1. EXECUTIVE SUMMARY

The title of this project is “Feasibility of Using Compressive Strength Test Results for Acceptance Testing of Concrete Pavements.” The principal and co-principal investigators are Dr. Jiann-Long Chen, P.E. (chenjl@ncat.edu) and Dr. Miguel Picornell, P.E. (mpicorne@ncat.edu), respectively. Both investigators are faculty members of the Dept. of Civil, Arch., Agri., and Environ. Engrg. of the North Carolina A&T State University, 1601 E. Market St., Greensboro, NC 27411. The estimated budget of the proposed research is $94,776 and the duration is from July 1, 2003 to December 31, 2004.

NCDOT currently uses bending beam tests for acceptance testing of concrete pavements. The results of bending beam tests consistently show a large variability and, thus when low modulus of rupture are encountered in field work, the need arises to perform further testing on specimens that are poured, compacted, and cured under field conditions. This is intended to confirm whether the low modulus measured is representative of the slab material. However, in addition to being expensive and time consuming, this test imparts substantial damage to the slab by sawing a specimen from it.

The main purpose of the proposed research is to evaluate the feasibility of using other tests for acceptance testing of concrete pavements. Specifically, it is proposed to implement a laboratory research project to prepare specimens for bending beam tests, compressive strength tests, and split tension tests; furthermore, it is proposed to perform non-destructive free-free resonant column tests on every specimen prepared for the strength tests. The specimens will be prepared, cured, and tested in a laboratory setting. The results of the tests will be used to correlate the modulus of rupture obtained in the bending beam tests to the compressive strength measured on concrete cylinders, the tensile strength measured in the split tension tests, and to the low-strain dynamic modulus measured in the resonant column tests.

The compressive strength test and the split tension tests can be performed on specimens cored out of field slabs and the damage to the slab is minimal. The low-strain dynamic modulus can be easily measured in the field with non-destructive testing techniques based on the propagation of surface waves, these measurements can be performed quickly, inexpensively and do not impose any damage to the field slab. Existing research underway for the Texas DOT has shown very high correlation coefficients between some of the strength parameters and the low-strain dynamic modulus. The results of the proposed program will provide information about the possible correlation of the strength tests with the dynamic modulus for very little additional cost. In this fashion, any and all the proposed tests if proven suitable to substitute for the bending beam tests, will result in a significant improvement for the testing of field slabs over the bending beam tests.

The correlation of the modulus of rupture to other strength parameters generally exhibits large scatter. One of the main reasons is the variability introduced by the need to tests different specimens, since each of these tests are carried to failure. One of the chief advantages of measuring the dynamic modulus is that the test does not alter the specimen that can be later used to perform any of the strength tests. Thus the correlation of the dynamic modulus to any of the strength tests eliminates the specimen variability. Therefore, this measurement will provide a means to compare the repeatability of the different specimens in all the strength tests. With the use of the dynamic modulus, it will be possible to establish correlations between two different strength tests for all the specimens exhibiting similar dynamic moduli. The result would be to develop several correlations for different values of the dynamic modulus. This approach offers the possibility to make some sense of the scatter of the test results that would result if only one single correlation was implemented.

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3. RESEARCH PLAN

3.1. Introduction

The North Carolina Department of Transportation (NCDOT) uses bending beam (flexure) tests for acceptance testing of Portland cement concrete pavements. When the modulus of rupture measured in the flexure tests does not satisfy the specifications, the need arises for further testing of specimens sawed of field slabs to ascertain whether the field slabs comply with the contractual specifications. The retrieval of field specimens is costly, time consuming and imparts a significant damage to the field slab.

These considerations led to the perceived need to look for alternative tests that could be correlated with the flexural tests and that could be performed on field slabs causing a much lower level of damage to the sampled slab. Other strength tests that could be correlated to the flexure tests include the compressive strength test, and the split tension test [1]. Other tests that are being intensively investigated at the present time include the measurement of the dynamic modulus with seismic techniques [2 & 3], which has also been found to correlate with the strength tests listed above.

In all the strength tests, the specimens are loaded to failure and, thus, it is not possible to reuse the specimens. It is rather necessary to prepare duplicate specimens to run each of the strength tests. The result is that the variability in the concrete specimens prepared is added to the normal testing variability, and thus provides an additional source of scatter for the correlation of the two parameters being considered. One advantage of the ultrasonic test is that the test is not only not carried to failure, but the specimen is unaffected by the test, and thus the specimen can be reused in another test. Since the seismic modulus can be measured on all the specimens used in the strength tests, it provides a tool to “rate” the specimens. With this rating tool, it would be possible to compare all the specimens for the strength tests and separate the specimens in categories of specimens with similar dynamic modulus. For each category, a different correlation could be developed, thus reducing or explaining the much larger scatter observed when all the tests are lumped together.

The present proposal describes a laboratory program to provide data to correlate the strength tests and the dynamic modulus to the rupture modulus measured in the bending beam test.

3.2. Problem or Need Definition

A main limitation of the bending beam test is that obtaining field poured and cured specimens for testing will cause significant damage to the slab sampled. This precludes comprehensive field tests to monitor the strength gain in the field for acceptance testing and/or for evaluation of the opening of Portland Cement Concrete (PCC) pavements to traffic. Subsequently, this could lead to opening of the road to traffic before the concrete has gained adequate strength, resulting in compromising the pavement performance. Thus, to increase the reliability of assessing the strength of PCC pavements, alternative methods that cause less damage to the pavements are necessary.

Compressive strength, with the advantages of being more consistent and requiring smaller sample size than the bending beam test, is the method being considered by NCDOT as an alternative test for PCC pavement acceptance. This project will evaluate the feasibility of using compressive strength test for PCC pavement acceptance. Furthermore, several additional tests are proposed as potential alternatives for the bending beam tests. The additional tests proposed are the following:

1). Split Tension Tests

This test specimen fails in a mode quite similar to the bending beam tests. Thus, the tensile strength measured in this test could potentially show better correlation with the modulus of rupture than the compressive strength.

2). Low-strain Dynamic Modulus (LSDM) Measurements

The modulus measured in a free-free resonant column has been shown to exhibit a high correlation coefficient with some other strength parameters in research in progress for the Texas DOT. The approach used in Texas is to measure the dynamic modulus on the concrete cylinders poured during the construction of the slab, and then correlating the dynamic modulus to the strength measured on the cylinders. The slabs are then surveyed with a surface wave analyzer that allows quick and easy determination of the dynamic modulus of the field poured and cured slab. These measurements are then converted to strength using the correlation developed on the concrete cylinders. Under these conditions, the correlation coefficients obtained in Texas is approximately 0.95.

All the three proposed alternative methods have the advantage of causing less damage to the PCC pavements than the bending beam test. However, there are other advantages that are provided by the split tension test and the LSDM test as described below.

The split tension test does not require a specimen as long as the one required by the compressive strength test; a six inches long specimen would be sufficient for split tension, whereas the compressive strength would require twelve inches long specimens. This would facilitate the investigation of field slabs less than twelve inches thick. Although there is the alternative to reduce the diameter of the core barrel to say four inches, it seems more reliable to require a minimum diameter of six inches. Nevertheless, considering the NCOT policy of testing compression specimens, a series of compression tests using 4 inches diameter by 8 inches length will be conducted in this research. The results will be compared with the results using 6 inches diameter by 12 inches length specimens.

The low-strain dynamic modulus, measured in a free-free resonant column test, has the following potential benefits:

1.) The test is non-destructive and can, thus, be performed on all the specimens prepared for the strength tests. The measurement does not require much time (about a couple of minutes) or capital investment in equipment. Thus the inclusion of this test does not increase significantly the cost of the proposed research project.
2.) The measurement of dynamic modulus will allow a simple and fast comparison of the different specimens prepared for the strength tests. This provides a quantitative tool to compare the specimens prepared for the bending beam, the compressive strength, and the split tension tests and, thus, permit an evaluation of the repeatability of these specimens.
3.) The dynamic modulus measured can be used to establish correlations with the strength measurements of all the strength tests. As the LSDM test and the bending beam tests will be performed with the same sample rather than on two different samples, it permits a more accurate evaluation of the potential correlation coefficients between the two measurements.

3.3. Research Objectives

The long-term goal of these activities is to develop a testing protocol to substitute for the need of preparing, curing, and testing bending beams and the need to saw bending beams from field poured slabs. The ultimate goal of this proposed study is to evaluate the reliability of switching from bending beam tests to some other alternative strength testing method. The study will be performed for one common type of Portland cement concrete.

For this purpose, the first objective of the proposed research is to establish correlations between the rupture modulus in a flexural test, the compressive strength, the split tension test, and the rupture modulus of likely prepared and cured specimens.

Previous experiences in these correlations between strength parameters have shown considerable scatter in the test results. Anticipating that scatter will also be present in the results of the presently proposed study, the second objective is to elucidate the causes of the scatter and propose an approach to reduce it in further investigations.

3.4. Literature Review

The most recent semi-mechanistic approaches for the design or determination of the remaining life of Portland cement concrete pavements are based on the strength parameters of the PC concrete such as flexural strength, split tensile strength, or compressive strength. These parameters are usually determined on field cores or on laboratory poured and cured specimens or are obtained through empirical correlations with other parameters.

For most concrete pavement applications, the flexural strength is the most common PCC property used to evaluate load capacity. Flexural strength provides an assessment of the maximum tensile stress acceptable at the bottom of the PCC slab. However, flexural strength test are very sensitive to the quality of the test beam and the testing procedure. This results in a lot of variability. Some state and federal agencies have realized this shortcoming and have opted to use some alternative test [6]. These considerations have led NCDOT to explore the use of compression test and are the impulse behind the research idea that the present proposal is responding to.

The results of strength tests on field cured specimens are often significantly different from those of cores of the concrete in the pavement, because it is difficult to impose similar compaction, bleeding and curing conditions in the field specimens and the slabs. For this reason, there is a need to determine the strength of PCC with “in-situ” techniques. The most common “in-situ” techniques are based on measuring a property of concrete that is related to the strength of concrete. Usually, the relationship is established empirically based on testing standard-cured specimens [2]. The accuracy or reliability of the strength estimates from the empirical correlation depends on the scatter observed in the data; a possible measure of the goodness of fit is the correlation coefficient.

There has been much effort in trying to correlate the different strength properties of PCC. The results of one of such efforts are shown in Figure 1, which relates the modulus of rupture from a bending beam test to the compressive strength of duplicate specimens.

The results in Figure 1 illustrate graphically the scatter to be expected in the correlation of the two strength properties. For example, for a compressive strength of 4000 psi the modulus of rupture ranged from 500 psi to about 900 psi, almost a factor of two. The amount of the scatter to be expected is clearly influenced by the number of parameters that are included in the population of specimens. Clearly, if the specimens were only from a one type of aggregate, it is reasonable to expect somewhat lower scatter of the results. This implies the need to develop correlations for each type of aggregate used, thus presumably for each job site. Another source of scatter has to be found in the testing variability of duplicate specimens under the same exact test protocol. This aspect will be addressed later in this section. Still another source of error has to be found in the failure mechanism of each type of strength test.

The bending beam test specimen in the third point loading is subject to a pure bending moment in the central portion of the beam. The peak load measured in the test is interpreted by assuming that the stress distribution through the section where failure occurs is linear from the location of the neutral fiber; in other words, it is assumed that the concrete in the beam remains linearly elastic up to failure. In reality, it is more likely that the distribution of stress below the neutral fiber will be somewhat parabolic. The result is that the interpretation of the bending beam test indicates a tensile stress that is somewhat higher than the actual tensile stress that caused the failure of the test beam.

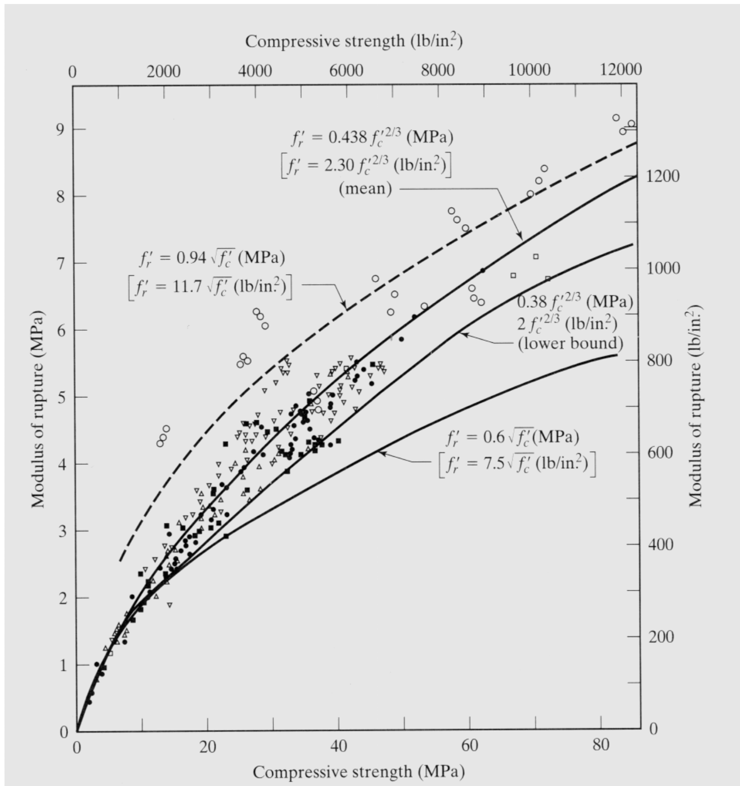

Figure 1. Modulus of rupture versus compressive strength for normal weight concrete (Adapted from [1])

The compressive strength specimen, it is notorious for the several variations of possible failure mechanism. Under some conditions normally attributed to the effects of friction on the end platens, failure will occur as vertical columns due to a splitting failure or in a shear mode where conical undamaged zones appear at one or both ends. The result is that the final strength recorded will not be consistent. This effect will definitely affect the correlation of the compressive strength to any other parameter. In other words the failure mechanism is not consistent in this test and thus it should be expected to show a higher variability than other strength tests. On the other hand, one of the main advantages of the compressive strength test is that the NCDOT personnel have been consistently trained and the equipment to perform the test is widely available throughout the Districts.

As most of the testing in compressive strength by NCDOT is performed on cylinders 4 in. in diameter and 8 in. long. It is an important test to be included in as the potential strength test. In this sense, two series of compressive strength tests will be included in the proposed work to accommodate the 4 in. and the 6 in. diameter specimens.

An alternative strength test that has been used in the past and it is proposed in the present proposal is the split tension test. In this test the specimen is a cylinder that is tested on its side in diametric compression. The result is that the specimen is loaded in tension in the vertical diameter and the horizontal plane is subject to compression. The tension stresses in the vertical diameter are nearly uniform for the middle two thirds of the specimen and the compressive stresses on the horizontal plane are very large towards the loading lines and decrease towards the center of the specimen. The specimen fails in tension consistently, this is precisely the mode of failure of the bending beam test, and thus offers the possibility that the correlation with the bending beam could be stronger than for the compressive strength test. Figure 2 shows an example of a correlation between the split tension test and the compressive strength test.

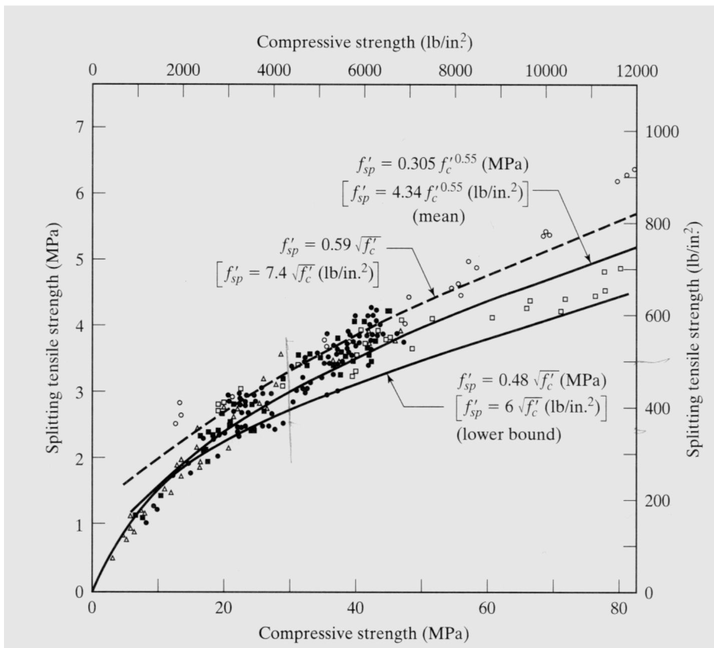

Figure 2. Split tension strength versus compressive strength for normal weight concrete (Adapted from [1])

Figure 2 shows significant scatter, although it appears to be less than in Figure 1. What is significant is that the split tension test yields consistently a tensile strength that is lower than the bending beam test. For example, looking at a 4000 psi concrete strength, the split tension strength is shown to range from 350 psi to about 500 psi. For the modulus of rupture, the range was 500 psi to 900 psi. In other words, the split tension strength is significantly lower than the modulus of rupture back figured from the bending beam test.

As the split tension test consistently fails in tension, it is potentially a better choice than the compression test to correlate to the bending beam test. At the same time, the split tension test can be performed on specimens shorter than the compressive strength and could be applicable to testing cores from a wider range of possible field cases. Also, the test does not require extra heavy testing equipment than required by the compression test.

The variability that is observed in the properties of PCC is normally attributed to testing errors, and to the variability of the materials that make up the duplicate specimens. The main reason is related to the fact that all these tests load the specimens to failure and that it is not possible to reuse the specimens. It is a daunting question, how much of the variability of test results is to be attributed to the material variability, the Bureau of Public Roads [5] indicated that the percentage of the variance observed in the compressive strength of PCC can be attributed in large part (from 50% to 90%) to the material variability. This result would suggest that the material variability is an important variable that probably has a large effect on the scatter of test results and thus has to be addressed to explain and improve the correlations between strength properties of PCC.

The proposed study has a two prongs approach to address this variability. The first is to prepare specimens with several degrees of control of the materials making the specimens; ranging from a strict control of all the size fractions of aggregate, the cement and the water for each specific specimen manufactured, to the common practice of preparing batches in a central plant, delivering to the site and sampling the fresh concrete to prepare the specimens. The specimens with the stricter control should exhibit the lowest possible effect of material variability and, thus, the correlations between the properties of these specimens should be representative of the best possible or show the least amount of scatter that could be expected. At the other end of the scale, the specimens prepared sampling fresh concrete from a central plant could be indicative of the scatter to be expected at a job site. Thus a comparison of the results for the different degrees of control of the manufacture of specimens will then provide an indication of the contribution of the material variability to the overall scatter.

The second approach is the use of nondestructive tests, which allow the reuse the same specimen to perform a destructive strength test. The last decade has seen large effort to develop nondestructive tests based on seismic methods [6 & 7]. One of such techniques is the measurement of the Low Strain Dynamic Modulus (LSDM) of concrete. One possible approach is to determine the LSDM in a free-free resonant column [5]. A sketch of the device is shown in Figure 3. The test consists of striking a cylinder or a beam along the longer axes with an instrumented hammer and monitoring the response at the other end of the specimen. The two signals are then processed and the amplitude spectrum is produced with appropriate software (Figure 4).

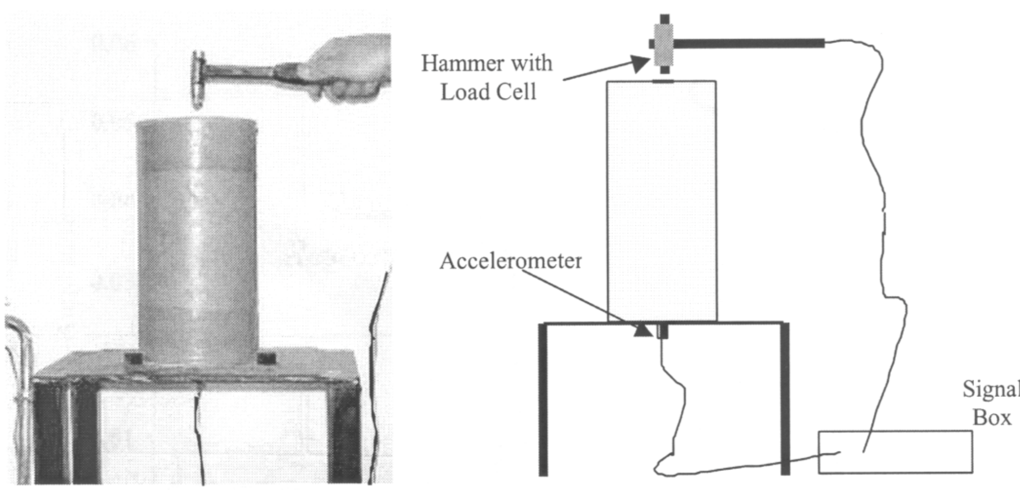

Figure 3**.** Sketch of a Free-Free resonant column

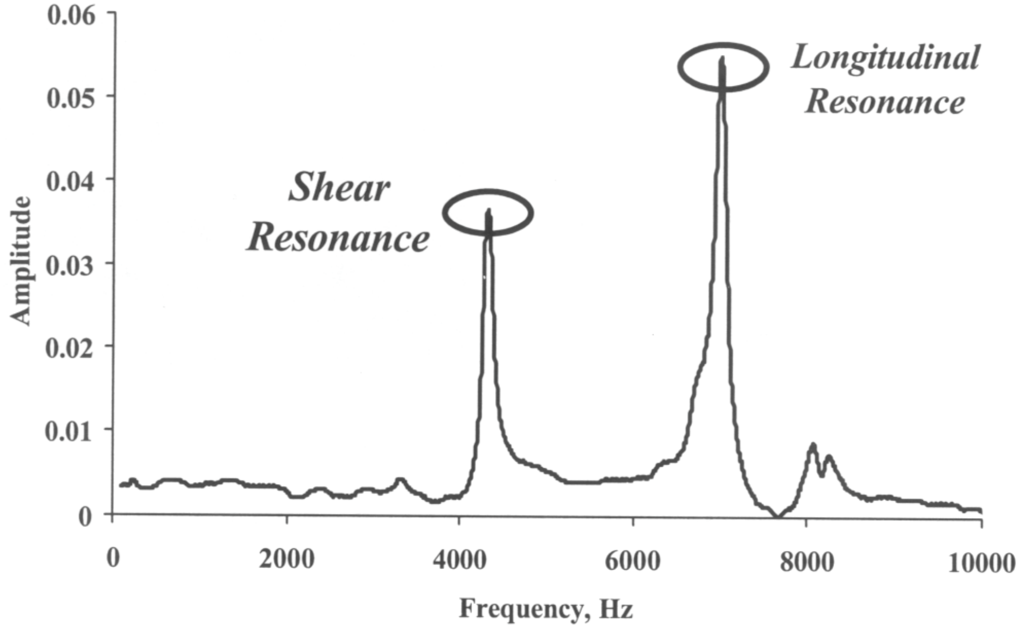

Figure 4**.** Typical response spectra of free-free resonant column test

The total test duration is less than one minute and from the resonant frequency and the sizes of the specimen the LSDM is calculated. Furthermore, the specimen is unaffected and can then be used to perform a strength test. The correlation of strength tests to the LSDM has been published [8] and it has been shown to exhibit high correlation coefficients. An example is presented in Figure 5. The correlation coefficients of approximately 0.9 is encouraging. If the same level of correlation were obtained in the proposed project, the substitution for the bending beam test with the proposed tests would be justified.

The repeatability of the LSDM measurements was exhaustively studied by the Army Corps of Engineers [2]. A summary of the findings for the free-free resonant column test is presented in Table 1. The results in Table 1 indicate a high degree of repeatability with coefficients of variation lower than 1%. The conclusions in the original study [2] states that the repeatability of the tests was better than using traditional strength tests.

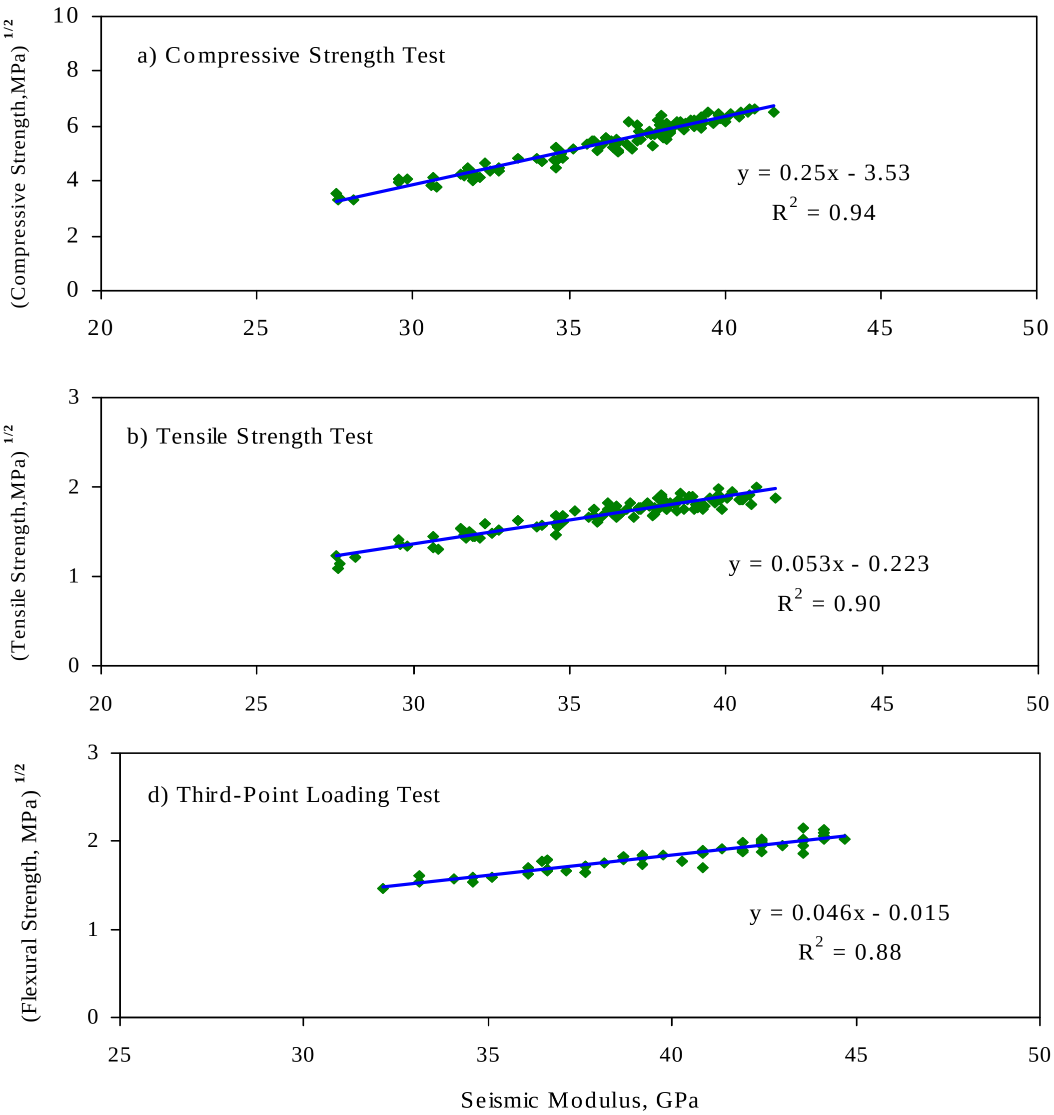

Figure 5**.** Relationships between LSDM and traditional strength parameters [8].

Table 1. Evaluation of repeatability of Free-Free Resonant Column and PSPA [2]

Test Type	No. of Data Sets [Replicates]	Range of Means	Range of Std. Dev.	Average and [Range] for CV(%)
Free-Free P-Wave Velocity for Sawn Beams - between replicates on a single beam	63 [3]	11545 to 14230 fps	0 to 845 fps	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 fps	39 to 465 fps	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 fps	0 to 110 fps	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 fps	45 to 1020 fps	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 fps	7 to 270 fps	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 fps	13 to 430 fps	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 fps	0 to 480 fps	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 fps	8 to 340 fps	1.0 [0.1 to 2.6]

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

3.5. Research Methodology and Itemized Tasks

3.5.1. Research Methodology

The first part of the project will be to assemble all the information that shows the correlation between strength properties. The laboratory program will be initiated by contacting a local supplier of PCC and aggregates to select a design mix to be used in all the laboratory-prepared specimens. The specimens will be cured in water under room temperature for 3, 7, 14, or 28 days. After the curing period, the specimens will be removed from the bath and allowed to air-dry for 24 hours.

The variance observed in the properties of PCC pavements is typically attributed to the testing protocol, the sampling of the fresh concrete, and to the variability of materials used in the preparation of concrete. The variability in these aspects will have an effect on the correlation coefficients that would be observed between the tests proposed. To clarify the effect that specimen preparation would have on these correlations, PCC specimens prepared with the following methods will be tested with the four methods.

1) Individual preparation

   All the components of each test specimen will be weighted and mixed separately. This would include all the aggregate size fractions, the cement, and the water.

2) Laboratory batch preparation

   All the components for each batch of specimens (3 specimen in each batch) will be weighted and mixed in a single batch. The fresh concrete will then be sampled and used in the preparation of the specimens of the same batch.

3) Commercial batch preparation

   Commercially available concrete mixed in a central plant will be purchased and delivered to our laboratory. All the specimens for the batch (48 specimens in each batch) will be formed at the same time. For this purpose, the fresh concrete will be sampled, poured and consolidated into the different molds.

For the individually and laboratory batch prepared PCC specimen, identical ingredients and proportions; that is, water, aggregate, and air-entraining cement will be used. The nominal grain size distribution of the aggregates will be the same for all batches. All the specimens will be cured in the laboratory under identical conditions. To characterize the strengths of the specimen as a function of curing time, the strengths will be measured at curing time of 3, 7, 14, and 28 days. Three replicates of specimens for each set of conditions will be prepared.

All the specimens will first be subjected to the free-free resonant column test and the LSDM will be calculated according to the ASTM method C215-97. After the free-free resonant column test, the specimens will be subjected to the corresponding strength tests. The ASTM methods will be followed for the strength tests and calculations: ASTM method C78-02 for the bending beam test; ASTM method C39/C 39 M-01 for the compression test; and ASTM method C496-96 for the split tension test.

3.5.2. Itemized Tasks

Task 1. Literature search

A nationwide information search will be conducted to collect all relevant materials and documents. The search will focus on the criteria and methods currently being used or under consideration by other states' DOT for the acceptance of PCC pavements. The following information will be shared and discussed with the project task forces of NCDOT during the project period and summarized in the final report.

- Types of methods being used for testing PCC strength,
- Types of methods being considered for testing PCC strength,
- What are the parameters being measured by the different methods,
- How well the parameters are correlated to the PCC strength,
- Size of samples required for each method,
- Equipments and instruments required for each method, and
- How easily (or difficult) each method can be performed.

Task 2. Equipment procurement and setup

The major instrument that needs to be purchased is the free-free resonant column analyzer. The equipment setup includes calibration of the compression machine and modification of the compression machine so that it can perform the bending beam and split tension test.

Task 3. Development of test protocols

After equipment setup, detailed procedures will be developed for the four tests: bending beam, compression, split tension and free-free resonant column tests following ASTM and NCDOT standard procedures. The different mixes used will be characterized using slump test, air entraining test etc.

Task 4. Characterize the strength of PCC specimens

The strength of PCC specimens will be tested with four methods as listed in the following. The 28-day strength of the PCC specimens will be between 3,000 and 6,000 pounds per square inch (psi).

1) Bending beam test: measures modulus of rupture; sample size: 6 inches by 6 inches by 21 inches
2) Compression test: measures compressive strength; sample sizes: a) 6 inches diameter by 12 inches length and b) 4 inches diameter by 8 inches length
3) Split tension test: measures tensile strength; sample size: 6 inches diameter by 12 inches length
4) Free-free resonant column test: measures LSDM; sample sizes: a) 6 inches diameter by 12 inches length, b) 4 inches diameter by 8 inches length, and c) bending beam specimen of 6 inches by 6 inches by 21 inches

Task 5. Analyze and characterize the relationship between the parameters measured

Using the results obtained in task 4, correlations will be developed between the following parameters:

1) Modulus of rupture vs. compressive strength,
2) Modulus of rupture vs. tensile strength,
3) Modulus of rupture vs. LSDM,
4) Compressive strength vs. LSDM,
5) Tensile strength vs. LSDM, and
6) Compressive strength (4 in by 8 in) vs. compressive strength (6 in by 12 in)

Since the resonant column is a non-destructive test, the test is performed on the same specimen that will later be used in the strength test. The uncertainty due to specimen variability is eliminated from affecting the correlation. Thus, it is expected that the correlation coefficient of the strength parameters to the LSDM will be higher than the correlation coefficient between the strength parameters.

The proposed correlations will be implemented separately for each of the three preparation procedures discussed in task 4. If warranted by the results, global correlations including the results of the tests for all three batches will also be evaluated.

Task 6. Reports

The report will conclude with recommendations on the feasibility of substituting the bending beam test for acceptance of concrete pavements. The recommendations will include the description of a testing protocol to be followed for implementation of the results documented in the report. These recommendations will be elaborated for each of the alternatives that are deemed feasible to substitute for the bending beam test.

4. ANTICIPATED RESULTS AND SIGNIFICANCE

The results from this research project will provide the correlation between the following parameters of PCC specimens with strength ranging from 3,000 to 6,000 psi.

1) Modulus of rupture vs. compressive strength,
2) Modulus of rupture vs. tensile strength,
3) Modulus of rupture vs. LSDM,
4) Compressive strength vs. LSDM, and
5) Tensile strength vs. LSDM.
6) Compressive strength (4 in by 8 in) vs. compressive strength (6 in by 12 in)

The correlation coefficients between the above parameters will decide if the results obtained from compression test, split tension test, and free-free resonant column test can be used as an indicator for the modulus of rupture. In addition, the variations results from specimen preparation will be characterized. This will provide us with the information of the effects of sample variation (i.e. different aggregate and cement compositions due to incomplete homogenization) on the parameters of PCC. In the case that the effects of sample preparation on the PCC parameters are insignificant, the results from the three sample preparation procedures will be combined together to generate overall coefficient correlations between the parameters.

In addition, the 95% confidence interval between different pairs of parameters will be characterized. The lower bound of the interval will be used and recommended for developing the testing protocol.

5. RECOMMENDATIONS FOR IMPLEMENTATION AND TECHNOLOGY TRANSFER

The results from this project will provide NCDOT with the information to identify alternative test methods for the bending beam tests currently being used. All the proposed alternative methods require smaller specimen size than the bending beam test, thus significantly reducing the damage to the slab being sampled. Depending on the level of correlation obtained, should one or more of the proposed methods are considered as a substitution for the bending beam test, the test procedures and protocols developed in this project can be modified and expanded to form a standard procedures implemented within NCDOT in the future. Adopting one of the proposed methods as the substitution for the bending beam test will save tremendous amount of time and money for NCDOT and minimize the damage to the slabs.

The recommendations and conclusions of this project will also formed the basis for conducting a filed-scale tests comparing the proposed alternative methods and the bending beam tests. The specimens in this project is cured in water and under room temperature, which is very different from the field conditions. Curing conditions and the scale of the tests are important variables affecting the strength of PCC. The results from this project will help the NCDOT subcommittee to decide whether additional research addressing the curing conditions and scale of tests are warranted.

6. RESOURCES TO BY SUPPLIED BY NCDOT

Interaction between NC A&T and NCDOT is required to ensure that the test procedures and protocols used are consistent with NCDOT guidelines.

7. EQUIPMENT AND FACILITIES

The tests will be conducted in the Construction Materials Laboratory located on the first floor of McNair Hall in the North Carolina A&T State University campus. The laboratory has a Forney Universal Testing Machine (model LT-920-D) with a maximum compression capacity of 400,000 lbs. The facility is also equipped with basic instruments and equipments for testing and preparation of concrete specimens.

8. TIME REQUIREMENTS

The time chart of this project is shown in Table 2. The chart is arranged according to the tasks that will be performed during the period of the project. Therefore, refer to section 3.5.2 titled "Itemized Tasks" for details of the research activities shown in Table 2.

Table 2. Schedule of Research Activities

Research Activities	FY 2003-2004												FY 2004-2005					
	J	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Task 1 Li[illegible]ture Search																		
Task 2 Equipment Procurement and setup																		
[illegible]opment of test protocols																		
Task 4 Strength of PCC: individually pre[illegible]																		
Task 4 Strength of PCC: laboratory batch prep[illegible]																		
Task 4 Strength of PCC: commercial batch prepared specimens																		
Task 5 Analyze and characterize the rela[illegible] measured																		
Task 6 Re[illegible]ts																		

9. BIOGRAPHICAL DATA OF THE RESEARCHERS

Dr. Jiann-Long Chen received his bachelor's degree in civil engineering from the National Taiwan University, Taiwan in 1987, master's degree in environmental engineering from Duke University in 1993, and doctoral degree in environmental engineering from the University of Cincinnati in 1997. After receiving the bachelor's degree, he supervised the construction of an air force communication facility and a barrack while serving as a first lieutenant in the Army Corps of Engineering of Taiwan. During this time, he gained substantial experience in testing and measuring the properties of concrete. After coming to the US to pursue postgraduate degrees, Dr Chen's research have been focusing on the properties of soil and aggregates that are more related to the environmental engineering discipline. However, there are many aspects in soil testing that can be applied to the testing of concrete: especially, the aspect of quality assurance/quality control (QA/QC). As concrete are prepared by mixing of sand, aggregates, cement, and water, its properties can vary as the composition is changed. Thus, in a project like this one, where the results from four different methods are being correlated, it is very important to have a QA/QC plan so that the variations in sample compositions can be distinguished from the variations that are due to the procedures of the methods. With Dr. Chen's experience in QA/QC and statistical treatment of test data, the results and conclusions of the proposed project will meet the highest requirements and criteria. Dr. Chen is a registered professional engineer and a member of the American Society of Civil Engineers. He has authored/coauthored thirteen peer-reviewed technical articles.

Dr. Miguel Picornell graduated with a civil engineering degree from Madrid Spain Polytechnic University in 1969. He worked in private practice until 1980, most of the time with a geotechnical consulting firm. At this time, he attended Texas A&M University and obtained his master and doctor degrees in civil engineering in 1985. From 1985 till 1998, he was a faculty of the University of Texas at El Paso, where he co-founded with Dr. Soheil Nazarian the "Center for Highway Materials Research." He was associated with about twenty projects with more than 3 million dollars of research funding for Texas DOT and federal government at this center. He authored and co-authored more than 50 journal and conference papers. Some of his publications that are most directly related to the proposed project are listed below.

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2.) Imran, I., Nazarian, S., Picornell, M., " Crack Detection Using a Time-domain Wave Propagation Technique," *Geotechnical Engineering Journal,* Vol. 121, No. 2, ASCE, New York, NY, 1995, pp.198-207.
3.) Lovelady, P.L., and Picornell, M., "Sample Coupling in Resonant Column Testing of Cemented Soils," *Dynamic Elastic Modulus Measurements in Materials,* ASTM STP 1045, Alan Wolfenden, Ed., American Society for Testing and Materials, Philadelphia, PN, 1989, pp. 180-194.
4.) Murthy, R., Nazarian, S., and Picornell, M., " Dynamic Properties of Cemented Silts of Southwest USA," *Proceedings,* 9th Panamerican Conference on Soil Mechanics and Foundation Engineering, Chile, 1991.
5.) Picornell, M., and Lytton, R.L., " Field Measurement of Shrinkage Crack Depth in Expansive Soils," *Transportation Research Record 1219,* Transportation Research Board, Washington, D.C., 1989, pp. 121-130.

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8. Nazarian, S., D. Yuan, E. Weissinger, and M. McDaniel, 1997, "Comprehensive Quality Control of Portland Cement Concrete with Seismic Methods" Transportation Research Record 1575, Washington, DC, 102-111.