM D 3665.

The FAA has adopted 90% PWL as the acceptable quality limit (AQL) and 55% PWL as the rejection quality limit (RQL). This indicates that design parameters are assumed to meet the designer's intent if they vary by only one standard deviation on either side of the mean. Nominal design strengths of 600 psi (for flexural strength) and 4450 psi (for compressive strength) are commonly specified for FAA projects.

The pay factor for each individual lot is calculated in accordance with Table 4.2. This pay schedule incorporates a bonus pay from 90% PWL to 96% and a penalty payment from 75% PWL to 55% PWL.

Table 4.2 - Existing Pay Adjustment Schedule

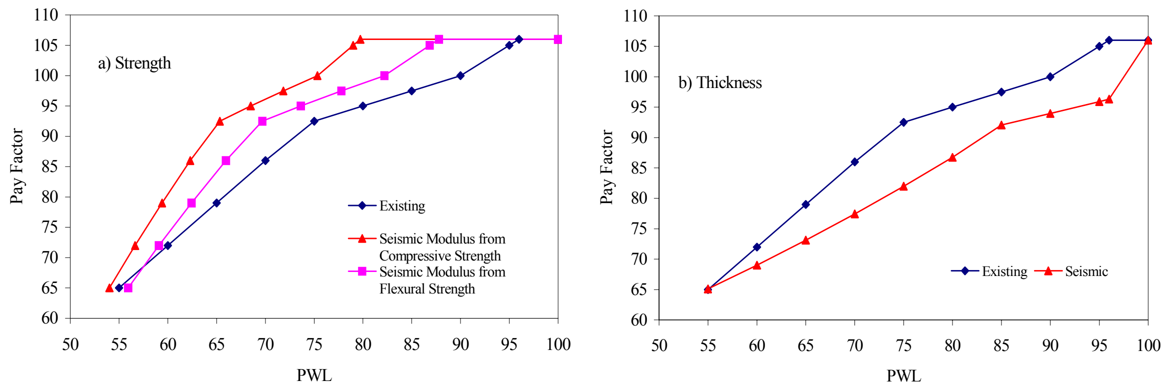
Percentage of Material Within Specification Limits (PWL)	Lot Pay Factor (Percent of Contract Unit Price)
96 – 100	106
90 – 95	PWL + 10
75 – 89	0.5PWL + 55
55 – 74	1.4PWL – 12
Below 55	Reject

The transformation of the existing P-501 PWL-based pay schedules to equivalent pay schedules based on seismic measurements consists of the following steps:

1. Develop regression models for determining the equivalent design seismic modulus from the design flexural strength or compressive strength.
2. Estimate the ratios of the coefficient of variation for determining the equivalent seismic modulus standard deviation for any flexural (or compressive) strength standard deviation.
3. Simulate a large number of lots with various combinations of means and standard deviations for each existing quality characteristic (e.g., flexural strength).
4. Compute the PWL of flexural strength and compressive strength for each simulated lot.
5. Compute the equivalent mean and standard deviation of the seismic modulus obtained from PSPA using the correlations developed in Steps 1 and 2.
6. Compute the PWL of the seismic modulus obtained from PSPA for each simulated lot.
7. Develop regression correlations between the PWL of the seismic modulus obtained from PSPA and flexural (or compressive) strength.
8. Convert the existing PWL-based pay schedule using the regression correlations developed in Step 7 for the seismic modulus obtained from PSPA.

A full explanation of each step is included in Appendix D. Based on this procedure, the preliminary PWL-based pay schedules are included in Figure 4.7. For any given strength PWL, the seismic method receives higher pay factor, especially for the compressive strength tests.

For the thickness, the traditional PWL and pay factor procedures can be implemented since no transformation is needed. Since the IE method is less precise than the actual measurement of the core length, the pay factor will be less at a given PWL as shown in Figure 4.7b.



(a) **(b)**

Figure 4.7 - Comparison of Existing Pay Schedule with Seismic-based Pay Schedule

Appendix D also contains a statistical analysis of sample size as a function of specifications tolerance, buyer's risk, seller's risk, and the standard deviations of the test parameters under study. That appendix also contains a cost analysis. Table 4.3 shows the sample size requirements for three probabilities of the standard deviation of the quality control specimens to be less than the standard deviation of the testing methods, P(S≤σ). The probabilities of 50%, 75%, and 95% at buyer's risk (β) of 0.1 and seller's risk of (α) of 0.1 were considered. The average unit costs in Texas were used to calculate the costs associated with each method of testing. Considering the results from P(S≤σ) of 50% as the current level of acceptance testing under the FAA, the seismic tests will cost about 1/7 for the flexural tests and 1/3 for the compressive tests. Alternatively, the seismic testing can be performed at many more points for the same costs as the current acceptance testing. For example, for the cost of five specimens for flexural strength tests, about 35 seismic tests can be completed with the PSPA. At that rate the P(S≤σ) is greater than 95% (as opposed to 50% for flexural strength tests). Similarly for costs comparable to acceptance using compressive strength tests at P(S≤σ), of 50%, a P(S≤σ), of 80% is obtained with the PSPA tests.

Table 4.3 - Sample Size Requirements and Associated Costs at α and β Risks of 10%.

Parameter	P(S≤σ) = 50%	P(S≤σ) = 75%	P(S≤σ) = 95%
Flexural Strength	5 ($750)	9 ($1,350)	19 ($2,750)
Compressive Strength	7 ($280)	14 ($700)	28 ($1,400)
PSPA Seismic Modulus	5 ($100)	9 ($180)	19 ($380)

5. EVALUATION OF PROPOSED METHODOLOGIES.

5.1 STRENGTH.

A number of experiments were performed to study the impact of material-related, environmental-related, and construction-related parameters on the accuracy and reliability of the proposed methods. The experimental matrix designed and executed for this purpose is shown in Table 5.1.

The first column in the table contains the parameters of interest. The rationale for selecting the levels of each parameter is discussed in Appendix F.

The second column summarizes the levels of variation that were considered. Most parameters were varied over a broader range than would normally be seen on an actual construction project. As such, the patterns observed may be more significant than those observed in day-to-day construction.

The next three columns in Table 5.1 indicate which of the three project team members performed the testing, and whether small slabs or laboratory-prepared specimens were utilized. Any strength/modulus/maturity parameter studied using the slabs were accompanied by tests on molded specimens cured in the laboratory (for calibration purposes) and cores and beams extracted from the slabs (for validation purposes). The following three coarse aggregate types were used in three different laboratories in this study:

- granite (GRN) aggregates from the Southeast at ERDC
- limestone (LS) aggregates from the Midwest at UIC
- siliceous river gravel (SRG) aggregates from the Southwest at UTEP

The materials and the final mix designs used in this study were in compliance with the requirements of the P-501 specification. The control (standard) mix design for each group is summarized in Table 5.2.

5.1.1 Laboratory Study.

The step-by-step laboratory procedures followed to establish the strength-maturity and strength-seismic modulus relationships are described in Appendix B. Figure 5.1 illustrates the activities carried out on the laboratory specimens. Twelve to fifteen cylinders and beams were prepared and moist-cured for each mix as per ASTM C31. I-buttons were embedded in one beam and one cylinder to measure the maturity of the specimens. Two or three cylinders and beams were tested for strength at ages of 1 day, 3 days, 7 days, 14 days and 28 days. The FFRC tests were conducted on the same beams and cylinders prior to conducting strength tests.

5.1.2 Small Slab Study.

A number of small slabs were constructed at UTEP and ERDC to simulate field conditions. Each small slab was typically 42 in. wide, 72 in. long and about 12.5 in. thick as sketched in Figure 5.2.

Table 5.1 - Summary of Strength-Related Activities

a) Material-Related Parameters

Parameter		This Study	UTEP		ERDC		UIC
			Slab	Specimen	Slab	Specimen	Specimen Only
Cement content		• As designed • 10% higher • 10% lower		✓	✓	✓	✓
Water-cement ratio		• As designed • 10% higher • 10% lower	✓	✓	✓	✓	✓
Air content		• No air-entrainer • Low air-entrainer • High air-entrainer					✓
Aggregates	Type of Aggregates*	• Siliceous river gravel • Limestone • Granite	✓	✓	✓	✓	✓
	% total aggregates	• As designed • 10% higher • 10% lower					✓
	Coarse Aggregate Factor	• As designed • 10% higher • 10% lower		✓	✓	✓	✓
	Fineness Modulus	• As designed • 5% Passing Sieve #50 • 25% passing Sieve #50					✓

b) Construction-Related Parameters

Parameter	This Study	UTEP		ERDC		UIC
		Slab	Specimen	Slab	Specimen	Specimen Only
Curing	• No curing compound • Curing compound • Blanket	✓		✓		
Compaction	• Appropriate compaction • Overcompaction	✓				
Grooving	• Broom finish • Standard FAA grooving			✓		
Thickness	• 6 inches • 12 inches • 18 inches	✓				

c) Environmental-Related Parameters

Parameter	This Study	UTEP		ERDC		UIC
		Slab	Specimen	Slab	Specimen	Specimen Only
Ambient Temperature	• Cold (50^o F) • Warm (70^o F) • Hot (90^o F)	✓				
Ambient Humidity	• Low (30 to 40%) • High (90 to 95%)	✓				

*** Each institution used a different coarse aggregate**

Table 5.2 - Three Standard Mix Designs Used in This Study

Institution	UTEP	UIC	ERDC
Coarse Aggregate Type	SRG	Limestone	Granite
Type I-II Cement (lb/yd^3)	564	622	586
Sand (lb/yd^3)	1115	1278	1212
Coarse Aggregate (lb/yd^3)	1900	1712	1825
Water (gal/yd^3)	28.9	33.6	29.5
Air Entraining Admixture (oz/yd^3)	2.0	N.A.	1.5
Water Reducer (oz/yd^3)	17.0	0	17.5

a) Specimens with I-buttons

b) FFRC Test

c) Flexural Strength Test

d) Compressive Strength Test

Figure 5.1 - Activities Carried out on Specimens

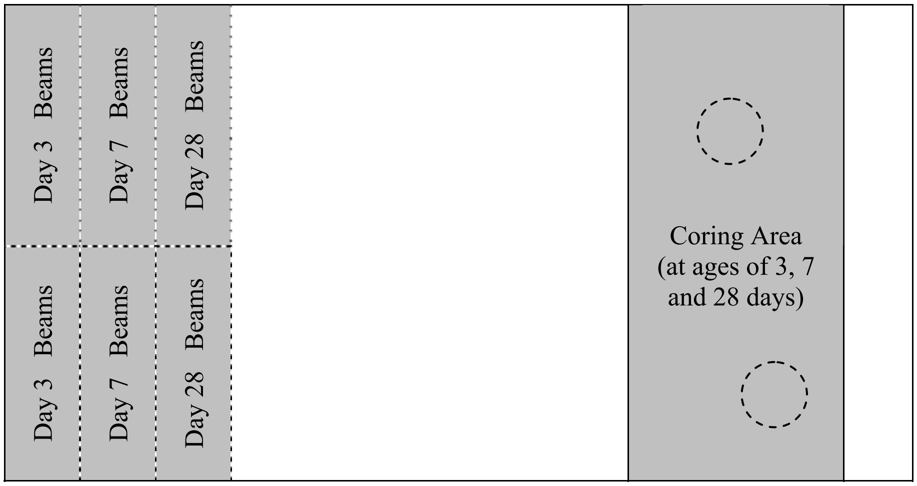


Figure 5.2 - Typical Layout of a Small Slab

Figure 5.3 illustrates the typical activities carried out on the small slabs. Two i-buttons were embedded in each slab during construction to obtain the in-place maturity of the slab up to 28 days. Two cores and four beams were extracted from the slab and tested at the ages of 3, 7 and 28 days. Before coring or sawing the beams, the slabs were tested with the PSPA to obtain the in-place seismic modulus.

a) Embedding I-button in Slab

b) PSPA Test for In-place Modulus

c) Saw-Cutting for Beams

d) Drilling for Cores

Figure 5.3 - Activities Carried out on Small Slabs

The extracted cores were tested in compression with minimal preparation. A 6 in. slice of the slab was saw-cut along the width to extract beams for flexural tests. The 12 in. thick beam was then cut in half lengthwise and again along the depth to obtain 4 standard beams. The average flexural strengths for the four beams were used in this study. Extracting intact specimens especially beams after 1 day was abandoned.

5.1.3 Results and Evaluation**.**

The purpose of the test program for the acceptance based on strength was to validate the following five objectives:

1. Laboratory relationships (calibration curves) can be accurately, readily, and conveniently developed between strength and maturity and/or seismic measurements for a specific mix.
2. Changes in mixture-related, construction-related, and environmental-related parameters that are inevitably encountered during construction practices of adequate quality do not significantly impact the calibration curves developed in Item 1.
3. The field and laboratory developed relationships are similar or strongly related and are not impacted by the size of specimens or method of testing.
4. Changes in concrete strength, as may be caused by changes in materials, construction, or environment with poor-quality construction practices, are appropriately detected by corresponding changes in maturity and/or seismic measurements.
5. All test methods are robust, repeatable, and reproducible.

A summary of the test results and pertinent conclusions drawn with respect to the primary project objectives are described below.

Objective 1: Accuracy and Precision of Calibration Curves

Thirty-two individual mixes from three different coarse aggregates were available to develop laboratory strength-maturity/seismic calibration curves (see Table 5.1). The quality of the calibration curves was judged based on the corresponding R^2 values, the standard errors of estimate (SEE) and the uncertainty in estimating the strength parameters. The results from each mix are included in Appendix G and are summarized in Table 5.3.

All calibration curves yield R^2 values that are greater than 0.84, with an average of better than 0.94. As an example, the flexural strength-TTF calibration curves yield a maximum SEE of about 48 psi. For a flexural strength of 600 psi, such a SEE yields an uncertainty in strength estimation of about 8%. The average uncertainty is less than 5% because the average SEE is 28 psi. The quality of the laboratory-developed relationships is very reasonable considering the variability in flexural strength tests.

The strength-seismic modulus calibration curves yield an average R^2 value of greater than 0.95 with an uncertainty of about 4%. This indicated that the seismic modulus and strength are highly correlated.

Table 5.3 - Typical Quality of Calibration Curves for Individual Mixes

Relationship	R^2		SEE*		Uncertainty**	
	Min.	Avg.	Max.	Avg.	Max.	Avg.
Flexural Strength vs. Maturity Parameter	0.84	0.94	48	28	8%	5%
Compressive Strength vs. Maturity Parameter	0.94	0.97	484	233	12%	6%
Seismic Modulus vs. Maturity Parameter	0.91	0.95	351	137	7%	3%
Flexural Strength vs. Seismic Modulus	0.81	0.95	49	23	8%	4%
Compressive Strength vs. Seismic Modulus	0.87	0.98	454	178	11%	4%
Flexural Strength vs. Seismic Modulus and Maturity Parameter	0.86	0.97	39	17	7%	3%
Compressive Strength vs. Seismic Modulus & Maturity Parameter	0.89	0.98	683	126	16%	3%

***SEE = Standard Error of Estimate in psi for strength parameters and ksi for modulus**
**** Uncertainty: based on a flexural strength of 600 psi, compressive strength of 4200 psi and modulus of 5300 ksi**

The R^2 values when a strength parameter was related to the combination of the TTF and seismic modulus are slightly increased and the SEE values slightly decreased as compared to the corresponding relationships developed solely on seismic moduli. This indicates that the combined parameters can slightly improve the predictive power of the relationships.

Objective 2: Impact of Mix-Related Parameters on Calibration Curves

Variations in mix proportions during paving operation from the approved mix design are inevitable. A robust calibration curve should provide an accurate estimate of the strength given small changes in the mix proportions. The evaluation of the robustness of the seismic/maturity calibration curves is presented in detail in Appendix G and summarized below.

The variations in flexural strength with TTF for the 32 individual mixes are accumulated in Figure 5.4a. The data are separated into three groups based on the source of the coarse aggregates. Eight individual mixes were available for the SRG and granite coarse aggregates and 16 for the limestone aggregates. The calibration curves for the standard mixes for the three aggregates are also shown in the figure. The strength-TTF data points generally follow their corresponding calibration curves, but with some scatter. Therefore, when the constituents of a mix vary from the approved mix design, the strength based on the measured TTF may contain some uncertainty.

The variations in the flexural strength with seismic modulus for the same 32 mixes are shown in Figure 5.4b. In this case, the data points from each coarse aggregate type are concentrated around their corresponding calibration curve. This means that the strength estimated from the seismic modulus is more robust than that estimated from maturity when the constituents of a mix vary from the approved mix design.

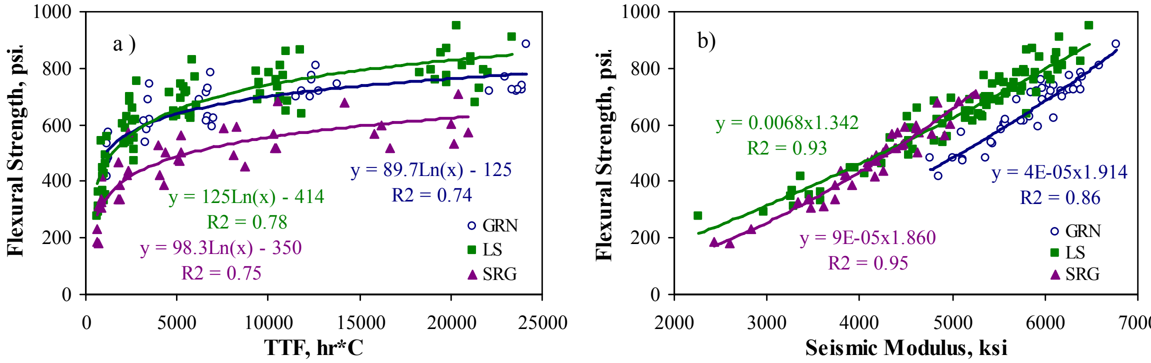


Figure 5.4 - Comparisons of Strength-Maturity and Strength-Seismic Calibration Curves with Data from Nonstandard Mixes

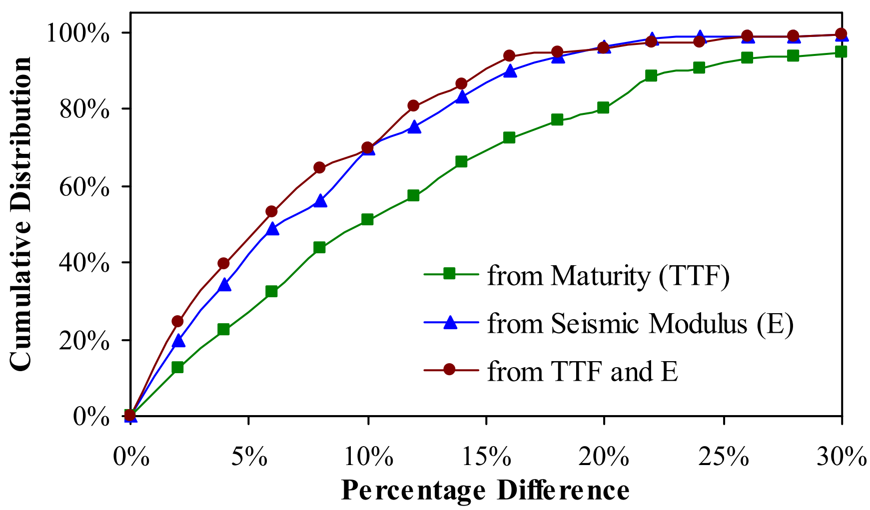


Figure 5.5 - Comparison of Differences between Predicted and Measured Flexural Strengths for all Mixtures

The differences between the measured and estimated strength were determined to quantify the anticipated uncertainties in estimating the strengths using:

$$Difference(\%) = \frac{|Measured\ Strength - Estimated\ Strength|}{Estimated\ \ Strength} x100 \qquad (5.1)$$

The cumulative distributions of the differences between the estimated and measured flexural strengths are shown in Figure 5.5. The misestimation errors based on maturity and seismic measurements are 10% and 6%, respectively. At a level of confidence of 90%, the differences are 24% and 16%.

Table 5.4 contains the levels of misestimation errors observed for all the calibration curves considered in this study. The seismic-based calibration curves are the most robust, followed by the combined maturity/seismic-based ones.

Table 5.4 - Typical Uncertainty in Estimation Strength due to Change in Mix Proportion

Relationship	Mis-estimation Error	
	Average	Confidence Level = 90%
Flexural Strength vs. Maturity Parameter	10%	24%
Compressive Strength vs. Maturity Parameter	14%	30%
Flexural Strength vs. Seismic Modulus	6%	16%
Compressive Strength vs. Seismic Modulus	7%	16%
Flexural Strength vs. Seismic Modulus and Maturity Parameter	6%	15%
Compressive Strength vs. Seismic Modulus & Maturity Parameter	9%	25%

This study demonstrates the need for diligent process control at the batch plant to ensure that the proportions of the coarse aggregates, fine aggregates, cement, and water are maintained. This is particularly critical for the maturity-based process.

Objective 3: Similarity of Lab and Field Results

To supplant the strength tests in the FAA P-501 specifications with an alternative field testing method, one should be confident that the calibration curves developed in the laboratory are representative of the field conditions as well. The laboratory calibration curves were compared with the relationships between strength and maturity or seismic modulus measured on slabs for this purpose.

Data from 22 small-scale slabs poured at UTEP with SRG and ERDC with granite were used. The 10 slabs at ERDC were all placed inside a building where the temperature and humidity were controlled, whereas the12 slabs at UTEP were placed outside and were fully exposed to environmental elements. As such, the ERDC results document the impacts of mix-related and construction-related parameters, and the results from UTEP reflect the impacts of all mix-related, construction-related, and environmental-related parameters.

A complete analysis of the results is provided in Appendix G. As a baseline, the differences between the strengths measured from the cores and beams extracted from the slabs (f_{field}) were compared with corresponding strengths measured on companion lab-cured specimens (f_{lab}). The cumulative distributions of the difference between lab and field strengths are shown in Figure 5.6 and summarized in Table 5.5. The differences are determined using

$$Difference(\%) = \frac{\left| f_{lab} - f_{field} \right|}{f_{lab}} x100 \qquad (5.2)$$

For the ERDC slabs, where the specimens and slabs were cured under similar conditions, the differences are less pronounced as compared to UTEP slabs that were fully exposed to environmental elements. The differences in flexural strengths between the cast and sawed beams are less pronounced than those from the compressive tests. This has to do with the differences in patterns of gain in flexural and compressive strengths in the field. More details are provided in Appendix G.

Based on this study, a difference of more than 10% to 15% between the actual strengths of the pavement and the strengths measured under P-501 specifications should be anticipated.

Table 5.5 - Typical Differences in Strengths Between Lab-cured Specimens and Corresponding Specimens Extracted from Slabs

Parameter	Difference			
	Average		Confidence Level = 90%	
	ERDC	UTEP	ERDC	UTEP
Flexural Strength	8%	10%	18%	>25%
Compressive Strength	15%	18%	25%	>30%
Seismic Modulus	4%	6%	7%	12%

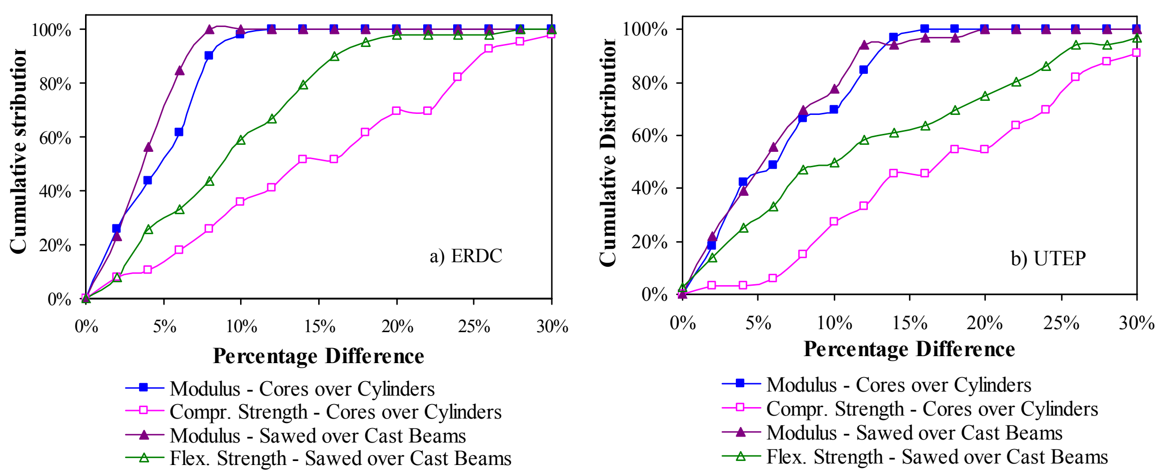


Figure 5.6 - Comparison of Differences between Measured Strength Parameters from Standard Specimens and Those Extracted from Slabs

Differences in seismic moduli from the FFRC method measured on the lab and field specimens are also shown in Figure 5.6. The seismic moduli from FFRC tests on the cast and sawed beams follow similar trends as for the cast cylinders and cores. The maximum difference observed is about 14%. , the end conditions of the specimens (unlike compressive and flexural tests) do not impact the results of the seismic tests.

The utilization of the seismic-based calibration curves with confidence will only be possible if the moduli measured with the PSPA on the pavement agree with the moduli measured with the FFRC method on specimens extracted from the pavement. The differences between the lab and field moduli are about 5% on the average (less than 15% at a confidence level of 90%), as illustrated in Figure 5.7. As such, PSPA can be used with confidence to estimate the modulus of the PCC.

The differences in the maturity measurements from the lab specimens and slabs are also presented in Figure 5.7. For the ERDC experiments, the lab and the field values exhibit an average difference of 4% because of similar curing regimes. For the UTEP experiments, the average lab and field maturities differ by more than 30%.

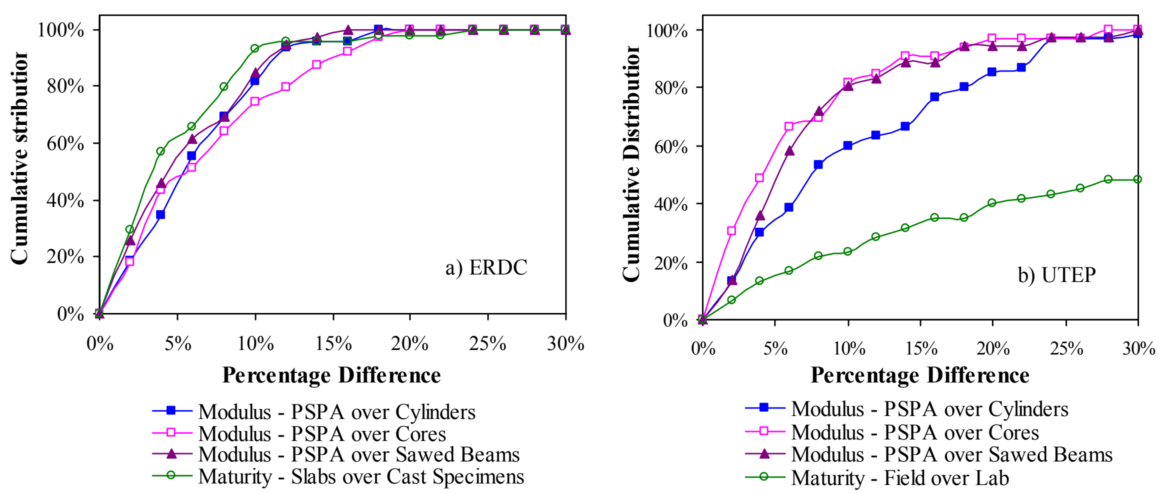


Figure 5.7 - Comparison of Differences between Measured Seismic Moduli with PSPA on Slabs and FFRC Moduli of Cylinders, Cores and Sawed Beams

Objective 4: Delectability of Construction-Related Issues

The maturity-based calibration curves from the standard mixes used at UTEP and ERDC are compared with the results from tests on slabs in Figure 5.8. Each figure contains two dashed lines that define 10% error bands. The ERDC experiments illustrate less scatter because the slabs and the lab specimens were cured under similar environmental regimes. The field TTF values for a number of UTEP slabs are significantly greater than those for the companion lab specimens, even though the slab strengths were lower. In these cases, the maturity method over-estimates the strength of the slabs.

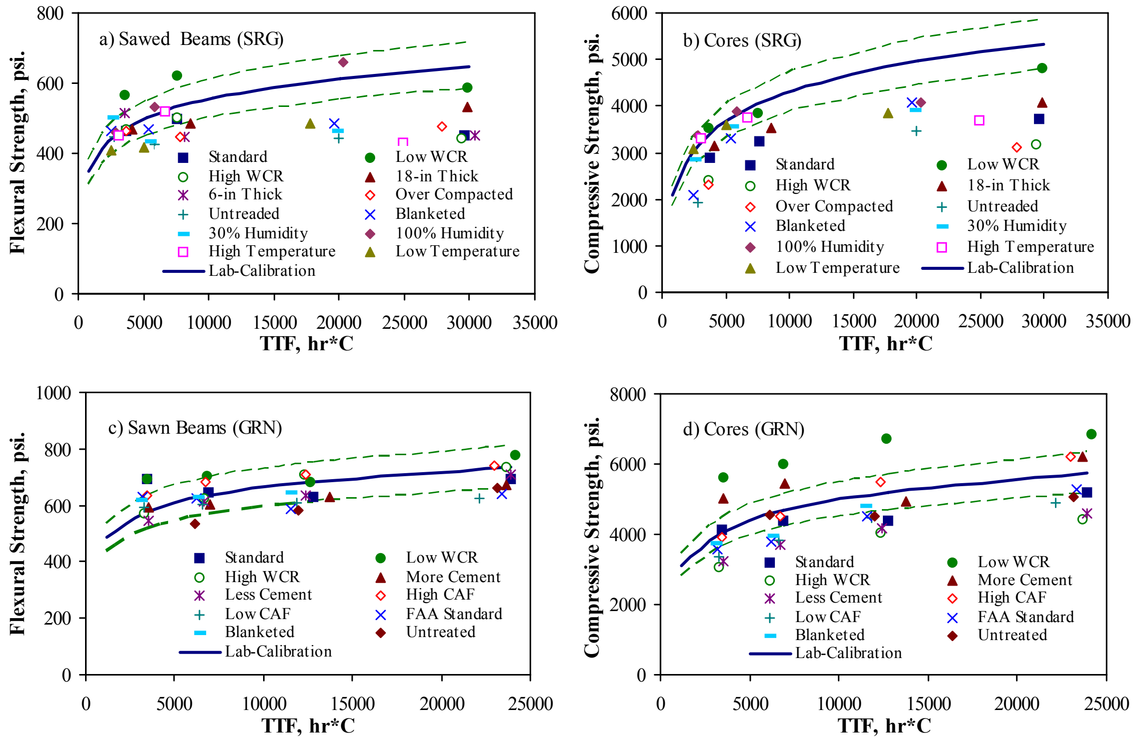


Figure 5.8 - Variations in Strength with Maturity from Slabs

The variations in slab strength with seismic modulus also show some deviations from the calibration curves (Figure 5.9). The flexural strengths for the most part are estimated with an accuracy of about 10% except for the slabs with the higher-than-designed water-cement ratios.

For the UTEP experiments, the compressive strengths are under-estimated for the thick slab, the mix with higher than designed water-cement ratio, and the standard slab cured with curing compound. The compressive strengths are over-estimated for the slab subjected to blanket-curing, the slab that was over-compacted, and the slab cured without treatment. The compressive strengths for the ERDC experiments for the slabs cured under blanket (marginally) and the mixture with lower-than-designed water-cement ratio are over-estimated.

Objective 5: Repeatability of Methods

The repeatability of the methods was determined based on field and lab tests by the three team members. The cumulative distributions of COVs, developed from replicate specimens from all three coarse aggregates are shown in Figure 5.10 and summarized in Table 5.10. The PSPA COVs contain variability related to both the test method and the material variation because the results are from a number of points along the slab. The COVs for the other tests correspond primarily to the variability due to the test method. The COVs at a confidence level of 50% are less than 1% for FFRC, less than 3% for compressive strength, and less than 5% for the flexural strength and the PSPA measurements.

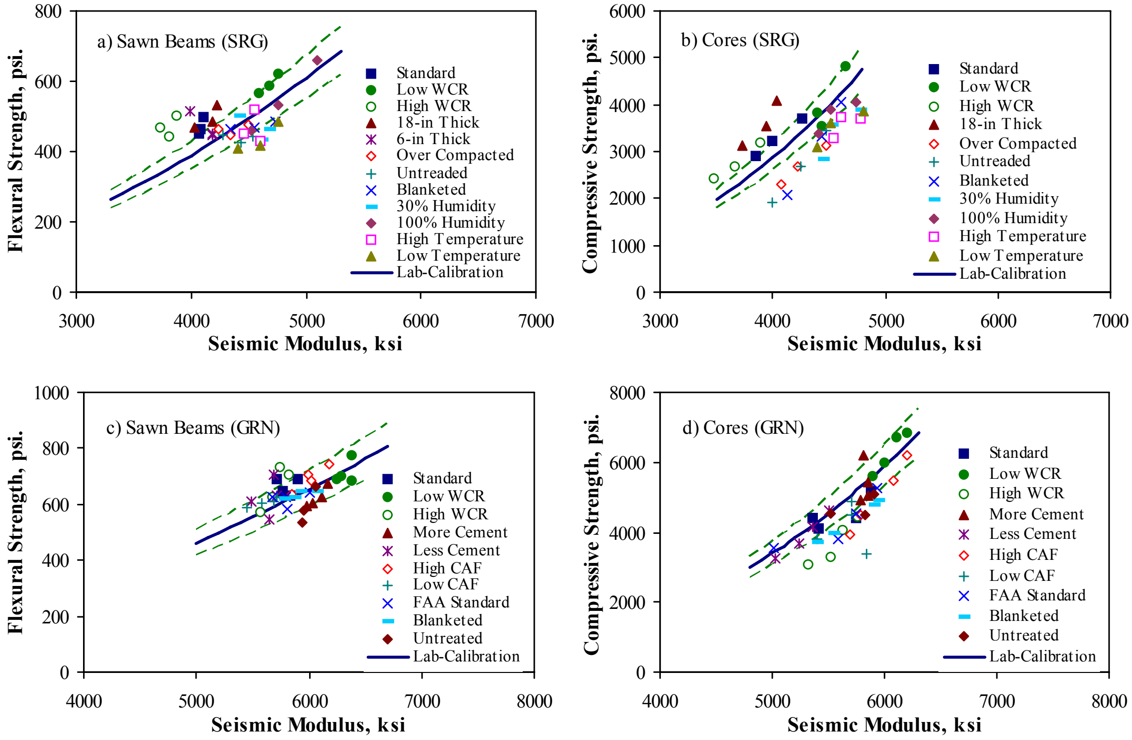


Figure 5.9 - Variations in Strength with Seismic Modulus from Slabs

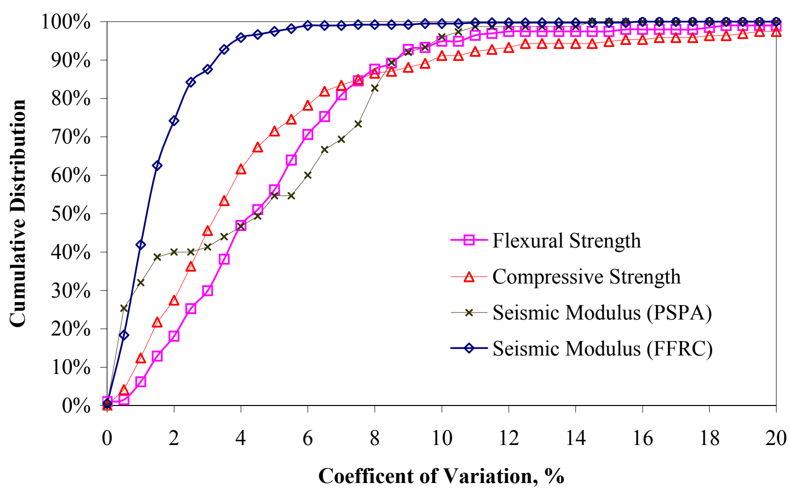


Figure 5.10 - Cumulative Distribution of Coefficient of Variation for all Testing Methods

Table 5.6 - Coefficients of Variation of Different Methods at 50 and 90 Percentile Cumulative Distribution

Parameter	COV (%)	
	50 Percentile Cumulative Distribution	90 Percentile Cumulative Distribution
Flexural Strength	5	9
Compressive Strength	3	10
FFRC Seismic Modulus	1	3
PSPA Seismic Modulus	5	9

To incorporate some conservatism into the process, a confidence level of 90% can be used. , The COV for the FFRC tests is about 3% and for the other methods are about 9% as shown in Table 5.6.

5.2 THICKNESS.

The determination of thickness with the impact-echo method was studied with similar objectives as for the strength determination. The primary objectives of this activity were to evaluate the following:

1. The accuracy of the method.
2. The impact of construction-related parameters on the accuracy of the method.
3. The repeatability of the method.

The small slabs (42 in. by 72 in.) constructed at UTEP were used for the thickness study. The IE tests were conducted at several locations on each slab at ages of 1 day, 3 days, 7 days, 14 days, and 28 days. Cores extracted from each slab were used for thickness validation. Additionally, a long slab with varying thickness was constructed as shown in Figure 5.11. The slab was 6 ft wide

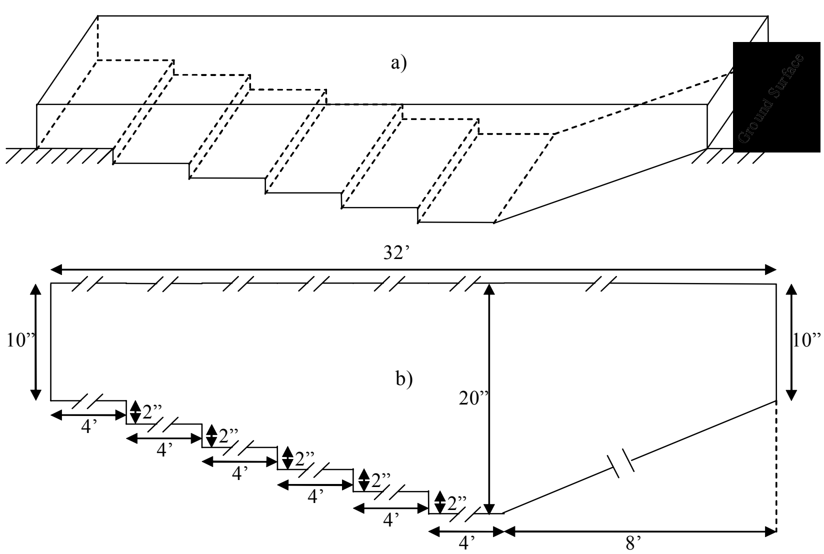


Figure 5.11 - Layout of Long Slab for Thickness Measurement

and 32 ft long. On a 24-ft long section of the slab, the thickness was varied every 4 ft from a minimum of 10 in. to a maximum of 20 inches, in increments of 2 in. For the rest of the slab, the thickness was gradually varied from 20 in. to 10 in. to provide a means for evaluating the impact of subtle changes in thickness. The slab was constructed without steel because past studies have shown that the impact-echo method is not significantly impacted by the presence of reinforcing steel.

Objective 1: Accuracy of Method

The uncertainty in thickness estimate with the impact-echo method depends on a pooled error of the return frequency measurement and the P-wave velocity determination. A detailed discussion on the activities carried out to determine the accuracy and precision is included in Appendix H. A brief summary is included here.

The actual thicknesses are compared with the thicknesses from the IE method for the long slab in Figure 5.12. The thicknesses are globally underestimated by about 4%. This observation is reasonably close to those reported in the literature (e.g., Maser et al., 2003).

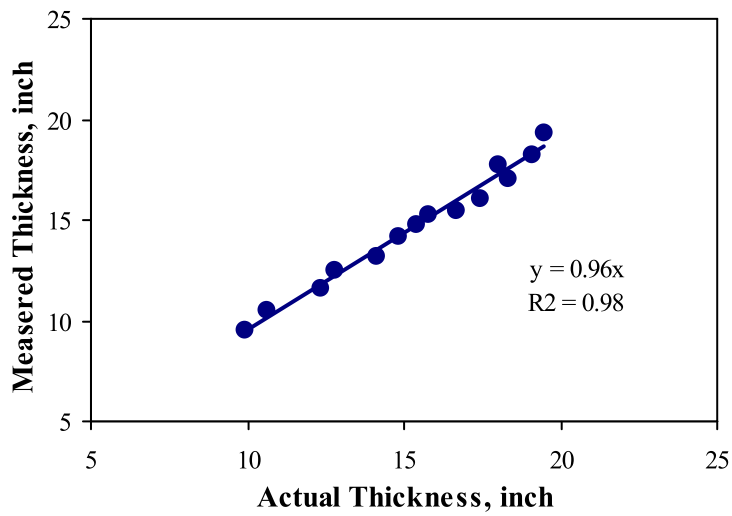


Figure 5.12 - Comparison of Measured Thicknesses from IE Tests with Actual Ones

Figure 5.13 includes the thickness estimates for a 12.5-in.-thick slab using the P-wave velocities obtained from different sources. The best thickness estimates were obtained by using the P-wave velocity from the FFRC tests on cores. This confirms the notion that one or more cores should be extracted from the slab for proper utilization of the IE method.

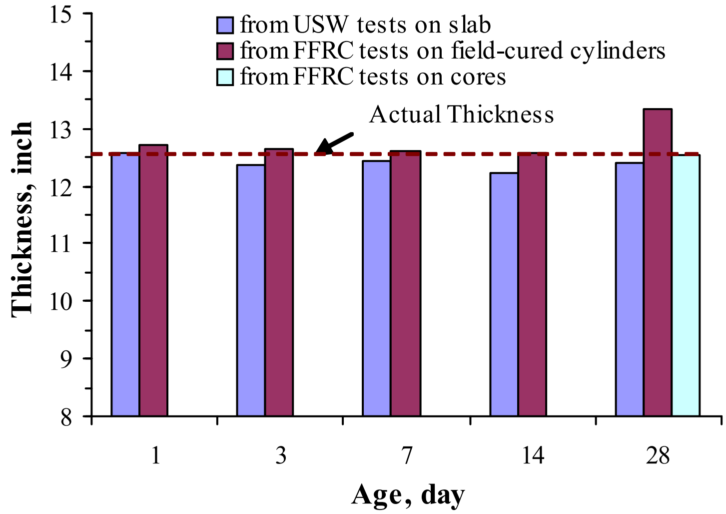


Figure 5.13 - Comparison of Thickness Estimates Based on Different P-wave Velocities

Objective 2: Impact of Construction-Related Parameters

The impact of the base layer stiffness, pavement edges, and pavement surface grooving on the IE measurements were evaluated under this objective. A detailed discussion is provided in Appendix H. The stiffness contrasts between the concrete pavement and the underlying materials can impact the accuracy in pavement thickness estimate with the IE method. Three types of base layers — compacted soil, cement-treated base (CTB), and asphalt concrete base (ACB) — were used.

The differences in the thickness estimates for the slabs placed on the compacted soil and CTB were within the measurement errors. The estimated thicknesses for the slab placed on the ACB are typically representative of the composite thickness of the concrete pavement and the ACB layer because the contrast in stiffness between the two materials is not large enough.

One practical item to be addressed is how close an IE test should be performed relative to the edges of a pavement to obtain a reliable return frequency. The IE measurements should be conducted at a distance at least two times the thickness of the pavement to minimize the edge reflection effect (see Appendix H for details).

The effect of surface grooving on pavement thickness measurements with the IE method was studied on a small slab. The thickness return frequencies were measured parallel to the grooves and perpendicular to the grooves. The maximum difference in average return frequency was about 2.5% and was independent on the placement orientation. Such a difference is within the uncertainty in return frequency measurements.

Objective 3: Repeatability of Method

The precision of the IE return frequency measurements without moving the PSPA between measurements was about 1%. The precision varied by about 2% to 5% when the PSPA was moved several inches between measurements. Such variation can be attributed to the coupling between the impact source and the slab surface and the non-uniformity in the properties of concrete, especially at early ages.

6. CASE STUDIES FOR AIRPORT PROJECTS.

The practical use of maturity and seismic technologies was demonstrated in conjunction with two construction projects. The first project was carried out in October and November 2004 as part of quality assurance for the construction of a taxiway at the Aurora Municipal Airport near Chicago. The second project was carried out from September to November 2005 in conjunction with Ramp 1 taxi-lane reconstruction at the Hartsfield-Jackson Atlanta International Airport. The objective of the second experiment was to investigate the effect of the concentration of the lithium nitrate ($LiNO_3$) admixture on the early-age properties of production concrete.

6.1 AURORA MUNICIPAL AIRPORT.

Taxiway A at Aurora Municipal Airport, reconstructed under FAA P-501 specification featured an undoweled 9-in. thick jointed concrete pavement (JPCP) on a granular base course. A 150-ft long section of the taxiway (see Figure 6.1) was randomly selected for field testing.

The field activities are included in Table 6.1. These activities included preparation of molded specimens for strength and modulus tests, installation of thermocouples and/or i-buttons in specimens and slabs for maturity measurements, and coring and PSPA tests at selected times to estimate the pavement thickness and the in-place modulus.

The concrete mix design used is summarized in Table 6.2. The slump and the air content were measured during construction for loads of concrete placed near the i-button locations. The average slump was 1.7 in. (target 2 in.), with a standard deviation of 0.3 in., and the average air content was 6.2% (target 6%), with a standard deviation of 0.7%.

Figure 6.1 - Newly Constructed Taxiway Segment Selected for Field Testing at Aurora Airport

Table 6.1 - Summary of Field Testing Activities at Aurora Airport

Date	Testing Day	Field Activity	Lab Activity
10/14/04	0 (paving)	–Installing i-buttons –Casting 22 beams/22 cylinders –Burying beams/cylinders in sand/dirt on site	
10/15/04	1	–Obtaining PSPA readings –Transporting 11 beams/11 cylinders to lab for standard curing	–Accepting 11 beams/11 cylinders for standard curing –Testing 2 beams/2 cylinders
10/18/04	4	–Retrieving 2 cores –Obtaining i-button readings –Obtaining PSPA readings –Transporting 2 beams, 2 cylinders, and 2 cores to lab for testing	–Accepting 2 beams/2 cylinders (4-day field cured) –Accepting 2 cores (4-day) –Testing 2 beams/2 cylinders (4-day std cured) –Testing 2 beams/2 cylinders (4-day field cured) –Testing 2 cores (4-day)
10/21/04	7	–Retrieving 2 cores –Obtaining PSPA readings –Transporting 2 beams, 2 cylinders, and 2 cores to lab for testing	–Accepting 2 beams/2 cylinders (7 day field cured). –Accepting 2 cores (7-day) –Testing 2 beams/2 cylinders (7-day std cured) –Testing 2 beams/2 cylinders (7-day field cured) –Testing 2 cores (7-day)
10/28/04	14	–Obtaining i-button readings –No PSPA obtained due to device malfunction –Transporting 2 beams and 2 cylinders to lab for testing	–Accepting 2 beams/2 cylinders (14-day field cured) –Testing 2 beams/2 cylinders (14-day std cured) –Testing 2 beams/2 cylinders (14-day field cured)
11/11/04	28	–Retrieving 2 cores –Obtaining i-button readings –Obtaining PSPA readings –Transporting remaining beams and cylinders and 2 cores to lab for testing	–Accepting remaining beams/cylinders (28-day field cured) –Accepting 2 cores (28-day) –Testing 2 beams/2 cylinders (28-day std cured) –Testing 2 beams/2 cylinders (28-day field cured) –Testing 2 cores (28 days)

Table 6.2 - Concrete Mix Design for New Taxiway at Aurora Municipal Airport

Item	Material #	Producer	Quantity/yd^3
Coarse Aggregate 1 (Crushed Limestone)	022CA11	Fox River Stone	1456 lbs
Coarse Aggregate 2 (Crushed Limestone)	022CAM16	Fox River Stone	430 lbs
Fine Aggregate	027FA01	Kaneland Sand & Gravel	1165 lbs
Cement (Type I)	37601	Illinois Cement, LaSalle	490 lbs
Fly Ash	37801	Lafarge America	150 lbs
Water			249 lbs
AEA	42147M	W. R. Grace Co	6.2 oz
Water Reducer	43709M	W. R. Grace Co	25.6 oz

The i-button assemblies were installed at three different locations on the day prior to the paving (Figure 6.2). Each i-button assembly was placed approximately half-way between the transverse joints and about 4 ft in from the longitudinal edge. Two i-buttons were employed in each assembly to provide temperature data at two different pavement depths and also to provide a "back-up" in case one of them failed. A steel rod was driven into the base course and two i-buttons were affixed to the rod at approximately 2 in. and 5 in. above the base to avoid being hit by the vibrators on the paver. The wires from the i-buttons were run out to the edge of the pavement in a narrow trench dug in the base course and secured in a location away from where the paver tracks would travel.

a) Three i-button locations

b) I-buttons in front of paver

Figure 6.2 - Installation of I-Buttons at Aurora Airport

6.1.1 Strength-Modulus/Maturity Calibrations.

Two dozen standard cylinders and two dozen standard beams were cast at the site using the mix delivered by the ready-mix trucks. Thermocouples were installed in four cylinders and four beams for maturity measurements. After 24 hours, the specimens were divided into two equal groups. One group was transported from the site to the UIC for laboratory curing and testing, and the other group was kept at the site for field curing. Field-cured specimens were covered with damp burlap, plastic sheeting, and a nominal 1-ft layer of gravel (see Figure 6.4b). Two beams and two cylinders from the field-cured specimens were removed from the site at 4, 7, 14, and 28 days for testing in the UIC laboratory.

At nominal ages of 1 day, 4 days, 7 days, 14 days and 28 days, eight specimens (two lab-cured cylinders, two lab-cured beams, two field-cured cylinders and two field-cured beams) were tested with the FFRC device to obtain their seismic moduli. These specimens were then tested to obtain their strengths.

The flexural strength, compressive strength and seismic modulus gradually increased with time with time as shown in Figure 6.3. The lab-cured specimens exhibited higher values than those from the field-cured specimens.

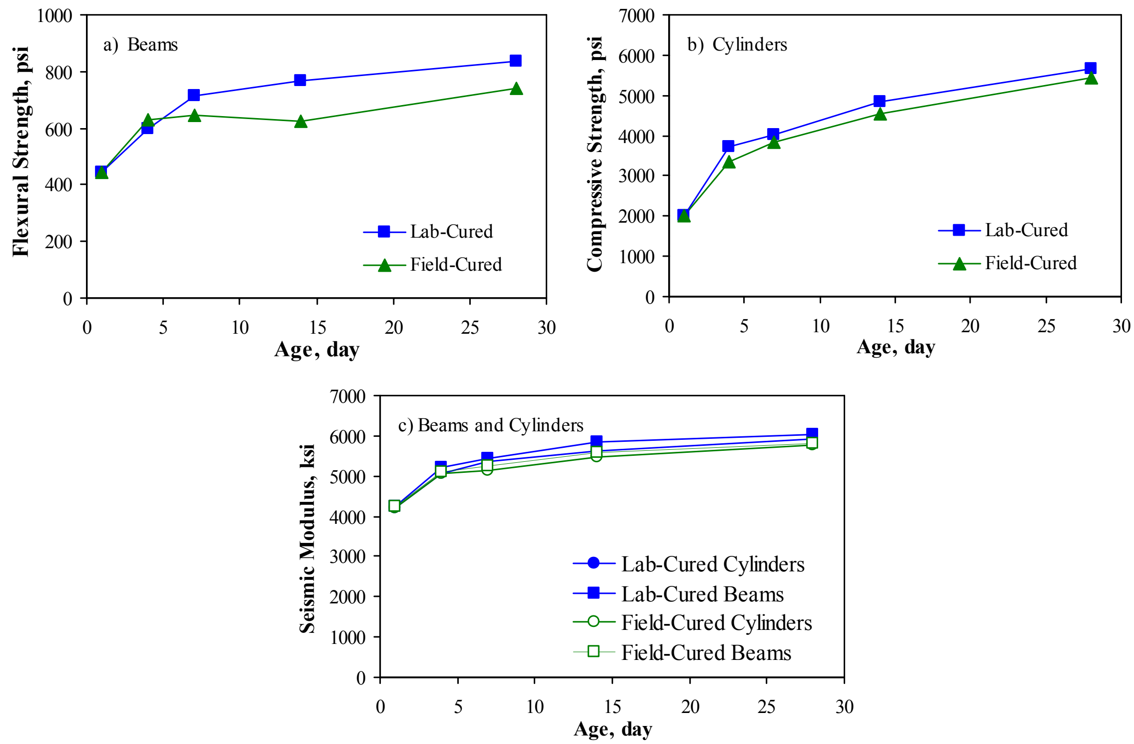


Figure 6.3 - Variations in Flexural Strength, Compressive Strength and Seismic Modulus of Molded Specimens with Time at Aurora Airport

The laboratory strength–seismic modulus calibration curves are shown in Figure 6.4. The results from tests on the field-cured specimens are also included in the figure. The calibration curves represent the data well for both flexural and compressive strengths, independent of the curing regime.

The laboratory strength-maturity calibration curves are shown in Figure 6.5. The two strength parameters are generally correlated well to maturity, with the exception of the flexural strength data from the field-cured beams.

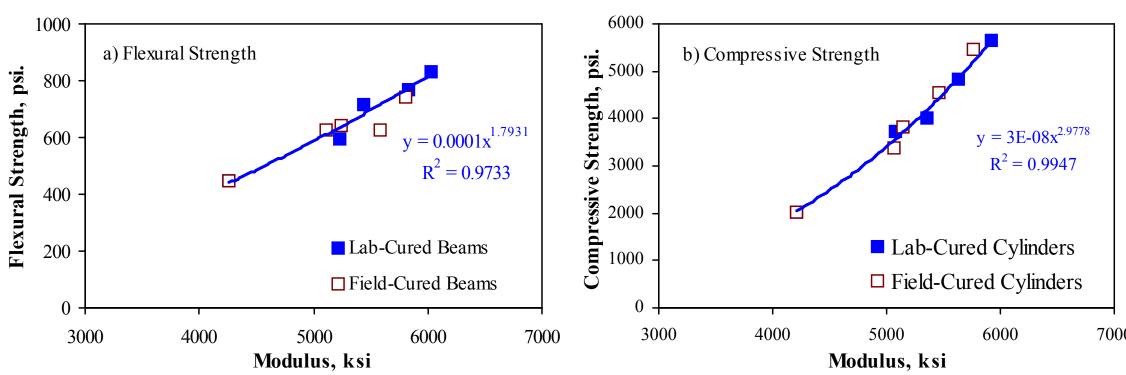
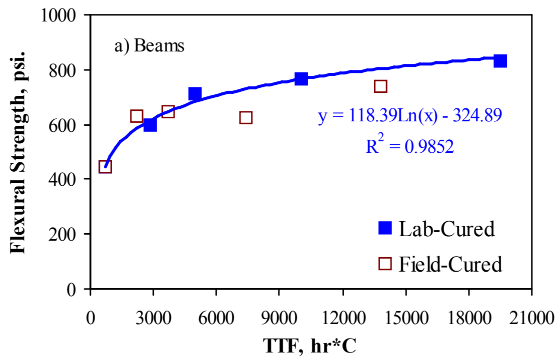


Figure 6.4 - Comparisons of Results from Field-Cured Specimens with Laboratory-Developed Calibration Curves for Strength Parameters vs. Seismic Modulus at Aurora Airport



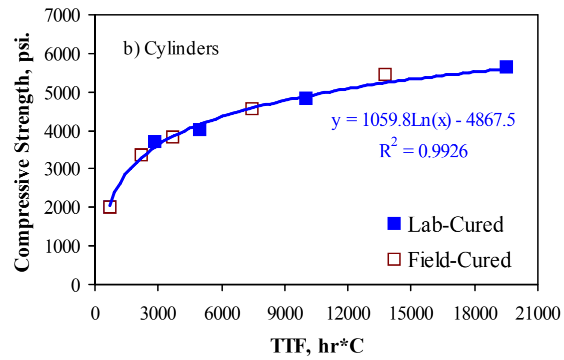


Figure 6.5 - Comparison of Results from Field-Cured Specimens with Laboratory-Developed Calibration Curves for Strength Parameters vs. Maturity at Aurora Airport

6.1.2 Correlation of Results from Lab and Field Tests.

A PSPA was used at ages of 1, 4, 7, and 28 days to determine the thickness and the in-place modulus of the pavement at 7-ft intervals along the section (see Figure 6.6). Two 4-in. diameter cores were retrieved from the pavement at each age of 4, 7, and 28 days for thickness verification and also for seismic modulus and compressive strength testing in the laboratory.

The variations in compressive strength and modulus with time are summarized in Table 6.3. The compressive strengths measured from cores were multiplied by a factor of 1.05 to adjust for the differences between the diameter of the cores (4 in.) and the lab specimens (6 in.) as suggested by Kesler (1966). The patterns are all consistent except for the core modulus at the age of 7 days.

The strength-modulus and strength-maturity calibration curves are compared with all relevant data collected at this project in Figure 6.7. The seismic modulus-based calibration curve represents all data well (figure 6.7a). The strength-maturity data are also consistent (Figure 6.7b) with a small shift due to the difference in curing temperature between the lab and the field.

a) PSPA Setup **b) PSPA Sensor Unit**

Figure 6.6 - Testing with a PSPA on Taxiway A at Aurora Airport

Table 6.3 - Compressive Strengths and Moduli Measured at Aurora Airport

Age, day	Compressive Strength, psi			Seismic Modulus, ksi			
	Lab-Cured Cylinders	Field-Cured Cylinders	Cores	Lab-Cured Cylinders	Field-Cured Cylinders	Cores	Slabs (PSPA)
1	2028	2028	--	4210	4210		4196
4	3718	3365	3824	5078	5067	3824	5024
7	4013	3836	4308	5352	5149	4308	5566
14	4845	4561	--	5631	5456	--	--
28	5663	5454	5616	5918	5767	5616	5744

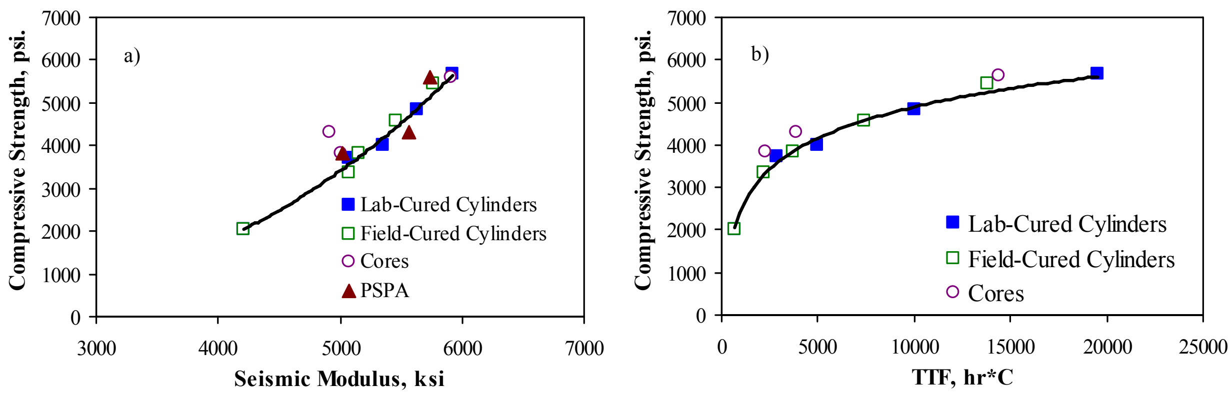


Figure 6.7 - Correlations of Compressive Strength with Seismic Modulus and Maturity for Results from both Lab and Field Tests at Aurora Airport

6.1.3 Pavement Thickness Measurement.

The data collected with a PSPA were also be used to estimate the pavement thickness through the impact-echo method. The average length of the six cores extracted from the taxiway pavement was 9.3 in., with a standard deviation of 0.3 in. The average estimated thickness from the impact-echo measurements conducted at different ages of the pavement was 9.4 in. with a standard deviation of 0.1 in.

6.2 HARTSFIELD-JACKSON ATLANTA INTERNATIONAL AIRPORT.

Five concrete mixes with different concentration of lithium admixture ($LiNO_3$) were used to prepare five experimental sections on Ramp 1 taxi-lane at the airport. The thickness of the concrete slabs was about 22 inches.

6.2.1 Description of Experiment.

The control mix design (without using lithium admixture) for this project is provided in Table 6.4. The mix ID, lithium dosages and other relevant information for the five mixes are

Table 6.4 - Control Mix Design for Field Production Concrete at Atlanta Airport

Material	Source/Producer	Amount/yd^3
Type I Cement	LaFarge (Roberta)	611 lb
Class F Fly Ash	SEFA (Cumberland)	153 lb
Coarse Aggregate 1 (No. 4 Crushed Granite)	Florida Rock (Mountain View, GA)	619 lb
Coarse Aggregate 2 (No. 67 Crushed Granite)	Florida Rock (Mountain View, GA)	1445 lb
Fine Aggregate (Natural Sand)	Martin Marietta (Shorter, AL)	910 lb
Air Entrainer	Euclid (Cleveland)	4.5 oz
Retarding Admixture (Eucon NR)	Euclid (Cleveland)	15.3 oz
Water Reducer (Plastol 341)	Euclid (Cleveland)	30.6 oz
Water	Potable Supply	230 lb

Table 6.5 – Lithium Dosage Used and Setting Data for All Five Mixes at Atlanta Airport

Mix/Section ID	0%-Li	50%-Li	100%-Li	200%-Li	400%-Li
Lithium Compound Dosage (gal/yd^3)	0	0.6	1.2	2.4	4.8
Placement Date	28-Sep	05-Oct	29-Sep	06-Oct	06-Oct
Placement Time	9 PM	9 PM	9 PM	9:30 PM	11 PM
Air Temperature (^{o}F)	72	70	64	72	70
Mix Temperature (^{o}F)	84	82	86	84	81
Lab Air Content (%)*	6.0	5.4	5.5	5.8	5.8
Field Air Content (%)**	4.4	4.4	5.0	4.0	4.5
Lab Slump (in.) *	1 3/4	1 1/2	1 1/4	1 3/4	2
Field Slump (in.) **	1 1/2	1 1/2	1 1/4	1 1/4	2
Unit Weight (lb/yd^3)	142.5	143.4	143.5	144.3	144.5

*: Measured at batch site; **: Measured at construction site

summarized in Table 6.5. The water to cementitious material ratio was strictly kept at 0.3 for all five mixes.

For each mix, 52 cylinders and 18 beams were cast at the batch site, and cured as per ASTM C-31. Maturity sensors were installed in two cylinders for maturity measurements. Three maturity sensors were also installed at one location in each experimental section (see Figure 6.8). The depths of the three sensors were 6 in., 12 in. and 18 in.

In each experimental section and at each test age, seismic tests with the PSPA were carried out at several points including at least one point near the maturity sensors (see Figure 6.9). In 50%-Li and 100%-Li sections, the PSPA tests took place as early as 3 to 4 hours after concrete placement. To minimize the interruption to the airport's operation, the last PSPA tests were carried out on the same day (November 3) where the ages of concrete varied between 28 and 36 days.

Figure 6.8 – Maturity Meter Installation

Figure 6.9 – PSPA Test

Two cores were retrieved from each section on November 3 and 4. All cores were maintained in a curing tank until November 18 when they were saw-cut into two halves. The top and bottom portions were then subject to FFRC and compressive tests. Even though it would have been desirable to conduct the lab tests shortly after coring, these tests were carried out on specimens that were water-cured roughly for additional fifteen days from the date that the PSPA tests were carried out.

6.2.2 Results and Analysis.

The means and coefficients of variation (COV) from laboratory tests on standard cylinders and beams are summarized in Table 6.6. All test results are considered repeatable because the maximum COV is around 5% for the strength tests and about 2% for the FFRC tests. The flexural strength for the 0%-LI mix after 36 hours was greater than those measured after 2 days and 3 days. The reason for this matter is not known.

The variations of strength with age are graphically shown in Figure 6.10. The compressive strengths for mixes of 0%-Li and 50%-Li were greater than those for other three mixes. Starting at the age of 7 days, the compressive strength generally decreased with increasing lithium dosage. The differences in flexural strengths amongst the five mixes were within the precession of the flexural tests at all ages.

The seismic moduli for all mixes were similar at all ages as shown in Figure 6.11. The maturity indices (TTF) for all mixes were almost identical at each age.

The global calibration curves between the seismic modulus and strength for all five mixes are shown in Figure 6.12. The compressive and flexural strengths relate to the seismic modulus well with R^2 values of about 0.9. Even though the strength parameters and seismic moduli vary with lithium dosage, both strength-seismic modulus calibration curves are independent of the dosage.

Table 6.6 – Summary of Results from Laboratory Specimen Tests at Atlanta Airport

Mix	Age (day)	Maturity (hr-°C)	FFRC Modulus		Compr. Strength		Flex. Strength	
			Average (ksi)	C.V. (%)	Average (psi)	C.V. (%)	Average (psi)	C.V. (%)
0% Lithium	1.5	940	3361	1.5	3028	4.8	613	0.5
	2	1221	3540	1.5	3317	3.8	560	2.4
	3	1798	3784	0.8	3669	3.9	605	5.0
	7	4111	4169	1.5	4167	2.4	642	3.8
	28	15640	4774	1.4	5164	2.8	722	5.4
50% Lithium	1.5	846	3386	1.3	2861	3.5	552	3.2
	2	1130	3549	1.3	3216	2.8	573	5.3
	3	1707	3802	1.5	3643	2.8	620	2.1
	7	3986	4313	1.7	4226	2.5	662	2.7
	28	15173	4752	1.6	5395	2.1	763	3.1
100% Lithium	1.5	896	3252	1.8	2586	4.3	538	1.9
	2	1189	3447	1.1	2906	3.3	555	4.1
	3	1750	3626	1.9	3151	2.1	600	4.4
	7	4019	4202	1.6	3926	4.5	678	2.3
	28	15404	4788	1.4	5035	3.6	785	1.7
200% Lithium	1.5	855	3412	1.4	2576	2.8	535	6.7
	2	1131	3561	1.7	2888	2.4	558	6.4
	3	1683	3820	1.1	3272	2.4	610	2.2
	7	3971	4327	0.9	3776	4.5	667	2.4
	28	14985	4640	1.2	4746	3.1	742	2.2
400% Lithium	1.5	862	3545	2.5	2654	5.2	498	10.1
	2	1138	3680	2.0	2924	4.1	588	0.5
	3	1690	3892	1.4	3202	4.3	635	1.6
	7	3987	4321	1.2	3654	5.6	725	3.2
	28	15138	4414	1.6	4364	3.2	777	3.2

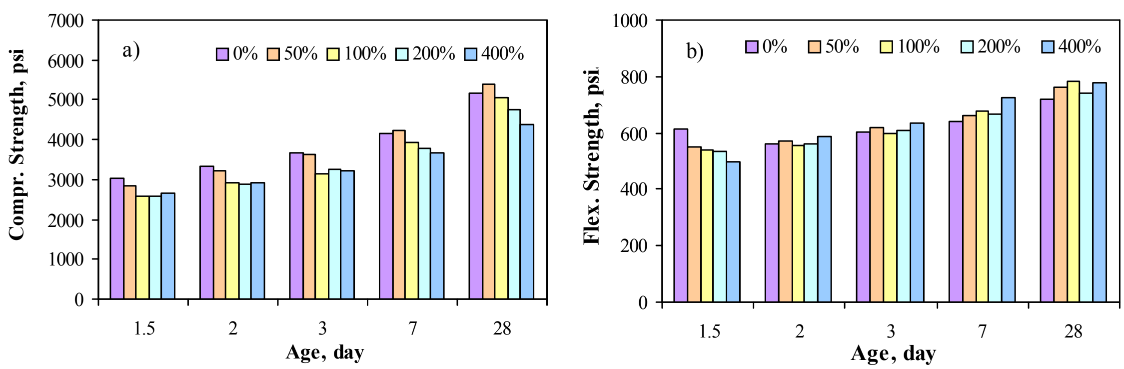


Figure 6.10 – Variations of Compressive Strength (a) and Flexural Strength (b) of Lab-Cured Specimens with Curing Age at Atlanta Airport

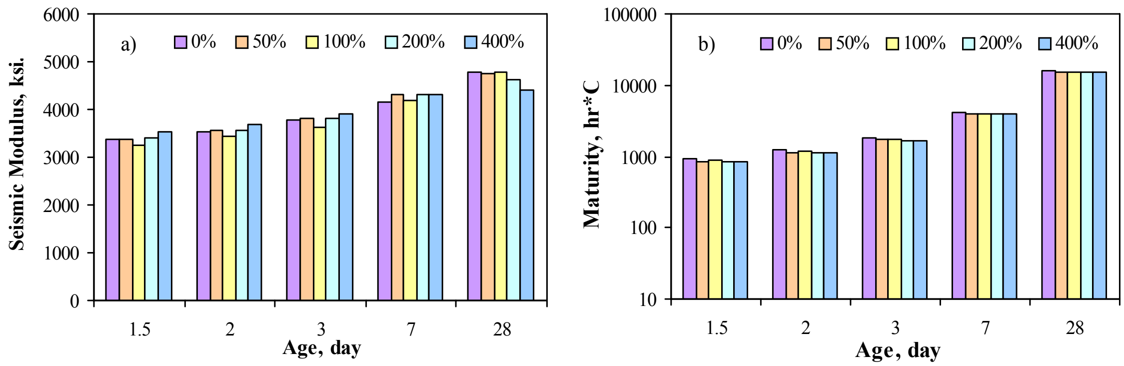


Figure 6.11 - Variations of Seismic Modulus (a) and Maturity (b) of Lab-Cured Specimens with Curing Age at Atlanta Airport

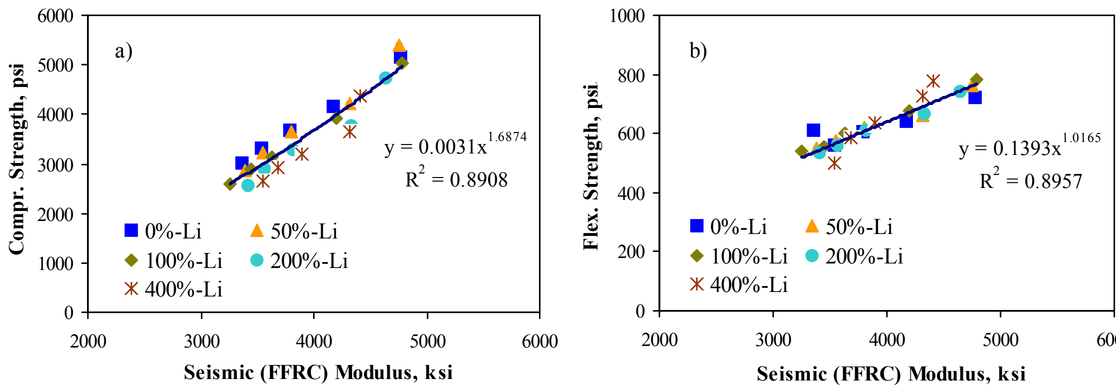


Figure 6.12 – Correlations of Seismic Modulus with Compressive Strength (a) and Flexural Strength (b) for Lab-Cured Specimens at Atlanta Airport

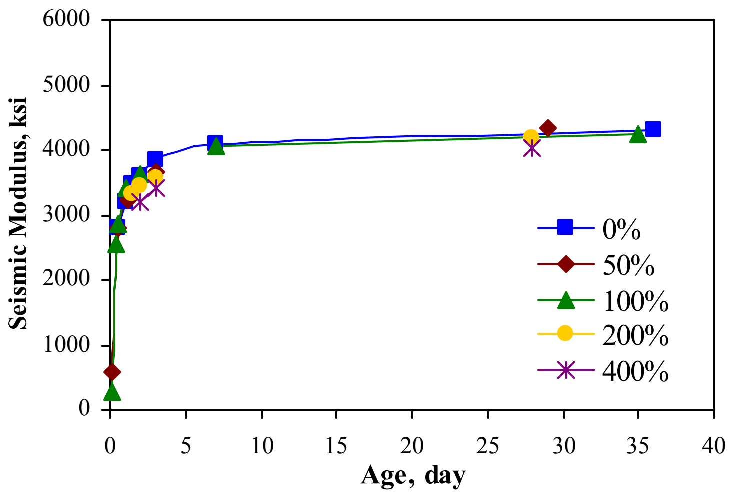


Figure 6.13 – Variation of Seismic Modulus with Age Measured with a PSPA on Slabs of Ramp 1 at Atlanta Airport

The variations in seismic modulus measured using the PSPA with age for all five sections are shown in Figure 6.13. Similar to the results from the FFRC tests on cylinders, the differences among the five mixes are small.

The in-place strengths estimated from either maturity or seismic measurements are compared to those actually measured from tests on specimens in Figures 6.14 and 6.15 for the ages of 3 days and 28 days. Both the maturity and seismic methods estimate the strengths with a maximum difference of less than 10%.

The maximum difference between the 28-day core seismic moduli and 28-day PSPA moduli is about 6% (Figure 6.16). These results indicate that the field and lab seismic moduli are compatible.

As shown in Figure 6.17, the average difference between 3-day compressive strengths estimated from the field seismic moduli and those measured on lab-cured cylinders is about 5%, while the difference for maturity-based 3-day strength is about 18%. The seismic-based 28-day compressive strengths are on average 13% lower than those measured on cylinders, while the 28-day maturity-based strengths on average differ by 8%.

Similar trends are also found for flexural strengths (see Figure 6.18). The seismic-based 3-day flexural strengths are about 5% lower than those from the lab-cured beams, and the 28-day strengths are lower by about 11%. The maturity-based flexural strengths are about 5% and 3% different from the strengths measured from the lab-cured beams. The trends from seismic-based estimates are consistent with the results from strength tests on the lab-cured specimens.

Based on the field evaluation, the seismic/maturity methods provide reliable test results for actual field construction projects. The estimated strengths from the seismic moduli and maturity are similar to those measured from cores. Even though more sites have to be tested before a final conclusion is drawn, based on the practices at the Aurora Municipal Airport and the Hartsfield-Jackson Atlanta International Airport, the proposed technologies are ready for implementation.

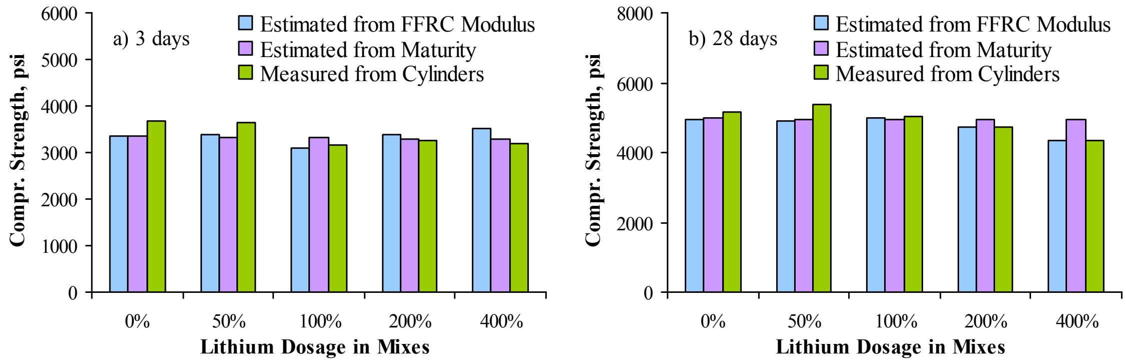


Figure 6.14 - Comparison of Compressive Strengths of Lab-Cured Cylinders Obtained from Different Methods at Atlanta Airport

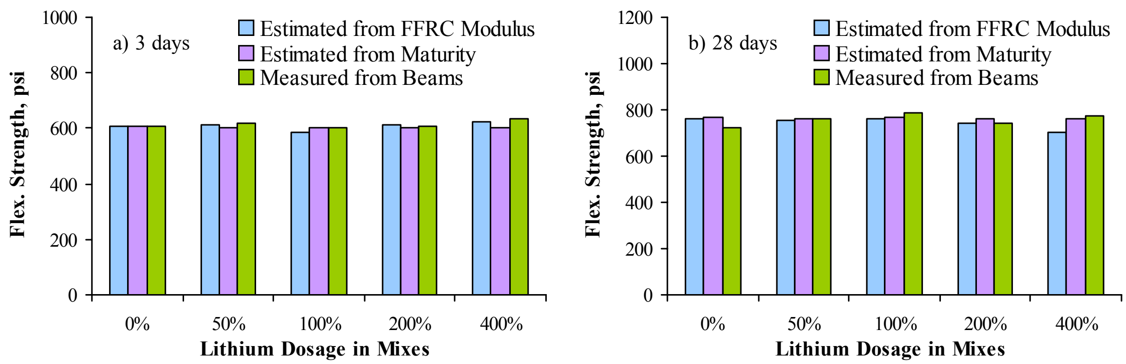


Figure 6.15 - Comparison of Flexural Strengths of Lab-Cured Beams Obtained from Different Methods at Atlanta Airport

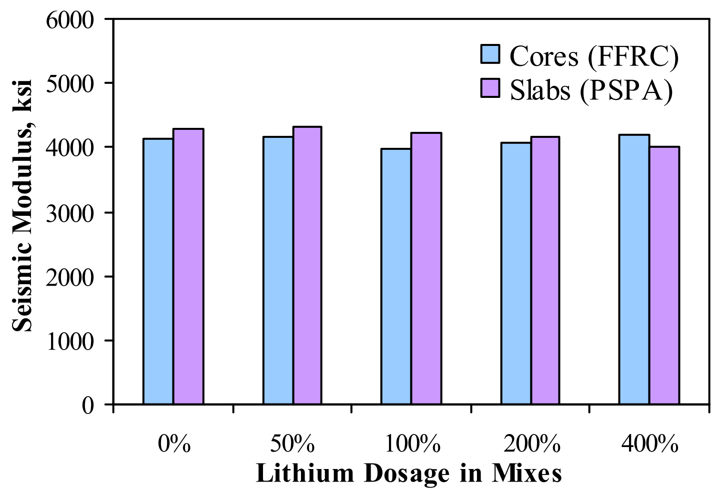


Figure 6.16 - Comparison of Seismic Moduli Obtained from PSPA and FFRC Tests at Atlanta Airport

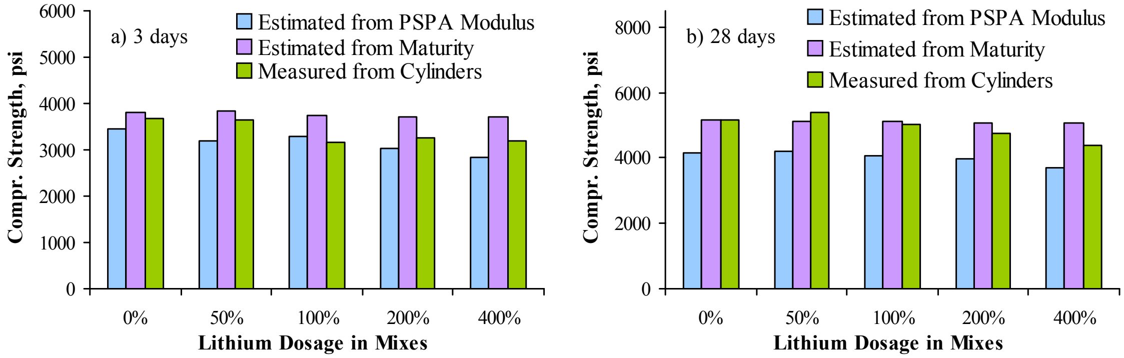


Figure 6.17 - Comparison of In-place Compressive Strengths Estimated from Two NDT Methods with Those Measured on Lab-Cured Cylinders at Atlanta Airport

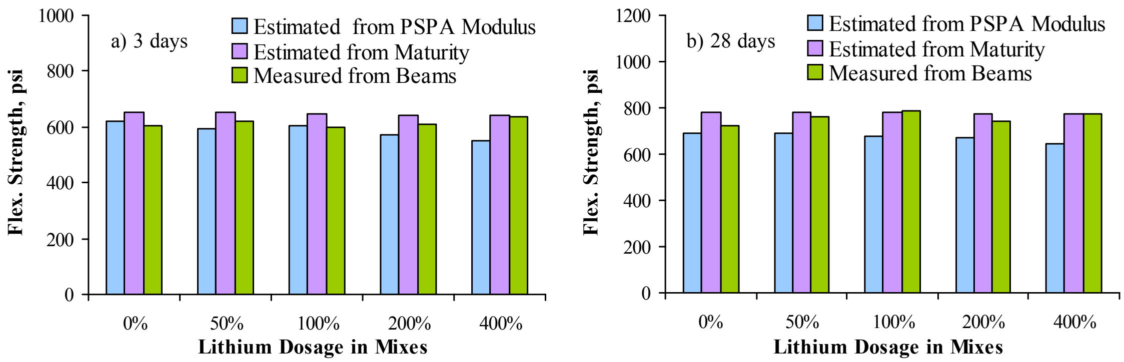


Figure 6.18 - Comparison of In-Place Flexural Strengths Estimated from Two NDT Methods with Those Measured on Lab-Cured Beams at Atlanta Airport

7. SUMMARY AND CONCLUSIONS.

7.1 SUMMARY.

The P-501 specification calls for the following acceptance tests for the structural pavement:

- Flexural Strength: The average of two samples taken from each sublot from the plastic concrete is used to determine flexural strength. Sampling locations are determined in accordance with random sampling procedures contained in ASTM D 3665, the concrete is sampled in accordance with ASTM C 172, specimens are made in accordance with ASTM C 31, and the flexural strength of each specimen is determined in accordance with ASTM C 78.
- Thickness: Three cores per lot are taken to determine pavement thickness. Sampling locations are determined in accordance with random sampling procedures described in ASTM D 3665. The thickness of the cores is determined by the average caliper measurement in accordance with ASTM C 174.

Several drawbacks to the conventional P-501 acceptance tests are documented. The differences between lab-cured and field-cured specimens (due to differences in placement and curing conditions) and the lack of repeatability and precision in flexural strength testing are foremost drawbacks for strength acceptance. Coring is a logical and straightforward way of measuring pavement thickness, but it is time-consuming, expensive, destructive, and the results are representative of only a small portion of the pavement structure. Nevertheless, because these limitations are well known and understood, they are not viewed as impediments to the use of the tests.

Table 7.1 summarizes some of the characteristics associated with the acceptance tests of a conventional P-501 specification and the related testing technologies evaluated in this project. These characteristics are compared in terms of the testing preparation, form of testing, capital equipment required, speed of testing, number of data points, output/result, accuracy, personnel requirements, and overall summary comments.

While the current, conventional P-501 tests constitute an accepted standard, one of their drawbacks is the time that it takes to carry out the sampling and to perform the test. Furthermore, the testing may be limited by its "destructive" nature and the fact that the number of tests is ultimately limited by the number of samples created while the concrete is still plastic.

Maturity and seismic testing technologies were evaluated as a basis for developing new acceptance criteria for concrete airfield pavement construction. The study included extensive experimental work on concrete specimens and slabs of different mixes that were exposed to different curing conditions. Common characteristics of the alternative tests (seismic and maturity) are that they are nondestructive, are not limited by the creation of field samples, and the data can be rapidly collected and analyzed. This is expected to provide improved testing results that are more reflective of the actual, in-place material. In addition, the alternative tests can be used to provide early indications of possible strength problems, allowing contractors to make needed adjustments without having to wait for 28 days to obtain beam results.

Table 7.1 - Comparison of Concrete Pavement Acceptance Tests

	Strength			Thickness	
	Beams	Maturity	Seismic	Cores	Impact Echo
Testing Preparation	Specified number of beams are cast in the field during paving from plastic concrete, stored under specified conditions for 28 days, and then transported to the laboratory for testing.	Calibration beams and/or cylinders are cast and tested in the laboratory (maturity and strength testing) to develop mix-specific strength-maturity relationships.	Calibration beams and/or cylinders are cast and tested in the laboratory (FFRC and strength testing) to develop strength-seismic modulus relationships.	—	—
Form of Testing	Mechanical flexural strength testing (destructive)	Collection of pavement temperatures over time (nondestructive)	Seismic testing (nondestructive)	Mechanical extraction of concrete core (destructive)	Amplitude spectrum measurements (nondestructive)
Capital Equipment	Beam breaker	Beam breaker and/or compression machine Data logger and probes (or i-buttons)	Beam breaker and/or compression machine FFRC device and PSPA	Coring rig	PSPA
Speed of testing	5 to 10 minutes per beam	Continuous readings (data automatically uploaded)	<1 minute per reading	15 to 30 minutes per core	<1 minute per reading
Number of Data Points	4 beams for each lot, yielding one average value	3 data locations over 150 ft length (tied to number of maturity logger installations)	3 to 5 locations per lot	3 cores per lot	3 to 5 locations per lot
Output/Result	Strength computed based on load force	Time-temperature factor related to strength	Seismic modulus related to strength	Thickness (direct measurement)	Thickness (semi-direct reading)
Accuracy	Fair to Good. Curing conditions can affect results, which may not be reflective of in-place concrete properties.	Good. Sensitive to mix proportions and extreme curing conditions.	Good. Results are more sensitive to properties of the top half of the pavement.	Excellent. But gives limited information because of fixed number of coring locations.	Good. Still some uncertainty (about 3%) associated with the method.
Personnel	1 certified testing technicians	1 certified testing technician 1 maturity-trained technician	1 certified testing technician 1 FFRC/PSPA-trained technician	1 coring technician	1 PSPA-trained technician
Summary Comments	Beams difficult to handle and transport, and can have little correlation to properties of in-place concrete. Beams are notorious for giving highly variable results	Proven test method but sensitive to mix proportions and extreme curing conditions. Cost of device and software: $1,000 to $2,500. Cost of probe: $10. Cost of i-button: $35.	Nondestructive method providing rapid test results over wide area. Cost of seismic equipment and software: $25,000.	Accepted method providing “ground truth” thickness data, but limited to number of coring locations. May require formal facility closure	Essentially a by-product of the strength testing (PSPA). Amenable to testing active facilities on “give way” basis May be appropriate for use in a pass/fail scenario, but may not be accurate enough for acceptance.

Two airfield projects demonstrated that the seismic/maturity tests address some of the technical drawbacks of the conventional P-501 acceptance test, and that they are faster and less expensive to perform.

This report provides the rationale behind the selection of the promising technologies for further consideration, develops a process to evaluate their technical merits, and presents a methodology to develop protocols for the practical implementation of the new technologies. In addition, a proposed percent within limits (PWL) specification for the new acceptance criteria is also presented.

7.2 CONCLUSIONS.

Based on the outcome of this study the following statements are made:

- The strengths measured on standard lab-cured specimens are different than those measured from corresponding specimens extracted from pavement, especially when the pavement is exposed to the natural environmental conditions at construction sites.
- Flexural (or compressive) strength-maturity calibration curves can be established with confidence in the laboratory. However, the laboratory strength-maturity relationships are affected by the change in the mix proportions, especially by the cement content and water cement ratio. If the maturity method is used alone, rigorous process control procedures are needed to ensure that the lab-developed calibration relationship can be used with confidence in the field.
- Laboratory calibration curves between the strength and seismic modulus can be developed with confidence. The seismic-based calibration curves are less sensitive to the mix proportions as compared to the maturity-based relationships.
- The seismic moduli measured on a pavement with a PSPA generally correspond well with the seismic moduli measured with an FFRC device on cores and beams extracted from the same pavement.
- The predicted strengths of the in-place concrete from the seismic and maturity methods are close to the values measured on cores and beams extracted from the pavement. For cases when the curing conditions or the mix proportions were inadequate or poorly designed, the maturity method tended to over-estimate and the seismic method tended to under-estimate the in-place concrete strength.
- The thickness of a pavement can be estimated with the impact-echo method with an accuracy of about 4%. The impact-echo method is not appropriate for acceptance of thickness because its precision cannot satisfy the current thickness accuracy required by the FAA's P-501 specification.
- A PWL analysis based on the seismic/maturity technology would be more favorable to both the owner and the contractor. These methods are more precise than conventional concrete strength tests, and tests can be carried out at a larger number of locations on a pavement. A larger sample size with a more precise method provides greater confidence in the quality of concrete under the PWL acceptance criteria.

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