A Work Plan Toward Implementation of Acceptance Criteria Based on Innovative Testing of Concrete Pavements

Conducted for:

Innovative Pavement Research Foundation (IPRF)

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March 2004

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A Work Plan Toward Implementation of Acceptance Criteria Based on Innovative Testing of Concrete Pavements

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Research Project Number 01-G-002-02-2
Innovative Testing Standards for Acceptance Criteria
for Concrete Pavement

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CHAPTER 1

INTRODUCTION

In portland cement concrete (PCC) pavement construction, the acceptance of the completed pavement is based on several factors, most notably strength. However, the current acceptance criteria based on the flexural strength of beams (or occasionally on the compressive strength of cylinders) have several limitations. First, the results of tests on field-cured beams and cylinders are often significantly different from those of in-place concrete because it is often impossible to ensure identical bleeding, compaction, and curing conditions in the cylinders and in the pavement. In addition, the lack of repeatability and precision of mechanical testing, especially flexural strength testing, requires that the contractors produce concrete that is much stronger than the design strength. Furthermore, the gain in strength in concrete is governed by complex and inter-related mix parameters (such as cement and water content, type of cement, sand/aggregate gradation), construction parameters (such as curing method, air content and consolidation), and environmental parameters (such as ambient moisture, temperature and wind) during construction. As such, timely acceptance testing of an airfield concrete should ideally be made based on the in-place strength of concrete.

Of equal importance to PCC strength in acceptance testing is the verification of the slab thickness. Similar to PCC strength testing, the current procedures for determining slab thickness are less than ideal. The most commonly used method of slab thickness determination is through the retrieval of cores, a process that is time-consuming, expensive, destructive, and representative of only a small portion of the pavement structure. Due to these limitations, newer technologies that can rapidly, precisely, and nondestructively provide the strength and thickness of concrete shortly after placement are necessary.

The new technologies for measuring thickness, if proven successful, can be readily used in practice. In terms of strength, the current design methodologies and performance models utilized by the FAA and other entities dealing with airfields are based on the flexural strength of the PCC. As such, eliminating the flexural strength as an acceptance test is not feasible. As detailed in the following chapters, a suitable direct replacement for flexural strength test that can be implemented as a rapid quality acceptance test does not exist. Any new technology implemented has to be inevitably correlated to the flexural strength test results. The variability in the flexural strength tests as per

ASTM C78 has to be statistically dealt with during the development of the PWL. Alternatively, some attempt can be made to slightly modify the flexural test in order to reduce the associated variability. In this study, the feasibility of reducing the variability by introducing a notch in the specimens will be explored.

Objectives

Under this project, new and innovative technologies will be evaluated as a basis for developing new acceptance criteria for the implementation by the FAA and other agencies involved in constructing rigid pavements. The main goals of this report are to provide the rationale behind the selection of promising technologies for further consideration, a process to evaluate their technical merits, a methodology to develop protocols for practical implementation of them and a field test plan to evaluate their merits in a side-by-side field testing program conducted as a part of an actual airfield pavement construction project. In addition, the resource requirements for the proposed methods, such as upfront cost of equipment, required training and additional man-power necessary, are also considered.

The focus of the proposed study is primarily on implementing maturity and seismic technology. Many agencies have incorporated maturity to facilitate the estimation of the in-place concrete strength, and it has been shown that the maturity concept can contribute to a more accurate estimation of concrete strength. However, since temperature monitoring devices are placed in discrete points and the maturity concept is dependent on pre-construction calibration, any variability in the strength of concrete caused by batching errors, construction, equipment-related problems or the curing process might not be identified. As a means of overcoming some of these limitations, seismic technology has shown promise to estimate the strength of in-place slab. Recent studies have shown that, unlike the strength-maturity correlation that is sensitive to variation in aggregates and additives, the strength-seismic relationships are primarily sensitive to the nature of the coarse aggregates.

In terms of thickness, the technologies to be investigated include: seismic measurements (e.g. impact-echo), and manual probing measurements while the concrete is still fresh.

Organization

To develop a concise yet comprehensive document, the body of the report is rather short. Supporting background information is liberally provided in a number of appendices that can be inspected and studied as deemed necessary.

The parameters that are important to the acceptance of PCC pavements are defined in Chapter 2. Current methods of measuring them and their limitations are summarized in that chapter. The newer methodologies that can potentially address these limitations are also introduced. A special section is dedicated to the pros and cons of utilizing the process control as a tool for quality acceptance.

Chapter 3 contains a summary of the lessons learned from a number of new fast-track projects that were reviewed for the purpose of identifying the new and innovative quality acceptance procedures utilized.

The rationale behind the development of Phase II work plan is included in Chapter 4. The overall philosophy followed to develop the work plan is first described. The material-related, construction-related and environmental-related parameters that are included in Phase II work plan are identified and their relevance is discussed. A hierarchical approach that is developed to maximize field and lab testing is presented. The plans for side-by-side testing at an actual site described in Chapter 2 are also included. Since the development of a "percent within limits" specification is of outmost interest, a section is dedicated to the process needed to achieve that goal.

Chapter 5 builds on the information provided in Chapters 2 through 4 to provide a specific implementation plan for the duration of Phase II. For each significant construction-related, material-related or environmental-related parameter identified as important, a specific step-by-step procedure (including a testing plan, the data reduction process and the data analysis procedure) is included. The timeline to implement the plan and the responsibilities of each team member are also included in that chapter.

A number of appendices are also included to support the information included in these five chapters.

CHAPTER 2

DEFINING AND ASSESSING PARAMETERS IMPORTANT TO ACCEPTANCE OF PCC

This chapter reviews the key factors associated with construction control and acceptance of PCC pavements, primarily slab thickness and concrete strength. These two specific factors are emphasized because of their impact on pavement performance and the need for improved methods of measuring and monitoring their as-constructed quality. Current methods for measuring these two important parameters are reviewed, with a more detailed summary of these methods presented in Appendix A. Based on the review, recommendations on the methods and technologies to be evaluated under this project are made.

Important Structural Design Parameters

A number of materials and construction factors related to a PCC slab may have significant effects on the performance of a PCC pavement. Adequate slab thickness, effective concrete strength, effective consolidation, correct dowel alignment, proper application of the curing compound, and proper timing and location of the saw-cuts (to establish the joints) all contribute to achieving maximum performance. From a structural design standpoint, slab thickness and concrete strength are the two most important parameters, and are critical components of every concrete pavement structural design methodology. The importance of these design parameters is illustrated in Figure 2.1, which was produced using a design nomograph from the FAA rigid pavement design procedure (FAA 1995). As shown 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 slab thickness produces an estimated 60 percent reduction in life. Similarly, a 5% reduction in PCC flexural strength produces a 40% life reduction. Because of the sensitivity of performance to these parameters, considerable attention must be given to their control during construction.

Slab Thickness

For airport pavements, the thickness of the slab is selected as part of the design process to provide the structural requirements needed to sustain the anticipated aircraft loadings over the

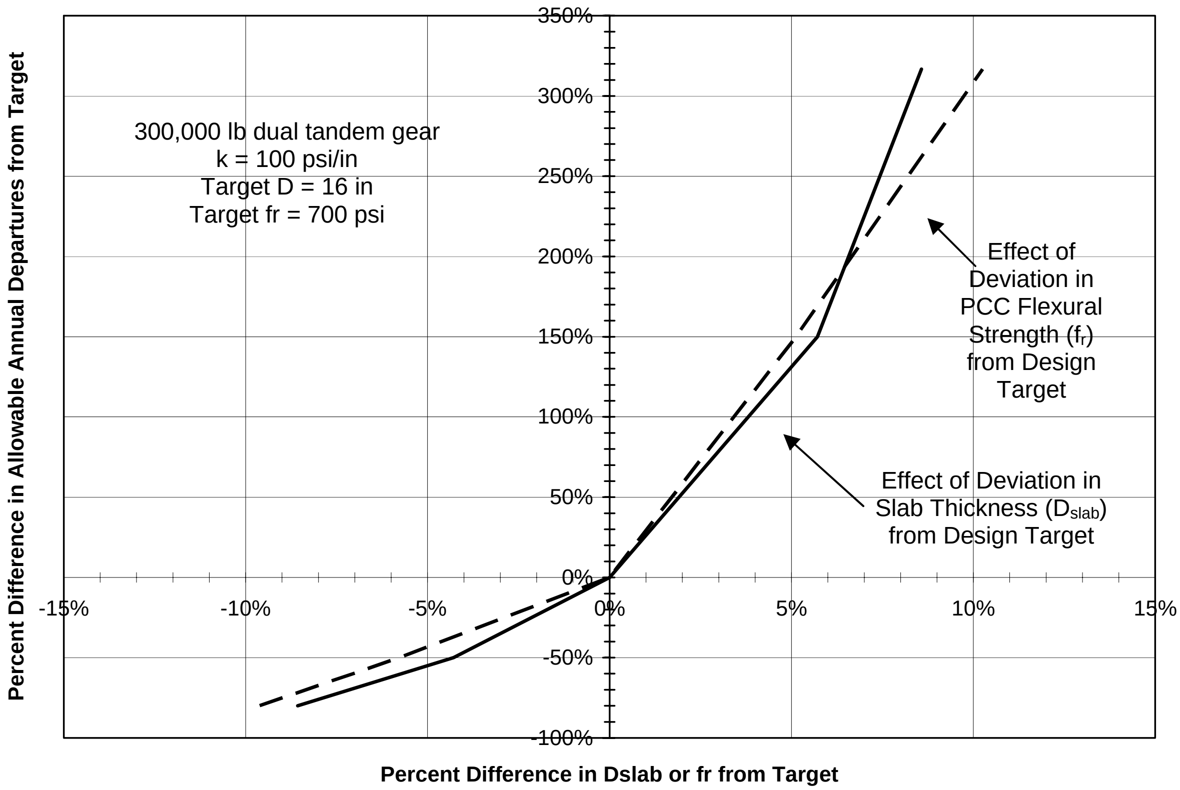

Figure 2.1 - Sensitivity of Pavement Performance to Key Design Parameters.

design life. Thickness control during construction is typically achieved through the use of a stringline to maintain the target surface elevation of the slab.

Concrete Strength

Like slab thickness, concrete strength has a significant impact on pavement performance. Generally, a concrete mix design is developed to satisfy a minimum strength requirement corresponding to an accepted standard or specification. In construction, the control of strength is achieved through close control of the mixing and placement operations.

Two measures of concrete strength are typically employed for airfield pavement applications: flexural strength and compressive strength. Flexural strength is the desirable measure of strength because it characterizes the strength under the state of stress that the concrete experiences under the typical field loading conditions. For airfield applications, the range in flexural strength used for design is typically between 600 psi and 800 psi. The disadvantage of flexural strength as a measure is that it requires the preparation of relatively large beams in the field as test specimens.

Compressive strength is determined from smaller, easier to handle cylindrical concrete specimens; however, the state of stress induced under this test method is not representative of the conditions under which pavements typically deteriorate. For these cases, engineers rely on correlations between compressive and flexural strength.

Parameters Impacting Concrete Strength

Mixture characteristics are selected based on the intended use of the concrete. In the case of pavements, besides compressive and flexural strengths, other characteristics such as environmental conditions will affect decisions regarding the design of the mixture. Most of the desirable properties of hardened concrete depend primarily upon the quality of the cementitious paste, and therefore, the water-cement ratio is the primary parameter in a mix design. Differences in concrete strength as related to mix design for a given water-cement ratio result from:

1. Changes in the aggregate size, grading, surface texture and shape
2. Differences in types and sources of cementing materials.
3. The entrained-air content.
4. The presence of admixtures.
5. The amount of water.
6. The length of curing time.

Some agencies (e.g., the Port Authority of New York and New Jersey and Minnesota DOT) have started using water-cement ratio in lieu of flexural strength for acceptance purposes and pay adjustment. The main reason for this practice is the simplicity and speed of water-cement material ratio tests compared to existing strength tests.

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.

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. However, they also indicated that these two parameters as well as a number of other parameters may be quite useful in terms of quality control but they do not seem strong enough indicators 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. A more direct measurement of the in-place concrete strength is necessary for acceptance.

Current Methods of Measuring Important Parameters

A key element of the construction quality control and quality assurance processes for PCC pavements is the measurement of the as-constructed slab thickness and PCC strength. The accurate measurement of these parameters under a valid quality control program provides essential information to the contractor that can be used to correct materials and/or construction problems, improve process control, and limit the production of defective pavement. At the same

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 (Bureau of Reclamation)

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

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 slab thickness and PCC strength. The direct methods shown refer to those 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 *indirectly* related (either mechanically or statistically correlated) with either slab thickness or concrete strength. In most rigid pavement airfield construction, the current "standard" for assessing slab thickness is the measurement of drilled cores, whereas the current "standard" for expressing PCC strength is flexural strength testing of fabricated beams.

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

Table 2.3 - Test Methods for Slab Thickness and Concrete Strength

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

Limitations of Current Methods

As described in Appendix A, there are limitations associated with each of the current test methods used for determining slab thickness and concrete strength. In general, the limitations of the current conventional test methods are associated with the need to obtain samples in the field, transport them to the laboratory, and test them.

In the case of conventional concrete strength testing using beams, the samples must be fabricated in the field, are relatively heavy and bulky to transport (particularly the beams used for flexural strength testing), 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 slab is normally not accepted and the contractor is not compensated until the 28-day strength results are obtained.

In the case of conventional slab thickness testing using cores, the samples must be obtained through a destructive coring process, the coring can not be performed until after the concrete has hardened, and the core holes must be repaired.

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

An example of where a test method could benefit from such improvements is ASTM C78. In essence, the test involves third point loading of rectangular concrete beams. Flexural strength or modulus of rupture is evaluated based on the assumption that the fracture initiates in the tension surface within the middle third of the span length. Since concrete is heterogeneous by nature, fracture does not often happen within the middle third of the span. For this reason ASTM provides an alternative relationship for the evaluation of flexural strength accounting for approximate location of the fracture. ASTM C78 allows the use of the alternative relationship if the fracture occurs in the tension surface outside of the middle third of the span length by not more than 5% of the span length. If the fracture occurs in the tension surface outside of the middle third of the span length by more than 5% of the span length, then ASTM mandates discarding the test results. Large scatter has been reported even for those tests that report occurrence of the fracture within the middle third. As noted earlier, the heterogeneous nature of concrete does not allow for recurrence of fracture at the same point within the middle third section of the span. 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. A possible improvement to ASTM C 78 is fabrication of beams with a notch at their mid span. Since concrete is notch-insensitive, existence of notch does not alter the modulus of rupture of the material, but ensures recurrence of the fracture at the same location within the specimen. This should improve the precision for the measurements. A series of complementary side-by-side tests will be carried out to determine whether notching the beams will improve the precision of the flexural strength tests. However, the basis of this research is on relating the results of NDT tests to those from the standard ASTM C78 tests carried out by FAA.

In the last 20 years, new and innovative technologies have evolved because of the need to address the limitations of conventional test methods. The maturity method (ASTM C1074) is one major innovation that essentially eliminates the need for field sampling and testing in order to monitor concrete strength gain. By conducting laboratory strength testing on the PCC mix before construction and then using the results to establish a concrete maturity relationship, the strength gain of the in situ concrete can be determined by simply monitoring the in situ concrete temperature with time after construction. There is a significant up-front cost associated with this method and a separate maturity relationship must be established whenever there is a change in the mix design, but these limitations of this method are minimal. Maturity method is being routinely employed on highway projects by at least one agency (Iowa DOT), and an evaluation of the applicability of maturity method to airfield projects was recently conducted under an IPRF project (Rasmussen et al. 2003).

ASTM C1074 does not mandate that the datum temperature used in the maturity relationship has to be determined and therefore arbitrary values (i.e. 0^{o} C) could be employed. However, numerous studies have indicated the error associated with the results. In general, maturity method based on the Arrhenius function (practiced in Europe) employs the activation energy of concrete, which results in a nonlinear function. The maturity method based on the Saul's function, which is practiced in U.S., employs a datum temperature and assumes that the maturity function is linear. In general, the linear function is not very accurate. However, for simplicity and ease of application during the construction process, it is more appropriate to use the linear function. In this case, the datum temperature has to be determined for temperatures appropriate for the actual thermal experiences at the construction site. Mortar cube tests are performed for this activity for temperatures below as well as above the field climate. Cube tests will be performed in this study for the mixes in order to determine the appropriate datum temperature for the concrete mixes.

The seismic NDT methods also 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 microchip technology has made it possible to develop equipment and software that can process the complex information in split seconds rather than hours. For the impact-echo test, reliable equipment is commercially available that can measure the velocity of stress waves reflected off the bottom of the slab to estimate slab thickness. Its basic limitation is that calibration is typically required to achieve the required accuracy. For the pulse-velocity test, equipment is also commercially available that can measure the speed of ultrasonic waves (that are generated and travel along the surface of the slab) and use them to estimate both the dynamic modulus and associated strength of the in situ concrete. The primary limitations of the pulse-velocity method are the effect of large-size aggregate on the propagation of the waves and the need for good acoustic contact of the sensors with the pavement surface. The portable seismic pavement analyzer (PSPA) is another device that employs an impact load and measures the speed of lower-frequency, larger-amplitude surface waves to estimate concrete dynamic modulus and corresponding strength. The use of surface waves instead direct arrival of compression waves as done with the pulse velocity tests, minimizes many limitations of ultrasonic devices (such as v-meters) that are discussed in Appendix A.

The integrated maturity-seismic method is an approach that represents a blend of the concrete maturity and seismic methods. The advantage of the maturity method is in estimating the strength of concrete in the field; however, it does not provide any information on the construction quality. On the other hand, the seismic method is quite sensitive to construction-related parameters. Under this combined approach, which was recently developed for PCC highway applications in Texas (Yuan et al. 2003), laboratory specimens are prepared for compressive and/or flexural strength testing in accordance with the typical maturity test method. However, before they are subjected to the strength test, they are tested with the free-free resonant column (FFRC) method (ASTM C215) to determine the dynamic modulus and, if needed, the Poisson's ratio. The result is a database that can be used to produce relationships between seismic wave velocities or dynamic modulus and concrete strengths. With these relationships, it then becomes possible to estimate concrete properties using the PSPA device at numerous locations throughout the project. The only real limitations of this method are the cost associated with the up-front lab testing effort and the quality of the correlations between the PCC strengths and the wave velocities measured by the seismic equipment.

As detailed in Appendix A, the ground penetrating radar (GPR) has several distinct advantages since it can provide rapid and continuous measurements. 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 will not be carried out.

Recommended Technologies for Further Evaluation

From the review of the current technologies, the maturity and seismic based approaches are recommended for further evaluation under this project to assess their applicability for use in airfield rigid pavement construction, for the following reasons:

- The probing of fresh concrete as a means of obtaining thickness is considered because of its simplicity. If found accurate, the method will provide tremendous time and cost savings.
- The maturity test 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. It relies simply on monitoring the time and in situ temperature of the in-place concrete. To improve the accuracy of the method upfront calibration and periodic validation of the mix and site-specific strength-maturity relationship are required.
- Seismic methods can be used to estimate slab thickness (via impact-echo testing) and the concrete dynamic modulus (via lab and field NDT testing). One device in particular, the PSPA, was developed specifically for these applications and employs a combination of the equipment/instrumentation used for both impact-echo and ultrasonic testing. It avoids most of the limitations associated with concrete heterogeneity and the need for calibration. Like most seismic equipment, the PSPA is also rapid and nondestructive, requires no specimen preparation or lab testing, and can be easily performed at numerous locations throughout a

project. Similar to maturity method, upfront calibration and periodic validation of strength-modulus relationships are necessary.

The combined maturity-seismic based 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.

ASTM C 918 provides a convenient relationship based on maturity to estimate the 28 days strength from the one-day age maturity tests. That technique will be investigated to see if it could be extended to the seismic method through mapping of the strength-maturity and seismic-strength data to a maturity-seismic relationship and then invert the relationship back to strength at later ages based on early age seismic tests.

It would be beneficial to address the resource requirements for the technologies recommended above. This topic is discussed in detail in Appendix A. The highlights are summarized in Table 2.4.

For thickness probing, the initial and material costs are minimal. Basically, a graduated rod is needed. The required training is also minimal since no interpretation of data is needed. The only logistical problem reported is that the test is time-sensitive; the test has to be performed while the concrete is fresh.

Maturity tests are quite straightforward as well. 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. Based on our experience, 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 2.4 – Operational Aspects of Proposed Technologies

Parameter	Device		
	Thickness Probing	Maturity	Seismic
Initial Cost	Minimal	$1000-$2,500	$20,000-$30,000
Material Cost (per point)	None	$10-$35	None
Measurement Speed	2 minutes	Continuous	2 minutes
Skill Level of Operator	Conscientious Technician or Engineer		
Skill Level for Interpretation	Conscientious Technician or Engineer		
Training Requirement	Minimal	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. The initial cost is about $20,000 to $30,000. However, with the acceptance of the technology, the initial cost should reduce. Under production mode, up to 300 points can be tested daily. Based on our experience, about one day of training is needed to operate such equipment, with a second follow up training for hashing out the details. Seismic devices work based on the determination of traveltime of waves; as such, the calibration of the device is infrequent. It is prudent to periodically test the device on a cured concrete slab to ensure that it is working properly.

Similar to maturity systems, a laboratory strength-modulus calibration curve has to be developed for each mix. This task also requires about a dozen beams or cylinders that can be coordinated with the mix design verification. Based on our current experience, the strength-modulus relationship is less sensitive to changes in the mixture as compared to the strength-maturity relationship. 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.

CHAPTER 3

REVIEW OF RECENT FAST-TRACK PAVING PROJECTS

Introduction

Airports routinely operate under demanding constraints that limit access to and closure of airside pavements. These constraints have made scheduling and conducting pavement rehabilitation and reconstruction projects problematic. The problem becomes even more complicated at busy airports with active cargo operations, where operations extend almost around the clock. Where the pavement infrastructure is not extensive and taxiing and arrival/departure alternatives are limited, access can be even more limited. As an indication of the seriousness of construction constraints, the situation has evolved over the years to the point where the owner specifies the desired outcome from a project (say, a minimum strength of a new concrete pavement at a specified time), and attempts to ensure that outcome by imposing significant penalties, such as $10,000 for every 15-minute delay in opening the pavement beyond the allowable closure.

The concrete paving industry has responded positively to these constraints, developing and using innovative materials, processes, and other tools to ensure that concrete pavements continue to have a place in the airfield pavement market. The approach that is used is often referred to as "fast-track" paving or "accelerated construction." While initially fast-track paving may have been synonymous with the use of high-early-strength concrete materials, over the years this definition has evolved to include any concrete construction project in which steps are taken to complete the work and open the project within a reduced schedule. These steps could include one or more of the following to accelerate the construction process:

- Specialized materials and equipment.
- Special construction procedures.
- Unique contracting methods.
- Unique planning or phasing innovations.
- Special quality control or quality assurance testing techniques.

Over a period of less than 20 years, the use of fast-track paving has progressed from experimental to almost routine. For example, under a parallel, on-going study for the IPRF, over 40 major concrete airfield paving projects from just the past 10 years were identified that featured some element of fast-track paving technology.

One critical aspect of fast-track paving remains the ability to provide rapid and reliable assessments of the in situ concrete strength. This is particularly important for fast-track projects because of the need to determine if the completed concrete pavement may be opened to traffic, and the typical time during which this decision must be made occurs long before conventional 28-day strength results are available. As described in chapter 2, the traditional method of assessing concrete strength has been through the fabrication and testing of laboratory specimens, typically beams for most airfield pavement construction. However, as was also described, this method has distinct disadvantages, including the need for fabrication, handling, and testing (typically at 28 days) of beams, the variability of flexural strength testing, and known differences between concrete specimens and in-place concrete that have been placed, consolidated, and cured under different conditions.

To illustrate the need for rapid methods of assessing in-place concrete strength, fast-track paving projects at six airports were reviewed. These projects are summarized in the following sections, and identify what fast-track methods were used, why they were needed, and the outcome. In addition, the benefits that innovative testing methods could have provided to each project are also discussed.

Review of Selected Airfield Pavement Projects

Hartsfield Jackson Atlanta International Airport

In June 2001, Hartsfield Jackson Atlanta International Airport replaced forty-five concrete slabs on Runway 9L-27R and Taxiway M during a week-long closure in which construction activities proceeded around the clock. The entire existing pavement structure was removed down to the subgrade, including 16 inches of concrete, 6 inches of cement-treated base, and 6 inches of cement-stabilized soil. Repairs were made to the existing underdrain system (which was clogged), and the pavement was then reconstructed with 28-inch concrete slabs placed directly on the subgrade.

The concrete used in the slab replacement program conformed to FAA's P-501 specification. The mix was designed to develop a flexural strength 600 psi at 3 days. Flexural strength tests were performed on beams at 24, 48, and 72 hours for assessing the strength of the in-place pavement. Strength testing was not performed at 28 days.

Although not employed in this project, the use of nondestructive testing technology for monitoring strength gain could have had a significant impact in determining the actual strength of the in-place concrete. Because the heat of hydration for the 28-inch thick concrete slab will be significantly different from that of a typical beam of dimensions 6 inch x 6 inch x 21 inches, the in-place strength will likely be much higher than that indicated by the beams. This could have significant ramifications in terms of when the replaced slabs could be opened to traffic, and may have even indicated an earlier opening time that could have reduced the overall closure time of the runway and associated taxiway. Both maturity and seismic methods would be effective in indicating these in-place properties.

Phoenix Sky Harbor International Airport

Runway 8-26 was reconstructed and extended at Phoenix Sky Harbor International Airport in 2001. A full closure of Runway 8-26 was deemed unacceptable as a reconstruction alternative, which forced the reconstruction to be completed while keeping portions of the runway operational at all times. The original runway was 11,000 feet long, and it was determined that a shortened portion of the runway (6,000 feet long) must remain open during the day for aircraft operations. This configuration allowed closure of each end of the runway for construction activities while aircraft used the other end. However, because a 1,000-foot long safety area was necessary in case of an aborted take-off, the runway could not remain active when the center 1,000 feet of the runway was to be reconstructed. As a result, it was decided that the center 1,000 feet of the runway would be reconstructed during night closures.

The contractor was responsible for developing the mix design for the center section of the runway and required a *compressive strength* of 750 psi by opening each morning. Such a value was considered adequate because it was believed that the center section of the runway was unlikely to receive any appreciable traffic. In addition to the opening requirements, the center section concrete was also required to meet the same 28-day strength as the remaining portions of the runway, which were placed with conventional P-501 concrete. Standard FAA thickness requirements were used for the entire runway. Although innovative testing methods for testing and acceptance of concrete were not considered for this project, the benefits of using such methods were considered by the project team.

Innovative testing techniques may have proven useful to this project in determining the thickness and rate of strength development of the reconstructed pavement. In the case of thickness, the current practice is to obtain thickness measurements by coring the new pavement at predetermined intervals along the length of the pavement. The use of other methodologies, such as impact-echo, can be used to produce a thickness profile along the length of the runway and is more likely than coring to detect significant thickness variations. Variations in thickness are likely on a project with construction phasing such as this one, where frequent opening and closing requirements are encountered before the entire segment is reconstructed.

For monitoring the strength of the PCC, as a result of the center section of Runway 8-26 being reconstructed exclusively using night closures and opened each morning, the use of innovative methods such as maturity or seismic for monitoring strength gain would have provided rapid and reliable information in determining when the newly placed pavement could be opened to traffic. Furthermore, if the newly placed pavement was to experience early aircraft traffic, knowledge of the in situ strength would allow assessment of the potential damage to the fresh pavement, and provide useful information to determine whether the new pavement has experienced sufficient damage to require replacement.

Washington Dulles International Airport

In October 2003, Washington Dulles International Airport undertook a slab replacement program on Runway 12-30. Because of runway closure restrictions, all work (except the presawing of slabs) was performed over a 72-hour period. A rapid set concrete was used for the patching, which contained accelerators and admixtures in order to achieve a design flexural strength of 750 psi. Plastic sheeting and blankets were used to help accelerate concrete strength development.

In evaluating the concrete strength, the contractor recommended using cylinders (for compressive strength testing) instead of beams (for flexural strength testing). This was because of the difficulties associated with fabricating and transporting beams. A rapid-setting concrete was used, with the mix designed to achieve a flexural strength of 750 psi in 6 hours. The concrete was placed over a 6 to 8 hour period, and cylinders were tested approximately 1 hour before opening to assess strength characteristics.

This project could have benefited from innovative testing technologies for monitoring concrete strength gain. Instead of breaking beams immediately before opening, concrete strength gain could have been monitored continuously after placement. This would have given the contractor and airport engineers an indication of the current strength of the concrete as opening approached. For a fast-track project such as this, continuous monitoring of concrete strength gain could potentially lead to more rapid re-opening of closed facilities.

<u>JFK International Airport</u>

Critical portions of Apron Taxilane L-A at JFK International Airport were reconstructed in 1998 during 20 working nights. Taxilane L-A links twelve gates between Terminals 2 and 3, and the existing taxilane pavement consisted of fatigue- and block-cracked asphalt pavement sections and shattered and spalled concrete slabs, and regularly required debris removal. High-strength concrete was used to rapidly reconstruct portions of this pavement with minimal interruptions to taxiing aircraft.

The construction was phased such that only a portion of Taxilane L-A was closed at any given time, and all work was conducted at night. In order for a section of pavement to be re-opened in the morning, a minimum flexural strength of 450 psi was required. Flexural strengths of 650 psi at 3 days and 750 psi at 28 days were also required. The concrete specifications for this project required that a minimum of two beams be cast per day of concrete production. In addition to the flexural strength tests performed to determine if the concrete was suitable to open to traffic, beams were also tested at 24 hours, 3 days, and 28 days. If at any time the 28-day flexural strength of 750 psi was met, beam testing was stopped.

Innovative testing methods for concrete acceptance were encouraged by the concrete specification in anticipation of future construction by the same contractor or concrete producer. Ultimately, however, innovative testing methods were not pursued. Innovative methods such as maturity or seismic testing could have helped both the contractor and the owner in this project by significantly cutting down on the testing required to obtain concrete strength at opening, 3 days, and 28 days. Also, projects such as this that require opening to traffic shortly after concrete placement would benefit from obtaining in situ concrete properties instead of those obtained from a prepared sample.

<u>Seattle-Tacoma International Airport</u>

Slab replacements on Runway 16R-34L at Seattle-Tacoma International Airport have occurred about every other year since 1994. The last occurrence of this work was in 2003, and included a total of seventy-two concrete slab replacements over a period of 2 months. Night closures were used to replace distressed concrete panels with a rapid-set concrete that included citric acid as a retarder.

The construction process consisted of a series of continuous and progressive activities, with a 3-day period required to replace a given slab. To begin with, the slab repair boundaries were cut during the first night of construction, and on the second night the slab was removed and replaced with a temporary precast concrete panel. On the third night, a new slab was placed using rapid-setting concrete. Specified opening concrete strengths were obtained 3 to 4 hours after placement, and design strength was obtained 6 to 8 hours after placement. All concrete strengths were obtained from flexural tests on beams.

Overnight slab replacement projects have the potential to strongly benefit from innovative testing methods for monitoring concrete strength gain. Instead of waiting 3 or 4 hours to break beams to determine strength, innovative methods such as maturity or seismic allow continuous monitoring until the required strength is achieved. This often occurs earlier than the time specified in the strength requirements, which would allow for earlier opening to aircraft traffic. This is especially important at an airport with limited runway capacity and around-the-clock operations. As often occurs with projects of this nature, 28-day strength testing is not performed, but this information would be available without testing additional beams if continuous strength gain monitoring is performed.

William P. Hobby Airport

In 2002, the intersection of Runways 12R-30L and 4-22 was reconstructed at William P. Hobby Airport in Houston. This intersection had been replaced in 1995, but problems with the rapid-setting concrete used during the 1995 reconstruction required the intersection to be replaced again in 2002. An extensive mix design was performed in order to obtain better long-term performance using high-performance concrete. The 600-ft by 600-ft intersection was replaced in 19 days utilizing a full closure of both runways. A parallel taxiway was converted to a runway and used for aircraft operations during the reconstruction process.

The P-501 concrete used for the 2002 reconstruction was designed for a flexural strength of 550 psi in 3 days. Mix designs were developed such that the necessary flexural strength was achieved without the use of accelerating additives, which were blamed for the delayed ettringite formation and ASR that plagued the 1995 reconstruction. Compressive and flexural strengths were obtained at 3 days and 28 days, but only the flexural strength results were used for acceptance and payment. Construction equipment and trucks were not allowed on the fresh concrete until the standard FAA flexural strength requirement for opening to traffic was met. Innovative techniques were not used on this project, although they were considered. The Houston Airport System (HAS) has indicated that maturity meter techniques will be a specified alternative for contractor use in the future.

As the owner has noted, innovative testing techniques would have allowed continuous monitoring of the strength gain of the fresh concrete. Typically, a concrete mixture that meets a 3-day strength requirement will be designed such that the required strength is met prior to the deadline. If the strength development is monitored continuously, in most cases this will allow opening prior to obtaining the 3-day strengths from flexural tests. This could serve to further expedite the construction schedule, which would benefit all parties involved.

Summary

The key to applying fast-track paving techniques for concrete pavements lies in understanding the materials and strategies that are available, and when and how these should be applied. A range of materials are available for accelerating pavement opening times, but beyond the simple selection of appropriate materials lie many other strategies that can accelerate a paving project. Nevertheless, the monitoring and assessment of the in-place concrete arguably remains the most critical aspect of fast-track construction.

Six different concrete pavement airfield projects employing fast-track construction were reviewed in light of the ability for new testing technology to contribute to the construction process. Each of these projects involves the repair or replacement of pavement sections that are critical to the ongoing operations of busy commercial airports. In such conditions, the adage that "time is money" has a very real meaning, in that airline and cargo operations are disrupted and airport revenues from such operations adversely affected. While fast-track paving techniques were used to minimize the closure on these projects, there was an opportunity in each to potentially further accelerate the project through the use of nondestructive monitoring of concrete strength. This technology, which is used widely in other paving applications, allows the contractor to identify with much greater precision exactly when the concrete has reached the specified strength at which the pavement can be reopened to traffic. In eliminating the need to wait for the results of beam breaks at specified times, these rapid and innovative test methods allow traffic to resume as soon as possible, reducing to a minimum the disruption caused by work done on critical pavements.

CHAPTER 4

DEVELOPMENT OF WORK PLAN FOR PHASE II

As reflected in the previous chapters and as included in current FAA Item P-501, the most important acceptance parameters for PCC pavement construction are primarily flexural strength or compressive strength[1] and slab thickness. As also reflected in the work plan, the main new methods to be investigated to obtain strength parameters are seismic and maturity, and to estimate thickness are impact-echo and probing.

Strength Parameters

The strength parameters are studied in the following two stages:

1. Laboratory study (including small slab study) with the primary goal of ensuring adequate accuracy, precision, reliability and practicality of the proposed methods, and
2. Field study for a side-by-side comparison with current specifications, to primarily evaluate the practicality of the proposed protocol in the field conditions.

Each stage is described below.

Laboratory Study

The parameters that impact strength are placed in three categories of (1) material-related, (2) environmental-related, and (3) construction-related. Table 4.1 summarizes the relevant parameters in each category. It is well known that these parameters impact the long-term strength or the rate of gain in strength to various degrees.

In the previous chapters, it is described how under the current state-of-practice and the state-of-the-art, a means of measuring the flexural strength (or for that matter compressive strength) of the in-place material in a reasonable and direct manner is not feasible. It is also illustrated that through a careful calibration process during the development of appropriate concrete mix design,

[1] Compressive strength can be used for pavements designed to accommodate aircraft gross weights of 30,000 lbs or less

Table 4.1 – Parameters Impacting Strength of Concrete

Category	Relevant Parameters
Material-Related	• Cement content • Water-cement ratio • Air content • Type of aggregates • Gradation of aggregates • Additives
Construction-Related	• Curing • Placement • Grooving
Environmental-Related	• Temperature • Humidity • Wind

the strength parameters can be related to either seismic modulus or maturity parameter. The main goals of the Phase II work plan are then to validate the following items:

1. *Laboratory relationships can be accurately, readily and conveniently developed between a given strength parameter*[2] *and one or both of measured parameters*[3].

   To address this item, a number of molded beams and cylinders will be prepared using typical mix designs used by the FAA contractors (the details are given in Chapter 5).

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 laboratory-relationships developed in Item 1.*

   The approach to follow in order to address this item is summarized in Table 4.2.

3. *Changes in concrete strength, as may be caused by changes in materials, construction or environment during poor-quality construction practices are appropriately detected by corresponding changes in maturity and/or seismic measurements.*

   The approach to follow in order to address this item is also summarized in Table 4.2.

4. *The field and laboratory developed relationships are similar or strongly related and are not impacted by the size of specimens or method of testing.*

   To address this item, several small slabs will be poured (see Chapter 5 for details). Each slab will be tested at least at its nominal ages of 1 day, 3 days, 7 days and 28 days with the field devices (PSPA, see Appendix A). At least two beams and/or two cores will be extracted from the slab and will then be tested using the laboratory devices. The lab and field results will be evaluate in terms of relationships between strength parameters and maturity and/or seismic modulus.

[2] Strength parameter from hereafter refers to either compressive or flexural strength of a mix
[3] Measured parameter from hereafter refers to either seismic modulus or maturity value

Table 4.2 – A Summary of Approach to Address Impact of Parameters Impacting Strength on Laboratory-Derived Relationships

Category	Approach
Material-Related	• For parameters in Table 4.1, perturb the constituents of the mix from the nominal mix design, one at a time to levels reflecting batch-to-batch variation under typical concrete quality control. • Compare the original relationship between strength parameter and measured parameter with the one obtained from the perturbed mix design. • Conduct standard statistical analyses using the null hypothesis that the two relationships between strength and measurements remain unchanged. • Rank the significance of each parameter in Table 4.1.
Construction-Related	• Curing: Pour several slabs from standard mixtures and cure them under different conditions. Cure using ▪ Blankets ▪ Curing Compound that meets P-501 specifications Compare the original relationship between strength parameter and measured parameter with those obtained from different slabs. Conduct standard statistical analysis, using a null hypothesis that the relationships are the same, to determine the significance of each curing method on the accuracy of the results. Rank the significance of each curing method. • Placement: Pour several slabs from standard mixtures, place under ▪ Appropriate Consolidation ▪ Overconsolidation (vibrate at higher frequency and/or for longer period of time) Compare the strength of slab concrete with the strengths estimated by measured parameters. Conduct standard statistical analyses, using the null hypothesis that measured parameters show similar trends as strength. • Grooving: Has been extensively addressed in Geomedia (2001) which will be validated in this study
Environmental-Related	• Temperature: Pour slabs from standard mixtures. Cure in temperature-controlled room at ▪ Cold temperature (45°F) ▪ Normal temperature (70°F) ▪ Hot temperature (95°F) • Humidity: Pour slabs to be cured at different ambient humidity of 25% and 90%. • Wind: Difficult to control in lab study; the evaporation rate will be monitored as per ASTM C157 for field study

5. *All test methods are robust, repeatable, and reproducible.*

   Several replicate devices will be utilized to conduct the measurements on a number of appropriate field and lab specimens. The statistical analysis will then be carried out to ensure that the results are reproducible and repeatable. These results will be also used in the PWL analyses.

Field Study

As indicated before, the main goal of field study is to ensure the practicality of the proposed protocol under the field conditions. A preliminary protocol for achieving this goal is included in Chapter 5. One major objective of this activity is to demonstrate that the proposed protocol is addressing some of the shortcomings of Item P-501 as documented in Chapter 2. In this study, the focus is on estimating the strength parameters (flexural and/or compressive strength) of the slab at the time of testing and projecting its potential 7-day and 28-day strength of the slab. The current thinking is to initiate seismic and maturity tests from shortly after placement and to continue testing to about an age of 28 days.

Thickness

The determination of thickness is also studied in two stages with the same objectives as the strength parameters, namely:

1. Small slab study with the primary goal of ensuring the accuracy, reliability and practicality of the proposed methods.
2. Field study for a side-by-side comparison with current specifications, to primarily evaluate the practicality of the proposed protocol under the field conditions.

Each stage is described below.

Small Slab Study

These slabs would be typically 42 in. wide by 72 in. long. The parameters that impact thickness estimation are primarily construction related. These parameters consist of:

- The texture of the slab.
- The type of material underlying the slab.

The primary goal of this activity is to ensure that:

1. *Test methods are sufficiently accurate.*

   To address this item, several small slabs with different thicknesses will be poured (see Chapter 5 for details). Each slab will be tested at a number of pre-marked points at nominal ages of 1 day, 3 days, 7 days and 28 days with the selected technologies. The slabs will be cored after 28 days at the marked locations. The thicknesses measured on the cores and estimated with the proposed technologies will be compared. Statistical analysis will be carried out to determine the accuracy and utility of each method.

2. *Construction-related parameters do not significantly impact the accuracy of the method.*

   The theoretical and experimental aspects of the effects of texture on the impact-echo results are extensively studied by Geomedia (2001) and such the extent of studying this parameter will be limited as discussed in Chapter 5.

To address the impact of underlying layer, several slabs will be poured on different base materials (e.g. cement-stabilized base, asphaltic-concrete base and compacted subgrade). The response of the candidate test methods to these parameters will be studied.

3. *Test methods are robust, repeatable, and reproducible.*

   Several replicate devices will be utilized to conduct the measurements on a number of appropriate slabs (see Chapter 5 for details). The statistical analysis will then be carried out to ensure that the results are reproducible and repeatable. These results will be also used in the PWL analyses.

Requirements and Steps to Implement PWL

The FAA specification for rigid airfield pavements (P-501) uses “percent within limits” (PWL) computations for quality assurance and pay adjustment. To develop new pay schedules for the proposed acceptance quality characteristics (AQC’s), the following tasks will be completed:

- Establish appropriate variability levels and tolerance limits for the proposed AQC (e.g., seismic modulus).
- Establish correlations between the proposed AQC and the existing one (e.g., seismic modulus vs. flexural strength).

Using the above information, new pay schedules will be developed for the proposed AQC’s (e.g., impact-echo thickness and seismic modulus) for inclusion in the FAA specifications. The pay schedules will include new rejectable quality levels and PWL values. The new pay schedules will be essentially a conversion of the existing pay schedules.

The PWL computation is an effective method for ensuring that both the expected value and the variability of a measured quality parameter are acceptable. The development of sampling plans and limits to be associated with PWL computations allow for quantification of risks for both the project contractor and the owner. Therefore, the use of PWL for quality assurance ensures that the owner and contractor share risks that are associated with the project sampling plan fairly.

The development of PWL specifications for a given material property involves the identification of fair and effective values for (1) limiting values and (2) pay factors.

The limiting values are those boundaries for the magnitude of the measured material property that are deemed acceptable or desirable. These limiting values can include upper and/or lower values. The pay factors are multipliers for the contractor’s payment for the project. Pay factors typically have a range from zero (material rejection) to a value slightly greater than one. Values greater than unity provide a bonus for the contractor for exceptional work. Pay factors for flexural strength in Section 8.1 of P-501 range from zero to 1.06.

To calculate PWL, the distribution of material properties as estimated by a sample of tests is characterized by a mean and a standard deviation. The distribution is assumed to be symmetric. The shape of the distribution is typically defined by a beta distribution, as explained by Freeman and Grogan (1998). The PWL calculations for specification P-501, as defined in Section 110 of the General Provisions of the FAA specification, adhere to the use of the beta distribution. For a given mean and standard deviation, the beta distribution can assume shapes ranging from triangular to Gaussian (i.e. normal), depending on the sample size. This is why the beta distribution is effective for PWL computations. If sample sizes are small, the shape of the distribution approaches triangular and if the sample sizes are large, the shape of the distribution approaches a normal distribution. In this manner, for a given mean, standard deviation limits and estimates for PWL are conservatively high for small sample sizes. This is the opposite effect of Student's t-distribution, which would provide relatively low estimates for PWL for small sample sizes.

In order to establish fair and effective values for the limits and the pay factors for a PWL specification for new quality assurance tests, complete knowledge must be obtained for the following:

1. Variability associated with test procedures.
2. Variability associated with correlations between material properties.
3. Variability in material properties under "acceptable" circumstances.

The variability associated with test procedures will be quantified by conducting multiple replicate tests with maturity and seismic devices. As an example, the results from such study conducted by Alexander (1996) are included in Table 4.1.

Based on this study and a similar one by Ramaiah et al. (2000), these variabilities are smaller than the documented variabilities associated with flexural tests (ASTM C78) and compressive strength tests (ASTM C39).

The variability associated with correlations between material properties will be obtained during this study as mean strengths are correlated to mean values of maturity and seismic results. Given the various mixtures and ages of testing to be included in this study, the variability associated with correlations will be characterized thoroughly.

Variability in material properties under "acceptable" circumstances would have been accounted for in previous PWL developments for FAA P-501. Any new PWL specifications, where maturity and seismic are related to strength, will be developed in a manner that imposes commensurate expectations on the contractor. Also, advantage will be taken of previous documented experience related to the batch-to-batch variability in concrete material properties (see Tables 2.1 and 2.2). Based on these data, typical coefficients of variation in concrete material properties tend to range from 5 to 30 percent. Therefore, the study will include variations in material properties of 20 percent, which would equate to a "common" deviation from mean of two standard deviations.

Similar investigations of thickness variability will be completed. The main source of information about thickness variability will be from the literature search and the small slab study.

Table 4.3 – Evaluation of Repeatability of Free-Free Resonant Column and PSPA (from Alexander, 1996)

Test Type	No. of Data Sets [Replicates]	Range of Means, fps	Range of Std. Dev., fps	Average and [Range] for CV(%)
Free-Free P-Wave Velocity for Sawn Beams - between replicates on a single beam	63 [3]	11545 to 14230	0 to 845	1.2 [0 to 6.9]
Free-Free P-Wave Velocity for Sawn Beams - between beams for a single mixture	16 [4]	11670 to 14090	39 to 465	1.6 [0.3 to 3.6]
Free-Free P-Wave Velocity for Field Cores[a] - between replicates on a single core	24 [10]	12725 to 17265	0 to 110	0.2 [0.0 to 0.8]
Free-Free P-Wave Velocity for Field Cores[a] - between cores for a single mixture	6 [4]	12875 to 15880	45 to 1020	2.0 [0.4 to 6.4]
Free-Free P-Wave Velocity for Lab-Molded Beams - between replicates on a single beam	33 [3]	9870 to 14535	7 to 270	0.6 [0.1 to 1.9]
Free-Free P-Wave Velocity for Lab-Molded Beams - beams for a single mixture	12 [3]	9980 to 14390	13 to 430	1.0 [0.1 to 4.1]
Free-Free P-Wave Velocity for Lab-Molded Cylinders[b] - between replicates on a single cylinder	72 [3]	9650 to 14110	0 to 480	0.8 [0.0 to 3.7]
Free-Free P-Wave Velocity for Lab-Molded Cylinders[b] - between beams for a single mixture	24 [3]	12400 to 14020	8 to 340	1.0 [0.1 to 2.6]
PSPA R-Wave Velocity for Slabs[c] - between readings at the same location	2 [30]	7360 to 8090	31 to 40	0.5 [0.4 to 0.5]
PSPA R-Wave Velocity for Slabs[c] - between locations in close proximity	48 [3 to 5]	6020 to 8640	10 to 250	0.8 [0.1 to 3.5]

[a] includes 6-, 4-, and 3-inch diameter specimens
[b] 6x12-inch cylinders only
[c] 6-inch thick slabs

CHAPTER 5

IMPLEMENTATION PLAN FOR PHASE II

In this chapter, a detailed description of the laboratory and field testing program is included. For each parameter defined in Chapter 4, a detailed explanation of the work to be carried out is presented. The timeline to achieve each of the goals of this experimental program is discussed. The specific responsibilities of team members are delineated. The data analysis procedure to assess the strength and weaknesses of the methods proposed are also discussed.

Due to geographical locations of different team members, the focus will be on the following three primary mixtures:

- A mix design from the Southeast using granite aggregates (ERDC).
- A mix design from the Midwest using limestone aggregates (UIC).
- A mix design from the Southwest using siliceous river gravel (UTEP).

All materials used in the mixes and the final mix designs will be completely in compliance with the requirements of the P-501 specifications. As it will become obvious shortly, each team will focus on addressing one or more of the issues identified in the previous chapter. However, adequate overlap is included to ensure that the conclusions to be drawn are applicable to all regions.

Strength Parameters

As indicated in Chapter 4, the main objectives as pertaining to the strength parameters are to validate the following:

1. Laboratory relationships can be accurately, readily and conveniently developed between flexural or compressive strength and maturity parameter or seismic modulus.
2. Changes in mixture-related, construction-related and environmental-related parameters, that are inevitably encountered during real-world construction practices, do not significantly impact the laboratory-relationships developed in Item 1.

3. Changes in concrete strength, as may be caused by changes in materials, construction, or environment during poor-quality construction practices, are appropriately detected by corresponding changes in maturity and/or seismic measurements.
4. The field and laboratory developed relationships are similar or strongly-related and are not impacted by the size of specimens or method of testing.
5. Test methods are robust, repeatable and reproducible.

Test Protocol

The detailed test protocol is included in Appendix B. The following two types of test programs are considered: (1) laboratory study and (2) small slab study. Details of these studies are elaborated below.

Laboratory Study

The goal of the laboratory tests is to develop seven relationships for a given mixture under controlled conditions. These seven relationships are:

1. Flexural strength vs. maturity parameter.
2. Compressive strength vs. maturity parameter.
3. Seismic modulus vs. maturity parameter.
4. Flexural strength vs. seismic modulus.
5. Compressive strength vs. seismic modulus.
6. Flexural strength vs. seismic modulus and maturity parameter.
7. Compressive strength vs. seismic modulus and maturity parameter.

The first two can be utilized to predict the corresponding strength given the field maturity and to project the future strength of the material from early age strength. The third relationship allows the projection of the future seismic modulus of the material which can then be used with Items 4 or 5 to determine the strength. The fourth and fifth relationships will be used to estimate the strength given seismic modulus. The sixth and seventh relationships are developed in the hope of obtaining more representative relationships. Flexural strength tests are usually less precise than either maturity measurements or seismic measurements. It may be desirable to introduce the deformation characteristics of the concrete in the quality indicator to compensate for some of the variability. Since the modulus of elasticity is inherently an indicator of material stiffness and deformation potential, it is highly likely that the seismic measurements of modulus will be able to provide the necessary criteria for acceptance. The selected function will be optimized based on correlation with the strength parameter as specified in the design. The new approach might reduce the variability especially in fast track applications.

The results from each individual series of laboratory testing alone are ideal to address the first objective indicated above; that is all seven relationships yield high coefficients of determination (R^2). Secondly, the relationships developed from different sets of tests can be compared to validate the second objective that is for a given mixture, these relationships should be independent of the variations in mix design, construction-related parameters and environmental parameters.

In the laboratory study, about 12 cylinders and 12 beams will be prepared and moist-cured under standard conditions (as per ASTM C31) for each test set. The maturity parameter will be continuously measured on two specimens. At discrete nominal ages (i.e. 1 day, 3 days, 7 days and 28 days) two beams and two cylinders will be tested with the resonant column device (ASTM C215) and then will be tested in bending (as per ASTM C78) and compression (as per ASTM C39). In that manner all data needed to develop the seven relationships will be available. As an exception to this test program is the one to be followed by UIC. They will double the number of beams poured for the standard mixture so that they can investigate the possibility of improving the repeatability of the flexural strength tests as discussed in Chapter 2.

Small Slab Study

To ensure that the results from laboratory study are applicable to field conditions (i.e., that they address Objective 3 above, a number of slabs will be poured as well. The seven relationships described above will again be developed but from testing on slabs. The maturity parameters will be measured using thermocouples embedded in each slab. The seismic modulus will be measured in two ways: (1) nondestructively in situ using the PSPA on the slab and (2) on extracted cores and beams from the same slab using resonant column testing. Finally, the flexural strength and compressive strength will be determined using the beams and cores extracted from the slab. Concurrent with testing the slabs, a series of standard beams and cylinders made from the same mix cured under ideal condition will be tested for comparison purposes. The procedure described for laboratory testing will be followed for this purpose. The primary goal of this activity to compare the seven laboratory developed relationships with the ones obtained in the field.

Each of the slabs, as shown in Figure 5.1, will normally be 42 in. wide, 72 in. long and 12 in. thick. In that manner, the cores can be readily tested in compression. To obtain specimens for flexural tests, a 6 in. slice of the slab will be saw-cut along the width. The 12 in. thick beam will be cut

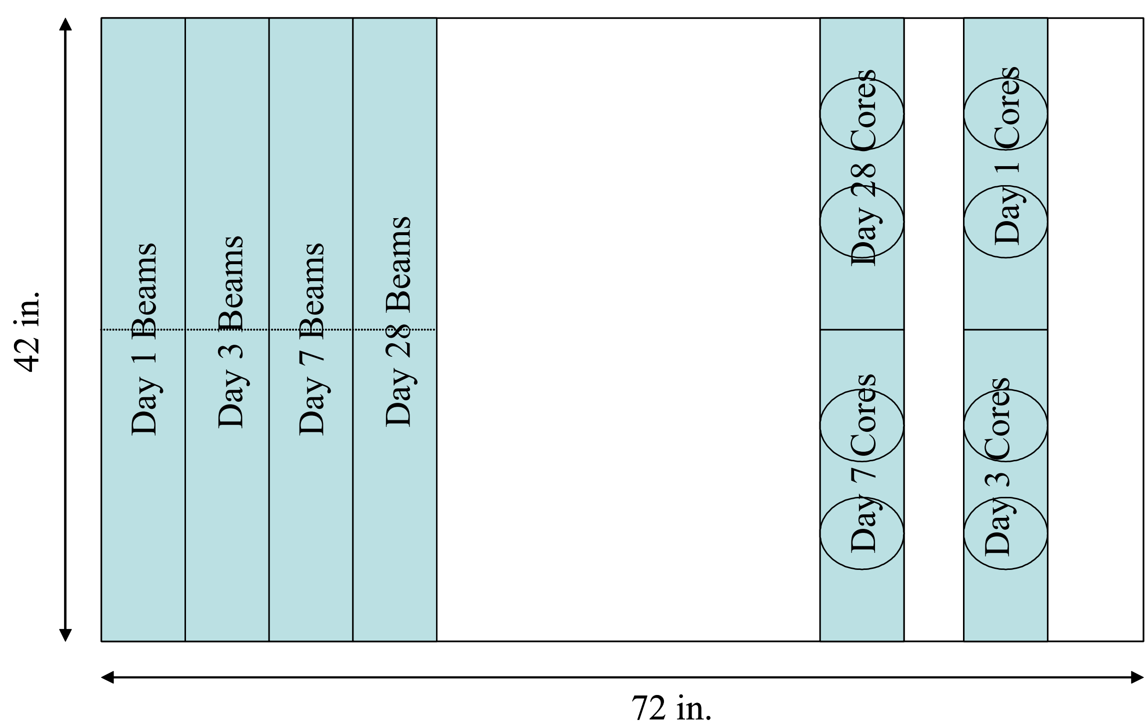

Figure 5.1 – Typical Layout of Small Slabs

in half lengthwise and once again along the depth to obtain 4 standard specimens. All four beams will be tested to obtain an average flexural strength to be used in developing the relationships. In addition, the flexural strength of the two bottom beams will be compared with the two top beams to assess the variability in the strength parameters along the depth of the slab.

Test Plan

Table 5.1 contains a proposed experimental matrix so that the first three objectives can be incorporated. The table is divided into several sections. The first column contains the parameter of interest as discussed in Chapter 4. The second column details the levels of variation that are considered. Of course the results from each test are compared with those from the corresponding standard mix or condition representing one of the three mixtures described above. The next three columns demonstrate which of the three project team members will undertake the testing. Also included in the table is whether the parameter will be studied through pouring small slabs or only through laboratory prepared specimens (beams and cylinders). It is emphasized that any strength/modulus parameter studied with slabs will also contain tests on molded beams and cylinders cured in the laboratory (for calibration purposes) and cores and beams extracted from the slab (for validation purposes). As signified by symbol "*" in the tables, any databases available from previous studies will be included to complement the results of this study. Each item in the table will be elaborated next followed by a thorough explanation for the test protocol to be followed in testing the small slabs and testing the specimens.

Cement Content

The impact of the cement content on the developed relationships will be studied by all three partners using beams and cylinders. Due to importance of this parameter, ERDC will also pour a slab to ensure that the laboratory results obtained under ideal curing condition will apply to the field results. The cement will be increased and decreased by 10% to simulate the worst case scenario. In this experiment, the water-cement ratio will be maintained at the designed value.

Water-Cement Ratio

The significant impact of this parameter on the gain in strength and modulus is well known. This parameter will be studied through small slabs to be poured at UTEP. In addition, ERDC and UIC will assess its impact through laboratory cured specimens. The water-cement ratio will be increased and decreased by 10% as compared with the design value.

Air Content

Air entraining agents play a major role on the durability of the concrete, especially in cold regions. Since UIC is concentrating on the cold weather concrete, this parameter will be studied by UIC. They will prepare laboratory-cured specimens that contain either no air-entraining agent or two levels (low and high) air-entraining agents. UTEP also has a limited database of results where the air-entraining agent was added or omitted. That database will also be used in the final analysis.

Table 5.1 – Summary of Strength-Related Activities

a) Material-Related Parameters

Parameter		This Study	UTEP		ERDC		UIC	
			Slab	Specimen	Slab	Specimen	Slab	Specimen
Cement content		Three Levels • As designed • Greater than design • Less than design		✓	✓			✓
Water-cement ratio		Three Levels • As designed • Greater than design • Less than design	✓			✓		✓
Air content		Three Levels • No Air-entrainer • Low Air-entainer • High Air-entrainer		*				✓
Aggregates	Type of Aggregates	Three Levels • Siliceous River Gravel • Limestone • Granite	✓		✓			✓
	% total aggregates	Three Levels • As Designed • High • Low						✓
	Coarse Aggregate Fraction	Three Levels • As designed • Greater than design • Less than design		✓	✓			✓
	Finess Modulus	Three Levels • As designed • 5% Passing Sieve #50 • 25% passing Sieve #50						✓

* a database with similar parameter is available and will be used in the final analysis

Table 5.1 (con't) – Summary of Strength-Related Activities

b) Construction-Related Parameters

Parameter	This Study	UTEP		ERDC		UIC	
		Slab	Specimen	Slab	Specimen	Slab	Specimen
Curing	Three Levels • No curing Compound • Curing Compound • Blanket	✓		✓			
Compaction	Two Levels • Appropriate compaction • Overcompaction	✓					
Grooving	Two Levels • Broom finish • Standard FAA grooving	*		✓			
Thickness	Three Levels • 6 in. • 12 in. • 18 in.	✓					

* a database with similar parameter is available and will be used in the final analysis

c) Environmental-Related Parameters

Parameter	This Study	UTEP		ERDC		UIC	
		Slab	Specimen	Slab	Specimens	Slab	Specimen
Ambient Temperature	Three Levels • Cold • Warm • Hot	✓					
Ambient Humidity	Two Levels • Low • High	✓					

Aggregates

The following four aggregate-related parameters will be studied: type of aggregate, percent total aggregates, coarse aggregate fraction and finess modulus.

Type of Aggregate. As indicated previously, the type of coarse aggregate seems to have the most impact on the strength-seismic modulus relationship, and will be a major focus of the laboratory testing. All three teams will study this parameter, UTEP and ERDC through small-slab studies and UIC through laboratory study. As indicated before, UTEP will focus on siliceous river gravel as coarse aggregate, UIC on limestone and ERDC on granite. All three coarse aggregates will be in compliance with the requirements of P-501 specifications.

Percent Total Aggregate. As indicated previously, the type of coarse aggregate seems to have the most impact on the strength-seismic modulus relationship. The impact of quantity of coarse aggregate on the developed relationship is unknown. As such, UIC will vary this parameter to understand its impact. The percent coarse aggregate will be increased and decreased by 20% from the baseline for this experiment.

<u>Coarse Aggregate Fraction</u>. A survey of the typical coarse aggregate fraction used in the Fort Worth area indicates that variability in the range of about 10% should be anticipated. The impact of this variability on estimating the strength parameters will be studied through specimens and small slabs by the three partners. UTEP and UIC will study this matter through tests on laboratory specimens whereas ERDC will investigate this matter through a small slab study. The coarse aggregate fraction will be increased and decreased by 20% from the corresponding design values.

<u>Finess Modulus</u>. The same survey of the Fort Worth area production also indicates that the finess modulus may vary by as much as 15%. Since it is anticipated that the impact of this parameter on the strength should be small, UIC will study this matter through a laboratory study on beams and cylinders. The finess modulus can be changed in a number of ways. In this study, the finess modulus will be changed by changing the percent materials passing Sieve No. 50 twice. First only 5% of the material will pass Sieve No. 50, and second about 25% is allowed to pass that sieve.

Curing Method

Curing method has a big impact on the final quality of the concrete. This matter can only be studied through slabs. UTEP will study the impact of using curing compounds and blanket for curing concrete. To study the worst case scenario, one slab will also be cured with no provision for curing. ERDC will also experiment with this matter by comparing mat curing with using curing compound on one of their slabs.

Consolidation

Proper consolidation of the in-place PCC is essential to performance. To study the impact of proper consolidation on the strength parameters of the concrete, a slab will be placed with the appropriate level of consolidation and another slab will be placed and over-vibrated. This activity will be carried out at UTEP.

Grooving

Even though grooving may not impact the strength, it may impact the in situ seismic measurements. Geomedia (2001) has carried out an extensive study of this matter, and the project team will rely heavily on the results of that study. However, ERDC will pour a slab to verify the results from that study. One slab will be dedicated to studying the effects of grooving on seismic measurements. One-half of the slab will be grooved in accordance to the FAA guidelines, while the other half remains ungrooved. Seismic moduli on the two halves of the slab, as provided by the PSPA, will be compared statistically to ensure that the grooves are not imposing a significant effect

Thickness

The motivation beyond studying the impact of thickness on curing is the concern with non-uniform strength gain along the thickness of the slab. To study the impact of this parameter, two addition small slabs will be poured and tested at UTEP with the control mix but with the thickness of about 6 in. and 18 in.

Ambient Temperature

Since the construction of PCC slabs are controlled by the schedule, the developed relationships should not be sensitive to the deviation of ambient temperature. UTEP will pour three slabs from the control mix and cure them in walk-in environmental-control chambers of three different temperatures (nominal 45°F, 70°F and 95°F). These slabs will be periodically tested for in situ gain in strength and seismic modulus. In addition, ERDC will carry out a study on lab-cured beams and cylinders on their mixtures.

Ambient Humidity

Similar to the ambient temperature, the impact of ambient humidity will be studied. Two slabs will be cured in walk-in environmental-control chambers with significant difference in relative humidity to ensure that the ambient humidity will not impact the robustness of the relationships developed. Both slabs will be covered with curing compound to minimize the loss of moisture.

Thickness Measurement

As a reminder, the two methods to be used for thickness measurement consist of the impact-echo and probing of fresh concrete. The efforts toward establishing the feasibility of these methods for acceptance are more straightforward. The three major objectives are:

1. The texture (groove pattern) of the slab.
2. The type of material underlying the slab.
3. The most suitable time for utilizing these methods.

Test Protocol

No laboratory study can be carried out for this study. Our effort will be focused on the slab studies. UTEP will conduct most of this study with the help from ERDC. Since the PSPA conducts the impact-echo tests concurrent with the SASW tests, all data gathered on the slabs poured for the strength tests will be reanalyzed to estimate the thickness so that they can be compared to the core thickness. This task will allow us to comprehensively study Objective 3 that deals with the best time to conduct each test.

Several 4 ft by 6 ft slabs will also be poured to address the first two objectives as it will be discussed shortly. The activities involved in this task consist of conducting the probe tests from shortly after pouring the slab until the concrete is set (see Appendices C and D). The impact-echo tests will be carried out from 24 hours after the pouring of concrete until an age of 28 days at about half-a-dozen points on each slab. After 28 days, cores will be extracted from each test point for validation.

In addition, a long slab is proposed as shown in Figure 5.2. The slab will be 6 ft wide and 32 ft long. For the first 24 ft, the thickness of the slab will be varied every 4 ft from a minimum of 10 in. to a maximum of 20 in. in increments of 2 in. For the last 8 ft, the thickness of the slab will be gradually varied from 20 in. to 10 in. so that the impact of subtle changes in thickness can be studied. The slab will only contain temperature reinforcement since past studies have shown that the impact-echo method is not significantly impacted by the structural reinforcement. Since dowel bars and tie bars are commonly placed in localized areas near the joints, they have been eliminated from this study. However, they will be studied in the field side-by-side tests.

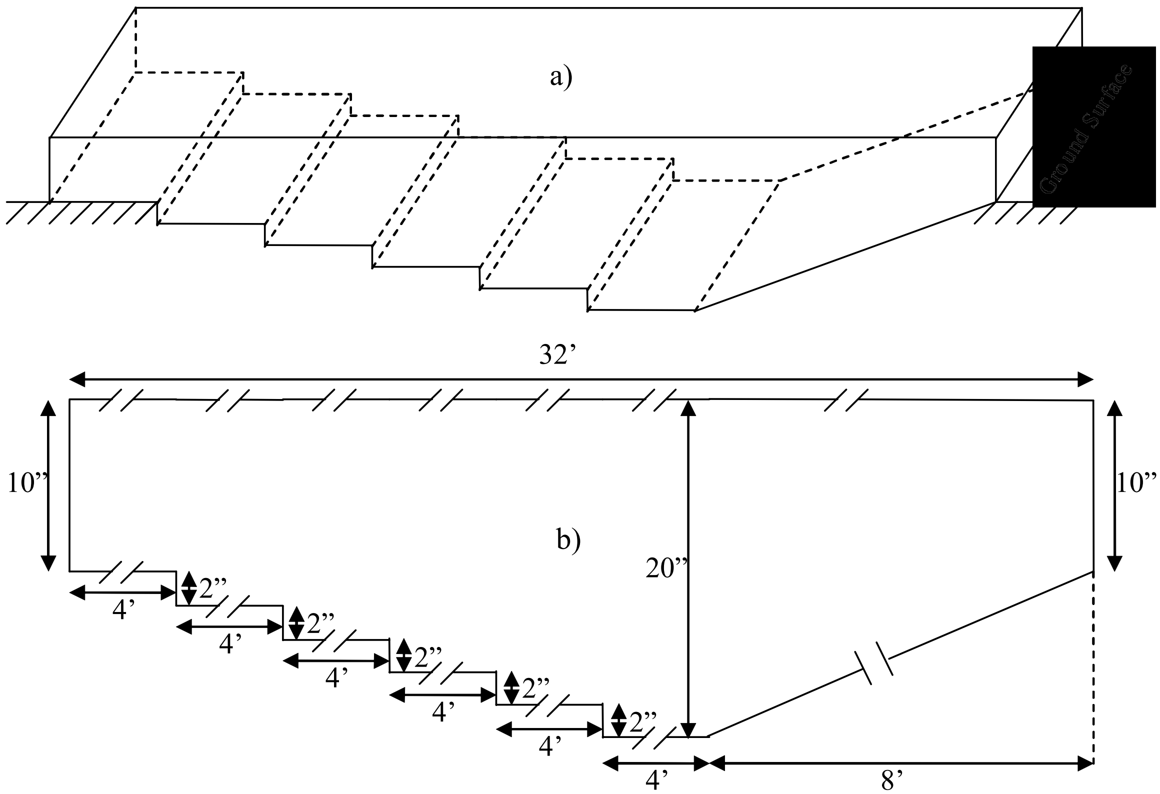

Figure 5.2 – Layout of Long Slab for Thickness Measurement

Test Plan

Grooving

As indicated before, an extensive study on the impact of the texture (grooving pattern) of the concrete on the impact-echo method has been carried out by Geomedia (2001). As such, the scope of this work will be mostly towards the validation for impact-echo method. To address this issue, two similar slabs will be poured, one with broom finish and another with standard runway grooving. Tests will be carried out on both slabs to illustrate the impact of the grooves on the impact-echo tests.

Underlying Layer

For the impact-echo, the boundary between two layers with similar mechanical impedance[4] will not be distinguishable. Since both the dielectric constant and the mechanical impedance of fresh concrete vastly vary with time, this matter has to be investigated. We will compare the responses from three 12-in. thick slabs poured simultaneously but one placed on compacted subgrade, one on an AC layer and one on a cement-stabilized base. The results from tests on the three slabs

[4] Mechanical impedance is the product of the propagation velocity and the density

will be used to determine at what age (if any) the contrasts in the mechanical impedance are adequate for accurate thickness estimation.

Data Analysis and Modification of Protocol

Comprehensive preliminary test protocols to be followed during this study are included in Appendix B. As indicated in the proposal, this protocol will be modified as necessary to ensure its robustness and usefulness. Some of the highlights of the protocol are summarized below.

Data Reduction

The data reduction refers to determining the parameter of interest to this study from the raw data. Table 5.2 contains the raw data and the reduced data anticipated from each method. Data should be reduced on the same date that is collected.

Data analysis

The data analysis consists of appropriate statistical analysis and development of appropriate relationships from the reduced data. For strength parameter, this will be carried out at three levels. The first level consists of developing the seven relationships between the average strengths, average seismic moduli and average maturity parameters obtained from tests at corresponding ages. The end results to be reported is the equation of the best fit curve for each of the seven relationships with corresponding R^2 value and the standard error . In addition, the coefficient of variation from repeat tests for each test at each test day should be reported. The data should be incorporated in the appropriate database as the test progresses with the final results reported to UTEP within three days of the completion of a series of tests.

The second level of analysis consists of conducting appropriate statistical analysis with the null hypothesis that the parameter being studied is not impacting the relationships developed. For example, for the flexural strength-seismic modulus compared for three levels of cement content (see Table 5.1), the null hypothesis will be that the three relationships from the three levels of cement contents belong to the same population. The reported results, in addition to an accept/

Table 5.2 – Data Reduction Process for each Test

Method	Raw Data	Reduced Data	Materials to be Archived
Strength-Related Parameters			
Flexural Strength	Load to failure	Flexural strength	
Compressive Strength	Load to failure	Compressive Strength	Load Curve
Resonant Column	Resonant Frequency	Seismic Modulus	Time Records Frequency Spectrum
PSPA (modulus)	Variation in Velocity with Wavelength	Seismic Modulus	Time Records
Maturity	Temperature	Time-Temperature Factor	Temperature Time History
Thickness-Relate Parameters			
Probing	Thickness	Thickness	N/A
PSPA (Impact-echo)	Resonant Frequency	Thickness	Time Records

reject answer of the null hypothesis, will be a plot of measured values vs. estimated ones for a more practical view of the results.

The third consists of conducting appropriate statistical analysis with the null hypothesis that the lab-developed and field-developed strength-seismic modulus and strength-maturity relationships are statistically the same. The reported results will be similar to the ones discussed for the second level of analysis.

For the thickness, the analysis consists of the average and coefficient of variation of the thickness at each point and the percent difference between the thickness measured nondestructively and the thickness measured from coring. Paired t-tests will also be carried out to determine whether the differences between the measured and estimated values are significant.

Documenting Shortcomings and Upgrading Protocols

In case the result of an experiment does not follow the anticipated results as reflected in the protocol, the following steps will be followed: Upon the completion of an experiment, the reduced data should be analyzed and its impact on the preliminary protocol should be evaluated. Before the next experiment is carried out any modification to the protocol will be made. To do this effectively, the problems encountered during data collection and data analysis will be documented and categorized in one of the following categories:

- Simple-to-fix: Ordinary malfunctions in equipment, software or protocol that is reversible and can be readily repaired.
- Intermediate: Problems with equipment, software or protocol that can be identified, is not reversible and can be repaired for next series of tests.
- Hard-to-fix: Problems with equipment, software or protocol that can be identified, is not reversible and can be repaired over an extended period of time.
- Limitations: Problems with equipment, software or protocol that cannot be identified, and would be unlikely to be fixable in the scope of this project.

In that manner, the upgrading of the protocol is systematic and well-documented. Based on the results from this study, some of the methods may be eliminated from field implementation. The modified protocol will then be utilized for field tests.

Side-by-Side Field Implementation

The primary goal of the side-by-side field study is to ensure that the developed protocol is reasonable under actual field conditions. UTEP and APTech are directly involved in this activity. The protocol will consist of the following steps:

1. Preconstruction Activity consisting of:
    - Meeting with the engineer in charge and the concrete producer to discuss our plan.
    - A collaborative effort (if possible) for pre-construction development of strength-seismic modulus and strength-maturity curves.
2. During Construction Activity consisting of:
    - Installing the necessary instrumentation and pouring a number of beams and cylinders.

- Intense sampling of the aggregates, cement at the batch plant for statistical information to validate the possibility of utilizing process control for quality control.[5]
- Intense sampling and testing of the concrete as delivered to the site for the possibility of utilizing this information for quality acceptance.

3. Post Construction Activity consisting of:

   - Intense field testing, coring and laboratory mechanical strength testing during the early-age (the first 72 hours).
   - Field testing, coring and mechanical strength testing at nominal ages of 7 days, 14 days, 28 days and 90 days.

4. Analysis of results in a manner similar to the lab testing procedure described above including:

   - Reducing the data.
   - Evaluating the strengths and weaknesses of the protocol.
   - Recommending improvements to the protocol.
   - Identify areas that need further evaluation.

The strength tests on the molded specimens and those extracted from the field will be carried out for flexural strength and compressive strength. The maturity tests will be carried out by either using maturity-meters or well-calibrated temperature data loggers, or newer disposable devices (such as i-buttons). The laboratory seismic test will be carried out using the resonant column device. The field seismic tests on slabs will be carried out using the PSPA.

Implementation of PWL

The main goal of this task is to develop new pay schedules for the proposed AQC's (e.g., impact-echo thickness and seismic modulus) for inclusion in the FAA specifications. The pay schedules will include new rejectable quality levels and PWL values. This task will be completed using the following steps:

- Establish appropriate variability levels and tolerance limits for the proposed AQC (e.g., slab thickness from impact-echo).
- Establish correlations between the proposed AQC's and the existing once. (e.g., seismic modulus vs. flexural strength).
- Convert the PWL values in the existing pay schedule to equivalent PWL values for the proposed AQC's.

Table 5.3 shows the source of data for each of the above steps.

Scheduling

Based on the test plans for the laboratory study and small slab study, the tentative time tables presented in Tables 5.4 to 5.6 will be followed by UTEP, UIC and ERDC. The duration for lab testing suggested in the proposal is about 8 months. The start of this task is assumed as March 1, 2004 with a completion by October 31, 2004. In terms of funding, this plan can be carried out with no difficulty. However, the team members feel that a four-month, no-cost time extension for this task would be very beneficial. This additional time will permit the team members to conduct much

[5] Our current thinking is that quality acceptance based on process control may not be feasible

Table 5.3 – Data Sources for Developing New Pay Schedules

AQC Parameter	Variability	Mean Correlations
Strength-Related Parameters		
Resonant Column	Literature & lab study	Lab study: Regression between flexural or compressive strength and Seismic Modulus
Seismic Modulus	Literature & lab study	Lab study: Regression between flexural or compressive strength and Seismic Modulus
Maturity	Literature & lab study	Lab study: Regression between flexural or compressive strength and Time-Temperature Factor
Thickness-Relate Parameters		
Probing	Literature & small slab study	Small Slab Study: Regression between core thickness and Probing thickness
Impact-echo	Literature & small slab study	Small Slab Study: Regression between core thickness and PSPA thickness

more sophisticated analysis of data and provide a higher quality end-product with no additional cost to the FAA or IPRF. As such, as reflected in Tables 5.4 through 5.6, it is respectfully requested that the completion of this work task be moved to February 28, 2005.

If this extension is approved, the side-by-side field testing will be initiated in August 2004 and should be completed by October 2004. A tentative plan for this task is included in Table 5.7. APTech is in charge of the coordination with the airport authority, arranging for the field testing, collecting the samples and specimens, and arranging for destructive testing (if not carried out by the contractor). UTEP will provide assistance in training for field and lab testing, conducting field and lab testing, developing the appropriate relationships and conducting the statistical analyses.

Outcome

Upon completion of Phase II, a draft report will be submitted to the IPRF technical panel, and the research team will participate in a 60% on-board review with the IPRF technical panel. Aside from the modified quality management protocol, the report will contain recommendations about adopting new technologies or modification of technology evaluated as a part of the research. These recommendations will include draft specifications. A draft Advisory Circular will be provided to facilitate implementation of the findings of the research.

As part of the outcome, a memorandum that included the work plan for Phase III (Tasks 5 and 6 of the proposal) will be provided to IPRF for further discussion and guidance from the panel during the 60% on-board review meeting. In addition to the activities proposed in tasks associated with Phase III, some additional work may be undertaken. Depending on the outcome of Phase II, these additional activities may consist of additional lab and small slab tests to clarify some of the findings, additional field tests for equipment demonstration, and more advanced analyses of the existing database.

Phase III Activities

Activities associated with Phase III are contained in two tasks: Tasks 5 (Advanced Final Report) and Task 6 (Final Report).

Under Task 5, the project team will prepare an advanced final report, representing a 90% complete document. This document will build on the draft report developed in Task 4, and will incorporate comments and suggestions raised by the IPRF technical panel from the 60% review and additional information gathered as approved by the panel during the 60% on-board review. The advanced final report will be very close to a final document, and will contain all final formatting and virtually all artwork and graphics. As part of this task, the research team will participate in a 90% on-board review with the IPRF technical panel.

Under Task 6, comments and feedback received from the IPRF technical panel on the 90% document submitted in Task 5 will be incorporated into a final report. This document will be complete in all aspects and will be prepared in accordance with IPRF reporting standards. After submission of the final report, the research team is prepared to work with the IPRF to assist with any minor editing as the document goes through the publication process.

Table 5.4 – Tentative Schedule for Laboratory and Small Slab Study for UTEP

Placement Date	Code ID	Parameter to be Studied	Mix Design / Condition	Specimens				
				Slab	Molded Beam	Cylinder	Cut Beam	Core
03/15/04	0	Practice	Standard		10	10		
03/30/04	1	Slab thickness with AC/CT base	Standard	2 (42"x72")	10*	10*		2 x 3**
04/13/04	2	Slab thickness with CTB/compacted soil	Standard	1 (6' x 32')				
05/11/04	3	Curing method	No curing compound	1 (42"x72")			4 x 3	2 x 3
			With blanket	1 (42"x72")			4 x 3	2 x 3
05/25/04	4	W/C ratio	Low (- 10 %)	1 (42"x72")	12	12	4 x 3	2 x 3
			Standard	1 (42"x72")	12	12	4 x 3	2 x 3
			High (+ 10 %)	1 (42"x72")	12	12	4 x 3	2 x 3
06/08/04	5	Cement content	Low (-10 %)		12	12		
06/22/04	6	Cement content	High (+10 %)		12	12		
07/13/04	7	Effect of slab thickness	6"	1 (42"x72")			2 x 3	2 x 3
			18"	1 (42"x72")			6 x 3	2 x 3
08/05/04	8	Effect of compaction	Over compaction	1 (42"x72")			4 x 3	2 x 3
08/31/04	9	CAF	Low		12	12		
09/14/04	10	CAF	High		12	12		
10/05/04	11	Ambient temperature	Cold (in cold water)	1 (21" x 48")			2 x 3	2 x 3
			Hot (in hot water)	1 (21" x 48")			2 x 3	2 x 3
11/09/04	12	Ambient humidity	Low (in dry room)	1 (21" x 48")			2 x 3	2 x 3
			High (in curing room)	1 (21" x 48")			2 x 3	2 x 3
11/23/04	13	Additional if needed						

*** - Will be field-cured; * * - Specimens from the slabs for velocity calirbation**

Table 5.5 – Tentative Schedule for Laboratory Study for UIC

Date	Experiment No.	Parameter to be Studied	Mix Design / Condition	Molded[1] Beam	Cylinder[1]	Saw Cut Notch Beam[2]	Molded Notch Beam[2]
3/14/04	UIC-1	General	Standard	15	15	-	-
3/18/04	UIC-2	General	Standard	-	-	15	-
3/22/04	UIC-3	General	Standard	-	-	-	15
4/16/04	UIC-4	Cement content	Low	15	15	-	-
4/28/04	UIC-5	Cement content	Low	-	-	15	-
5/10/04	UIC-6	Cement content	Low	-	-	-	15
5/22/04	UIC-7	Cement content	High	15	15	-	-
6/3/04	UIC-8	Cement content	High	-	-	15	-
6/15/04	UIC-9	Cement content	High	-		-	15
6/27/04	UIC-10	Water content	low	15	15	-	-
7/9/04	UIC-11	Water content	High	15	15	-	-
7/21/04	UIC-12	W/C ratio	Low	15	15	-	-
8/2/04	UIC-13	W/C ratio	High	15	15	-	-
8/14/04	UIC-14	CAF[3]	Low	15	15	-	-
8/26/04	UIC-15	CAF[3]	High	15	15	-	-
9/7/04	UIC-16	FM[4]	Low	15	15	-	-
9/19/04	UIC-17	FM[4]	High	15	15	-	-
10/1/04	UIC-18	Air entrained	No AEA	15	15	-	-
10/13/04	UIC-19		low	15	15	-	-
10/20/2004	UIC-20		High	15	15	-	-
10/25/04	UIC-21	% total aggregates	low	15	15	-	-
11/30/04	UIC-22		High	15	15	-	-
Total				240	240	45	45

1 Three replicate specimens per test age will be prepared. However results for two specimens will be reported. If the results for the first two specimens fall within the 10% as per ASTM, they will be reported and the third specimen will be discarded.
2 Both molded and saw cut notched beams will be prepared which are supplemental to C-78 un-notched beam tests. These beams will be tested to evaluate if they will be capable of reducing the variability of C-78.
3 CAF = Percent of aggregates retained above 3/8 in sieve ÷ Percent of aggregates retained above #8 sieve
4 The effect of FM on the strength-seisimic modulus relationship will be studied . The finess modulus will be adjusted as described in Table 5.1 by adjusting percent passing #50 Sieve

Table 5.6 – Tentative Schedule for Laboratory and Small Slab Study for ERDC

Starting Date	Test Identifier	Parameter to be Studied	Mix Design/Condition	Specimens				
				Small Slab	Sawn Beam	Core	Molded Beam	Molded Cylinder
05/04/04	1	General	Standard	1	16	8	12	15
05/18/04	2	Cement Content	Low (-10%)	1	16	8	12	15
06/08/04	3	Cement Content	High (+10%)	1	16	8	12	15
07/06/04	4	W/C Ratio	Low (-10%)				12	15
08/10/04	5	W/C Ratio	High (+10%)				12	15
08/24/04	6	Aggregate CAF	> Standard	1	16	8	12	15
09/28/04	7	Aggregate CAF	< Standard	1	16	8	12	15
10/12/04	8	Curing Method	No Curing Compound	1	16	8	12	15
11/09/04	9	Curing Method	Blanket	1	16	8	12	15
11/30/04	10	Grooving	FAA Standard	1	16	8	12	15

Table 5.7 – Work Plan for Side-by-Side Field Testing by UTEP and APTech

Schedule	Test Items
30 to 2 days before construction	Pre-construction effort (if possible): 1. Prepare 12 cylinders and 12 beams using the same mix designed for construction and moist-cured under standard condition. 2. Set up for maturity measurements up to 28 days. 3. Perform FFRC, compressive strength and flexural strength tests at ages of 1, 3, 7, 14 and 28 days.
One day before construction	1. Check all devices, tools and equipment needed for the experiment on construction to make sure they work properly.
Construction (day 0)	1. Start recording air temperature, humidity and wind speed 2. Densely sample the constituents of the PCC at source 3. Densely measure temperature, slump and air content of the fresh concrete mix delivered. 4. Measure thickness of slab using probing method. 5. Prepare 22 cylinders and 22 beams using the mix delivered. 6. Connect maturity meters to molded specimens and slabs: one to a cylinder and a beam used for standard cure, one to a cylinder and a beam used for field cure and at least two to the slab. 7. Keep all molded specimen in the construction site for 24 hours.
Day 1 (24 hrs)	1. Place 10 cylinders and 10 beams with molds in sand to represent field cure condition 2. Remove molds from 12 cylinders and 12 beams; put 10 cylinders and 10 beams in a standard-curing room 3. Perform FFRC, compressive strength and flexural strength tests on 2 cylinders and 2 beams. 4. Measure seismic modulus on the slab with a PSPA. 5. Measure thickness with IE method.
Days 3, 7 and 28	1. Perform FFRC, compressive strength and flexural strength tests on 2 standard-cured cylinders, 2 field-cured cylinders, 2 standard-cured beams and 2 field-cured beams. 2. Measure seismic modulus on the slab with a PSPA. 3. Measure thickness with IE method. 4. Extract two 6-in. diameter cores of and two beams from the slab (if possible) and trim them to standard sizes. 5. Compare thicknesses from the cores with the estimated thicknesses by various devices. 6. Perform FFRC, compressive strength and flexural strength tests on the specimens.
Day 29	1. Organize and document all data from the experiment. 2. Core several locations for thickness comparison
Repeat the process three times	

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APPENDIX A

REVIEW OF EXISTING METHODS FOR DETERMINING PCC SLAB THICKNESS AND STRENGTH

APPENDIX A

REVIEW OF EXISTING METHODS FOR DETERMINING PCC SLAB THICKNESS & STRENGTH

Introduction

As discussed in Chapter 2, slab thickness and strength are two important materials and construction factors that have significant effects on portland cement concrete (PCC) pavement performance. Accordingly, these parameters are carefully designed or specified, and significant attention is given to their control during the construction process. In general, the different methods currently used to assess PCC slab thickness and strength can be effective, but these procedures do have certain weaknesses with regard to their basis, accuracy, ease of measurement, and ability to represent in situ conditions. Because of these limitations, some new methods and new technologies have been developed with the potential for significant improvements in the characterization of slab thickness and strength on a construction project. This appendix summarizes the characteristics, advantages, and disadvantages of both traditional methods and newer technologies that may be employed for the assessment of PCC slab thickness and strength.

Slab Thickness

ASTM C174 Method

By far the most widely used method for slab thickness determination is a destructive process involving the extraction of cores (typically 100 mm [4 in] in diameter) from the constructed pavement. The method of obtaining the drilled cores is covered under ASTM C42, while the actual method of measurement is covered under ASTM C174. Cores used as specimens for length measurement should be in every way representative of the concrete in the structure from which they are removed.

The ASTM C174 method employs a special testing apparatus consisting of a three-point callipering device. The apparatus is designed so that the specimen is held with its axis in a vertical position by three symmetrically placed supports bearing against the lower end. The specimen is placed in the calipers so that the smooth end is placed down. Nine measurements then are taken on each specimen, one at the central position and one at eight additional positions spaced at equal intervals along the circumference of the circle. The individual observations should be recorded to the nearest 0.05 in, with the average of the nine measurements expressed to the nearest 0.1 in.

Core measurements represent the most accurate means of thickness determination and are used as the basis for calibrating nondestructive techniques. The principal disadvantage of coring, obviously, is that it is a destructive process that can only be performed after the concrete has set. Furthermore, the thickness of the core is representative of only a small area, and an extremely large number of cores may be required if significant variability exists. Also, the coring operation can be costly and time consuming, and additional time and effort are required to fill the holes after the cores have been extracted.

Thickness Probing

An alternative procedure for the determination of slab thickness is by rodding the fresh PCC pavement and directly measuring the resultant thickness. This procedure is employed by at least one highway agency (Texas DOT, under specification Tex-423-A) and reportedly has been well received. The procedure employs a rigid straight steel rod at least 4 in longer than the thickness of the pavement and a standard tape measure or ruler readable to the nearest 1/16 in. The process requires the steel rod to be inserted full depth into the concrete in a position perpendicular to the pavement surface. The rod is then retracted and the depth of the pavement is measured using the tape measure or ruler. One test point represents the average of three readings taken at points located one-quarter, one-half, and three-quarters across the width of the pavement. No information is provided on how frequently the testing measurements are recorded along the length of a project.

Ground Penetrating Radar

Ground penetrating radar (GPR) refers to a method for locating structural objects and evaluating material properties and layer thicknesses. The technology was originally developed by the military in the 1960s to detect land mines and shallow tunnels (Morey 1998).

GPR has been used as a pavement evaluation tool since the late 1970s. For pavement applications, GPR is an attractive tool because of its ability to collect large volumes of continuous data (roughly 200 lane-mi per day by an air-coupled GPR) in a nondestructive manner with limited traffic interruptions. Thus, it can provide a cost effective means for determining pavement layer thicknesses while also providing widespread coverage and insight into variability that would not be possible through conventional coring procedures. Other applications of GPR on PCC pavements include the location of embedded steel and the detection of voids beneath slab corners.

GPR is based on pulse-echo principles similar to those used in ultrasound technology, except that GPR uses radio waves instead of sound waves to penetrate the material (Maser 2000). During GPR testing on a pavement, short pulses of radio wave energy are transmitted into the pavement surface by either an air-launched horn or ground-coupled antenna. This energy travels down

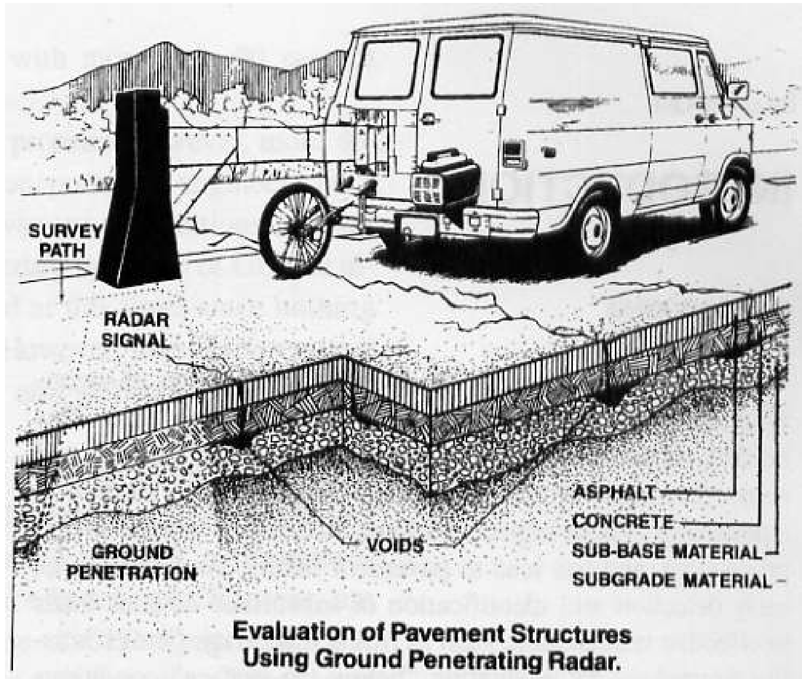


Figure A.1 - Illustrated Example of a Van-Mounted GPR (Morey 1998).

through the material and echoes are created at boundaries of dissimilar materials; the arrival time and strength of the echoes can be used to determine depths or layer thicknesses (Maser 2000).

Each type of pavement layer material (as well as embedded items such as dowel bars) has a different dielectric constant that affects the amplitude and the wavelength of the reflected signal, with stronger signals being created when there are greater differences in electromagnetic properties (for example, all of the signal is reflected at a metal surface and none is transmitted through the metal surface) (Morey 1998).

The primary components of a GPR system are illustrated in figure A-1 (Morey 1998). The antenna is lightweight and easily positioned over the area to be investigated. The typical transmit/receive unit consists of a transmitter for signal generation, a receiver for signal detection, and timing electronics for synchronizing the transmitter and receiver. The control unit is the operator interface that controls the overall operation of the radar system.

The antenna unit can be a single antenna that transmits and receives radar signals or separate antennas for transmission and reception. These antennas can be either "air-coupled" or "ground coupled," referring to the location of the antenna relative to the pavement surface. In an air-coupled configuration, the antennas are located about 10 in above the ground, whereas in a ground-coupled operation, the antenna unit rests on the surface of the pavement (Morey 1998).

Both the air-coupled and the ground-coupled configurations have advantages and disadvantages. The air-coupled configuration can be used at highway speeds (up to about 50 mi/hr), but is less able to distinguish between certain materials. The ground-coupled configuration provides a better signal penetration into the ground, but is limited to much slower test speeds because of its contact with the pavement surface. ASTM D4748 provides a standard test method for determining the thickness of bound pavement layers using GPR.

Pavement thickness evaluation using GPR technology is based on the measurement of the time difference between layer reflections and the velocity of propagation within the layers (Morey 1998). The reflections from the interfaces must be sufficiently strong to be monitored and interpreted for consistent results. Unfortunately, experience has shown that GPR has certain limitations in its ability to assess PCC pavement thickness (Morey 1998; Maser 2000; Wells and Lytton 2001):

1. A PCC layer has very similar dielectric properties as the granular base layer usually located beneath it. Without a large contrast in layer properties, changes in radar waves are slight and difficult to discern.
2. Concrete exhibits a significant electromagnetic attenuation due to its moisture content and dissolved salts. The greater electromagnetic attenuation decreases the strength of the radar reflections and makes GPR more difficult to interpret.
3. The presence of reinforcing steel in the concrete pavement also greatly affects the thickness estimates of the GPR, as the steel fully reflects the signal making the interpretation much more difficult.
4. The range or depth to which GPR is effective is a function of several parameters, such as material conductivity, water content, transmitter pulse width and power output, antenna gain and efficiency, and receiver sensitivity.
5. Experienced operators and regular calibration are required in order to achieve the best results.

Overall, these limitations can translate into some significant measurement error. For example, one study determined a thickness range of ±1.66 in. for concrete layers between 9 and 12 in thick (Willet and Rister 2002). Maser (2000) reports an expected "accuracy" level between 5 and 10 percent for concrete pavements, provided there is an adequate contrast between layer materials.

Impact-Echo Method

The impact-echo method is a nondestructive, seismic-based approach used to analyze the stress (or mechanical) waves generated in a solid object after some type of impact load is applied. For PCC pavement applications, it is best suited for the determination of slab thickness, although it has also been used to detect delaminations, flaws, and other discontinuities within the slab. Sansalone and Carino (1991) developed the methodology for testing of thin concrete structures, and a methodology is now available as a standard test method (ASTM C1383). Equipment used in impact-echo testing includes an impactor (which can be a hand-held hammer, a small steel bearing, or a mechanically actuated impact device), a receiver (to monitor surface motion and record waveforms), and a data acquisition tool (see figure A-2).

Figure A.2 - Impact-Echo Testing Equipment (FHWA 2003)

During testing, the pavement is struck with the impactor, which creates three types of stress waves that propagate in all directions through the medium: P-waves (pressure or compression waves), S-waves (shear waves), and R-waves (surface or Rayleigh waves) (Nelson 2003). P-waves are most important to impact-echo testing, as well as to pulse velocity testing, and R-waves are important to SASW testing. P- and S-waves travel together along spherical wavefronts, whereas R-waves propagate along the surface in a circular movement similar to ripples in a pond (see figure A-3).

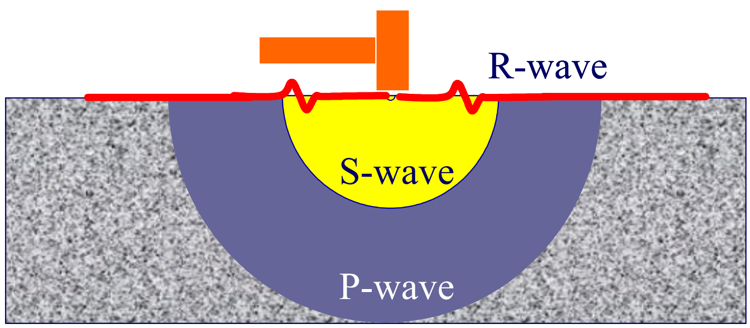


Figure A.3 - Stress Waves Occurring in Concrete Pavement upon Impact (FHWA 2003).

The P-waves travel down through the pavement and are reflected back from the bottom of the pavement, as shown in figure A-4; the reflection occurs due to the difference in wave velocity and density between the pavement and the base (Infrasense 2003).

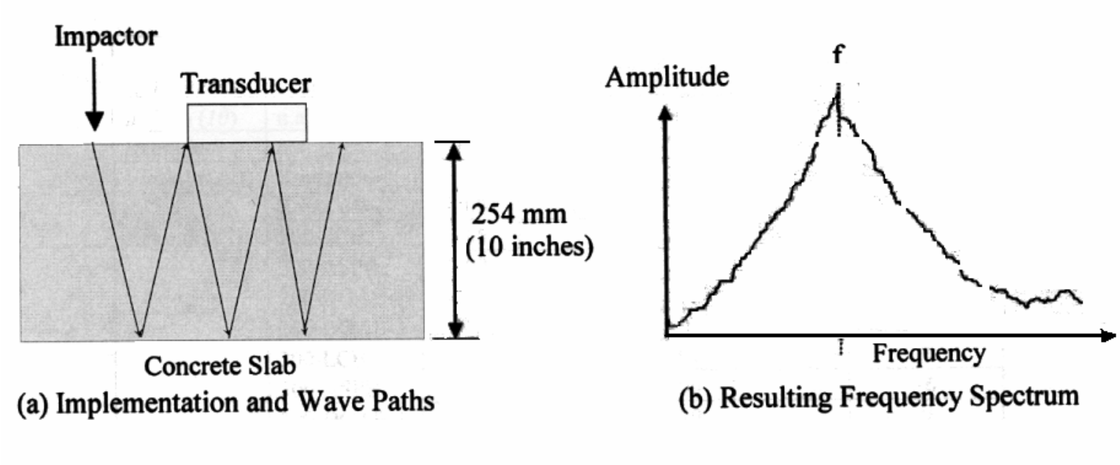


Figure A.4 - Impact-Echo Testing (Infrasense 2003).

As indicated by figure A-4, the P-wave travels twice the thickness of the slab before returning to the surface. Thus, the relationship between slab thickness (h), wave velocity (V_p), and travel time (t) is (Sansalone, Lin, and Streett 1997; Infrasense 2003):

$$h = V_p (t / 2) \quad \text{(A-1)}$$

Rather than measuring travel time, however, a more effective technique is to measure the frequency spectrum of the reflected signal. In the graph of wave amplitude versus frequency in figure A-4 (b), the frequency peak (f), or "thickness resonance," represents the repetition of reflected arrivals (in arrivals per second). The inverse of f is travel time, so equation A-1 then becomes:

$$h = V_p / 2 f \quad \text{(A-2)}$$

The ASTM specification for this method calls for a 0.96 correction factor to this equation to account for the "plate effect" on the wave velocity. The P-wave velocity required for this calculation needs to be determined independently (Infrasense 2003). One method for determining V_p involves the use of two transducers arrange in a linear fashion along the surface of a PCC slab. An impact is made near one of the transducers and the arrival time of the P-waves at both transducers is determined. Knowing the distance between the transducers and the difference in arrival time, the speed of the P-wave can be determined. The problem with this approach, however, is that the determination of P-wave arrival times at the two transducers is often difficult to interpret (Infrasense 2003).

A second method for determining V_p is to use calibration cores (Infrasense 2003). By measuring the travel time of the P-waves generated in several representative cores of known thickness, an average V_p for a given material can be established using equation A-1. To account for the heterogeneity of concrete, however, several representative cores should be used in the calibration process.

Infrasense (2003) describes an alternative impact-echo technique that involves the use of multiple receivers. The multiple receiver technique (MRT) still relies on P-waves reflected off the bottom of the slab to estimate its thickness; however, because of its ability to interpret information from the additional receivers, it does not require external calibration or concrete property assumptions. Unlike the standard one-receiver technique, however, experience with this technique is limited. A detailed description of the equations for slab thickness determination is presented in Infrasense (2003).

In testing PCC slabs for thickness determination, the impact-echo method is both rapid and efficient. It is conducted on a point-by-point basis, with each reading taking less than 20 seconds to acquire and process. Accuracies are reported to be within 3 to 5 percent, provided that clear readings are obtained and there is sufficient differentiation between the PCC slab and the underlying base course (FHWA 2003). However, a study conducted by Infrasense (2003) indicated that the impact-echo method consistently underestimates concrete thickness, for tests conducted on slabs at the FAA Technical Center. The findings suggest that the use of the 0.96 correction factor (as recommended by ASTM C1383) may lead to systematic errors in some circumstances.

Although a new and promising technology, there are some limitations to the use of impact-echo, including the following (Sansalone, Lin, and Streett 1997; FHWA 2003; Nelson 2003):

- Interpretation of the test results can be difficult, and an experienced operator is needed.
- The presence of a lean concrete base (with similar mechanical properties as the PCC slab) can mask the interlayer and make it difficult to discern the pavement thickness.
- The impactor can significantly affect the results, so it is important to select an appropriate impactor for measuring the thickness of pavement. Moreover, it is important that the contact time of the impact be selected to optimize the potential for determining the slab thickness.

Concrete Thickness Gauge

The concrete thickness gauge (CTG) is a nondestructive testing device that can be used to determine the thickness of plate-like concrete structures (Nelson 2003). It is an automated piece of equipment that operates on the impact-echo technology described in the previous section, and is governed by ASTM standard C1383, the same standard governing impact-echo technology. The CTG is a proprietary product developed by Olson Engineering in 2000, and is marketed for quality assurance applications.

The CTG consists of a test head that is connected to the main body by a hardware connection (see figure A-5). An extension pole is available to allow users to stand up during the testing process. The testing procedure and concepts are similar to the impact-echo technology. The test head impacts the pavement surface, generating a stress wave that travels into the pavement and gives rise to the transient resonance (Nelson 2003). The main body receives the signal and analyzes the data to produce the resonant spectrum that represents the concrete thickness.

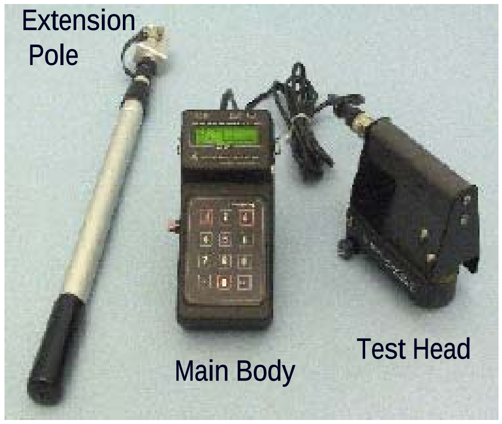


Figure A.5 - CTG Equipment and Testing (FHWA 2003).

As with impact-echo testing, the wave speed and travel time need to be known in order to determine the slab thickness. This requires calibration of the device to a slab or concrete member of known thickness, although some default P-wave speeds are provided by the manufacturer in lieu of actual project values.

The CTG was designed to be simple to operate, with users able to get up to speed on the use of the equipment in about 10 minutes (Nelson 2003). The testing is very rapid, with typically 60 tests being performed in one hour. The device provides a direct readout of the slab thickness, so there is no interpretation required. Reported accuracy is 2 to 5 percent of the actual thickness, provided that the device has been properly calibrated (Nelson 2003).

Among some of the limitations of the CTG are (Nelson 2003):

- The impactor is not controllable, meaning that different impact duration times are not possible.
- A relatively smooth surface is required for testing.
- The recommended thickness range for the device is 3.5 to 18 in, with most reliable thicknesses in the 5 to 16-in range.
- Calibration of the equipment to a concrete core is recommended for greatest accuracy.

PCC Strength

Standard ASTM Methods

ASTM has published standards for the assessment of concrete strength, with the most common strength measures being compressive, flexural, and split tensile. Compressive testing is by far the most common measure of PCC strength, although in pavement applications the flexural strength is of critical importance because of its relation to structural cracking of the slab under bending. In this section, the standard ASTM procedures for measuring and expressing PCC strength in failure modes are described.

Compressive Strength

For good or bad, PCC compressive strength is almost universally used as an indicator of concrete quality. The standard method of determining the PCC compressive strength involves sampling, specimen preparation, curing, and compression testing of cylindrical specimens obtained either from molded cylinders (made from fresh concrete sampled at the job site) or cores retrieved from hardened PCC. Specimens should be at least 4 inches in diameter and should have a length-to-diameter ratio of about 2 (e.g., a 4-in diameter core should be about 8 in long). The standard practice for sampling fresh concrete for molded cylindrical specimens is covered by ASTM C172; the cylinders are prepared in the field, transported, and cured in a temperature and moisture controlled environment in accordance with ASTM C31. The standard practice for retrieving drilled cylindrical core samples is described under ASTM C42.

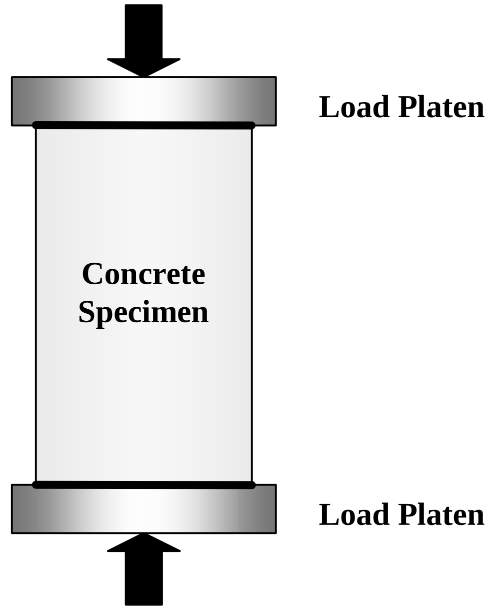


Figure A.6 - Schematic of Compressive Strength Test.

The standard method of compression testing is performed according to ASTM C39. In this test, the specimen is first capped to provide a uniform top and bottom surface and then placed into a universal testing machine that loads the specimen in uniaxial compression (see figure A-6). The load is applied at the rate of 20 to 50 psi per second until the specimen fails. The maximum load sustained by the specimen is used to calculate its compressive strength.

Depending on the specifications, a concrete cylinder may be tested at different times during the curing process. For PCC pavements, the times are usually determined based upon the anticipated time before opening to traffic and range between 2 hours for fast-track mixes to 28 days for less critical mixes.

This method is relatively easy to conduct and is a well- established test with a long history of use for concrete strength assessment. The primary disadvantages include the effort required to prepare, transport, and test the specimens and the error associated with differences between curing of the specimen and the in situ pavement. Furthermore, for testing drilled samples, there is concern about the damage caused by the drilling operation to the retrieved specimen

Flexural Strength

Flexural strength is a measure of the extreme fiber stress developed under slab bending, and is an important parameter in PCC pavement design. The standard method of determining the flexural strength of concrete involves sampling, specimen preparation, curing, and flexural testing of rectangular beams that are 6 in wide and 6 in high and at least 21 in long. These rectangular beams can be made from the fresh concrete sampled from the job site (obtained in accordance with ASTM C172 and prepared, transported and cured in a temperature and moisture controlled environment according to ASTM C31) or may be sawed from an existing pavement (obtained in accordance with ASTM C42).

Flexural testing can be conducted under either center-point or third-point loading conditions. The third-point loading configuration, described under ASTM C78, is more commonly used in pavement design and provides a more conservative estimate of the flexural strength than the center-point test. In the third-point test, the sample is placed in a special loading device that applies the load at points one-third from each end of the specimen (see figure A-7). This configuration provides a uniform bending moment and uniform maximum tensile stress in the bottom fiber of the middle third of the beam. The load is applied at a rate of 125 to 175 psi per minute until the specimen ruptures. The maximum load sustained by the specimen is used to calculate its flexural strength.

Depending on the specifications, a flexural beam may be tested at different times during the curing process. For PCC pavements, the times are usually determined based upon the anticipated time before opening to traffic and range between 2 hours for fast-track mixes to 28 days for less critical mixes.

The advantages and disadvantages of this method are essentially the same as those for the concrete cylinders. For pavement design purposes, the resultant strength values are believed to be more meaningful than compressive strength values, but the beams are heavier and more difficult to work with. Moreover, recent research conducted by Roesler (1998) indicates that the flexural strength as measured using ASTM C78 is not a unique parameter describing the in situ strength of concrete.

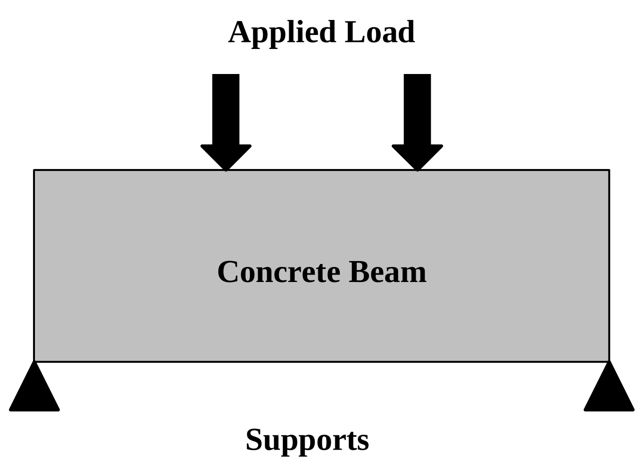


Figure A.7 - Schematic of Third-Point Flexural Testing.

Splitting Tensile Strength

The splitting tensile test, also called the indirect tension test, is used primarily to determine the tensile strength of cores obtained from concrete pavements. The procedure is described in ASTM C496. The test involves applying a vertical load at a constant rate of deformation (0.05 in per min) on the diameter of a cylindrical sample (as shown in figure A-8). The sample will fail in tension along the vertical diameter of the sample and the indirect tensile strength is calculated from the maximum applied load and the dimensions of the specimen.

This test can be performed on the same cores obtained for slab thickness determination. The advantages of this method include the relative small specimen size, the speed and ease of testing, and, because the specimens are cured "in-place," they are more representative of the in situ pavement. The primary disadvantage of this method is that it is a destructive test that requires patching after sampling.

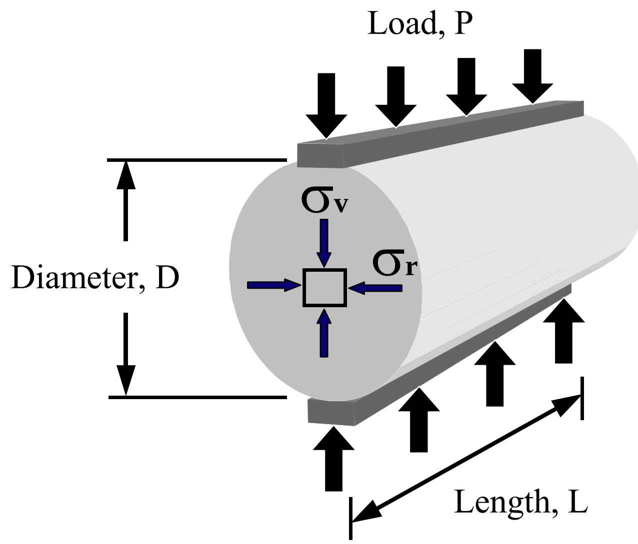


Figure A.8 - Schematic of Splitting Tensile Test.

Maturity Testing

The strength of a given concrete mixture, which has been properly placed, consolidated, and cured is a function of its age and temperature history (Saul 1951). Longer cure times lead to greater strength, and an increase in temperature during concrete curing can speed up the hydration process and, thus, the rate of strength development. The maturity method of testing accounts for this combined effect of time and temperature and provides a basis for estimating the in situ strength gain of concrete by monitoring its temperature over time.

Maturity was developed in the 1950s and ASTM first published its first standard practice for estimating concrete strength using maturity in 1987 (Mohsen 2002). With recent advancements in equipment and technology and more emphasis on high-speed construction, the technology is gaining more widespread use and acceptance, including on many airfield construction projects (Rasmussen, Cable, and Turner 2003).

Maturity can be calculated using one of two methods. The first method, the Nurse-Saul maturity relationship, was developed in the 1950s and is the most widely accepted means of computing maturity (Crawford 1997). It is the accumulated product of time and temperature:

$$M(t) = \Sigma\ (T_a - T_o)\ \Delta t \qquad \text{(A-3)}$$

where:

$M(t)$ = Maturity at age t.
T_a = Average concrete temperature during time interval.
T_o = datum temperature.
Δt = time interval.

Maturity may also be determined using the Arrhenius method, which accounts for nonlinearity in the rate of cement hydration. It involves a slightly more complicated equation, but has gained

Figure A.9 - Temperature Sensor in Concrete Pavement Repair Area.

widespread acceptance in Europe (Crawford 1997). According to Carino (1984), the Arrhenius equation is a better representation of time-temperature function than the Nurse-Saul equation when a wide variation in concrete temperature is expected. Both maturity functions are outlined in ASTM C1074.

Maturity measurement in the field consists primarily of monitoring the internal temperature of the concrete with respect to time. To measure the maturity of concrete in the field, a maturity meter is used to record the concrete temperature as a function of time. Most maturity meters rely upon temperature sensors embedded in the concrete to report mix temperature (see figure A-9), although new sensor technologies (such as the iButton®) are also available (Rasmussen, Cable, and Turner 2003). The maturity meter converts the reported temperatures and time history into a maturity value. The temperature sensors are usually placed at mid-depth of the slab.

Laboratory testing of the mix must be performed before any field work in order to establish the strength-maturity relationship for a particular mix. Test specimens or slabs, with embedded temperature sensors, are used to develop maturity-strength curves for a given concrete mix. To develop the strength-maturity curve, a sample of the concrete mix planned to be used for the project is prepared. Test specimens are then cast and monitored from this prepared sample. Control of curing to conditions that the pavement will undergo is essential to obtaining accurate maturity results. The maturity of the individual specimens is monitored until they are tested.

The specimens are tested at consistent time intervals and should span a range in strength that includes the opening strength (ACPA 2002). The values obtained from the test specimens are plotted on a strength vs. maturity graph and a best-fit curve is drawn to represent the strength-maturity relationship for the project.

An example strength-maturity curve is shown in figure A-10 (ACPA 1994). As an example in using the graph, if the required compressive strength for opening to traffic is 3,000 psi, figure A-10 shows that this corresponds to a temperature-time factor of approximately 50 degree-days. Thus, when the combination of time and temperature from the data logger or maturity meter indicate a maturity of 50 degree-days, the pavement can be opened to traffic. This correlation curve is valid as long as the mix design (and all mix ingredients) remains constant. If the mix is changed in any way, a new calibration curve must be developed.

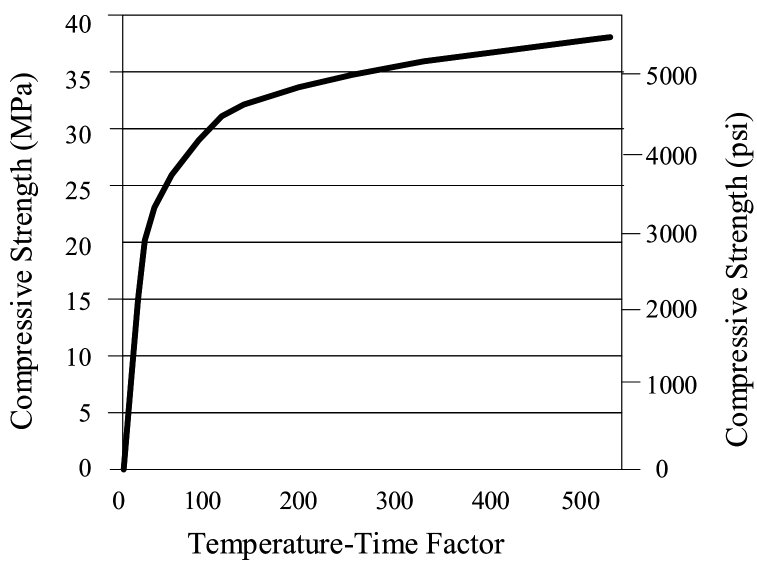


Figure A.10 - Example Strength-Maturity Curve (ACPA 1994).

Many studies have been conducted to test the accuracy and cost effectiveness of the maturity method. A study was conducted in California to determine if maturity concepts could be used to predict the early strength of fast-setting hydraulic cement concrete. The test concluded that the maturity method predicts the early age flexural beam strength with a reasonably high degree of certainty (Mullarky and Wathne 2001). The authors also recommended that maturity testing be implemented for major conventional paving projects where the cost savings associated with reduced testing are significant, and rapid testing information is needed to facilitate early opening to traffic.

A study in Georgia attempted to predict early strength gains of concrete repair slabs using the maturity method. The temperatures were monitored throughout the depth of the test slab for the first eight hours of curing. The study concluded that maturity method was effective (Okamoto and Whiting 1994). The results obtained using these techniques agreed favorably with strengths of cores extracted from repair sections before opening to traffic. The study also pointed out the need to use consistent materials throughout the project for the maturity method to be effective. Changes in mix design or materials during construction can lead to significant predictive errors. Since the use of this method requires a substantial amount of preparation and calibration effort, it is estimated that it will be most cost-effective on large projects (Okamoto and Whiting 1994).

In summary, maturity testing is an effective means of monitoring the early strength gain of concrete pavements. The primary benefit is that it provides a relatively fast, nondestructive means for continuously monitoring concrete strength that can be used to determine when the pavement can be opened to traffic. The primary disadvantages include its inherent assumption that adequate curing is being applied, that the same materials and mix proportions used in the lab are also being used in the field, and its significant up-front effort and costs associated with establishing the maturity curve for a given mix.

Pulse Velocity Test

The standard pulse velocity test is designed to measure the velocity of ultrasonic waves traveling through PCC that are generated as a result of an external pulse. The pulse velocity is proportional to the square root of the elastic modulus and inversely proportional to the square root of the mass density of PCC. Since elastic modulus of PCC is also proportional to the square root of the PCC compressive strength, which may also be correlated to the modulus of rupture, the pulse velocity can be correlated to either the PCC compressive strength or modulus of rupture. The pulse velocity test method has been used successfully to evaluate the quality of concrete for over 50 years and is standardized under ASTM C597.

In the standard pulse velocity method (see figure A-11), an ultrasonic pulse is created at a point on the test object using a high-frequency vibratory transducer, and the time of its travel from that point to another is measured. Knowing the distance between these two points, the velocity of the pulse can be determined. Pulse velocity equipment measures the arrival time of the first (fastest) wave, a compression or P-wave (Crawford 1997). It should be pointed here that there is a potential problem in using ultrasonic pulse velocity (UPV) for concrete testing because of the high frequency and low amplitude of the USW, which make them more susceptible to the non-homogeneity of the concrete, particularly the influence of the embedded coarse aggregate.

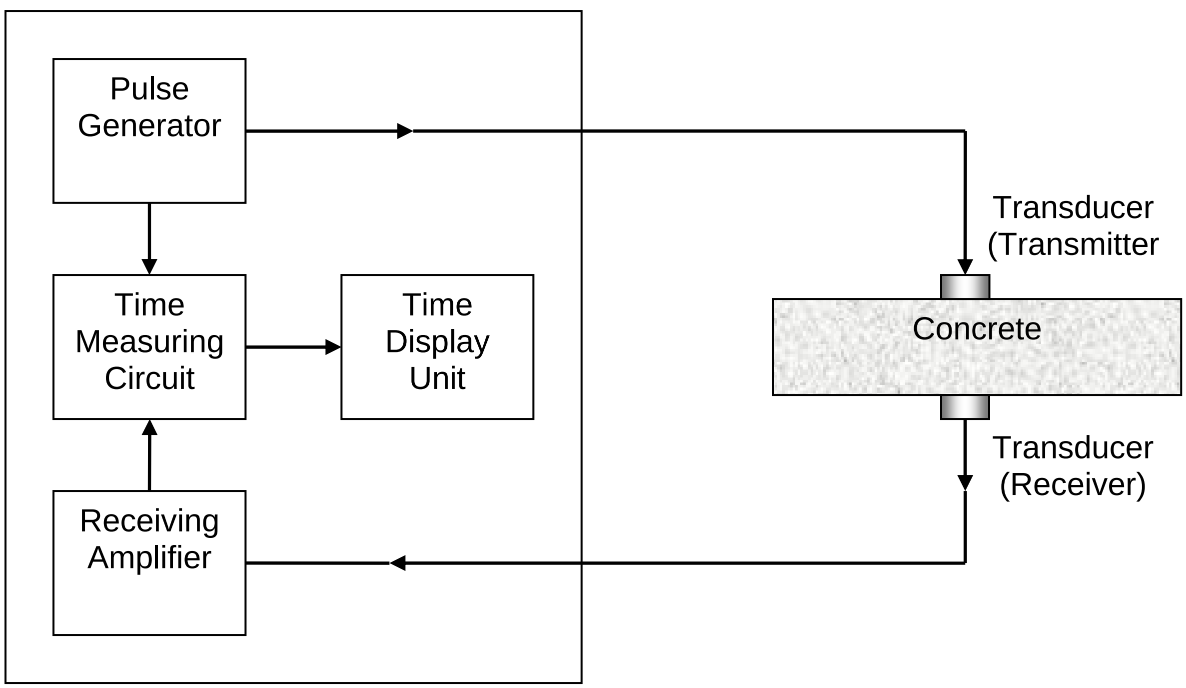


Figure A.11 - Schematic of Pulse Velocity Device (Crawford 1997).

There are three possible ways the transducers can be configured, as shown in figure A-12 (Crawford 1997). The *direct* method has the transmitter on one side of the concrete and the receiver directly opposite on the other. This method gives the most reliable results. The *semi-direct* method has the transmitter and receiver located perpendicular to one another. This method is reliable but the transducers can not be placed so far apart that the signals are attenuated and undetectable. This method has been used to avoid concentrations of steel. The third configuration is called the *indirect* or *surface transmission* method and contains both transducers along the same side of the concrete. This method is often used for PCC pavement applications, but it is the least accurate because the amplitude of the received signal is only a small fraction of that associated with the direct transmission method. Also, to determine the pulse velocity, a more complicated procedure involving additional receivers along a certain configuration is necessary. Another disadvantage of this method is that it only samples the waves traveling along the top of the concrete and, therefore, may not be representative of the properties of the entire slab. An example of equipment used to measure pulse velocity is shown in figure A-13. In this case, the configuration of the transducers is in the semi-direct mode.

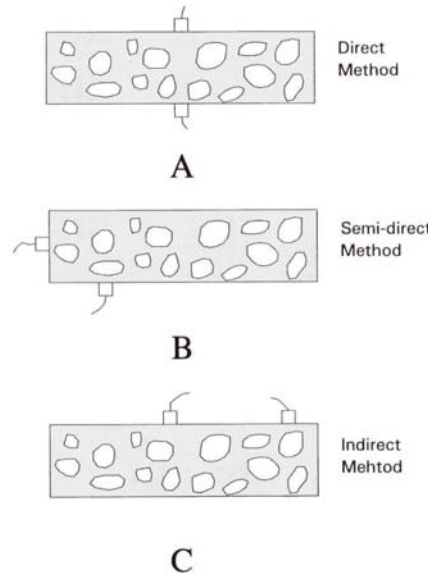


Figure A.12 - Methods of Pulse Velocity Measurement (Crawford 1997).

According to Naik and Malhotra (1991), the p-wave velocity (V) for an infinite, homogeneous, isotropic, elastic medium is:

$$V = (KE/D)^{1/2} \qquad \text{(A-4)}$$

where:

$$K = (1-\nu)g/(1+\nu)(1-2\nu) \qquad \text{(A-5)}$$

and:

E = Modulus of elasticity.
D = Unit weight.
g = Acceleration due to gravity.
ν = Poisson's ratio.

With these basic formulas, it is possible to determine the modulus of elasticity of concrete, given the measured p-wave wave velocity, the unit weight, and the Poisson's ratio of the material.

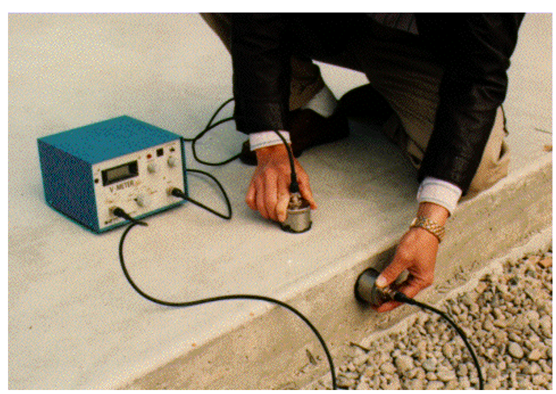


Figure A.13 - Pulse Velocity Equipment in Operation.

As with the maturity method, the pulse velocity method requires laboratory testing of the job mix to establish a correlation between the pulse velocity and the strength of the concrete. A typical plot of pulse velocity versus compressive strength is shown in figure A-14. As was the case with the maturity method, the correlations are specific to a given mix design, and a new correlation between pulse velocity and strength must be developed for any mix design changes (materials or proportioning).

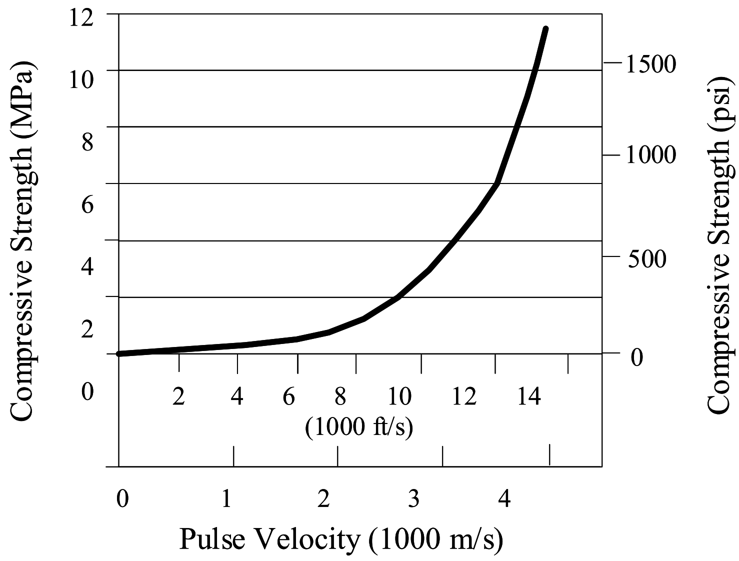


Figure A.14 - Example Pulse Velocity Curve (ACPA 1994).

A study in Georgia attempted to predict early strength gains using the pulse velocity method. The study concluded that pulse velocity techniques can be used to monitor early strength gain during the curing period in pavement repair slabs. The results obtained using these techniques agreed favorably with strengths of cores extracted from repair sections before opening to traffic (Okamoto and Whiting 1994). The study also pointed out the need to use consistent materials throughout the project for the maturity method to be effective. Changes in mix design or materials during construction can lead to significant predictive errors. Since the use of this method requires a substantial amount of preparation and calibration effort, it is estimated that it will be most cost-effective on large projects (Okamoto and Whiting 1994).

The primary application for the standard method of pulse velocity testing is in evaluating the quality of concrete used in various structures. With its capacity to measure the speed of ultrasonic waves it can be used to detect concrete deterioration due to an aggressive chemical environment, cracking, or changes due to freezing and thawing. The measured wave velocities can also be used to determine the dynamic modulus of elasticity, Poisson's ratio, PCC thickness, and to estimate the strength of concrete test specimens as well as in-place concrete.

The accuracy of pulse velocity testing depends on the operator's ability to precisely measure the distance between the transducers, and the equipment's ability to accurately to measure the transit time (FHWA 2003). If an accuracy of $\pm$2 percent desired in pulse velocity calculations, then the path length and transit time measurements must be within $\pm$1 percent accuracy. The accuracy of the readings is also dependent upon the testing configuration, the presence of steel and complex reflections from layer boundaries.

The primary advantages of the pulse velocity approach are that it is an easy, simple, and rapid test. The equipment is portable, and applicable to field and lab specimens regardless of their shape. Primary disadvantages of the equipment include the many variables that can affect pulse velocity measurements (moisture; steel; aggregate type, size, grading, and content; mix non-homogeneity) and the absence of a unique correlation between pulse velocity and concrete properties (mix-specific correlations are required). Moreover, the use of an appropriate transducer configuration (the *direct* and *semi-direct* methods are reliable, but the *indirect* method is prone to error) and ensuring good contact between the transducers and the surface of the concrete are needed in order to provide reliable measurements.

Free-Free Resonant Column (Impact-Resonance)Test

The free-free resonant column test device is particularly suitable for measuring the seismic modulus of concrete in the laboratory. As explained in ASTM C-215, when a cylindrical specimen is subjected to an impulse load at one end, seismic energy over a large range of frequencies will propagate within the specimen (see Figure A-15).

Depending on the dimensions and the stiffness of the specimen, energy associated with one or more frequencies is trapped and resonate as they propagate within the specimen. The goal with this test is to determine these resonant frequencies. Since the dimensions of the specimen are known, if one can determine the resonant frequencies, one can readily calculate the modulus of the specimen using principles of wave propagation in a solid rod. Results from a standard cylinder of concrete are shown in Figure A-16. 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. Distinguishing the two peaks is simple, since for typical concrete specimens, the longitudinal resonance occurs at a higher frequency than the shear resonance. Once the

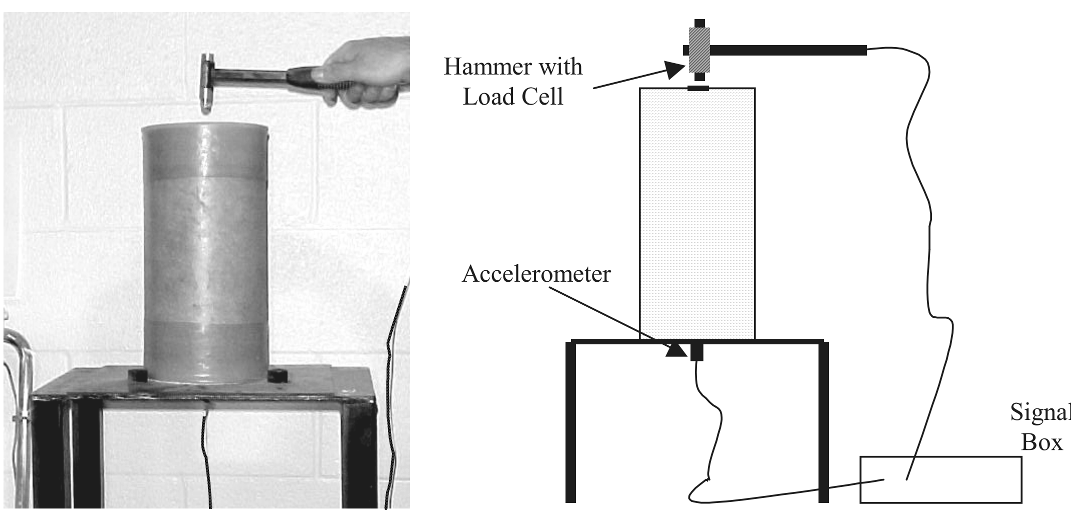


Figure A.15 - Schematic of Impact Resonance Device

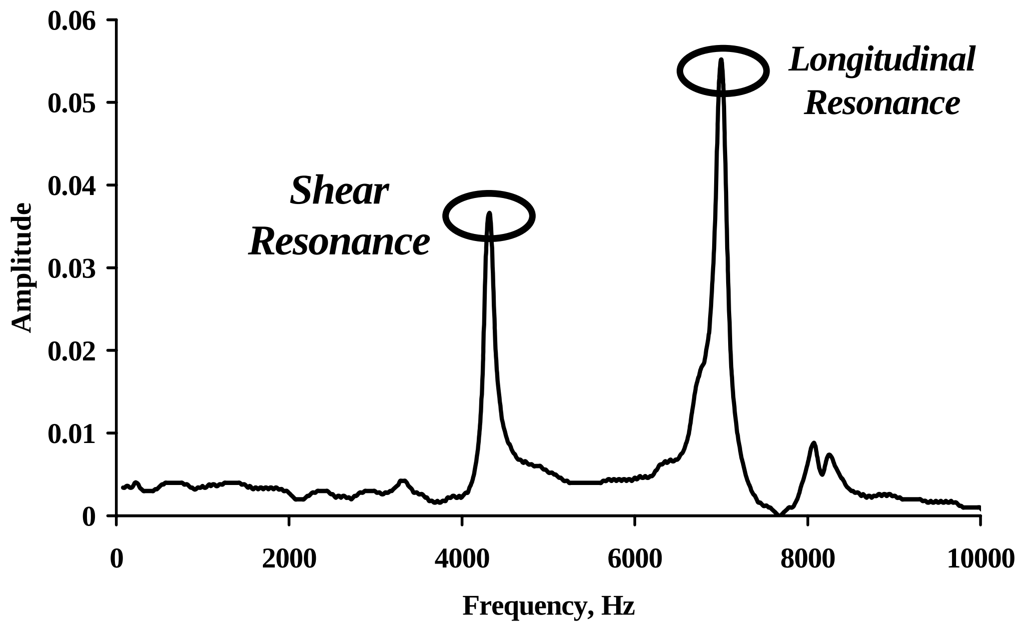


Figure A.16 - Typical Amplitude Spectrum from a Concrete Cylindrical Specimen

longitudinal resonant frequency, f_L, and the length of the specimen, L, are known, laboratory Young's modulus, E_{lab}, can be found from the following relation

$$E_{lab} = \rho\,(2\ f_L\ L)^2. \qquad \text{(A-6)}$$

where ρ is mass density. Poisson's ratio, ν, is determined from

$$\nu=(0.5\ \alpha\ -1)\ /\ (\alpha-1), \qquad \alpha=(f_L\ /\ f_S\ )^{2}\ C_{L/D} \qquad \text{(A-7)}$$

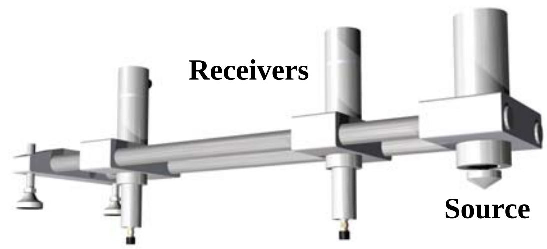
with $C_{L/D}$ being a correction factor which is not equal to one when the length-to-diameter ratio of the cylinder differs from 2.

This test although similar to the ultrasonic pulse velocity (UPV) is more robust and less impacted by the constituents of the concrete. Yuan, Nazarian and Medichetti (2003) have shown that the main parameter that impact the relationship between the modulus obtained with this parameter and strength on the same cylinders is the source of coarse aggregates. Other than this advantage, the other advantages and disadvantages of the UPV method is also applicable to this one. One disadvantage of the impact-resonance tests is that they can only be carried out on lab-prepared specimens or cores and beams extracted from a slab, and cannot be used as an in situ test.

Seismic Pavement Analyzer

Developed under the Strategic Highway Research Program, the Seismic Pavement Analyzer (SPA) is nondestructive testing device designed to automate and replace several time-consuming and complex methods of evaluating existing pavements (Nelson 2003). When used on concrete pavements, the SPA can provide information about the quality and thickness of the concrete, the existence of voids or delaminations within the concrete, and the presence of voids (or the loss of support) underneath the slab (Nazarian, Baker, and Crain 1993; McDaniel et al. 2000).

The PSPA (Portable Seismic Pavement Analyzer) is a more suitable version of the SPA for quality acceptance of concrete (see figure A-17). It has been used to evaluate concrete bridge decks and in rigid pavement applications as well (McDaniel et al. 2000; Yuan, Nazarian, and Medichetti 2003). The PSPA can be used within hours of construction for quality control of newly constructed pavements. It provides layer-by-layer estimates of pavement properties, like the seismic moduli, which can be related to other concrete properties such as compressive strength and modulus of rupture. Testing with the PSPA is very rapid, with the collection and preliminary reduction of data at one point taking less than 15 seconds.



b) Sensor unit

a) Complete device

Figure A.17 - Portable Seismic Pavement Analyzer (Yuan, Nazarian, and Medichetti 2003).

The PSPA incorporates the impact echo method with a simplified version of the Spectral-Analysis-of-Surface-Waves (SASW) method, called the ultrasonic surface wave (USW) method, into one device. In that manner, the thickness and the velocity of propagation of waves can be potentially measured simultaneously. As shown in Figure A-17, the PSPA consists of a source and two receivers. The source is a computer-controlled impactor that it is capable of generating stress waves at both the sonic and ultrasonic ends of the frequency spectrum. The two receivers are used to monitor the sonic waves generated by the impactor.

The ultrasonic-surface-wave (USW) method is an offshoot of the SASW method (Nazarian, Baker, and Crain 1993). The major distinction between these two methods is that in the ultrasonic-surface-wave method the modulus of the top pavement layer can be directly determined without an inversion algorithm. As sketched in Figure A-18, at wavelengths less than or equal to the thickness of the uppermost layer, the velocity of propagation 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 modulus of the top layer, E_{field}, can be determined from surface wave velocity of the layer, V_{ph} using

$$E_{field} = 2\rho\,[(1.13 - 0.16\nu)\,V_{ph}]^2\,(1 + \nu). \tag{A.8}$$

As a first glance, the USW method described above sounds very similar to the indirect method of ultrasonic pulse velocity (UPV) measurements described in Figure A-12c. However, a major distinction exists between the two methods. In the UPV method, the compression wave velocity of the concrete is measured; whereas in the USW method the velocity of propagation of the surface waves is measured. The compression waves measured with the UPV method propagate along a spherical front providing information about the near-surface properties of the material. In the contrary, the surface waves measured with the USW method propagate along a cylindrical front measuring the properties of the material throughout the thickness.

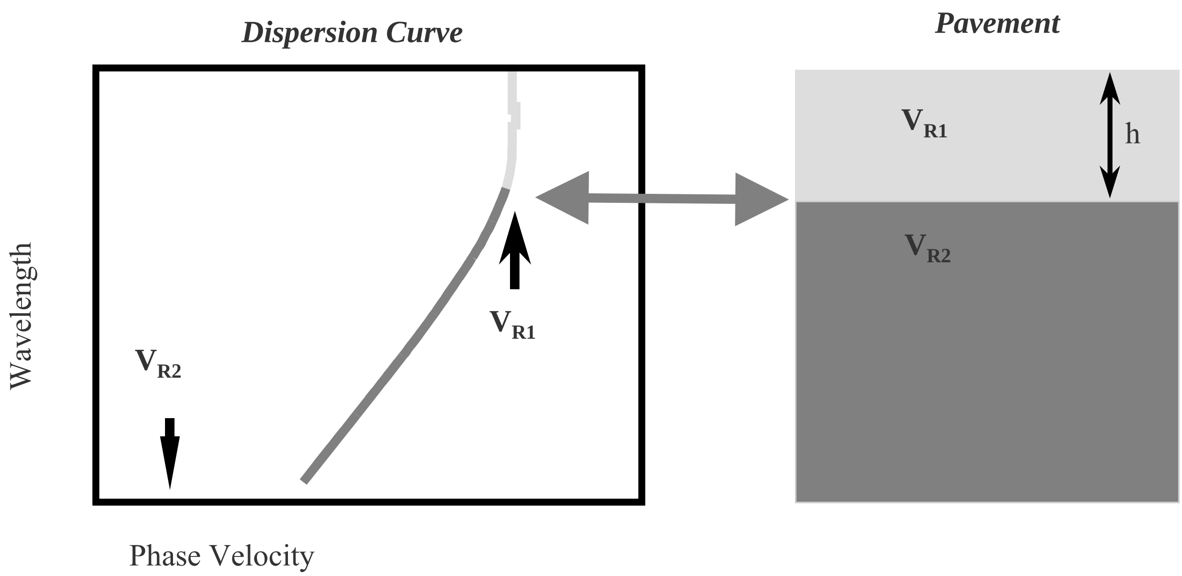


Figure A.18 - Schematic of USW method.

As with the UPV and the maturity method, the measurements with the USW method need to be calibrated for a given mixture. The method of choice is the impact resonance method described above.

<u>Integrated Seismic/Maturity Method</u>

A study conducted for the Texas Department of Transportation (Yuan, Nazarian and Medichetti, 2003) has shown that the combination of maturity and seismic methods complements one another quite nicely. The calibration process for relating strength and maturity can be readily adapted for laboratory seismic testing. In fact, the same specimens can be used for both tests. A proposed protocol that combines the two methodologies is illustrated using an example.

For compressive strength, a total of 12 standard 6 in. (diameter) by 12 in. (length) specimens are prepared. For flexural strength, a similar number of specimens but in the shape of standard beams is poured. During specimen preparation, thermocouples are inserted into 3 cylinders. The specimens are then cured in a water tank.

The protocol consists of four phases: maturity measurement, seismic modulus tests, strength tests and development of the correlations. Each of them is discussed below.

I. Maturity Tests: As usual, the specimens equipped with thermocouples are either connected to a maturity meter or a temperature data-logger. Either device records the variation in temperature with time automatically. The temperature is continuously measured for 28 days. The time and temperature history is converted to the time-temperature factor using Equation A-1.

II. Seismic Tests: Shortly before a specimen is subjected to strength test, the free-free resonant column test will be carried out on it. Since the test is nondestructive, this activity should not impact the results from the strength tests. In this case, the modulus and optionally the Poisson's ratio of the specimen are determined for correlation to strength and maturity.

III. Strength Tests: Standard compression or three point bending tests are performed on at least 3 cylinders or beams at ages of 1, 3, 7 and 28 days. The average compressive strength or the average flexural strength from the tests is obtained.

IV. Development of Correlations: A plot between the average compressive or flexural strengths and average maturity values at corresponding times is made and a best-fit curve is drawn through the plot. The curve is then used for estimating the strength of concrete based on maturity as it has been traditionally done. Similarly, a plot between the average compressive or flexural strengths and average seismic moduli is developed. A best-fit curve is also drawn through this data. Based on Equation 5, this relationship can be readily used with the PSPA for predicting the strength of the concrete at any location on the slab or other structures.

Typical variations in compressive strength from standard cylinders with maturity parameters and flexural strength with maturity parameter from standard beams are shown in Figure A-18. The seismic moduli measured at different times are related to the compressive and flexural strengths. in Figure A-19. The predictive power of he combined methodology in that study, especially at early ages, was better than the maturity alone.

Summary

This appendix summarizes some of the more commonly used methods for measuring two critical concrete pavement design elements: slab thickness and strength. Historically, these procedures have been destructive tests requiring preparation or retrieval of concrete samples, but more recent methods are nondestructive methods are geared to provide more rapid feedback. A summary of the advantages and disadvantages of the different test procedures is summarized in Table A-1.

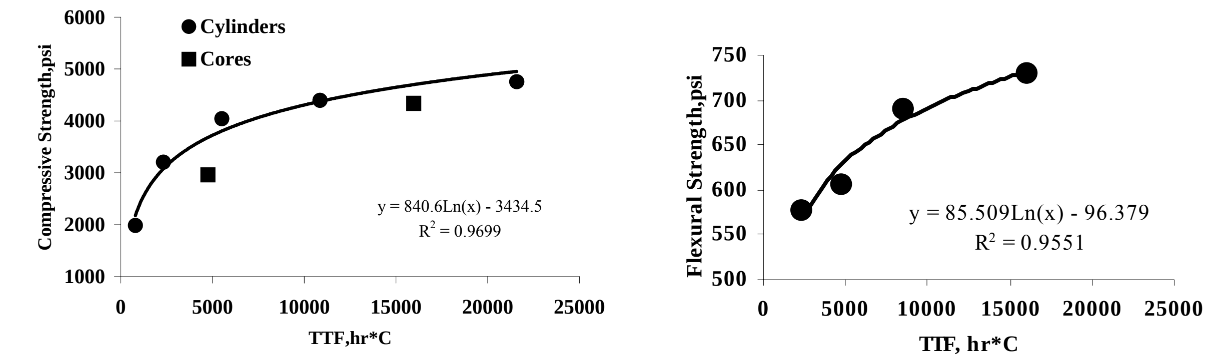


Figure A.19 - Variations in Strength with Maturity Parameter.

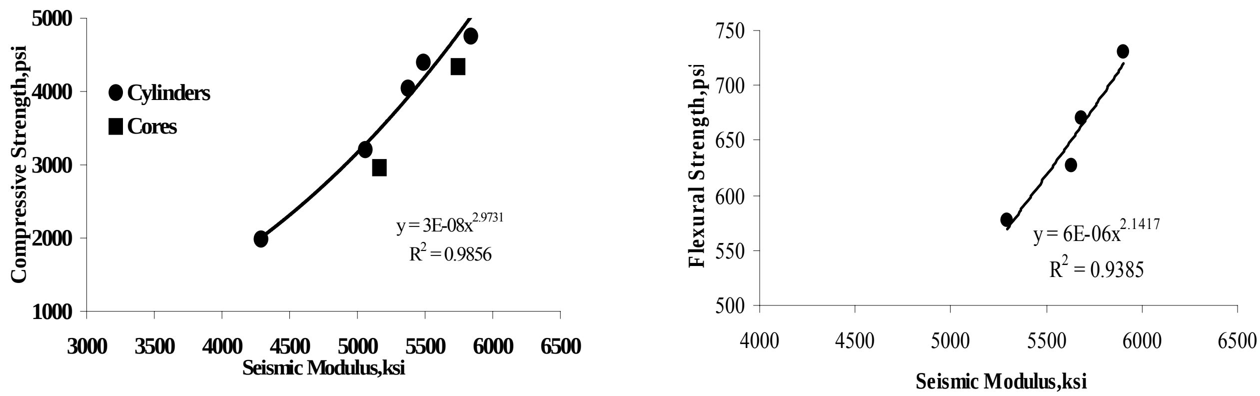


Figure A.20 - Variations in Strength with Seismic Modulus.

Table A.1 - Summary of Tests Used to Determine Slab Thickness

Test Method	Description	Advantages	Disadvantages	Accuracy
Core Thickness (ASTM C174)	Standard method of slab thickness determination. Nine measurements are taken on each specimen using a special callipering device.	• Most accurate method of thickness determination. • Can be used to calibrate other test methods.	• Destructive test performed only after the PCC has set. • Time and effort required to patch holes. • Thickness is representative of only a small area.	
Thickness Rodding (e.g., Tex-423-A)	Rigid straight steel rod is inserted full depth into the fresh concrete at specified locations.	• Quick and rapid test. • Greater number of test points possible.	• Less accurate on granular bases or soft soils.	Not established.
Ground Penetrating Radar (ASTM D4748)	Vehicle-mounted equipment is used to transmit and measure the speed of electromagnetic waves which, in turn, are used to determine surface layer thickness.	• Fast, nondestructive, and safe method for estimating surface thickness. • Can be performed at highway speeds. • Provides (almost) continuous coverage.	• Requires experienced operator to interpret results. • Requires project-by-project calibration. • Often ineffective for concrete pavements because of greater electromagnetic attenuation and similar dielectric properties with base course. • Presence of reinforcement makes interpretation difficult.	5 to10% (if adequate contrast exists between layers)
Impact-Echo Method (ASTM C1383)	A nondestructive, seismic-based approach used to measure and analyze the speed of stress waves generated in a solid object after the application of an impact load, which in turn can be related to PCC thickness.	• Equipment is easy to operate and provides rapid results. • Greater number of test points possible. • Can be performed soon after initial concrete set.	• Requires experienced operator to interpret results. • Requires project-by-project calibration. • The presence of a lean concrete base can make it difficult to discern pavement layers. • Impactor and impact contact time are important in determining thickness.	3 to5% (if adequate contrast exists between layers)

Table A-2. Summary of Tests Used to Determine Concrete Strength

Test Method	Description	Advantages	Disadvantages	Accuracy
Compressive Strength (ASTM C39)	Cylindrical concrete specimen is subjected to axial compressive forces and loaded to failure.	• Standard test method with long history of use in acceptance testing. • Relatively easy test to conduct.	• Test is not representative of the typical stress conditions which cause PCC pavements to deteriorate. • Some effort is required to prepare specimens in the field and transport them to the lab for testing. • Differences between lab and field curing conditions.	--
Flexural Strength (ASTM C78)	Rectangular beam subjected to bending under third-point loading until failure.	• Standard test method with long history of use in PCC pavement design and evaluation. • Test is representative of the typical stress conditions which cause PCC pavements to deteriorate.	• Beam specimens are relatively heavy and bulky. • Significant effort is required to prepare specimens in the field and transport them to the lab for testing. • Differences between lab and field curing conditions.	--
Maturity Method (ASTM C1074)	Accounts for the combined effects of time and temperature on strength gain. Method involves pre-construction testing of the concrete to establish the maturity relationship.	• Fast and simple nondestructive test method. • Accounts for in situ curing conditions.	• Determination of maturity relationship requires significant up-front effort. • Strength-maturity relationship is mix specific.	As yet to be established.
Ultrasonic Pulse Velocity Method (ASTM C597)	A nondestructive, sonic-based approach used to measure and analyze the speed of ultrasonic waves generated in concrete, which can be used to estimate the dynamic modulus of elasticity and strength.	• Fast and simple nondestructive test method. • Accounts for in situ curing conditions.	• Many variables can affect velocity measurements (moisture, steel, aggregate type/size, non-homogeneity of concrete). • Strength-pulse velocity relationship is mix specific. • Appropriate sensor configurations required (direct and semi-direct preferred). • Sensors must have good acoustical contact.	~5%
Seismic Method	Utilizes seismic surface wave velocity to estimate dynamic modulus of elasticity (which can be related to strength).	• Fast and simple nondestructive test method. • Accounts for in situ curing conditions.	• Strength-pulse velocity relationship is mix specific. • Sensors must have good acoustical contact.	~5%
Integrated Seismic-Maturity Method	Incorporates both the concrete maturity and seismic analysis technologies to accurately determine concrete strength and slab thickness.	• Fast and simple nondestructive test method. • Accounts for in situ curing conditions.	• Strength-pulse velocity relationship is mix specific. • Sensors must have good acoustical contact.	--

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ASTM C31/C31M-00e1, "Standard Practice for Making and Curing Concrete Test Specimens in the Field."

ASTM C39, "Standard Test Method for Compressive Strength of Cylindrical Specimens."

ASTM C42, "Standard Test Method for Obtaining and Testing Drilling Cores and Sawed Beams of Concrete."

ASTM C78, "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading."

ASTM C172, "Standard Practice for Sampling Freshly Mixed Concrete."

ASTM C174/C174M, "Standard Test Method for Measuring Thickness of Concrete Elements Using Drilled Concrete Cores."

ASTM C496, "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens."

ASTM C597, "Standard Test Method for Pulse Velocity Through Concrete."

ASTM C1074, "Standard Practice for Estimating Concrete Strength by the Maturity Method."

ASTM C1383, "Standard Test Method for Measuring p-wave Speed and Thickness of Concrete Plates Using the Impact-Echo Method."

ASTM D4748, "Standard Test Method for Determining the Thickness of Bound Pavement Layers Using Short-Pulse Radar."

APPENDIX B

ESTIMATING CONCRETE STRENGTH BY MATURITY/SEIMIC METHOD

ESTIMATING CONCRETE STRENGTH BY MATURITY/SEISMIC METHOD

This test method provides a procedure for estimating concrete strength by means of the combined maturity and seismic methods. The maturity method is based on relating strength gain to temperature and time. The seismic method is in turn based on relating the strength gain to seismic wave velocity and time.

The maturity method consists of three steps:
- Develop strength-maturity relationship
- Estimate in-place strength
- Verify strength-maturity relationship.

The seismic method consists of four steps as well:
- Develop strength-seismic modulus relationship
- Develop modulus-maturity relationship
- Estimate in-place strength
- Verify strength-seismic velocity relationship.

The Nurse-Saul "temperature-time factor (TTF) maturity index shall be used. The datum temperature should preferably be determined using the procedure outlined in Annex 1 of ASTM C-1074 using mortar cubes. Alternatively, the approximate values recommended in ASTM C-1074 should be used.

Apparatus

Maturity
- If the maturity meter has input capability for datum temperature, verify that the proper value of the datum temperature has been selected prior to each use.
- Commercial battery-powered maturity meters that automatically compute and display the maturity index in terms of a temperature-time factor, or both a temperature-time factor and an equivalent age, are acceptable.
- The same brand and type of maturity meters shall be used in the field as those used to develop and verify the strength-maturity relationship.
- A minimum of one maturity meter shall be provided for each thermocouple location. A multi-channel meter when several thermocouples are in close proximity can be used.
- Meters shall be protected from excessive moisture, and the LCD display shall be protected from direct sunlight.
- Thermocouple wire grade shall be greater than or equal to 20 awg.

Seismic

- An automated free-free resonant column test device that complies with ASTM C215 shall be used.

Calibration

- Calibration of the maturity device shall be verified prior to use by placing a thermocouple in a controlled-temperature water bath and recording whether the indicated result agrees with the known temperature water bath and recording whether the indicated result agrees with the known temperature of the water bath. At least 3 different temperatures, for example, 5 °C, 25 °C and 40 °C are recommended. The temperature-recording device shall be accurate to within +/- 1 °C.

- For seismic tests, no calibration process is needed. However, to ensure that the device is functioning properly, a calibration specimen provided with the device should be tested prior to the use on a project. If the measured modulus of the calibration specimen differs by more than 2% from those reported, the manufacturer shall be contacted.

Procedure to Develop Strength-Maturity/Seismic Relationships

Step	Action
1	For every concrete design that will be evaluated by the maturity/seismic method, prepare a minimum of 15 cylinders and/or beams in accordance with ASTM C-31. Additional specimens should be cast to avoid having to repeat the procedure. The mixture proportions and constituents of the concrete shall be the same as those of the concrete whose strength will be estimated using this practice.
2	Fresh concrete testing for each batch shall include concrete placement temperature, slump, and air content in accordance with ASTM C-31.
3	Embed thermocouples in a least two specimens. Thermocouples shall be placed 50-100 mm (2-4 inches) from any surface. Connect the thermocouple to maturity meters. Do not disconnect meters. Data collection must be uninterrupted.
4	Moist cure the specimens in a water bath or in a moist room in accordance with ASTM C-31
5	Perform compression and/or flexural tests at nominal ages of 1, 3, 7 and 28 days in accordance with ASTM C-39 and C-78, as appropriate. Test two specimens at each age and compute the average strength. The specimens with thermocouples are to be tested last. Prior to conducting compression or flexural tests on each specimen, perform free-free resonant column test. If a specimen is obviously defective (for example, out of round, not square, damaged due to handling), the specimen shall be discarded. If the difference in strength between two specimens is greater than 10%, test a third specimen.
6	At each test age, record the individual and average values of maturity, seismic modulus and strength for each batch on a permanent data sheet.
7	Plot the average strengths as a function of the average maturity values, with data points shown. Using a computer spreadsheet program such as Microsoft Excel, calculate a logarithmic best-fit curve through the data. Record the equation of the curve as well as the R^2 value. The resulting curve is the strength-maturity relationship to be used for estimating the strength of the concrete mixture placed in the field.

	Plot the average strengths as a function of the average seismic values, with data points shown. Using a computer spreadsheet program such as Microsoft Excel, calculate a logarithmic best-fit curve through the data. Record the equation of the curve as well as the R^2 value. The resulting curve is the strength-seismic relationship to be used for estimating the strength of the concrete mixture placed in the field. Plot also the average seismic modulus as a function of the average maturity values, with data points shown. Using a computer spreadsheet program such as Microsoft Excel, calculate a logarithmic best-fit curve through the data. Record the equation of the curve as well as the R^2 value. The resulting curve is the seismic modulus-maturity relationship to be used for estimating the modulus of the concrete mixture placed in the field.
8	The plot, with data points, of the strength-maturity, strength-seismic value, and seismic modulus-maturity relationships for each experiment shall be provided to UTEP for archival purposes

Procedure to Estimate In-Place Strength

Step	Action
1	Prior to concrete placement, install one thermocouple set in the slab. For each thermocouple set, install a thermocouple about 75 mm (3 inches) from the bottom and another about 75 mm from the top of the slab.
2	As soon as practical after concrete placement, connect and activate the maturity meter(s). Do not disconnect meters until the required maturity values are achieved. Data collection must be uninterrupted.
3	At age of 1 day, record maturity data on a permanent data sheet. Also perform a PSPA test. Perform *12* PSPA tests at predetermined locations on the slab.
4	Repeat Step 3 at nominal ages of 3, 7, 14, and 28 days,

Procedure to Verify Strength-Maturity Relationship

Step	Action
1	Core or cut a minimum of 2 cylinders and/or beams concurrent with pouring the slab in accordance with ASTM C-42..
2	Perform compression or flexural strength tests, on two beams and or cylinders in accordance with ASTM C-39 and/or ASTM C-78, and compute the average strength of the specimens. Prior to conducting compression or flexural tests on each specimen, perform free-free resonant column test.
3	Record the individual and average values of maturity, individual and average strengths, and seismic modulus established from the specimen breaks on a permanent data sheet. Also record the predicted strength based on the strength-maturity/seismic relationships established for that particular concrete design, and the percent difference between average and predicted values. Compare the average strength determined from the specimen breaks to the strength predicted by the strength-maturity/seismic relationships. The average strength of the specimens shall be within the verification tolerance specified for the item of work.

APPENDIX C

ESTIMATING CONCRETE THICKNESS WITH IMPACT-ECHO METHOD

ESTIMATING CONCRETE THICKNESS WITH IMPACT-ECHO METHOD

This test method provides a procedure for estimating concrete thickness impact-echo (IE) method using ASTM C-1383. The GPR is based on relating the speed of propagation of reflected sonic waves introduced into a concrete slab to its thickness.

Apparatus

An impact-echo device that conforms to ASTM C-1383.

Calibration

- Calibration of the IE device should initially be carried out as per manufacture's instructions and as per ASTM C-1383.

Procedure to Estimate In-Place Thickness

Step	Action
1	Test a point with known thickness on the slab for calibration purposes
2	Place the IE device on the twelve points marked on the slab at the age of 24 hours. Record the time records for analysis. Report thickness at each point. Also report the average and coefficient of variation for the slab
3	Repeat Steps 1 through 3 at nominal ages of 3, 7, 14, and 28 days.

Procedure to Verify Thickness

Step	Action
1	Core the six points marked on the slab as per ASTM C-42 at the age of about 28 days.
2	Measure the thickness of each core using ASTM C-174. Record the individual and average thickness of each core on a permanent data sheet
3	Compare the average thickness determined from the cores to the thickness predicted by the IE method.

APPENDIX D

ESTIMATING CONCRETE THICKNESS BY PROBING

(Directly from TxDOT Specifications)

Determining Pavement Thickness by Direct Measurement

Overview

This method describes the procedure for determining the thickness of fresh Portland cement concrete pavement.

Equipment

- A rigid straight steel rod with a blunted tip measuring at least 100 mm (4 in.) greater in length than the thickness of the pavement to be measured.
- A standard tape measure or rule readable to the nearest 1 mm (1/16 in.).

Procedure

The following steps detail the procedure for determining pavement thickness by direct measurement.

Step	Action
1	In a position normal to the pavement surface, insert the steel rod into the concrete the full depth of the pavement and mark the top surface of the pavement on the rod.
2	Retract the rod from the fresh concrete.
3	With the tape measure or rule, determine the depth of the pavement by measuring from the tip of the inserted end of the rod to the mark.
4	Record the reading and location.

NOTE: The average of 3 readings taken at 1/4, 1/2, and 3/4 points along the width of the pavement shall constitute one test.