EVALUATION OF ACCEPTANCE STRENGTH TESTS

FOR

CONCRETE PAVEMENTS

Research Project 2004-06
for
The North Carolina Department of Transportation

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16. Abstract

The North Carolina Department of Transportation has used traditionally flexural strength tests for acceptance testing of Portland cement concrete pavements. This report summarizes a research project implemented to investigate the feasibility of using other strength tests and nondestructive tests, to accomplish the same objective of ensuring an adequate modulus of rupture of the slab but avoiding or reducing the need to perform a large number of flexural strength determinations for acceptance testing. The present work has been laid around using a nondestructive test (a resonant column) to measure a seismic modulus that is used as a rating tool to evaluate the repeatability of duplicate specimens before the specimens are strength tested. This has been accomplished by developing regression lines and confidence and prediction intervals for the correlation of the seismic modulus to flexural, splitting tension, and compressive strength test. All these test show strong correlation coefficients and, thus, all have the possibility to be used in the prediction of flexural strength. The report suggests a new process for acceptance testing based on using a combination of compressive strength and seismic modulus. The selection of compression testing is based on the perceived know-how of the personnel of NCDOT throughout the State.

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Executive Summary

The North Carolina Department of Transportation "NCDOT" uses flexural strength for acceptance testing of concrete pavements. Bending beam in one-third point loading show a large variability of the strength and thus, in many occasions, when the beams of record do not pass the acceptance criteria, it is necessary to test the field slab. Due to the large sample size required, this test does not lend itself to obtain several specimens for testing of the cured field slab since significant damage is imparted on the slab. The main objective of the present research was to evaluate the feasibility of using other tests for acceptance testing at the same time that there is some degree of certainty that the required modulus of rupture is achieved.

The research project consisted of casting and curing specimens for a typical concrete mix used by NCDOT. The specimens upon curing were first tested using a free-free resonant column apparatus to measure the seismic modulus, and then were strength tested in flexural strength, splitting tension, or compressive strength. The specimens were prepared using several different batching procedures ranging from ready mix concrete delivered to our lab, to specimens mixed and cast in our lab in two types of batches: batches of several specimens mixed at one time, and batches for a single specimen at a time.

The strength measurements and the seismic modulus, measured on the same specimen as the strength, were then correlated. Two types of correlations were developed: the first using all the results and the second using only the averages of each batch. This consisted of averages of six ready mix specimens, and averages of three for laboratory mixed specimens. For the second type of correlation, the coefficients of determination hover around an "R^2" of 0.95 for all strength tests.

The relationship of flexural strength to seismic modulus and that of compressive strength to seismic modulus are then used to define the regression of flexural strength to compressive strength. This regression line and the confidence or prediction interval lower bounds can be used to select a reliability based "Rejection" value. An example, for an arbitrary set of limits and acceptable risk levels is documented. The same approach can be used using the splitting tensile strength or the seismic modulus itself.

The compressive strength and the splitting tension strength can be performed on specimens cored from existing slabs with minimal damage to the slab. The seismic modulus can be measured in the field with nondestructive surface wave measurements that can be performed quickly, inexpensively and do not impart any damage to the slab. The present research project has shown that any of these techniques can be successfully used for acceptance testing of concrete pavements, while the risk of accepting a slab with a low modulus of rupture can be kept reasonably low.

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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 from 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 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 "Seismic Modulus" with seismic techniques [2 & 3], which have also been found to correlate with the strength tests listed above.

In all the strength tests, the specimen is 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 of the concrete in the duplicate specimens 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 seismic modulus 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 to perform a strength test; hence it is possible to correlate the strength property to the seismic modulus measured on the same exact specimen. 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 is possible to compare the strength of the different specimens by correlating the strength measured on each different specimen to the seismic modulus measured on the same specimen, and then comparing strengths corresponding to similar seismic modulus. In this manner, the variability of the concrete in duplicate specimens can be eliminated from the correlation.

The compressive strength, with the advantages of being the most common test and more consistent and requiring smaller specimen size than the bending beam test, was the test initially being considered by NCDOT as an alternative test for acceptance testing of Portland cement concrete pavements. An additional test that was proposed as potential alternative to the bending beam test was the splitting tension test. This last test specimen fails in a mode quite similar to the bending beam test; thus, the tensile strength measured in this test could potentially show better correlation with the modulus of rupture than the compressive strength.

All the three proposed alternative methods have the advantage of causing less damage to the PCC pavements than the bending beam test. The seismic modulus tests can be performed without affecting the field slab; the compressive and splitting tension tests require much smaller specimens than the bending beam tests. Thus either one of the three alternative tests would facilitate the investigation of field slabs should the need arise.

The ultimate goal of the present research study is to evaluate the feasibility of replacing the bending beam tests in acceptance testing for some other alternative testing method that could provide a reasonable degree of certainty that the field slabs had achieved the desired modulus of rupture.

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

Previous experiences in these correlations between strength parameters have shown considerable scatter in the test results. The second objective was to elucidate the causes of the scatter and propose an approach to incorporate the observed correlations into a reliability-based acceptance scheme.

2. Review of Previous Work

2.1 Literature Review

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

For most PCC 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 tests 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 or other tests and are the impulse behind the research performed in the present research project.

The results of strength tests on field cured specimens are often significantly different from those of cores of concrete from 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 "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, that is testing laboratory specimens [2] and correlating the strength property to the "in situ" measurement. 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 determination coefficient "R^2".

There has been much effort in trying to correlate the different strength properties of PCC [1]. The correlation of modulus of rupture from bending beam test to the compressive strength of replicated specimens has shown large scatter. For example, for a fixed compressive strength, the corresponding modulus of rupture can range by 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 one type of aggregate, it is reasonable to expect somewhat lower scatter of the results. This implies the need to develop different correlations for significantly different sources of aggregate; thus, there is a possibility of the need to develop these correlations 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 different type of strength test.

The beam specimen loaded in one-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.

The compressive strength test is notorious for the several possible mechanisms of failure. 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. One of the main advantages of the compressive strength test is that the NCDOT has personnel appropriately trained and the needed equipment to perform the test is widely available throughout the State.

Most of the testing in compressive strength by NCDOT is performed on cylinders 4 inch in diameter and 8 inch long. It is an important test to be included in as an alternative strength test to the bending beam. In this sense, two series of compressive strength tests were included in the present research project to accommodate four inch and six inch diameter specimens.

Another alternative strength test that has been used in the present research project is the splitting tension test. In this test the specimen is a cylinder that is loaded on its side in diametric compression. The result is that the specimen experiences tensile stresses in the vertical plane (passing through the vertical diameter) and the horizontal plane is subject to compression. The tension stresses in the vertical plane 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 outer surface 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. What is significant is that the split tension test yields consistently a tensile strength that is lower than the bending beam test [1]. The split tension strength is from two thirds to about one half of the modulus of rupture [1]. 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 modulus of rupture. 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 variability of tests 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 material variability. This result would suggest that the material variability is an important factor that probably has a large effect on the scatter of the test results and, thus, has to be addressed to explain and improve the correlations between strength properties of PCC.

The present study addressed this variability with a two prong approach. The first was 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 concrete to our laboratory and sampling the fresh concrete to prepare the specimens. The expectation was that 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 specimen's prepared sampling fresh concrete from a central plant could be indicative of the scatter to be expected at the job site. Thus a comparison of the results for the different degrees of control in casting the specimens was to provide an indication of the contribution of the material variability to the overall scatter.

The second approach was the use of nondestructive tests, which allow reusing the same specimen to perform a destructive strength test. The last decade has seen a 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 (Seismic Modulus) of concrete. One such possible approach is to determine the seismic modulus in a free-free resonant column [5]. The test consists of striking a cylinder or a beam along the longer axes with a hammer and monitoring the response at the other end of the specimen with an accelerometer. The signal received is then processed and the amplitude spectrum is produced by appropriate software. From the spectrum, the resonant frequencies for the "Primary" and "Secondary" waves are identified. These values together with the dimensions and weight of the specimen are used to calculate the seismic modulus and the Poisson's ratio of the material in the specimen.

The specimen is unaffected by the seismic modulus determination and can then be re-used to perform a strength test. The correlation of strength tests to the seismic modulus measured on the same specimen have been published [8] and these have been shown to exhibit high coefficients of determination "R^2", ranging from about 0.90 to 0.95 for the same strength test used in the present study.

The repeatability of the seismic modulus measurements was exhaustively studied by the Army Corps of Engineers [2]. A summary of their findings for the free-free resonant column test is presented in Table 2.1. These results indicate a high degree of repeatability with coefficients of variation lower than 1%. The conclusions in the original study [2] state that the repeatability of the tests was better than using traditional strength tests.

Table 2.1 Evaluation of Repeatability of Free-Free Resonant Column [2]

Test Type	No. of Data Sets [Replicates]	Range of Means	Range of Standard Deviation	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 Field Cores –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 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 Cylinders -between replicates on a single cylinder	72 [3]	9650 to 14110 fps	0 to 480 fps	0.8 [0.0 to 3.7]

2.2 Survey of Practices in the Rest of the Country

A telephone and e-mail survey was performed contacting the Departments of Transportation of all the States in the country. The first attempt was to locate an engineer, at each Department of Transportation, knowledgeable of the practices for acceptance testing of concrete pavements in his State Department of Transportation. In some States it was not possible to identify that person, and we resorted to pursue a review of their web-site in case that the policy was on the Web. A summary of the findings has been organized in table form and is included as Appendix A at the end of this report.

The table includes the following information: State, contacted person's name, telephone number used to contact, or/and Email address used in the communications, and the last column is a summary of the policy for acceptance testing of Portland cement concrete pavements. When the name of the State has an asterisk indicates that we were not successful in getting a response from that State, and the policy listed was obtained from a web-site and the web-site address is listed in the table together with the policy for acceptance testing.

In summary, sixty percent (60 %) of the States responding indicated that compressive strength test on cylinders are used for acceptance testing of concrete pavements. Roughly one third of those indicated that for early opening of concrete pavements they would use bending beams. About seventeen percent (17 %) of the respondents indicated that they use both compressive strength cylinders and bending beams for acceptance testing of concrete pavements. About nineteen percent (19 %) of the respondents indicated that bending beams are used exclusively, and in one case "Louisiana" the State is moving to require the use of bending beams in all the projects. The remaining four percent (4 %) indicated that their State did not use Portland cement concrete pavements, but rather all their pavements were asphalt pavements.

Three States indicated that are in the process of switching, or have already done so, to use compressive strength cylinders complemented with concrete maturity measurements. Some of the States using bending beams for acceptance testing indicated that compressive strength tests on cores were performed when the need arose of getting samples from the field rather than cutting beams from the pavement section under dispute.

3. Research Program

3.1 General

The basic approach consisted of preparing Portland cement "PC" concrete specimens that were first tested using a Non-Destructive "ND" wave propagation technique (a free-free resonant column device), and then the specimens were strength tested. The final goal was to provide enough data to establish correlations of the "Seismic Modulus" measured in the ND wave propagation technique to several different failure stresses that were required to reach failure of the specimen.

The same PC concrete mix was used throughout the program. This mix was an approved concrete mix by the North Carolina Department of Transportation. In order to investigate the effects of the variability in the components of the mix, several types of specimens were prepared as follows:

1. Commercially mixed and delivered PC concrete. This mix was supplied by Chandler Concrete Company, Inc. These are the specimens that are called "Ready-Mix," and
2. The "Laboratory-Mixed" that were mixed in our laboratory and were produced in two different ways:
    a. The "Laboratory Batch Mix" for which enough PC concrete was mixed to cast three beams at a time or six, six-inch diameter and three, four-inch diameter cylindrical specimens at a time, and
    b. The "Individual Preparation" for which enough PC concrete was mixed to cast only one specimen at a time.

The Ready-Mix concrete was delivered to our laboratory three different times and the following specimens were prepared each time:

1. Thirty beams,
2. Sixty six-inch diameter cylindrical specimens, thirty for compression testing and thirty for splitting tension testing, and
3. Thirty four-inch diameter cylindrical specimens for compression testing.

The Laboratory-Mixed included fifteen specimens of each type (fifteen each for compression on six-inch and four-inch diameters, fifteen bending beams and fifteen splitting tension tests) for "Laboratory Batch Mix" and fifteen specimens of each type for "Individual Preparations." That is a total of thirty beams, sixty six-inch diameter cylinders, and thirty four-inch diameter cylinders.

All of the specimens were cast, cured, and tested in our laboratory. All of the specimens were left one day in the molds, covered with a plastic tarp and wet towel rags. After de-molding, he specimens were placed in a limed-water bath with temperature controlled to 72^{o}F. The length of the curing period was fixed at the following five times: one day (no bath), two days, seven days, fourteen days, and twenty-eight days.

Upon removal of the specimens from the bath, the "Seismic Modulus" was measured first using the free-free resonant column, and then the specimens were wrapped in wet towel rags, until the strength test could be performed. In the case of the compressive strength specimens, the capping of the specimen was performed with sulfur compounds. After capping, these specimens were wrapped in wet towel rags to allow cooling of the capping compound before performing the compression test.

Materials

All the specimens prepared and tested attempted to reproduce the same concrete mix. This is mix design No. 401TV02PTCE of NCDOT that had been approved for a PCC pavement. Specifically, this is the following mix:

1. Cement, Holly Hill, 576 lbs/y^3
2. Fine aggregate, Hall Pit-Lemon Springs, 1194 lbs/y^3
3. Coarse aggregate, size #57M – Pomona Quarry, 1952 lbs/y^3
4. Water, Greensboro, NC drinking supply, 31.0 gallons
5. Air entrainment, MB AE 90, as needed
6. Water reducer, Pozzolith 80, as needed

The source of cement was not from Holly Hill, but rather Lafarge Cement from Harleyville, SC, which is the regular supplier for Chandler Concrete Company, Inc. These two sources use the same raw materials and the cements are very nearly identical.

The first Ready-Mix batch was prepared using the water reducer WRDA 35. However, due to the long time needed to prepare the 120 specimens of the batch, it was found not to be feasible. In agreement with the NCDOT steering committee, it was decided to use a retarder "DARATARD 17", which allowed for a more fluid mix without adding excess water so as not to exceed a three-inch maximum slump. The remaining two Ready-Mix batches and all the Laboratory-Mixed used retarder rather than water reducer. The air entraining agent used throughout the program was "DARAVAIR 1000."

The water used for mixing by Chandler and in our laboratories was from the drinking water supply from the City of Greensboro. Chandler Concrete Company, Inc. also provided the aggregates, the cement, and the additives to be used in the laboratory program. For the sake of completeness, some laboratory determinations were performed to ascertain that the supplied aggregates were similar to the materials specified in the mix design.

The grain size distribution of the fine aggregate supplied is presented in Figure 3.1 together with Quality Assurance/Quality Control data supplied by NCDOT on the same source of aggregates (Hall Pit-Lemon Springs.) The agreement shown in this graph confirms that the sand supplied is the natural sand requested.

The grain size distribution for the Pomona Quarry coarse aggregate #57M is summarized in Table 3.1 below:

Table 3.1 Percentage Passing for Coarse Aggregate

Sieve Size	NC DOT QA/QC	Project Samples		
		A	B	C
1 in.	97.85	93.07	96.47	98.34
½ in.	26.15	27.33	26.31	32.59

The values listed under this study are the results for three determinations on three different specimens.

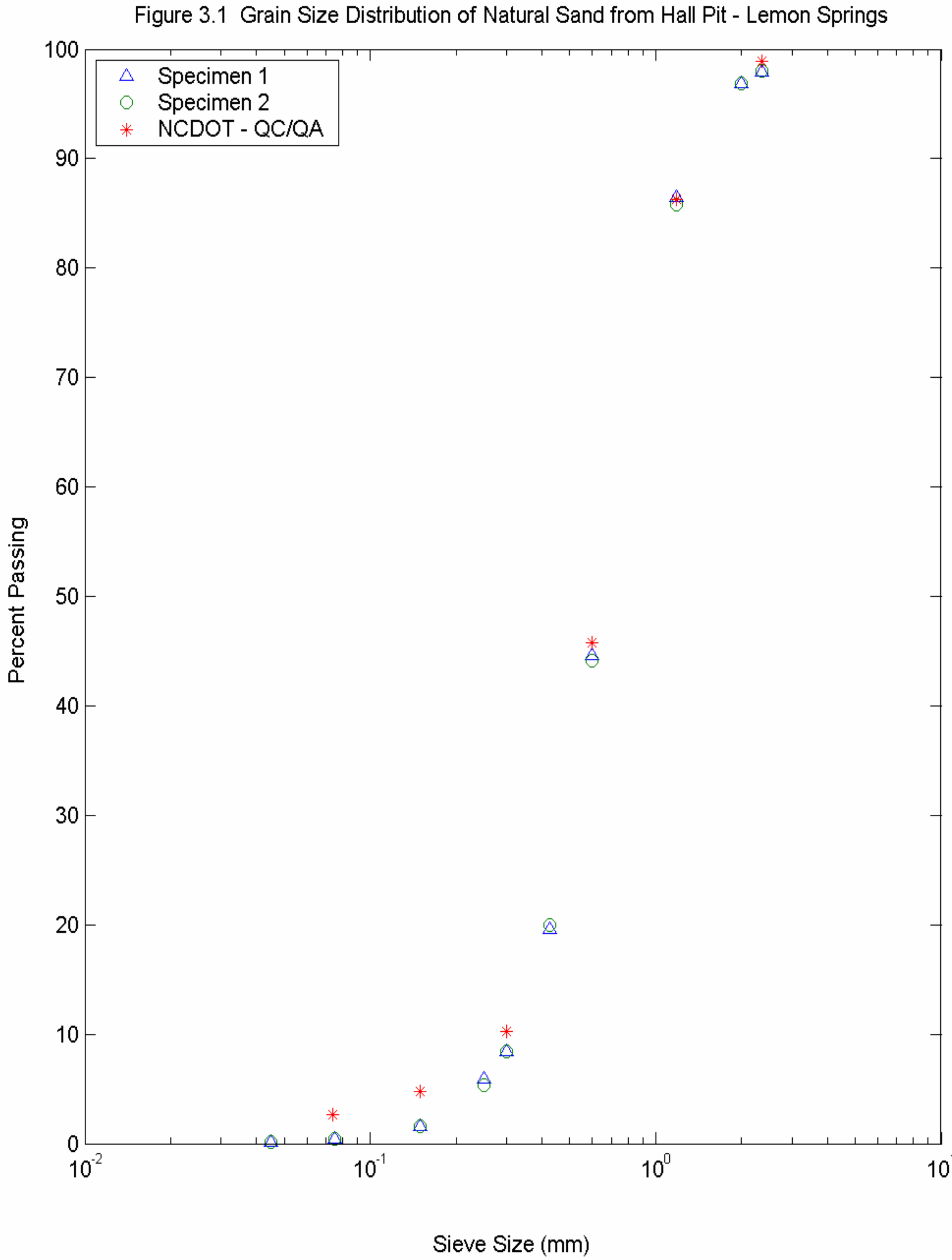


Figure 3.1 Grain Size Distribution of Natural Sand from Hall Pit - Lemon Springs
Specimen 1
Specimen 2
NCDOT - QC/QA
Percent Passing
Sieve Size (mm)
0
10
20
30
40
50
60
70
80
90
100
10^{-2}
10^{-1}
10^{0}
10^{1}

Two specimens of coarse aggregate #57M were found to have absorptions of 0.53% and 0.47% for specific gravities of 2.70 and 2.745, respectively. The absorption of the specimens of fine aggregate (natural sand) were recorded as 0.38%, 0.50%, and 0.45% and the corresponding specific gravities were 2.70, 2.67, and 2.61, respectively. All of these values are sensibly similar to the values specified in the NCDOT mix design summarized below:

1. Fine aggregate:
   Absorption % 0.5
   Specific gravity 2.65

2. Coarse aggregate:
   Absorption% 0.4
   Specific gravity 2.76

3.2 Methodology

Upon the arrival of the delivery truck, the air content and the slump tests were performed on the fresh concrete. The results are summarized in Table 3.2. At the beginning of the program, an initial batch of Laboratory-Mix was prepared to perform air content and slump tests. The results are also shown in Table 3.2.

The preparation of specimens of Ready-Mix was initiated by casting the beams and then, the six-inch diameter specimens and lastly, the four-inch diameter specimens. During the preparation of the specimens for the first batch, the concrete began to set when starting to prepare the six-inch specimens. The vibrator could not fluidize the concrete, and thus it was necessary to add additional water and remix the concrete. The as-delivered concrete was reserved for the 14-day and 28-day curing cycles; thus, the two and seven-day curing cycle specimens were prepared with remixed concrete. This led to the change from a water reducer to a retarder and an increase of the mixing water to an slump of approximately three inches.

Table 3.2 Fresh Concrete Properties

Batch	Dates	Air Content (%)	Slump (in.)
Ready-Mix 1	3/08/04	5.3	1 1/2
Ready-Mix 2	5/10/04	6.3	2 3/4
Ready-Mix 3	5/26/04	5.0	2 7/8
Laboratory Mixes	5/20/04	5.0	3/4

The preparation of Laboratory-Mixed required the separation of the coarse aggregate into three sizes, 1) retained on one inch sieve, 2) passing one inch and retained on one-half inch sieve, and 3) passing one half inch, but retained on sieve No. 4. Although the #57M from Pomona Quarry has some fine material passing the sieve No. 4, this fines were discarded and not included in the preparation of Laboratory-Mixed. Similarly, the fine aggregate was sieved through a No. 4 sieve and only the fraction passing that sieve was used in the Laboratory-Mixed. The coarse aggregate was then reconstituted to reproduce the desired grain size distribution. The actual concrete mix used for every specimen type is presented in Table 3.3. It is worthwhile to point out that all measurements were performed by weight and in Table 3.3, some are in grams, while the remainder are in pounds.

Table 3.3 Weights of Different Components for Laboratory Mixed Specimens

Component	Beam	Six Inch Cylinder	Four Inch Cylinder
Air Entrainer	0.59 gr	0.26 gr	0.08 gr
Retarder	14.43 gr	6.42 gr	1.89 gr
Water	4.510 lb	2.007 lb	0.592 lb
Cement	10.046 lb	2.471 lb	1.319 lb
Sand	20.830 lb	9.260 lb	2.73 lb
Retained 1-inch	0.715 lb	0.318 lb	0.094 lb
Retained ½ inch	24.410 lb	10.860 lb	3.206 lb
Retained on #4 Sieve	8.920 lb	3.969 lb	1.171 lb

The specimens were cast in molds and allowed to set and harden for one day before de-molding. During this initial stage, the specimens were kept covered with a plastic tarp weighted with wet towel rags.

Upon de-molding, the specimens were placed in a limed-water curing bath. The bath was heated, the temperature was set to 72^{o}F, and each bath had a re-circulating pump to homogenize the temperature of the bath. The beams were placed in the bath vertically (that is with the largest dimensions vertical) and the four-inch cylinders were stacked on top of the six-inch cylinders.

The specimens were kept in the bath until the day they were to be strength-tested. At that time, the specimens were measured and tested in the resonant column for seismic modulus and then strength tested. The size measurements were taken with calipers with a resolution of one thousandth of an inch (0.001 inch). To measure weights, several scales were used, ranging from a two hundred pound scale with a resolution of 0.5 pounds, to a metric scale with a capacity of 2000 grams and a resolution of 0.01 grams.

The sizes of the specimens were measured to allow an estimate of unit weight of the concrete. Each type of test specimen had different requirements. Appendix B includes copies of the forms used to track each specimen and record the measurements performed. The form includes warnings/observations on the quality of the specimen and the test as well as the condition of the specimen upon failure. The forms in Appendix B are included only as examples for the five different types of tests implemented.

Upon completion of the size and weight measurements, the specimen was tested using an “Automatic Free-Free Resonant Column Device” marketed by “Geomedia Research and Development.” This is a non-destructive test that allows the calculation of the elastic constants of the specimen based on the resonant frequencies of the specimen. For this determination, the specimens were placed with the longest dimensions vertical on a table and an accelerometer connected to the data acquisition system was held by hand on the top surface of the specimen. A hammer was used to strike the top surface of the specimen. The device picks up the frequencies of the “Primary” or compression wave and the “Secondary” or shear wave. From these two values and the sizes and weights of the specimens, it calculates the elastic modulus (mainly referred to in this report as seismic modulus) and the Poisson’s ratio. The data acquisition system requires that three measurements on three “hits” be averaged out. In the present study, at least three to four sets were performed on each specimen, such as two sets on one side, and the third or the third and fourth on the opposite face, after flipping the specimen. In this manner, it is worth stating that the seismic moduli reported in this report are averages from nine to twelve “hits” per specimen.

The strength testing of the bending beams were performed using a Rainhart portable beam tester that loaded the beams on one-third point loading. The device was on loan from the Materials and Tests group of NCDOT. The device was installed and calibrated at the beginning of the program by personnel of the Materials and Tests group.

The rest of the strength tests were performed using a FORNEY Compression Tester, model LT_0920-D of 400,000 pound capacity. Prior to initiation of the program, Southern Calibration and Service calibrated the device on December 17, 2003 and found it to be in compliance of the 1% tolerance required.

Upon reaching failure for each specimen, some additional data was collected on the failed specimen. The additional information was different for each type of specimen and is indicated on the examples of data collection sheets shown in Appendix B. Furthermore, a digital picture was recorded to illustrate the failure mode.

3.4 Results

3.4.1 Introduction

The final results for each test consisted of the strength measured upon failure of the specimen and the seismic modulus recorded on the specimen prior to strength testing. These results are presented in table form in the following appendices:

1. Appendix C -- Compressive Strength Results
   Obtained on Four by Eight Inch Specimens
2. Appendix D -- Compressive Strength Results
   Obtained on Six by Twelve Inch Specimens
3. Appendix E -- Results of Modulus of Rupture
   Obtained by One-Third Point Loading in Bending Beam Tests
4. Appendix F -- Split Tensile Strength Results
   Obtained on Six by Twelve Inch Specimens

In each appendix, the specimen identification is listed first. This identification consists of four fields. The first field indicates the type of specimen, such as the following:

1.) B0 - for a twenty inch long bending beam
2.) B1- for a twenty-one inch long bending beam

3.) SC - for a six-inch by twelve-inch specimen for splitting tension.
4.) C4 - for a four-inch by eight-inch specimen for compressive strength.
5.) C6 - for a six-inch by twelve-inch specimen for compressive strength.

The second field indicates the length of the curing period. For example, fourteen (14) indicates, one day hardening in the mold and 13 days in the curing bath. The third field indicates the type of concrete batch with the following key:

1. R – Ready-Mix concrete
2. L – Laboratory Batch Concrete, and
3. I – Individual Specimen Preparation

The fourth field indicates a specimen number unique to each specimen correlative for all the specimens in the category indicated in the first field. This explanation of the identification code is also presented in each form included in Appendix B.

The rest of data included in the tables of the appendices are the average specimen sizes, weights or unit weights, the average seismic modulus, and the calculated strength at failure.

3.4.2 Test Variability

The different tests used in the present research program have well established variability that can be found in the ASTM Standards or the AASHTO Materials Handbook. A summary of the coefficients of variation to be expected is presented in Table 3.4.

From these data, it is clear that the less repeatable tests are the flexural strength tests and the splitting tensile strength. The less variable of all is the resonant frequency determination, which has similar variability to the seismic modulus.

At the beginning of the research program and in order to train the student team, twenty-five cylinders and twenty-five beams of a PC concrete mix (different than the reported) were prepared and tested. The variability obtained in these series of tests was of the same order of magnitude than the values shown in Table 3.4. The compression tests results, especially, showed a coefficient of variation of 1.55% and the modulus of rupture exhibited a coefficient of variation of 6.67%.

Table 3.4 Coefficient of Variation of the Different Tests Used

ASTM STANDARD	TEST	COEFFICIENT OF VARIATION
C39-99	Compressive Strength	2.37%
C8-02	Flexural Strength	5.7%
C496-96	Splitting Tensile Strength	5%
C215-97	Resonant Frequency (average of three)	0.6%

The maximum number of repetitions for the same batch and the same curing time is the six specimens of Ready-Mix concrete. This number of repetitions is large to allow a reliable estimate of the coefficient of variation. Nevertheless, the coefficients of variation for all the test performed on Ready-Mix concrete specimens for the strength parameters and the seismic modulus are summarized in Tables 3.5 through 3.8.

The results in Table 3.5 show the coefficients of variation of bending beam tests. It is worthwhile to point out that the values reported for the modulus of rupture are similar to the value of 5.7% by ASTM. Since the beam specimens were always the first to be prepared, there appear not to have been much affected by workability of the Ready-Mix concrete batch. It is also important to notice that the corresponding values of coefficient of variation of seismic modulus are consistently lower, in some cases, by a factor of four. Furthermore, it is necessary to keep in mind that these coefficients of variation of the seismic modulus are on different specimens.

Table 3.5 Coefficients of Variation (%) for Ready-Mix Concrete Beams

Modulus of Rupture			
Curing Time (days)	**First Batch**	**Second Batch**	**Third Batch**
1	7.40	2.81	4.91
2	8.76	0.30	5.52
7	4.16	3.41	4.24
14	2.39	2.65	6.58
28	3.09	7.82	4.68
Seismic Modulus			
1	3.32	1.21	1.87
2	5.96	2.56	1.12
7	0.99	0.92	1.58
14	2.32	1.37	1.85
28	0.62	0.51	1.61

Table 3.6 Coefficients of Variation (%) for Ready Mix Concrete in Split Tension

Tensile Strength			
Curing Time (days)	**First Batch**	**Second Batch**	**Third Batch**
1	-	14.87	7.66
2	18.36	22.75	7.61
7	14.11	8.84	6.08
14	7.78	9.47	4.52
28	5.88	10.98	3.69
Seismic Modulus			
1	-	8.03	5.52
2	12.69	10.43	1.57
7	5.43	7.14	1.97
14	1.22	3.57	0.72
28	5.96	4.53	2.08

Table 3.7 Coefficients of Variation (%) for Ready-Mix Concrete Six-Inch Cylinders

Compressive Strength			
Curing Time (days)	**First Batch**	**Second Batch**	**Third Batch**
1	-	11.59	9.55
2	15.94	16.25	3.64
7	9.90	12.04	2.78
14	8.67	9.04	2.02
28	7.49	11.52	10.09
Seismic Modulus			
1	-	3.28	4.11
2	10.43	11.26	2.09
7	4.71	4.42	1.76
14	1.38	4.53	1.17
28	5.48	5.15	3.21

Table 3.8 Coefficients of Variation (%) Ready-Mix Concrete, Four-Inch Cylinders

Compressive Strength			
Curing Time (days)	**First Batch**	**Second Batch**	**Third Batch**
1	-	6.08	3.98
2	7.17	12.29	6.99
7	7.89	8.07	5.04
14	2.25	8.31	3.76
28	17.84	4.42	5.74
Seismic Modulus			
1	-	5.40	2.84
2	8.58	8.84	3.70
7	3.12	6.37	3.54
14	7.19	5.91	0.62
28	12.03	3.29	1.29

The results shown in Table 3.6 indicate that the coefficients of variation were significantly higher than the 5.0% reported by ASTM. This is especially true for batches one and two. It is important to realize that the fourteen and twenty-eight days were always the first specimens finished and thus the specimen variability should be lower. This fact is clear for the first batch. The results on the seismic modulus show similar patterns and, in general, the coefficients of variation are lower, in some cases, by a factor of four. The higher values of the coefficients of variation have to be attributed to the poor workability of the fresh concrete when these specimens were cast.

Very similar considerations can be drawn from the results presented in Table 3.7 on compressive strength of six-inch specimens. The coefficient of variation reported by

ASTM is 2.37%. The values for the third batch are of this order of magnitude. For the other two batches, the values are noticeably higher, probably indicating problems of workability of the fresh concrete mass when these specimens were cast. The seismic modulus did consistently exhibit somewhat lower coefficients of variation, in some cases by a factor of six.

The coefficients of variation observed on the results of four-inch compression cylinders are presented in Table 3.8. These results appear to be generally higher, especially for the third batch. This fact would be consistent with the poor workability of the concrete mass at the time of casting these specimens that were the last to be cast. The coefficients of variation of the seismic modulus are also consistently lower than those for the compressive strength.

The results presented in Tables 3.5, 3.6, 3.7, and 3.8 indicate that the coefficients of variations in the Ready-Mix batches of this program were clearly higher than the reported values by ASTM for each test. One possible reason, at least partially, is the fact that these values are based on only five or six repetitions and it is not reasonable to expect a very close approximation to the reported values. However, it appears that there are some trends indicating that the larger coefficients of variation can be attributed to problems of poor workability of the fresh concrete mass when casting the specimens.

One important aspect to highlight is the magnitude of the coefficient of variation of the seismic modulus that hovers around one to two percent when the corresponding coefficient of variation of the strength parameter is close to the ASTM reported value. This coefficient of variation was obtained using determinations on five or six different specimens. The coefficient of variation reported by ASTM is 0.6%.

More importantly, the coefficient of variation of the seismic modulus that is of interest to the present research project is the observed coefficient of variation on repeated determinations on the same specimen. For this purpose, two specimens were selected, one with a compressive strength of 265 psi representative of a soft, almost soil-like mass, and the second with a strength of 5,875 psi, more representative of the concrete specimens produced in the present research program.

The two circular faces were marked with a center point and four points, such as north, south, east, and west on two perpendicular diameters. The accelerometer was placed in each of the five locations, while the hammer strike was moved through the remaining points. This provided twenty measurements on each face, or a total of forty measurements per specimen. The coefficient of variation for each specimen was calculated for individual measurements, and for average of twelve measurements. The results are summarized in Table 3.9.

In the present research program, the seismic moduli reported are the result of the average of from three to four sets of measurements and each set is the average of three strikes. Thus it is expected that the coefficient of variation of the seismic modulus reported is between one and two-tenths of a percentage point.

Thus the variability of the seismic modulus is very small; when this value is compared with the coefficients of variation to be expected of 2.37%, 5%, and 5.7%, of the strength tests, it is from twenty to sixty times smaller. In this manner, the variability of the seismic modulus is considered negligible and the values reported are considered to be true values.

Table 3.9 Coefficients of Variation (%) of Seismic Modulus on a Single Specimen

Number of Test in Average	Soft Specimen	Hard Specimen
One	0.91	0.37
Three	0.5	0.23
Twelve	0.27	0.11

3.5 Statistical Analyses

One of the many advantages of the seismic modulus determination is that the test is non-destructive, and thus allows performing a destructive test on the same specimen. This fact permits ranking of each specimen based on the seismic modulus and eliminates the need to use other less reliable variables, such as curing time. This advantage will become apparently clear when the results of the test program are discussed in the next chapter in view of the large variability discussed in section 3.4

An added advantage, complementing the previous one, is the low variability of the seismic modulus. In the present report, the seismic modulus is the result of averaging nine to twelve determinations and, thus, it is considered to have negligible variability; in other words, it is considered to be a constant.

These considerations allow the analyzing of the results of the test program by plotting a regression line of each strength parameter to the seismic modulus determined on the same specimen. Two alternative approaches were used to characterize this relationship. The first consisted of using all data points (individual specimen results) and define the linear regression of the square root of the strength to the seismic modulus. The second approach consisted of averaging all the strength measurements and all of the seismic modulus measurements for all the specimens of each batch; that is for the Ready-Mix specimens, the average of six determinations and for the Laboratory-Mixed, the average of three determinations. Then the regression line was defined using the square root of the average strength to the average seismic modulus.

Using the regression line to predict the strength from the value of the seismic modulus would result in over-predicting the strength in fifty percent of the cases. Nevertheless, the regression line is obtained from a small sample of measurements and thus, will have some error. Quantifying the risk is necessary to consider the total number of observations and the variability of the results collected. This is traditionally approached by defining a confidence interval, which requires the selection of an acceptable error level. In this report, the ninety-five percent confidence interval is consistently reported. The meaning of this confidence interval is that if it is defined for several different sets of observations (the present study is only one set), the ninety-five percent confidence interval will have a probability of 0.95 to include the true regression line of the population; that is, this interval will include the true regression line in ninety-five percent of the cases.

The lower bound of this interval is the most useful to predict the strength from the seismic modulus. In the manner that we have a probability of 0.975 that the regression line would not be lower than this lower bound. Nevertheless, for individual observations, there is still a fifty percent chance that the strength would be over-predicted. To approach the risk for individual observations it is necessary to look at the prediction interval that will be discussed later in this section.

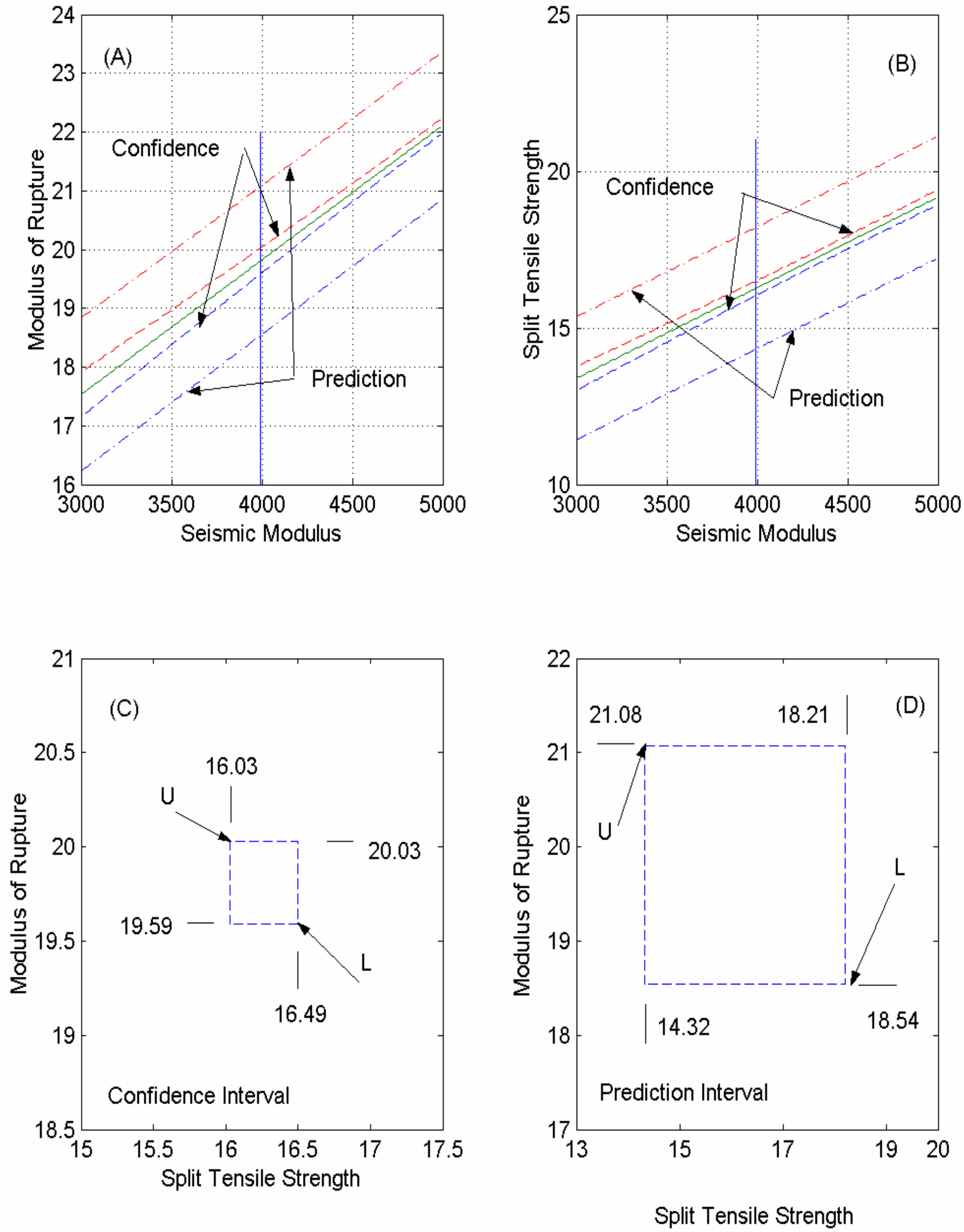
An additional aspect that has been analyzed is whether the results from several different batches (like Ready-Mix and Laboratory-Mixed) are different realizations from the same population. In other words, should all of the results be lumped into one single regression. The traditional approach is to perform a hypothesis test of whether the regression lines of the two data sets are equal for a chosen level of significance. If the level of significance chosen is five percent, the hypothesis test is equivalent to whether the ninety-five percent confidence intervals of the two sets overlap or not. If the two ninety-five percent confidence intervals do not overlap, indicates that the available data supports the rejection of the null hypothesis that the two regression lines are the same with only a five percent probability of error. If the null hypothesis is rejected, the two data sets have to be analyzed independently. As it is described in the discussion of results chapter, it was found necessary not to lump together the Ready-Mix batches and the Laboratory-Mixed batches.

Rather than using the regression line, to describe the relationship of the strength parameter and the seismic modulus, an alternative approach would be to define a "prediction interval" for any desired level of probability (in this report, the value chosen is ninety-five percent) that the interval will bracket any future observation of strength and seismic modulus. The confidence interval is intended to bracket a population parameter: the mean. The prediction interval is an interval that has a probability (0.95 as used in this report) of bracketing, not a population parameter, but a future value or observation. Thus as used in this report, the ninety-five percent prediction interval has a probability of 0.95 to enclose a future observation. The more relevant of the two bounds, to the present application, would be the lower bound. When this is used to predict the strength from the seismic modulus, a probability of 0.975 exists of not over-predicting the strength.

The two lower bounds discussed are probably the extreme cases to limit the set of all possible cases ranging from a probability of 0.975 of not over-predicting the mean strength for the lower bound of the confidence interval to 0.975 for the lower bound of the prediction interval. The main parameter that has to be selected is the acceptable risk level of not over-predicting the strength. This consideration will clearly involve the economic repercussions on the cost of the pavement. Thus a compromise acceptable to all parties (owner, design engineer, construction engineer, and contractor) would have to be selected.

A further advantage of performing seismic modulus measurements is the fact that this parameter allows to bridge between two different strength tests. A possible approach is illustrated in Figure 3.2. The graph A shows a hypothetical regression line and confidence and prediction intervals between the modulus of rupture and the seismic modulus, and the graph B shows the regression line of split tensile strength versus seismic modulus and the corresponding confidence and prediction intervals. For a value of the seismic modulus of 3,994.3 ksi, the two graphs indicate the following values of strength for the regression line:

Figure 3.2 Approach Used to Relate Strength Parameters through the Seismic Modulus



1. square root of Modulus of Rupture 19.81 (psi $^{1/2}$)
2. square root of Split Tensile Strength 16.26 (psi $^{1/2}$)

By defining pairs of these values for other values of seismic modulus, it is possible to establish the regression line between modulus of rupture and split tensile strength.

Similarly, for the 95% confidence interval, the same value of seismic modulus produces the following limits for the modulus of rupture:

1. upper bound 20.03 (psi $^{1/2}$), and
2. lower bound 19.59 (psi $^{1/2}$)

The limits for the Split Tensile Strength are the following:

1. upper bound 16.49 (psi $^{1/2}$), and
2. lower bound 16.03 (psi $^{1/2}$)

The graph C of Figure 3.2 shows these values defining a rectangular area in the plot of modulus of rupture versus split tensile strength. In this rectangle, there are two vertices labeled “U” and “L”. When the same exercise is performed for other values of the seismic modulus, the points “U” and “L” trace the upper and lower bounds of an “alpha” confidence interval on the regression line of the modulus of rupture versus split tensile strength. The value of “alpha” has to be based on the following considerations:

1. The probability that the mean modulus of rupture would be bracketed into 20.03 (psi $^{1/2}$) and 19.59 (psi $^{1/2}$) is 0.95;
2. The probability that the mean splitting tensile strength would be bracketed into 16.49 (psi $^{1/2}$) and 16.03 (psi $^{1/2}$) is 0.95;
3. The probability that both limits would bracket both means at the same time is the product of the two following probabilities :
   $P(A \cap B) = P(A) * P(B/A)$
   where:
   $P(A \cap B)$ is the probability that the rectangle shown in graph C of Figure 3.6 encloses the point defined by the two means,
   $P(A)$ is 0.95 the probability that the mean splitting tensile strength is enclosed by 16.03-16.49 (psi $^{1/2}$),
   $P(B/A)$ is the conditional probability that the mean modulus of rupture is enclosed by 19.59-20.03 (psi $^{1/2}$) given that A has already occurred. Although this probability is not known, the worst possible case would be if A and B are independent. In that case, $P(B/A) = P(B)$ which is also 0.95.

Thus, the probability of both confidence limits enclosing simultaneously the respective means is in the worst possible case 0.95*0.95; which is approximately 0.90. Therefore, the loci traced by the vertices “U” and “L” would be in the worst case, the ninety-percent confidence interval of the regression line of modulus of rupture versus splitting tensile strength.

A similar approach has also been followed with the prediction intervals and this is illustrated in graph D of Figure 3.2. The rationale is identical to the one described above for the confidence interval and the results indicate that points "U and "L" in graph D trace upper and lower bounds of ninety-percent (in the worst possible case) prediction interval.

Since these intervals are ninety-percent confidence or prediction intervals, when the lower bound is used as the limiting relationship acceptable, the probability of not over-predicting is 0.95. Since the 10% error would be distributed as 5% exceeding the upper bound and 5% under-predicting the lower bound. Thus if the modulus of rupture is predicted from the split tensile strength using these lower bounds, it would entail a risk of five percent of over-predicting the modulus of rupture. All of the regression lines and lower bounds of confidence and prediction intervals were produced numerically and are presented in graphs later.

3.6 Additional Work

As will be documented in the discussion of the results, the regression lines for Ready-Mix and Laboratory-Mixed were found to be significantly different for all the strength tests. The reason for this disparity was not apparent, and thus some additional compression tests on four by eight inch specimens with slight modifications of the concrete mix were implemented. This additional work was an attempt to gather some data that could indicate the source of this disparity.

In this manner, three modified concrete mixes were included and are labeled MOD1, MOD2, and MOD3. For each mix, fifteen specimens were cast and tested; the only exception was MOD2, since for that mix the batch was repeated. This was because in the first batch, there were a large number of specimens that swelled in the mold during the first day of hardening. The explanation of the phenomenon is not apparent. Nevertheless, the specimens were cut and tested and are included in the results; but as a precaution, the MOD2 was also repeated.

A summary of all of the weights of the different components needed to prepare a four-inch diameter by eight-inch long specimens are presented in Table 3.10 together with the same data for the regular mix used throughout the program.

Table 3.10 Regular & Modified Concrete Mixes for a Four Inch Diameter Specimen

Component	Regular	MOD1	MOD2	MOD3
Air Entrainer	0.08 gr	0.08 gr	0.09 gr	0.25 gr
Retarder	1.89 gr	1.89 gr	2.229 gr	1.24 gr
Water	0.592 lb	0.592 lb	0.698 lb	0.592 lb
Cement	1.319 lb	1.319 lb	1.319 lb	1.319 lb
Natural Sand	2.735 lb	2.735 lb	2.735 lb	2.735 lb
Retained 1-inch	0.094 lb	0.094 lb	0.094 lb	0.094 lb
Retained ½-inch	3.206 lb	2.886 lb	2.886 lb	3.206 lb
Retained #4	1.171 lb	1.171 lb	1.171 lb	1.171 lb
Passing #4	0	0.320 lb	0.027 lb	0

The main reason for the mix MOD1 was to elucidate the effect of the presence of fines in the coarse aggregate. This was attempted by decreasing the fraction of aggregate passing 1 inch and retained on 1/2 inch, and substituting it with the fraction of coarse aggregate passing the No. 4 sieve. This is clearly a possible difference between the Ready-Mix and the Laboratory-Mixed. Since all the coarse aggregate passing the number 4 sieve had been removed

The reason behind the MOD2 was to compare the effect of increasing the water to achieve a slump of three inches, thus most of the aggregate passing sieve No. 4 was replaced by water in the mix. The volume of water needed to achieve a three-inch slump, was subtracted from the volume of coarse aggregate passing the No. 4 sieve. The reason behind MOD3 was to investigate the effects of increasing the air entraining agent that was increased by a factor of three for this mix.

The results of the additional work are presented in Appendix G.

4. Discussion of Results

4.1 General

The relationship of each strength parameter to the seismic modulus is examined in separate sections. These are followed by two sections looking at the prediction capabilities of split tensile strength and compressive strength to estimate the modulus of rupture in flexural strength tests. The last section discusses the results of the additional work performed to help explain the difference between Ready-Mix and Laboratory-Mixed specimens.

For the purpose of clarity and to avoid an excessive number of figures in the body of the report, all of the regression lines are included in the following appendices:

1. Appendix H Regression Results of Modulus of Rupture vs. Seismic Modulus
2. Appendix I Regression Results of Split Tensile Strength vs. Seismic Modulus
3. Appendix J Regression Results of Compressive Strength vs. Seismic Modulus
4. Appendix K Regression Results of Modulus of Rupture vs. Split Tensile Strength
5. Appendix L Regression Results of Modulus of Rupture vs. Compressive Strength

In each of the appendices (H, I, and J) there is a set of eight figures. The figures show the regression line and the ninety-five percent confidence and prediction intervals and are ordered in the following sequence:

1. Includes the individual results on Ready-Mixed specimens, and is the regression of the square root of the strength;
2. It is the same as in number one, except for the natural scale of the strength;
3. Includes the individual results on Laboratory-Mixed, and is the regression of the square root of the strength;
4. It is the same as in number 3, except for a natural scale of the strength ;
5. Includes the average of six specimens of Ready-Mixed concrete, and is the regression of the square root of the strength;
6. It is the same as in number five, except for a natural scale of the strength;
7. Includes the average of three Laboratory-Mixed specimens, and is the regression of the square root of the strength; and
8. It is the same as in number seven, except for a natural scale of the strength.

In the remaining appendices (K and L) there are four figures in each appendix. These figures are enclosed in the following sequence:

1. It shows the regression line and the intervals obtained using the individual results for Ready-Mixed specimens.
2. It is a similar graph as in 1. but prepared using the individual results of Laboratory- Mixed specimens.
3. It is the same as in 1., but based on the averages of each batch of six Ready-Mixed specimens, and
4. It is the same as number two, but based on the averages of every batch of three Laboratory-Mixed specimens.

4.2 Results of Flexural Strength on Bending Beams.

All the individual results obtained are presented in Figure 4.1. The results are plotted with different symbols for the batches of Ready-Mixed and Laboratory-Mixed. From this figure, it is apparent that the Laboratory-Mixed batches reach higher strength and higher seismic modulus. This is consistent with the fact that the slump of the Laboratory-Mixed concrete was significantly smaller than the three inch slump of batches 2 and 3 of Ready-Mixed concrete.

It is also worthwhile to notice that the Ready-Mix concrete of batch 1 did have a slump of 1½ inch and no additional water was added to the concrete used in the casting of the beam specimens. Thus, at the early ages of one and two days, the strength of the batch 1 is somewhat higher than batches 2 & 3, but similar to the early strength of the Laboratory-Mixed concrete. This fact is a manifestation of the similarity in slumps of the concrete used in these two batches. It is also important to notice that, at this early stage, the seismic modulus is higher for the Laboratory-Mixed specimens. This fact could be related to the casting of the specimens that was more thorough for the Laboratory-Mixed specimens than for the Ready-Mix specimens.

Another apparent fact from this figure is the separation of the points plotting the Ready-Mixed specimens and the ones for Laboratory-Mixed specimens. These two sets of data do not appear to be random observations from the same population. To analyze this difference, a regression line and the corresponding ninety-five percent confidence interval was established for the two sets of data. The results are plotted in Figure 4.2. This figure shows that the trends indicated by both sets of data cannot be considered to be random observations from the same population. The implication is that for a ninety-five confidence level the two data sets do not have a common regression line and thus have to be analyzed separately. Consistent with this finding the two sets of data have been considered separately in the rest of this section.

The regression lines and intervals of the data are included in Appendix H. The determination coefficients (R^2) calculated for these two sets of data are the following:

1) Ready-Mixed batches 0.870
2) Laboratory-Mixed 0.905

Also included in Appendix H are the regression lines and intervals for the average of six Ready-Mixed specimens and the average of three Laboratory-Mixed. The determination coefficients (R^2) calculated with the averages indicated are the following:

1) Ready- Mix average of six 0.942
2) Laboratory-Mixed average of three 0.957

Clearly when the results of each batch are averaged, the coefficients of determination (R^2) increase for both sets of data, indicating a decrease of variability around the regression line.

To provide an example of the different limits developed in the regression line and the intervals detailed in Appendix H, an arbitrary value of the modulus of rupture of 500 psi was selected as the value required by the pavement design engineer. From the natural scale graphs, the required seismic modulus are read; these results are shown in Table 4.1 below.

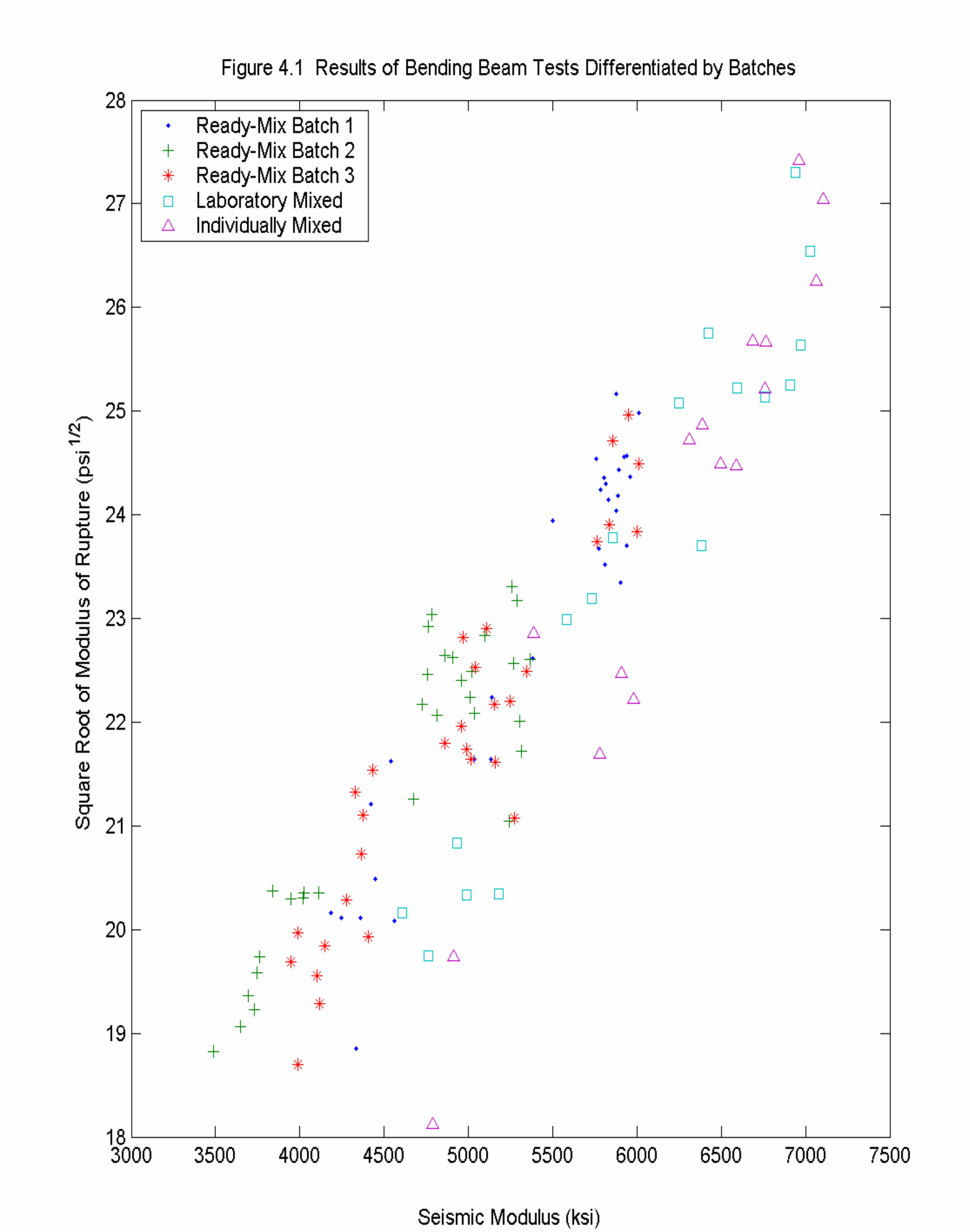
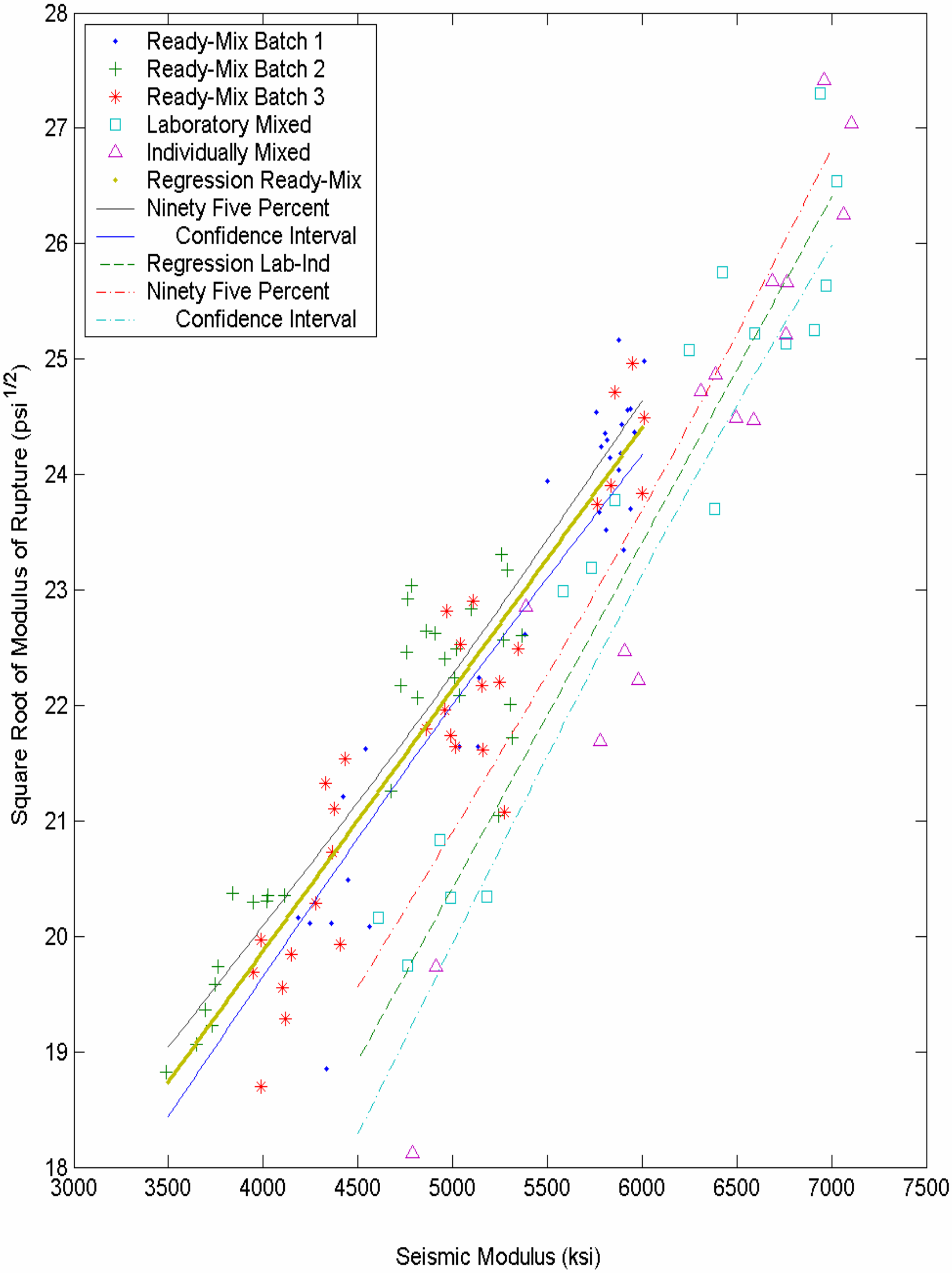


Figure 4.1 Results of Bending Beam Tests Differentiated by Batches
Ready-Mix Batch 1
Ready-Mix Batch 2
Ready-Mix Batch 3
Laboratory Mixed
Individually Mixed
Square Root of Modulus of Rupture (psi 1/2)
Seismic Modulus (ksi)
28
27
26
25
24
23
22
21
20
19
18
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500

Figure 4.2 Regression Lines for Bending Beam Test Results



The data suggests that the results for the Ready-Mixed batches are significantly different than the Laboratory-Mixed, as discussed earlier. Nevertheless, the patterns of the effects of averaging the results or using confidence versus prediction intervals are similar. Thus only the case of Ready-Mixed specimens is discussed below.

Table 4.1. Seismic Modulus (ksi) Required for a Five Hundred (psi) Modulus of Rupture

	Mean Regression	**95% Lower Bound of Mean**	**95% Lower Bound Prediction Interval**
Individual Ready-Mixed	5,084	5,132	5,663
Average of six Ready-Mixed	5,080	5,210	5,532
Individual Laboratory-Mixed	5,650	5,744	6,175
Average of Three Laboratory-Mixed	5,661	5,806	6,080

The average value of the mean of different random samples is 5,080 Ksi. The lower bound of the ninety-five percent confidence interval of the mean, of different random samples, is 5,132 Ksi when the regression is defined using all individual results and 5, 210 Ksi when the results of all six specimens in a batch are first averaged and the regression established using the averages. The decrease in variability produced by averaging the results does not offset the loss in number of observations, since six observations are reduced to one. This fact is confirmed by the increase to 5, 210 Ksi. The meaning of this value is that, when using batch averages, in order to achieve a mean of, the average modulus of rupture, 500 psi, it would be necessary to require an average seismic modulus of 5,210 ksi. For this value of the mean seismic modulus, the associated probability of not having over predicted the mean of the average of the modulus of rupture is 0.975. Alternatively, there is only a probability of 2.50% that the mean modulus of rupture would be lower than 500 psi.

The effect of averaging the results for each batch is the opposite for the prediction interval. The required seismic modulus decreases from 5,663 Ksi for the individual results to 5,532 Ksi for the averages. The implication is that the prediction interval is more sensitive to the variability of the data points than to the number of data points available to define the regression. Since averaging the results decreases the variability (increases the coefficient of determination) as discussed earlier. The meaning of this result is that for a mean modulus of rupture of 500 psi, it would be necessary to require a mean seismic modulus of 5,532 Ksi. The associated probability of not having over predicted the average of six is 0.975. Alternatively, the probability that an average seismic modulus of 5,532 ksi would result in an average modulus of rupture of less than 500 psi is 2.50%.

4.3 Results of Splitting Tensile Strength

All the splitting tensile strength test results obtained are summarized in Figure 4.3. In this graph, different symbols are used to show the different batches of Ready-Mixed and Laboratory-Mixed specimens. The Laboratory-Mixed specimens reached higher strength and seismic modulus. This fact is consistent with the lower slump of the Laboratory-Mixed specimens versus the slump of the batches 2 and 3 of Ready-Mixed specimens.

It is worth noticing that the 28 and 14-day specimens of batch 1 yield higher strength and seismic modulus than batches 2 and 3. The 7 and 2-day specimens of batch 1 had to be prepared with concrete remixed with an undetermined amount of water to achieve some workability of the fresh concrete. This additional water resulted in these specimens (7 and 2-day) yielding lower strength and seismic modulus. It is remarkable that despite of having to remix water with the concrete, the results still plotted around the same trend of the rest of the batches. This is a clear advantage of using a non-destructive testing tool to rate the specimens.

The separation of Ready-Mix and Laboratory-Mixed specimens is also apparent in Figure 4.3, in a fashion similar than observed for the flexural strength tests. Again to analyze the difference in trends, regression lines and the corresponding ninety-five percent confidence intervals were calculated for both sets of data. The results are shown in Figure 4.4. The implication of the lack of overlap of the two sets of ninety-five percent confidence intervals is that the two data sets cannot be considered to be from the same population. It is thus necessary to consider these two sets of data separately. In the rest of this section these sets of data are analyzed separately.

The regression lines and intervals for these two sets of data are included in Appendix I. The determination coefficients (R^2) calculated for the two sets of data are the following:

1) Ready-Mixed batches 0.896
2) Laboratory-Mixed batches 0.932

It is worthwhile to compare these coefficients to the corresponding ones for the modulus of rupture: 0.896 ought to be compared to 0.870 and 0.932 to 0.905. The results of the program indicate that the variability of splitting tension strength is somewhat lower than for the flexural strength. This finding is consistent with the variability reported in the literature for these two tests. When the results are averaged for each batch and then the regression is defined on the averages, the determination coefficients are the following:

1) Ready-Mixed average of six 0.958
2) Laboratory-Mixed average of three 0.942

These coefficients of determination are very similar to those obtained for flexural strength when averaging the results. Thus using the correlations developed with the averages could prove to be a more consistent approach.

To provide a descriptive example of the results included in Appendix I, an arbitrary splitting tensile strength of 400 psi. is selected as the minimum required. Using

Figure 4.3 Results of Split Tension Tests Differentiated by Batches

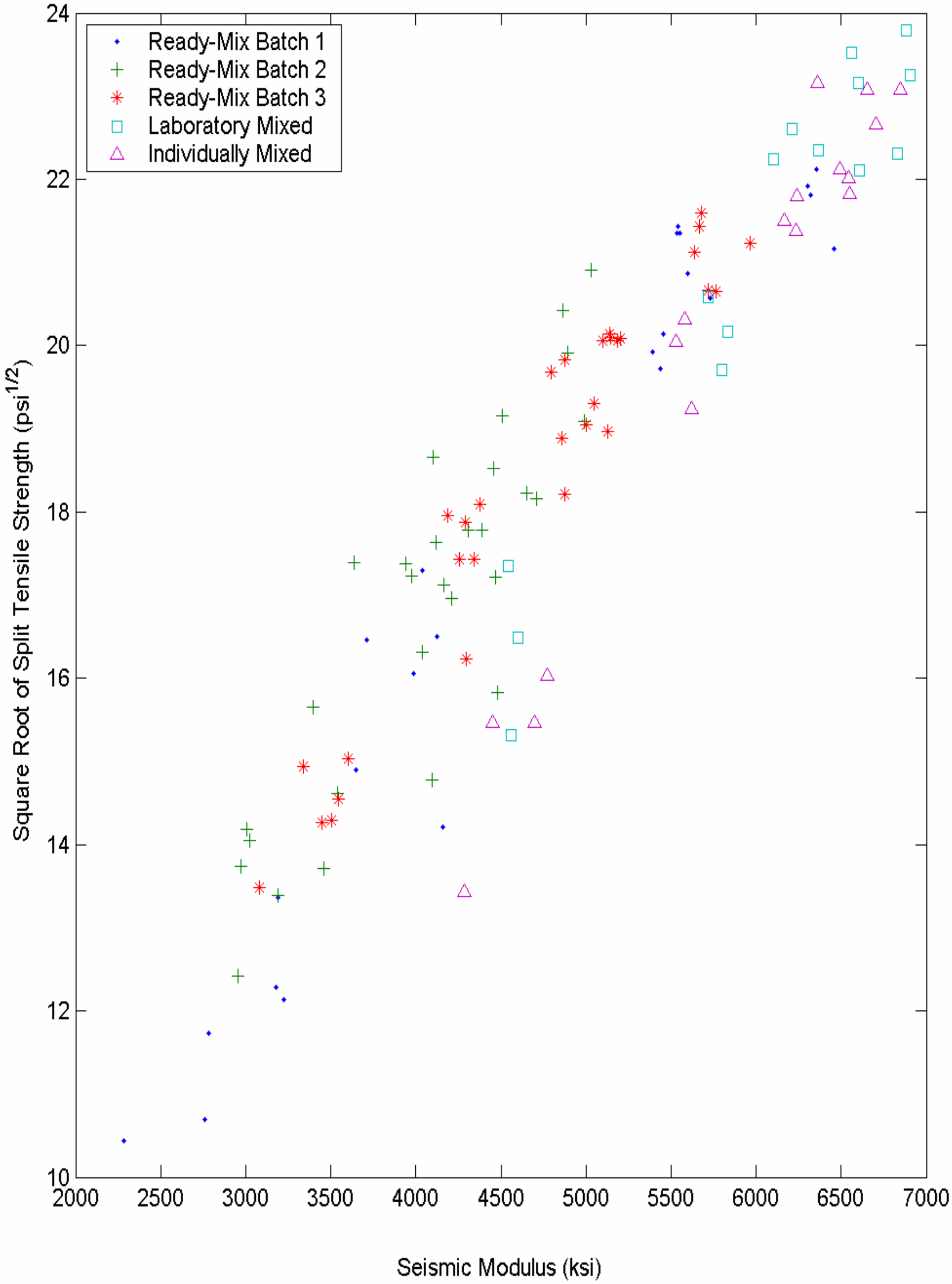
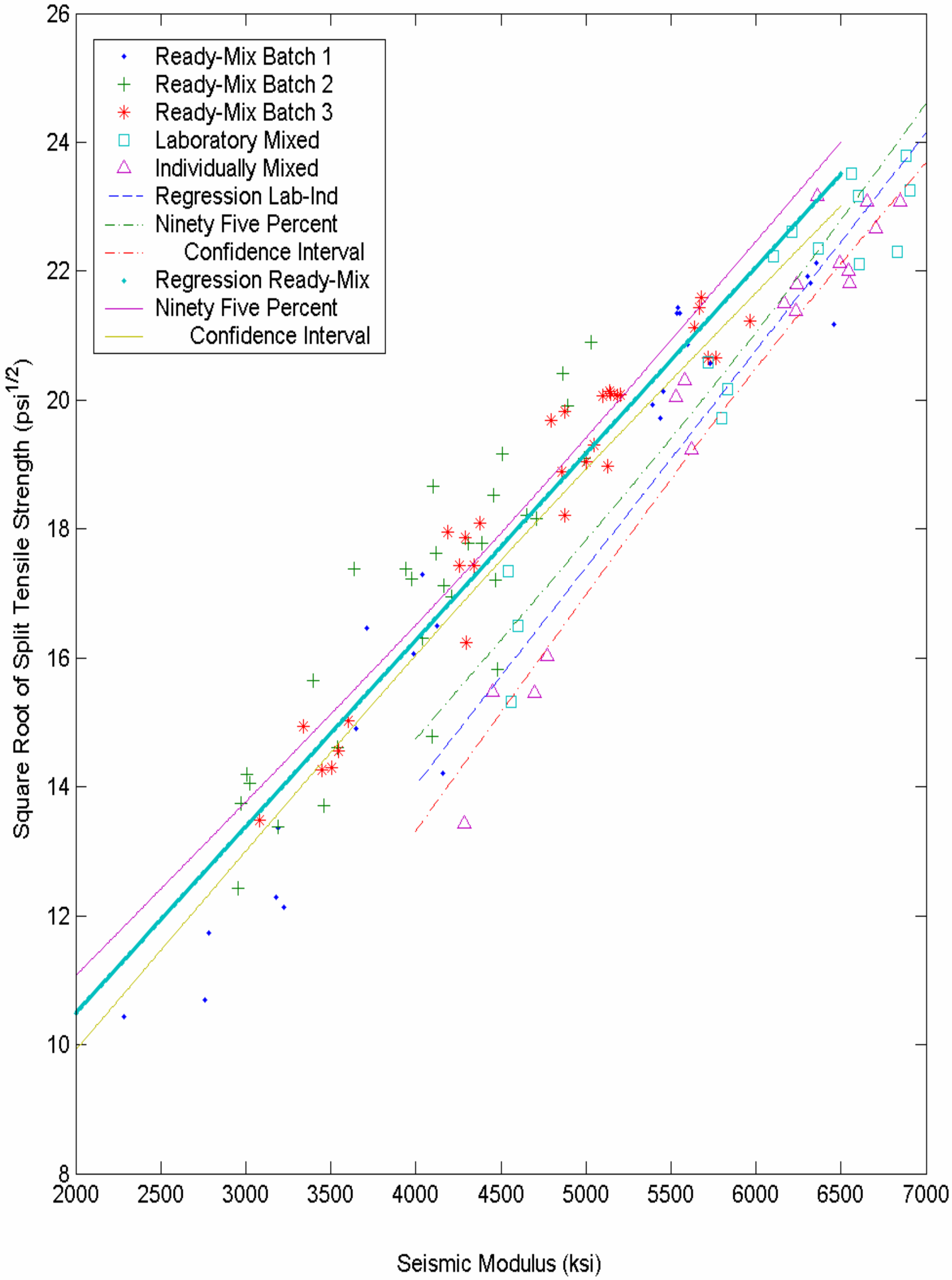


Figure 4.4 Regression Lines for Split Tension Tests Results



the graphs in natural scale, the required seismic modulus was read; these results are shown in Table 4.2.

Table 4.2 Seismic Modulus (ksi) Required for Four Hundred (psi) Split Tension Strength

	Mean Regression	95% Lower Bound of Mean	95% Lower Bound Prediction Interval
Individual Ready-Mix	5,290	5,387	5,968
Average of six Ready-Mix	5,274	5,446	5,769
Individual Laboratory-Mixed	5,769	5,882	6,258
Average of three Laboratory-Mixed	5,561	5,721	6,075

The patterns exhibited by these results are very similar to those described for the modulus of rupture. The only discrepancy occurs with the ninety-five percent confidence interval that the lower bound decreases when averages for batches of Laboratory-Mixed specimens are considered. It is also worth to point out, that the individual results in some cases include more specimens than the corresponding averages which were only performed on complete batches. These could explain some of the differences in the mean of the regression line. Another source of error can be attributed to errors in reading the data from a graph.

4.4 Results of Compressive Strength Test

The results of all compressive strength tests on six-inch diameter specimens are shown in graphical form in Figure 4.5. These results are plotted using different symbols for the different concrete batches. The results show nearly identical tendencies as those discussed for the flexural and splitting tension strength results.

The major advantage of using the seismic modulus to rate the specimens is indicated by all the Ready-Mix batches plotting very nearly a regression line. The slump, or perhaps the associated concrete unit weight as described later, determines how high the results plotted on the regression line. Again, the Ready-Mixed and the Laboratory-Mixed specimens also appear to come from different populations. To evaluate the possible differences, regression lines and the ninety-five percent confidence intervals were calculated for both sets of data. These results are shown in Figure 4.6. As discussed earlier for the other strength tests, the two lines show a significantly different slope and the confidence intervals of these lines do not overlap. This is equivalent to a ninety-five percent hypothesis test indicating that the results on Ready-Mix and Laboratory-Mixed specimens belong to two different populations and thus, should be considered separately.

The results of all compressive strength tests on four-inch diameter specimens are shown in graphical form in Figure 4.7. These results are also plotted using different symbols for the different concrete batches. The results show nearly identical tendencies

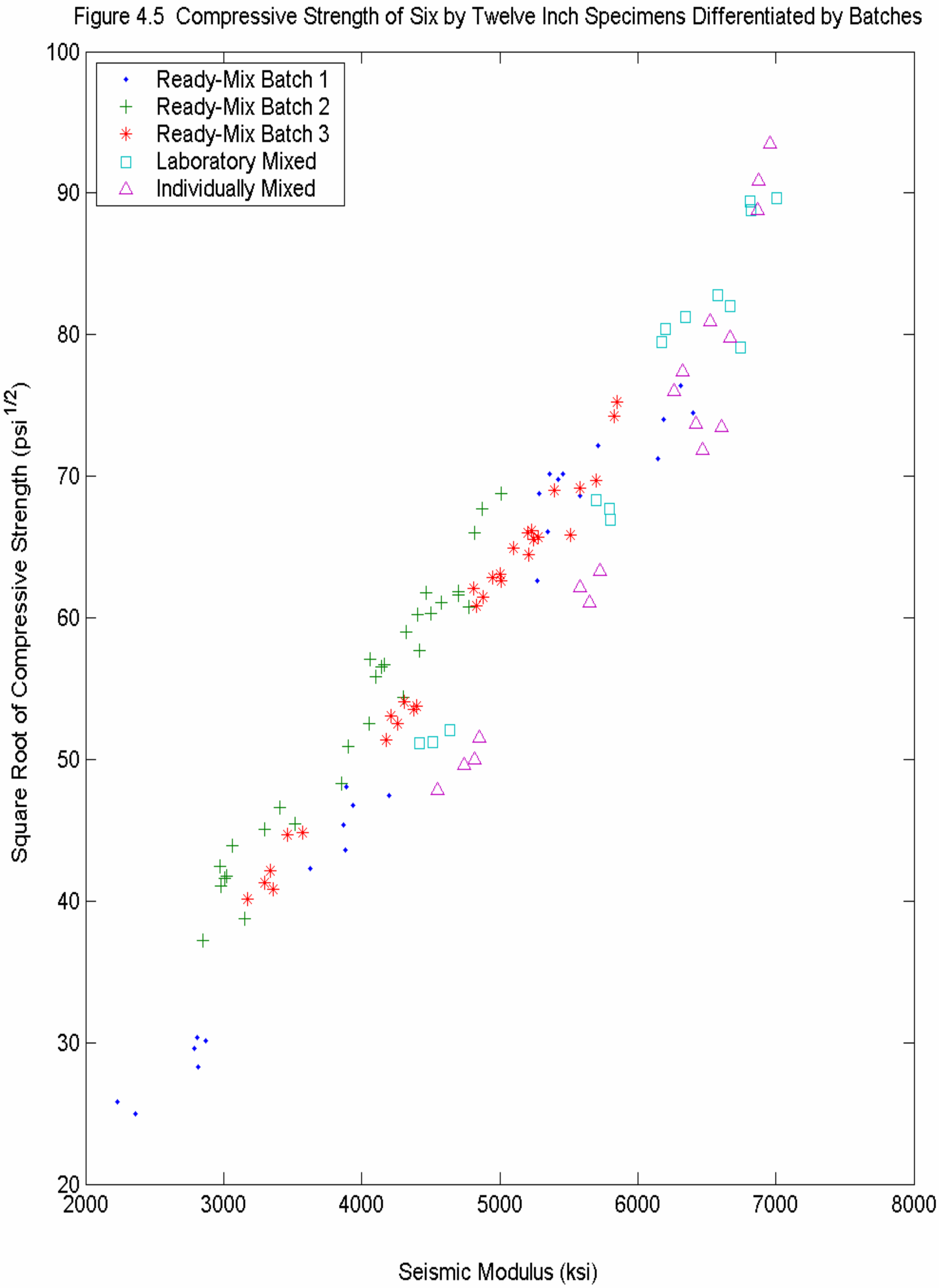


Figure 4.5 Compressive Strength of Six by Twelve Inch Specimens Differentiated by Batches
Ready-Mix Batch 1
Ready-Mix Batch 2
Ready-Mix Batch 3
Laboratory Mixed
Individually Mixed
Square Root of Compressive Strength ($psi^{1/2}$)
Seismic Modulus (ksi)
100
90
80
70
60
50
40
30
20
2000
3000
4000
5000
6000
7000
8000

Figure 4.6 Regression Lines for Compressive Strength of Six by Twelve Inch Specimens

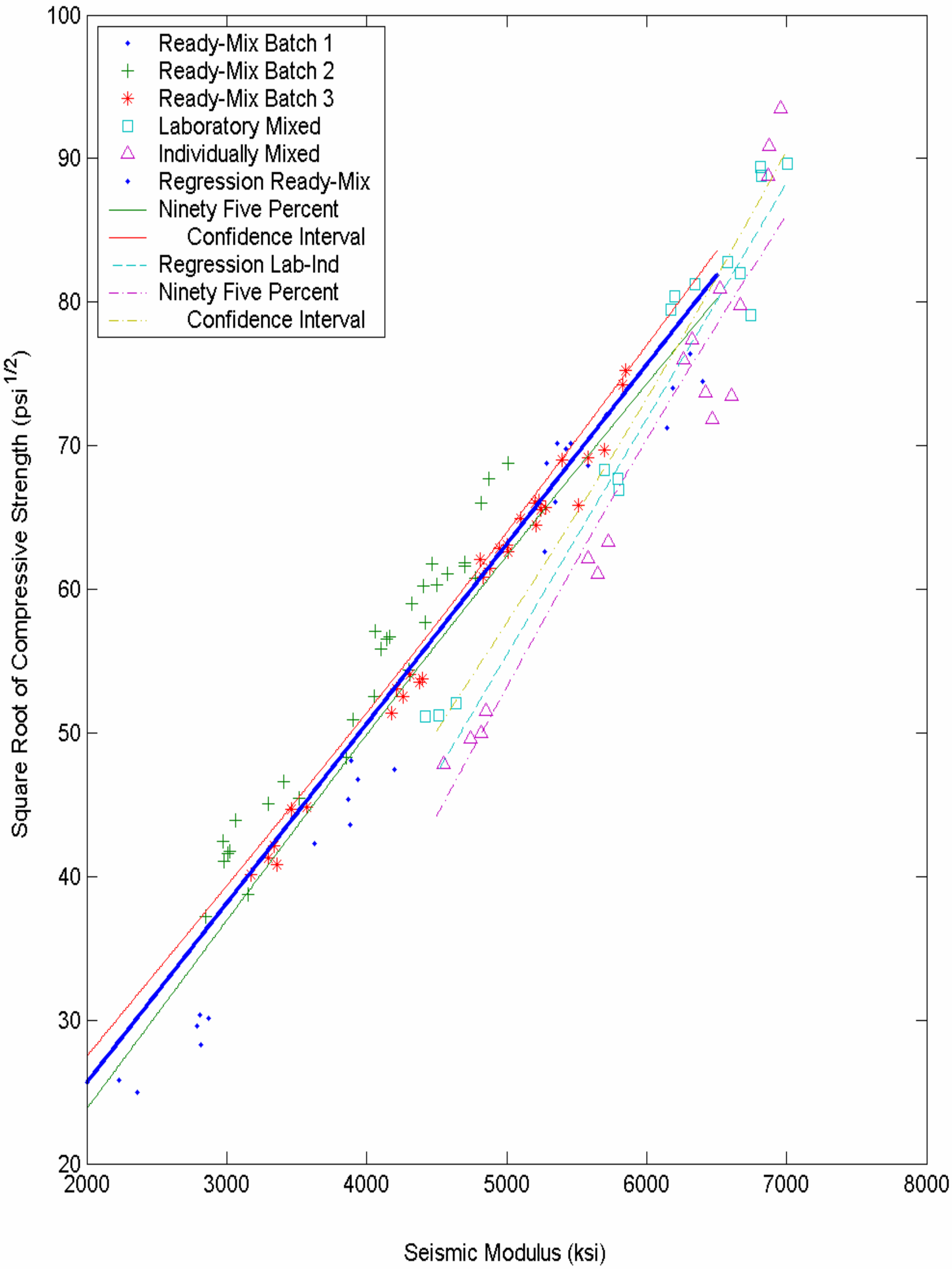
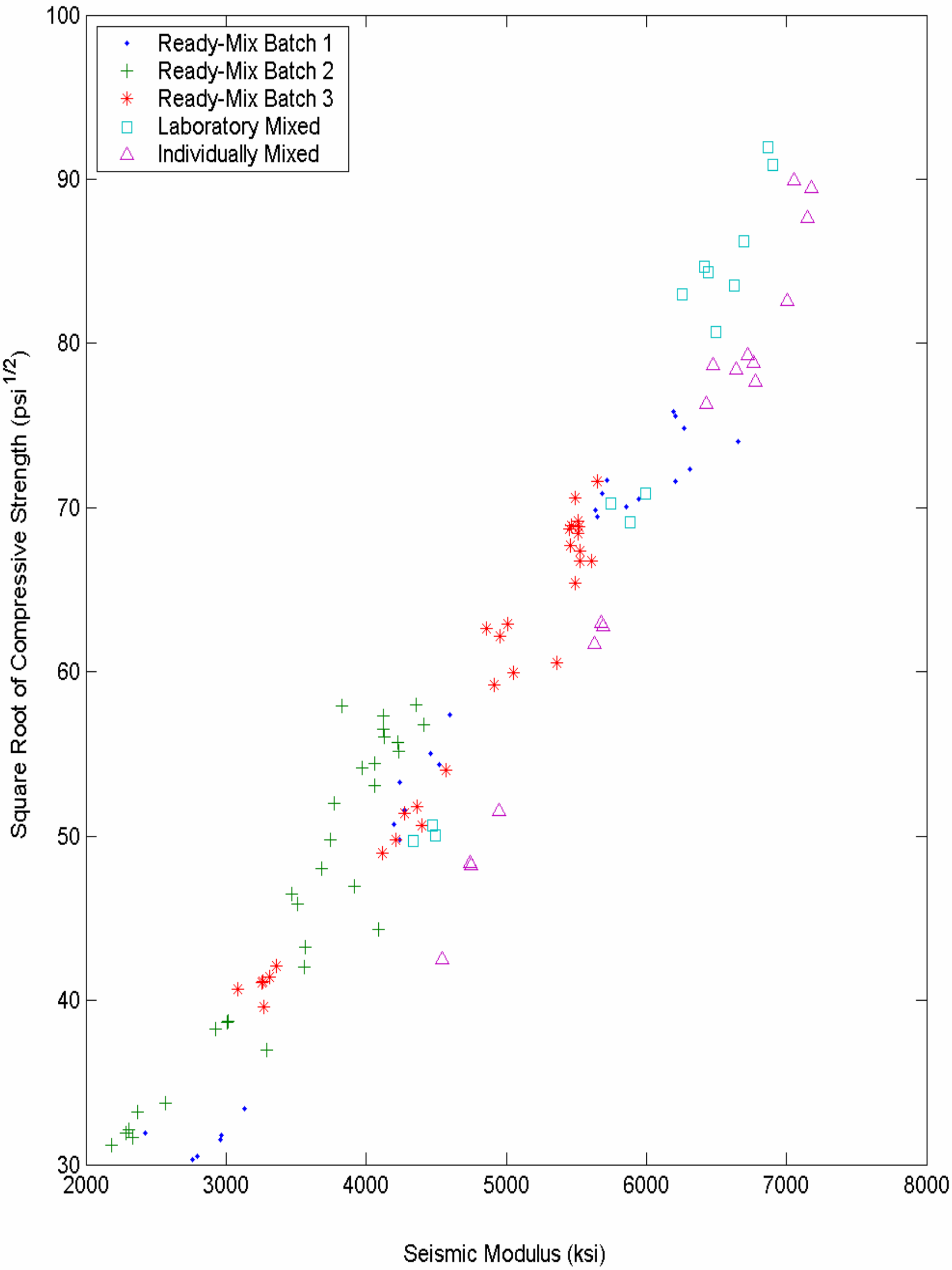


Figure 4.7 Compressive Strength of Four by Eight Inch Specimens Differentiated by Batches



as those discussed for the compressive strength tests on six-inch diameter specimens. The Ready-Mixed and the Laboratory-Mixed specimens also appear to come from different populations. The regression lines and the ninety-five percent confidence intervals were calculated for both sets of data and are shown in Figure 4.8. This result also follows very similar patterns as discussed for the six-inch diameter specimens. All the strength tests have indicated that there is a significant difference between the Ready-Mixed and Laboratory-Mixed specimens. Thus, in this report, these two sets of data are analyzed separately.

The question remaining is whether the size of the specimen has an effect on the compressive strength measured. A hypothesis test of a null-hypothesis that the two results are identical can be performed by comparing Figures 4.6 and 4.8. The results on Laboratory -Mixed specimens show the same slope of the regression line and the confidence intervals have an overall overlap. Thus the conclusion of the hypothesis test is that with the available data sets the null-hypothesis cannot be rejected. For the Ready-Mixed specimens the two lines have a slight difference in slope and the overlap of the confidence intervals occurs only for seismic modulus lower than 5000 ksi. So the conclusions would be that the available data permits to reject the null-hypothesis for seismic modulus above 5000 ksi.

To illustrate these results, the compressive strength on the two-sized specimens were plotted against each other through the elimination of the seismic modulus in the manner as described in section 3.5 and summarized in Figure 3.2. The results for all Laboratory-Mixed specimens are presented in Figure 4.9. The mean regression line is very nearly the line of equality. In all the range of seismic modulus measured, the line of equality plots within the ninety percent confidence interval. Thus, the available data do not allow rejecting the null hypothesis that the two strengths are the same.

The results for the Ready-Mixed specimens are presented in Figure 4.10. These results are not as conclusive as for the Laboratory-Mixed specimens. While the line of equality coincides very nearly with the regression line at the lower range of seismic modulus, it shows a slight difference in slope and above a seismic modulus of 4,000 to 5,000 ksi the line of equality is marginally outside the ninety percent confidence interval. Although, the null-hypothesis could be formally rejected, since it fails for very marginal values and the Laboratory-Mixed specimens show a clear indication that the size of the specimen should not affect the strength, it was decided to lump together the results on the six-inch and the four-inch specimens. Consistent with this decision, the regression lines and confidence and prediction intervals presented in Appendix J lumped together the results obtained on six-inch and four-inch specimens.

The determination coefficient (R^2) calculated for these two sets of data are the following:

1) Ready-Mixed batches 0.939
2) Laboratory-Mixed 0.927

These values indicate that the variability of the compressive strength test is lower than for flexural or splitting tension strengths. When the individual test results are averaged by batch, the new determination coefficients are the following:

1) Ready-Mixed average of six 0.952
2) Laboratory-Mixed average of three 0.946

Figure 4.8 Regression Lines for Compressive Strength of Four by Eight Inch Specimens

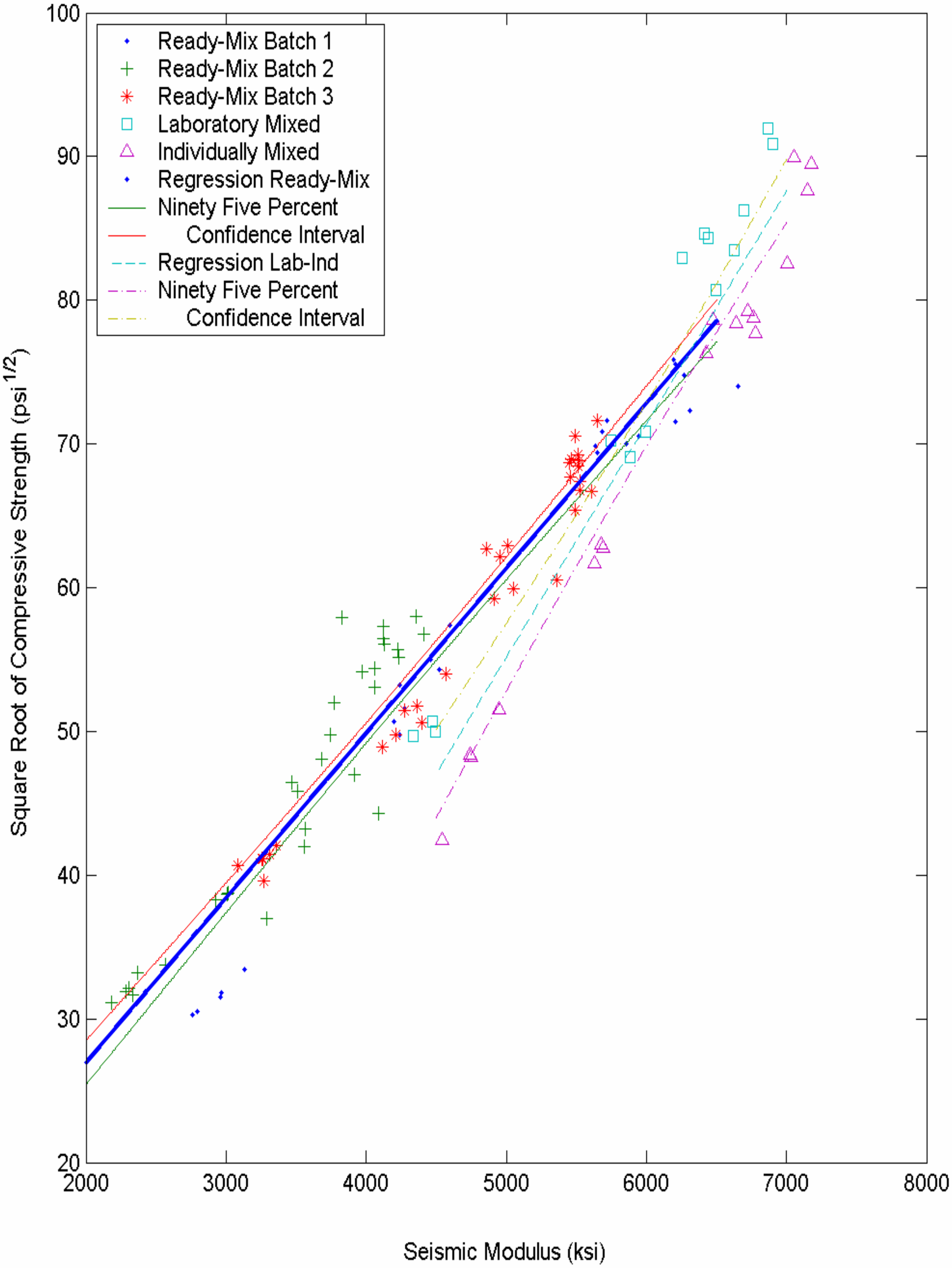


Figure 4.9 Regression of Compressive Strength Between Four and Six Inch Specimens

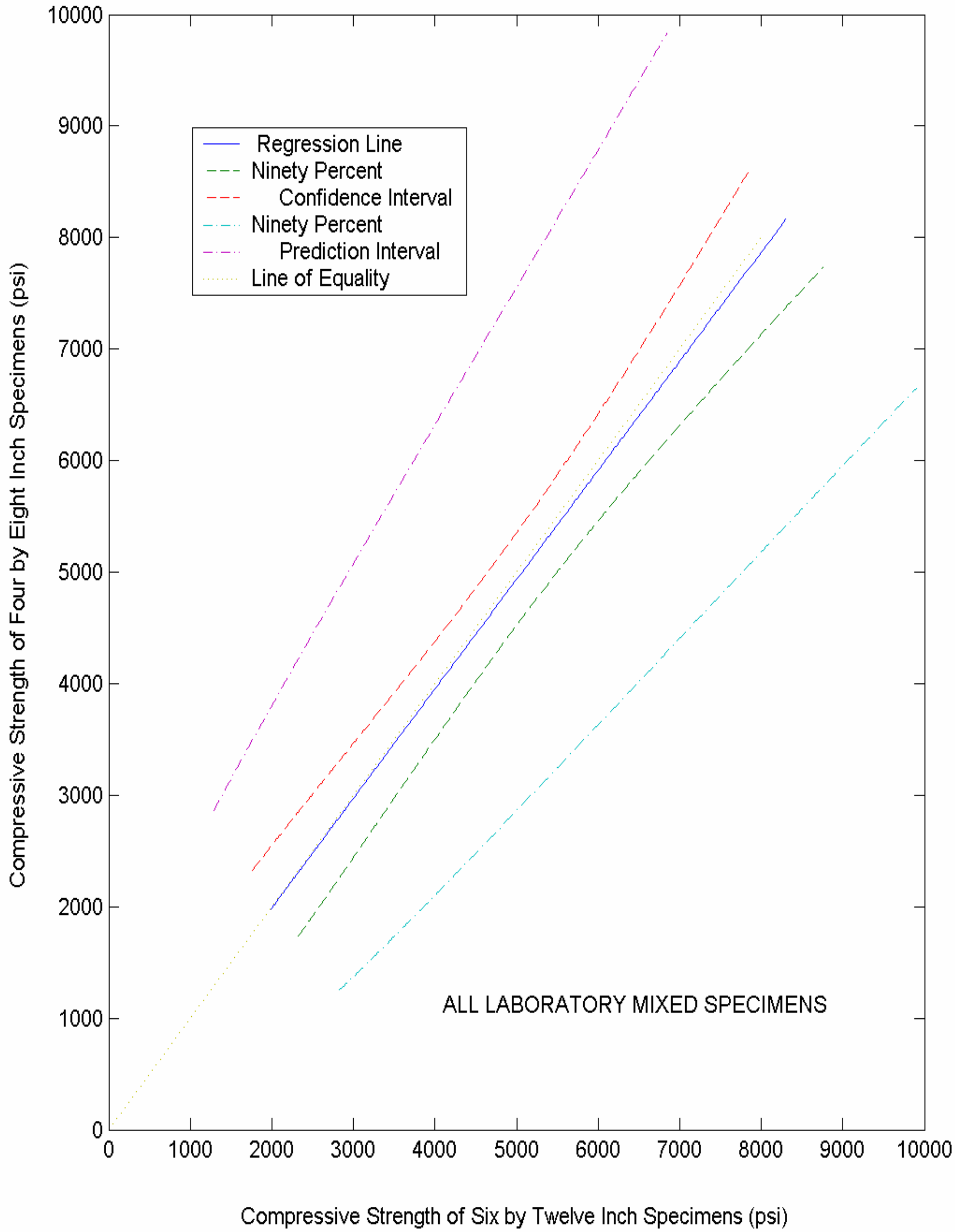
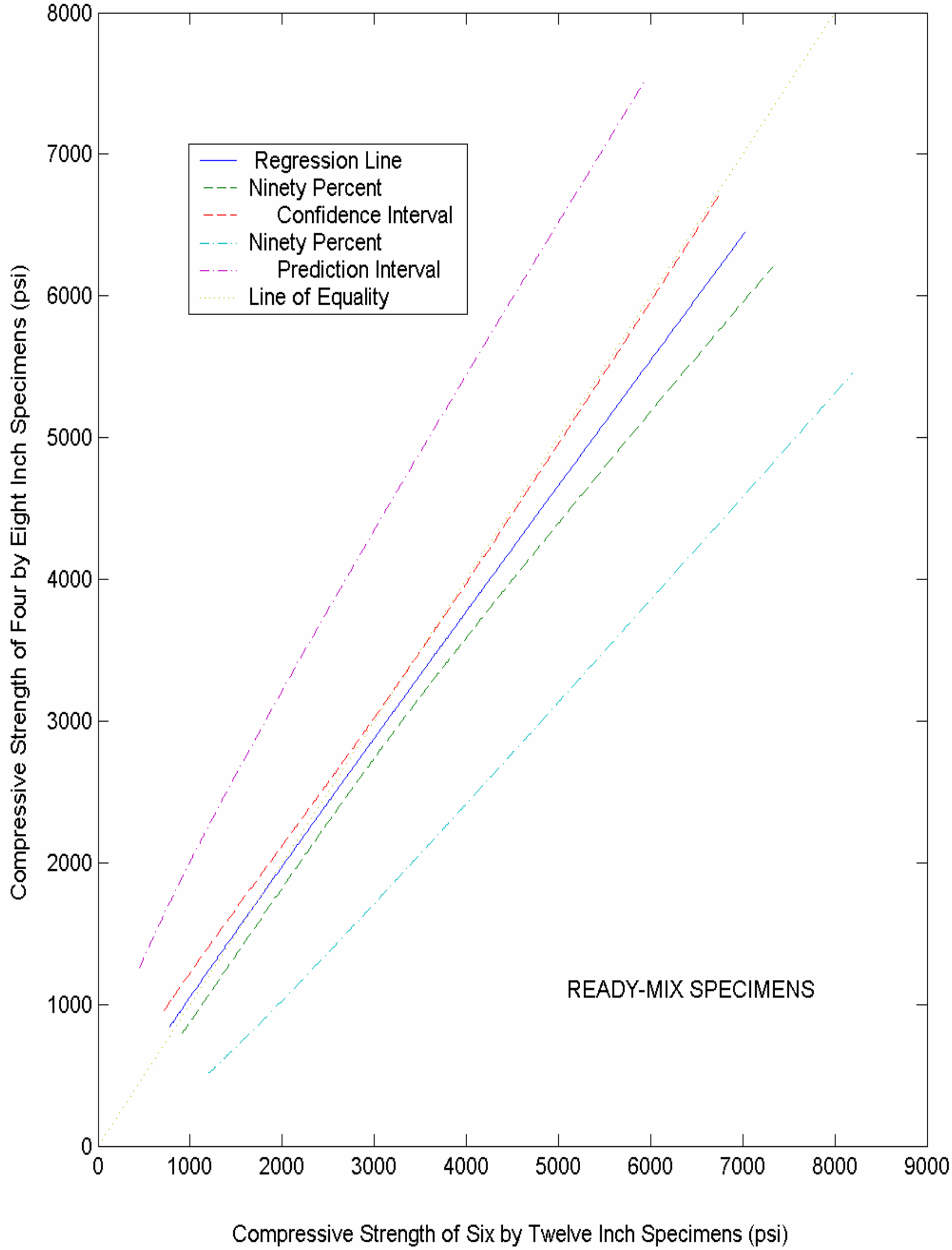


Figure 4.10 Regression of Compressive Strength Between Four and Six Inch Specimens



The determination coefficient of the averages are very close to the determination coefficients calculated using averages for splitting tension strength and flexural strength tests. Thus it appears reasonable that using averages would provide a more consistent approach.

To provide a descriptive example of the results in Appendix J, an arbitrary value of a compressive strength of 4,000 psi was selected as the minimum required. This value is used together with the graphs in natural scale of the appendix. The required seismic moduli needed to achieve 4,000 psi compressive strength are summarized in Table 4.3.

Table 4.3 Seismic Modulus (ksi) Required for a Four Thousand (psi) Compressive Strength

	Mean Regression	**95% Lower Bound of Mean**	**95% Lower Bound Prediction Interval**
Individual Ready-Mix	5,080	5,107	5,616
Average of six Ready-Mix	5,062	5,182	5,584
Individual Laboratory-Mixed	5,481	5,537	5,969
Average of three Laboratory-Mixed	5,462	5,575	5,912

The patterns exhibited by these results are very similar to those described for the modulus of rupture and the splitting tensile strength. For the Ready-Mixed specimens the mean of the required seismic modulus to achieve 4000 psi compressive strength would be 5,080 Ksi and the ninety-five percent lower bound of the confidence interval using the averages of six specimens per batch is approximately 5,200 Ksi. Thus, the probability of not having over predicted the average compressive strength of the specimens when requiring an average seismic modulus (measured on the same specimens) of 5,200 Ksi would be 0.975.

The lower bound of the ninety-five percent prediction interval indicates that it would be necessary to require a seismic modulus of a future batch of six specimens of about 5,600 ksi to have a probability of 0.975 that a future average of a batch of six specimens would have a compressive strength of 4000 psi or larger.

4.5 Prediction of Modulus of Rupture from Splitting Tensile Strength

The regression line and the ninety-percent confidence and prediction intervals for the relationship between flexural strength (modulus of rupture in psi) and the splitting tensile strength (in psi) have been established through the elimination of the seismic modulus in the manner summarized in Figure 3.2 and described in Section 3.5 of this report.

The results are included in graphic form in Appendix K. To compare the results for Ready-Mixed and Laboratory-Mixed specimens and the relative benefits of using all the individual results or averages for each batch, an arbitrary modulus of rupture of 500 psi was chosen as the minimum required. The minimum value of splitting tensile strength required for the mean and the two lower bounds were read from the graphs presented in Appendix K. The results are summarized in Table 4.4.

Table 4.4 Split Tensile Strength (psi) Required for a Five Hundred (psi) Rupture Modulus

	Mean Regression	**95% Lower Bound of Mean**	**95% Lower Bound Prediction Interval**
Individual Ready-Mixed	379	397	532
Average of Six Ready-Mixed	379	411	491
Individual Laboratory-Mixed	383	409	531
Average of three Laboratory-Mixed	403	441	513

The expected mean, of the splitting strength required, ranges from about 380 psi for Ready-Mixed specimens to 400 psi for the Laboratory-Mixed specimens. The lower bound of the ninety percent confidence interval is on the order of 400 psi. This value implies that there is a probability of 0.95, that if a 400 psi splitting strength is specified, the mean regression line would not be lower than a modulus of rupture of 500 psi. The lower bound of the ninety percent prediction interval is around 530 psi splitting strength. This strength would be required to have a probability of 0.95 that the modulus of rupture of a future-single determination would not be lower than 500 psi. If , rather than using individual test, the averages for batches are used, then around 500 psi of average splitting strength for the batch would be required to ensure that there is a 0.95 probability that the average modulus or rupture of a future batch would not be lower than the desired 500 psi.

It is worthwhile to note that despite the differences observed in the regression lines between each strength and the seismic modulus (for Ready-Mixed and Laboratory-Mixed specimens) the results in Table 4.4 are remarkable similar for Ready-Mixed and Laboratory-Mixed specimens. It is also important to realize that the regression lines and the intervals included in Appendix K, show the hypothetical relationship between the modulus of rupture and the splitting tensile strength tests performed on the same specimen. In reality this is not possible because both tests are destructive tests and the same specimen cannot be re-used. In this project, this is afforded by the use of seismic modulus as a rating tool of the concrete specimen before testing. The low variability of the measurements of seismic modulus are aiding in not introducing much variability in the correlations shown in Appendix K.

4.6 Prediction of Modulus of Rupture from Compressive Strength

The regression line and the ninety percent confidence and prediction intervals for the relationship between flexural strength (modulus of rupture in psi) and compressive strength (in psi) have been established through the elimination of the seismic modulus in the manner summarized in Figure 3.2 and described in Section 3.5 of this report.

The graphs produced are included in Appendix L. To compare the results for Ready-Mixed and Laboratory-Mixed specimens and the relative benefits of using all the individual results or only the averages for each batch, an arbitrary modulus of rupture of 500 psi was chosen as the minimum required. The minimum values of compressive strength required for the mean and the two lower bounds were read from the graphs included in Appendix L. These results are summarized in Table 4.5.

Table 4.5 Compressive Strength (psi) required for Five Hundred (psi) Modulus of Rupture

	Mean Regression	**95% Lower Bound of Mean**	**95% Lower Bound Prediction Interval**
Individual Ready-Mixed	4,029	4,200	5,871
Average of six Ready-Mixed	4,050	4,425	5,625
Individual Laboratory-Mixed	4,375	4,712	6,882
Average of three Laboratory-Mixed	4,471	5,002	6,496

The expected mean compressive strength required ranges from about 4000 psi for the Ready-Mixed specimens up to about 4400 psi for the Laboratory-Mixed. The lower bound of the ninety percent confidence interval ranges from about 4,200 for Ready-Mixed specimens to about 4,700 psi for the Laboratory-Mixed specimens. Thus there is a probability of 0.95 that for a compressive strength of 4,200 psi (or 4,700 psi) the mean regression line would not be lower than a modulus of rupture of 500 psi.

The lower bound of the ninety percent prediction interval is around a compressive strength of 5,900 psi for the Ready-Mix specimens and 6,900 psi for the Laboratory-Mixed specimens. Thus a compressive strength of 5,900 psi (or 6,900 psi) would be required to have a probability of 0.95 that the modulus of rupture of a future determination would not be lower than 500 psi. If, rather than using individual test results, the averages for the batches are used, then about 5,600 psi (or 6,500 psi) would be needed to ensure that there is a 0.95 probability that the average modulus of rupture of a future batch would not be lower than the desired 500 psi.

The effect of compressive strength on the modulus of rupture is much more drastically affected by the type of specimen used: Ready-Mixed versus Laboratory-Mixed. These results would suggest the need to develop correlations for the actual concrete mix being placed in the field rather than laboratory specimens.

4.7 Additional Work on Modified Concrete Mixes

This additional work was implemented in an attempt to explain the differences observed in the regression lines for Ready-Mixed and Laboratory-Mixed specimens. Due to time limitations and based on the fact that all strength test showed identical behavior, it was decided that the extra work would be limited to cast, cure, and test in compression four-inch diameter specimens. The results on three slightly modified concrete mixes are compared, in the present section, to the results obtained with the standard mix on specimens of four-inch diameter individually batched.

The mix labeled MOD1 contained the same amount of coarse aggregate as the "standard" or regular mix; however, ten percent of aggregate retained on ½ inch sieve was replaced by the fraction of coarse aggregate passing the No. 4 sieve. This size fraction had not been included in the regular mix. A comparison of the results obtained with the specimens of the regular and MOD1 mixes is presented in Figure 4.11.

The MOD1 mix specimens appear to show a trend of plotting on or just above the regular specimens. There are two exceptions out of 19 observations that plot considerably lower than the standard mix specimens. At least one of these points is questionable because of a sizable different unit weight of the specimen. Nevertheless, even disregarding these two possible outliers, the potential differences introduced by this change in gradation could not explain all the differences observed between Ready-Mix and Laboratory-Mixed specimens.

The MOD2 mix consisted of replacing most of the ten percent of coarse aggregate by the same volume of water without exceeding the water needed for a 3-inch slump. Two sets of specimens of this MOD2 mix were prepared. The "initial" set of specimens experienced difficulties in the initial phase of hardening. Five specimens swelled about ½ inch in the mold during initial hardening. These specimens were cured for 28 days and were sawed to the eight-inch length. These five specimens showed large number of small cavities and had sensibly lower unit weights. The significance of this finding will be discussed later.

An additional set of specimens of MOD2 mix were cast and tested. The results obtained using these specimens are shown in Figure 4.12. These results show that the increase in water would have an effect similar to the difference between Ready-Mixed and Laboratory-Mixed specimens described earlier. The regression line, for the duplicate MOD2 specimens, is parallel to the regression line for the regular specimens. Thus, it appears that the change in water content is not the whole difference between Ready-Mixed and Laboratory-Mixed specimens. The differences described earlier indicate that there is also a shift in the slope of the regression line.

To formulate a plausible explanation for the source of the difference in slope, is required to review the results of the initial set of MOD2 specimens that are presented in Figure 4.13. The five specimens that swelled during the initial hardening plot in the lower left hand corner of the graph; the square root of compressive strength ranging form 48 up to 55 ($psi^{1/2}$). These specimens had sensibly lower unit weights than the rest of the specimens in the set.

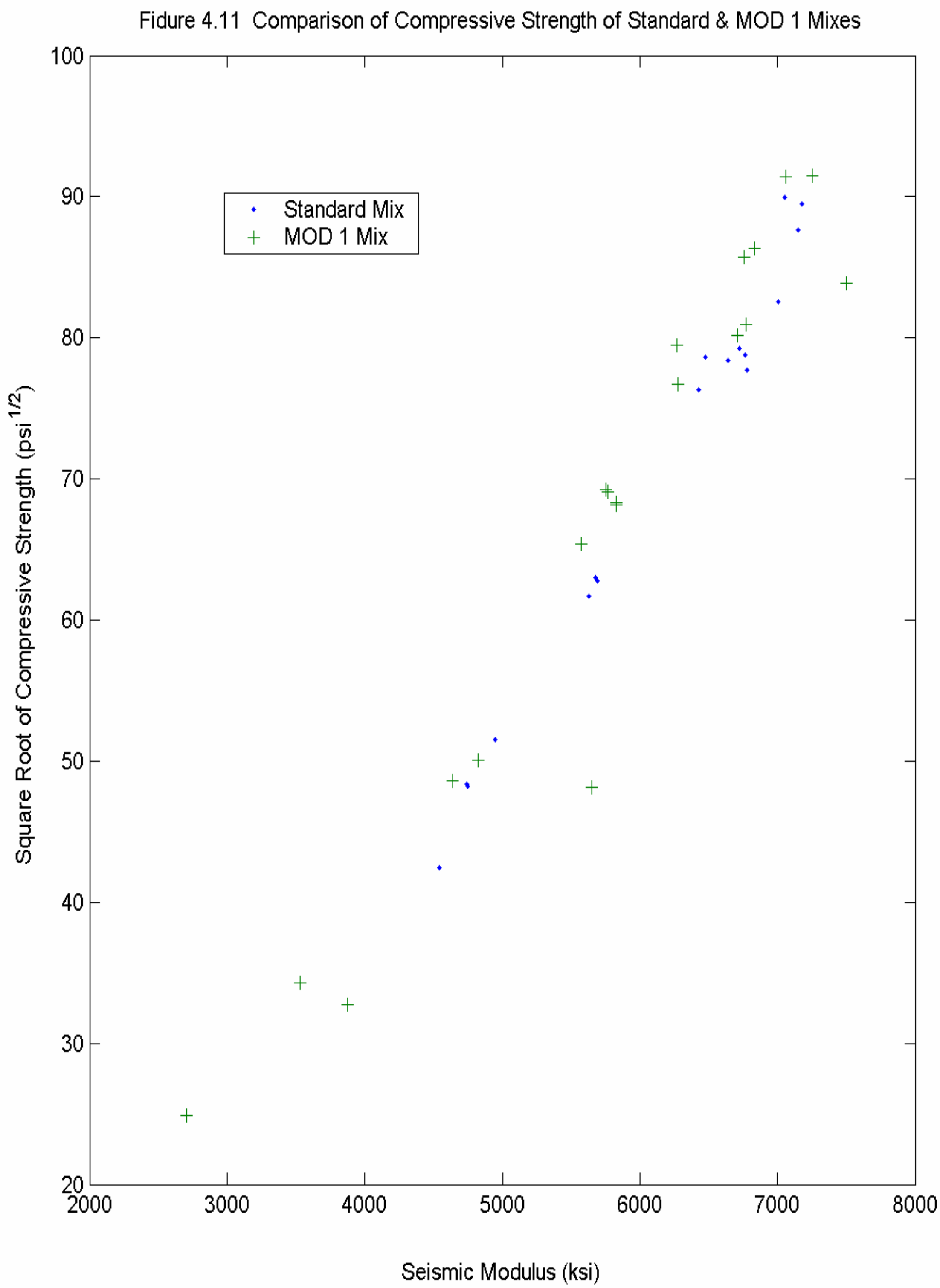
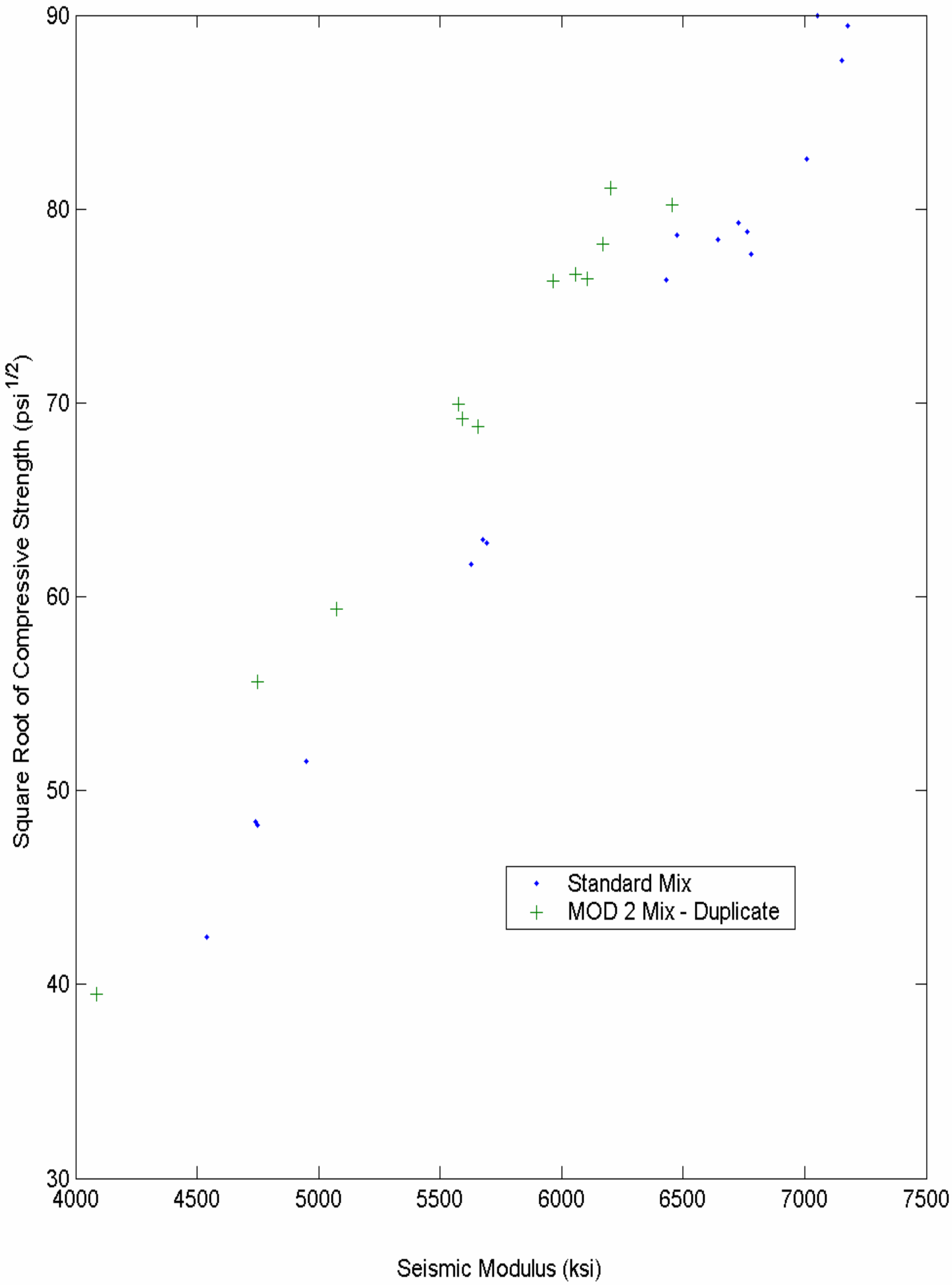

Fidure 4.11 Comparison of Compressive Strength of Standard & MOD 1 Mixes
Standard Mix
MOD 1 Mix
Square Root of Compressive Strength (psi$^{1/2}$)
Seismic Modulus (ksi)
100
90
80
70
60
50
40
30
20
2000
3000
4000
5000
6000
7000
8000

Figure 4.12 Comparison of Compressive Strength of Standard & MOD 2 (Duplicate) Mixes



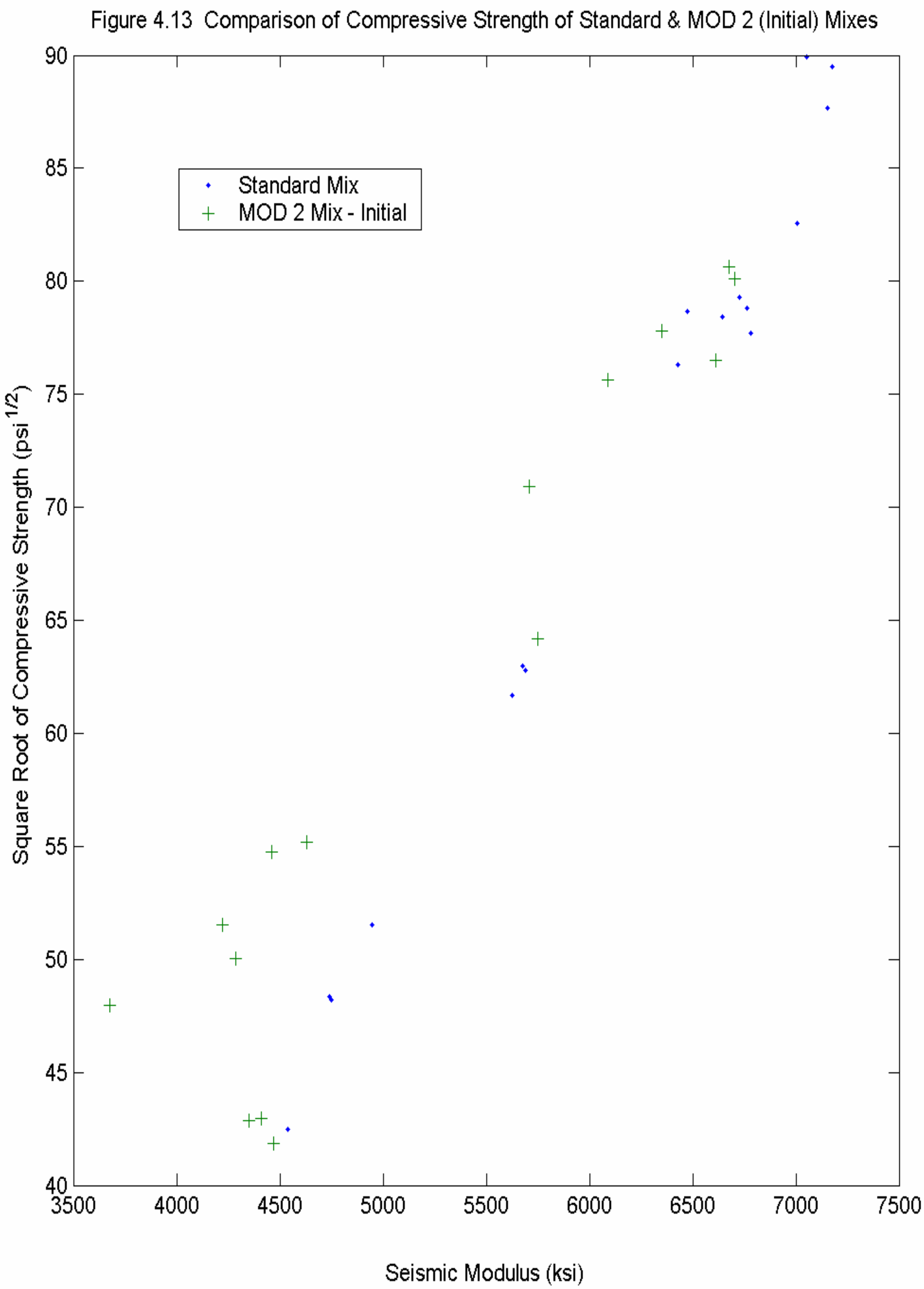


Figure 4.13 Comparison of Compressive Strength of Standard & MOD 2 (Initial) Mixes
Standard Mix
MOD 2 Mix - Initial
Square Root of Compressive Strength (psi 1/2)
Seismic Modulus (ksi)
90
85
80
75
70
65
60
55
50
45
40
3500
4000
4500
5000
5500
6000
6500
7000
7500

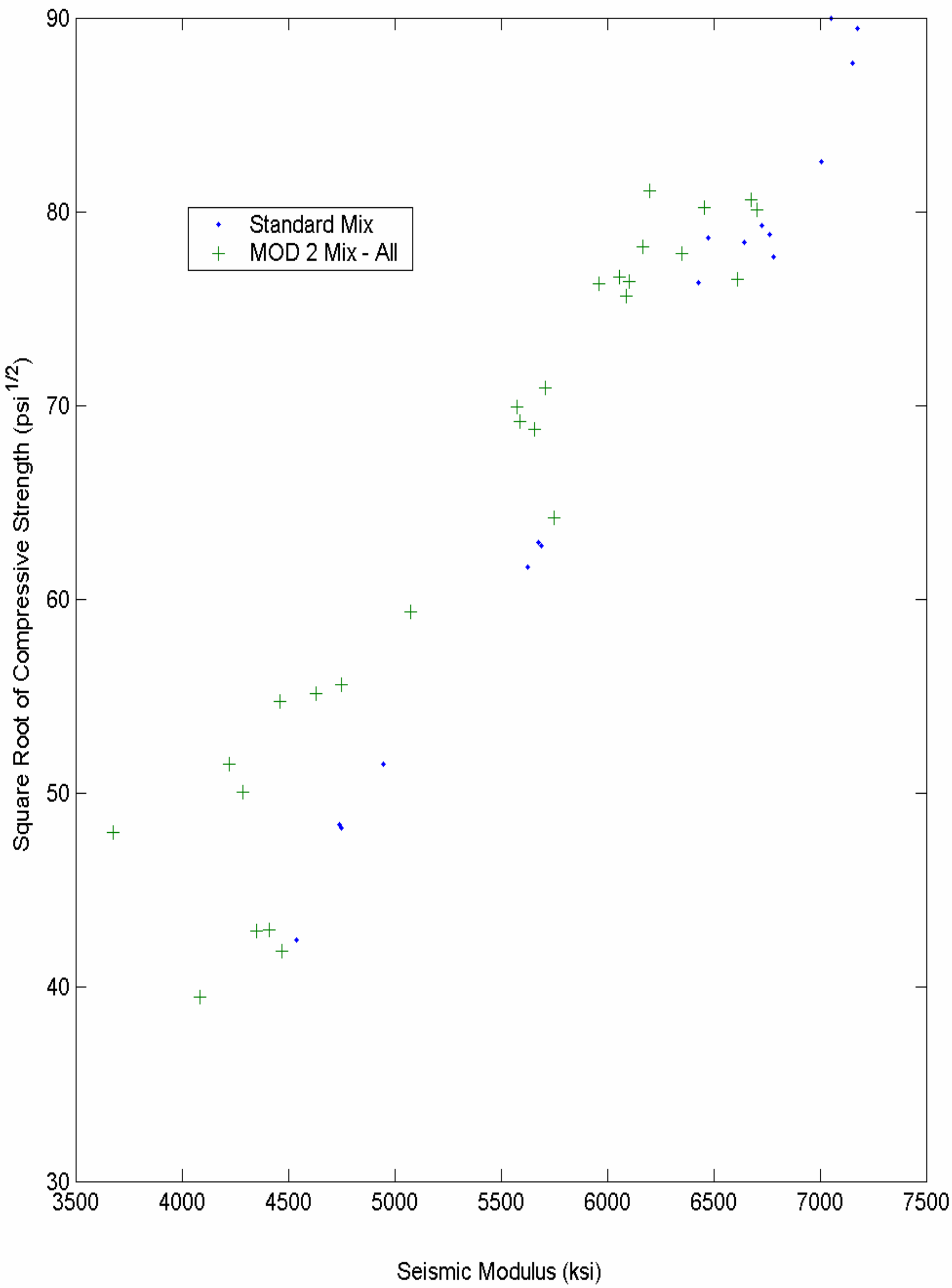
The “initial” and “duplicate” sets of MOD2 are plotted together in Figure 4.14. The pattern indicated by the set of “All” specimens of MOD2 mix, resembles the difference observed between Ready-Mixed and Laboratory-Mixed specimens. These considerations suggest that the differences in regression lines observed are probably the result of coarse aggregate/mortar being substituted for water (when the slump increases) and somehow a less thorough densification during casting of the Ready-Mix specimens.

To illustrate the differences in unit weight of the specimens, these values for the standard and MOD2 mixes are presented in Figure 4.15. In this figure, it is apparent that the standard and MOD2 (Duplicate) have a nearly constant difference unit weight from about 153 lb/ft3 down to 150 lb/ ft3. This difference translated to the two regression lines or trends shown in Figure 4.12 to be nearly parallel. This observation confirms that the parallel shift in regression line is induced by the decrease in unit weight cause by replacing coarse aggregate/mortar by an equivalent volume of water. The tendencies shown by the specimens of MOD2 (initial) are mixed. Some specimens had unit weights comparable to the MOD2 (Duplicate) specimens but there are five specimens with sensible lower unit weights mostly due to cavities, these are the five specimens that swelled during initial setting/hardening. These specimens reinforce the trend of reducing the slope of the regression line. The change in slope is clearly related to trapped air voids in the specimens. This consideration suggest that the change in slope seen between Ready-Mixed and Laboratory-Mixed specimens is the result of the limitations during casting of cylinders for the Ready-Mixed specimens associated with the large number of specimens to be cast within a limited amount of time.

The only difference between MOD3 mix and the standard mix is the amount of air-entraining admixture that is three times larger for MOD3. The results on this set of specimens are presented in Figure 4.16. No significant differences are observed between the standard and the MOD3 mixes.

In summary, it appears that for the main part, the differences in regression lines between Ready-Mixed and Laboratory-Mix specimens is the results of the change of slump of the fresh concrete from one and one half inch to three inch. To some extent, the casting of a large number of specimens at one time might have increased the trapped air volume in the Ready-Mixed specimens and has contributed to the change in slope of the regression line for Ready-Mixed versus the regression line for Laboratory-Mixed specimens. To a much lesser extent, the inclusion of fine fraction of the coarse aggregate could have contributed to the change in slope.

Figure 4.14 Comparison of Compressive Strength of Standard & MOD 2 (All) Mixes



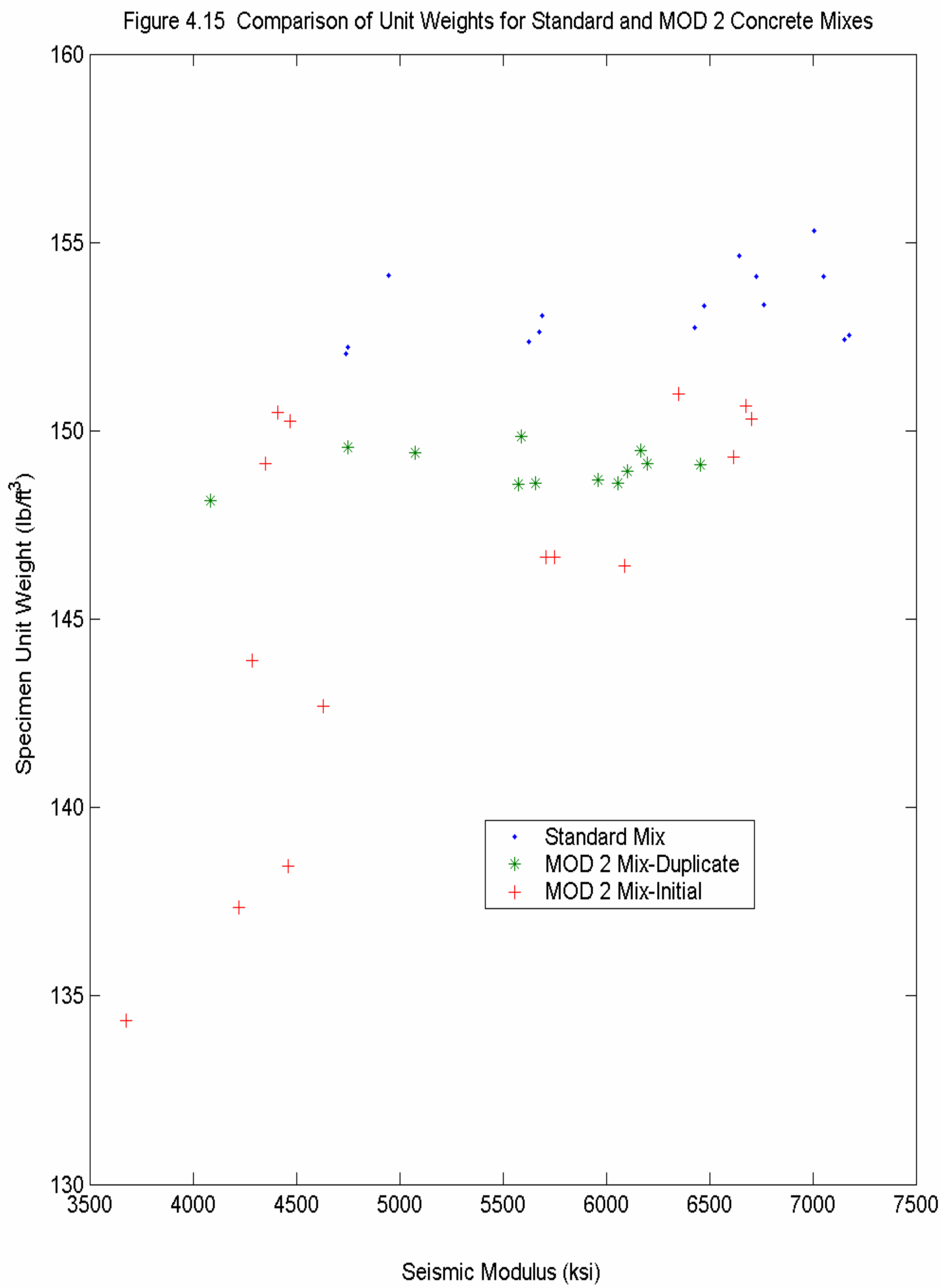


Figure 4.15 Comparison of Unit Weights for Standard and MOD 2 Concrete Mixes
160
155
150
145
140
135
130
3500
4000
4500
5000
5500
6000
6500
7000
7500
Specimen Unit Weight (lb/ft^3)
Seismic Modulus (ksi)
Standard Mix
MOD 2 Mix-Duplicate
MOD 2 Mix-Initial

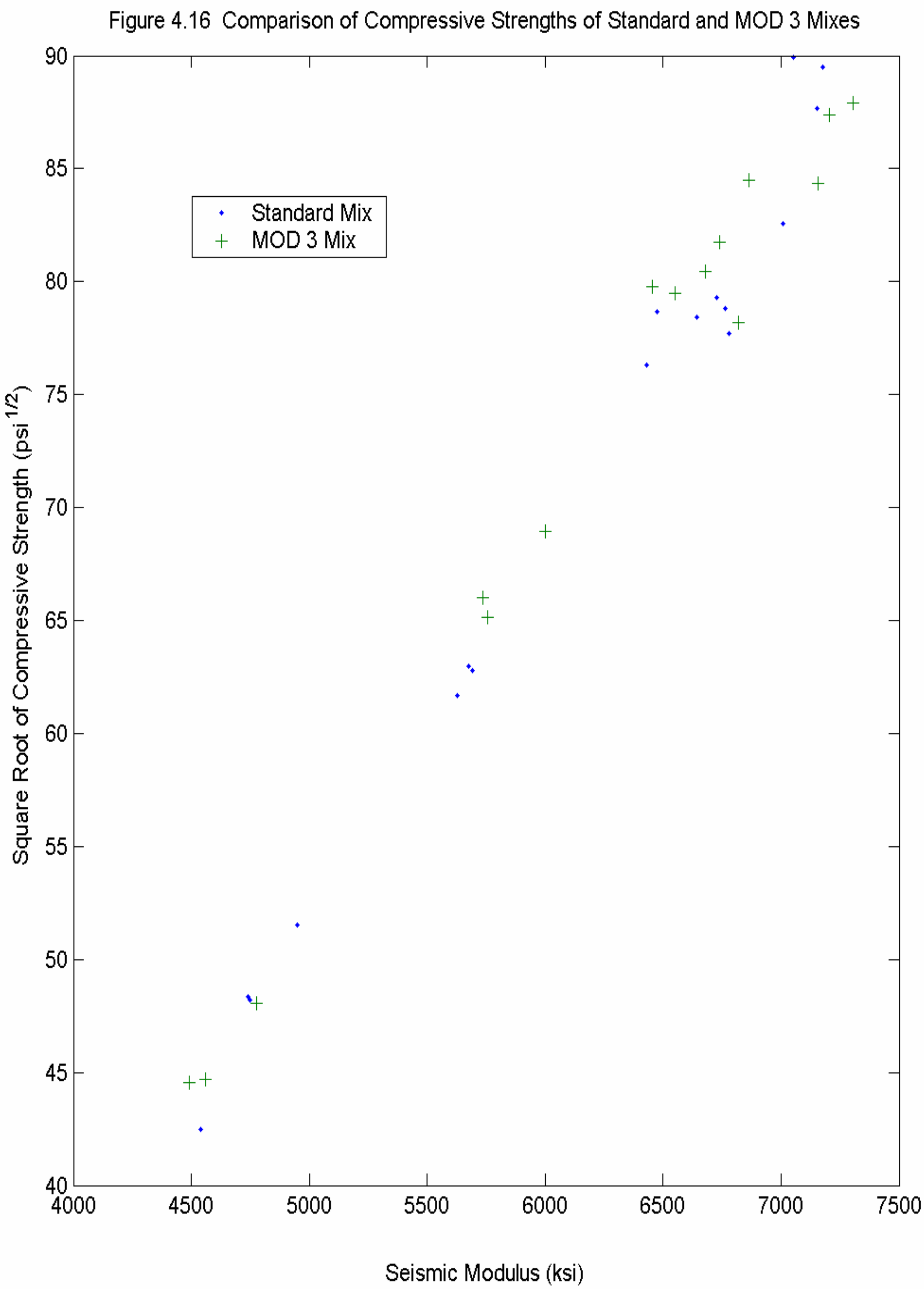


Figure 4.16 Comparison of Compressive Strengths of Standard and MOD 3 Mixes
Standard Mix
MOD 3 Mix
Square Root of Compressive Strength (psi 1/2)
Seismic Modulus (ksi)
90
85
80
75
70
65
60
55
50
45
40
4000
4500
5000
5500
6000
6500
7000
7500

5. Proposed Model of Acceptance Criteria

5.1 General

A reliability based approach for the present application can follow the model described in Appendix M. There is one additional complication in the present case, since it is desired to perform the acceptance testing with a different test than the strength test that measures directly the strength that controls pavement performance. The main concept is that it is necessary to achieve a minimum modulus of rupture at fourteen days of 600 psi; nevertheless, it is desired not to use bending beams for acceptance testing during construction, but rather some alternative strength test. This desire has led to the need to correlate the modulus of rupture to some other property that could satisfactorily be used in the field for acceptance testing.

The present research program has considered several alternative tests, and the correlations develop for each alternative are presented in the enclosed appendices. Specifically, the alternatives considered are the following:

1.) Compressive Strength Test. The results of the correlations developed that relate modulus of rupture to compressive strength are presented in Appendix L;
2.) Splitting Tensile Strength Test. The results of the correlations developed that relate modulus of rupture to tensile strength are presented in Appendix K; and
3.) Seismic Modulus Determination. The results of the correlations Developed which relate modulus of rupture to seismic modulus are presented in Appendix H.

All these correlations include the regression line, and the ninety or ninety five percent confidence interval of the regression line. Also included are the prediction intervals for a ninety or ninety five percent confidence level. The main reason for the calculation of these intervals is the need to incorporate the specimen and test variability in establishing appropriate reliability criteria.

The first two tests listed above are strength tests, while the third is a non destructive test. All three tests are potential candidates to be used in the field for acceptance testing, each presenting some advantages and some drawbacks. These advantages and drawbacks are discussed below for each of the three alternatives:

1.) Compressive Strength Test. It is the most frequently performed test and there is a large experience in the performance and analyses of this test; the test is clearly accepted by NCDOT engineers and contractors alike. Furthermore, most of the DOT in the USA, that use alternative tests to rupture modulus for field acceptance, use the compressive strength test. Additionally, NCDOT has field personnel adequately trained throughout the State of North Carolina. The major drawback is related to lack of consistency in the failure mode and the fact that most frequently the test fails in shear while the bending beams consistently fail in tension.

2.) Splitting Tension Test. The major advantage of this test is that the specimen consistently fails in tension like the bending beam. However, the test is much less frequently used than the compressive strength test and, thus, the experience and the level of confidence of the technical community is lower than the one for the compressive strength test. This test imposes a fixed failure plane on the specimen and the variability of the results is somewhat higher than for the compressive strength test. An additional disadvantage is that this test would require training of NCDOT personnel as well as some investment in equipment.

3.) Seismic Modulus Determination. Barring other considerations, this determination is the alternative that would provide the least amount of variability in the test results and, thus, in the correlations. Furthermore, it is a non-destructive test and this determination can be performed on the field slabs; thus, providing the ability to test non-destructively the concrete actually poured and cured in the field slabs, rather than testing the cylinders of record cast and cured under laboratory conditions. One disadvantage is that the determination is not an strength test, and the technical community might not trust the determination or show confidence in the abilities of the determination, since experience in its use is not widely spread. From the NCDOT point of view, this determination would also require some training of field personnel and some investment in new equipment.

The conceptual model described in this section, is based on using the compressive strength of 4 in. by 8 in. cylinders. This selection was based on the considerations summarized above, and on the additional fact that the initial aim of the present research project had been to evaluate the feasibility of using compressive strength, in place of modulus of rupture, for acceptance testing. In this manner, only the correlations presented in Appendix L are used in the rest of this section. The statistical framework discussed in Appendix M is used to develop this model.

The main concerns are how to choose the critical values **"μ_a"** and **"μ_t",** as well as the associated **"α or Type I error"** (acceptable to the contractor) and the **"β or Type II error"** (acceptable to NCDOT). Several possibilities are discussed below; however, it is necessary to keep in mind that these possibilities do not have any data to justify whether the pavement will perform adequately or, perhaps, that these will result in an acceptance criterion that is excessively difficult to be achieved by the contractor, thus producing a criterion that is unattainable.

To allay these concerns, it would be necessary to implement on a trial basis several of the proposed sets of parameters in an acceptance scheme on one or several construction sites that the job is contractually to be accepted using the modulus of rupture. From the comparison of the acceptance/rejection rates for the two methods, it would be possible to fine tune the parameters on which to base the reliability acceptance criterion.

5.2 Tentative Selection of Critical Values

There are several potential selections of the critical values **“μ_a”** and **“μ_t”.** All should be based on the correlations developed between modulus of rupture and compressive strength. In this section, the correlations that are used are those presented in Appendix L. Specifically, the regression of modulus of rupture to compressive strength for individual results on laboratory mixes is used in the rest of this section.

5.2.1 First Alternative. The regression figure referred above has been re-plotted at a larger scale in the vicinity of a 600 psi modulus of rupture, and it is shown in Figure 5.1. The discussion in this sub-section refers only to the regression line and the ninety percent confidence interval of the regression line.

The ninety percent confidence interval is defined in such a manner that there is a probability of ninety percent that the confidence interval so defined encloses the true regression line of the population; thus, there is a probability of ten percent that the true regression line of the population will not be enclosed by the confidence interval; of this ten percent, in five percent of the cases the true regression line will be outside and above of the confidence interval, and in the remaining five percent will be outside and below the confidence interval. In this manner, the lower bound of the confidence interval is the lowest regression line to be expected for ninety five percent probability of not being under estimated. That is, the lower bound of the ninety percent confidence interval is the same as the lower bound of the regression line for a ninety five percent confidence level.

Since the goal is to ensure that the modulus of rupture would be 600 psi, a horizontal line has been drawn in Figure 5.1 at this value of the rupture modulus. This line intersects the lower bound of the ninety percent confidence interval for the regression line at 6,490 psi compressive strength; thus, if it is required that the compressive strength is at least 6,490 psi, there will be a ninety five percent probability that the modulus of rupture is at least 600 psi. This value is a potential candidate for the first critical parameter **“μ_a”;** since if the average compressive strength of a lot is equal or exceeds **“μ_a”** the lot would be clearly acceptable because there is a ninety five percent chance that the rupture modulus exceeds 600 psi. Thus, the first critical parameter can be reasonable selected as the following:

$$\mu_a = \textbf{6,490 psi}$$

The intersection of the same horizontal line at 600 psi modulus of rupture, in Figure 5.1, indicates that the regression line would require a compressive strength of 5,969 psi to achieve the modulus of rupture of 600 psi. The regression line depicted in Figure 5.1 is the most probable regression line based on the data obtained in the laboratory program; thus, there is a chance of fifty percent that the true population

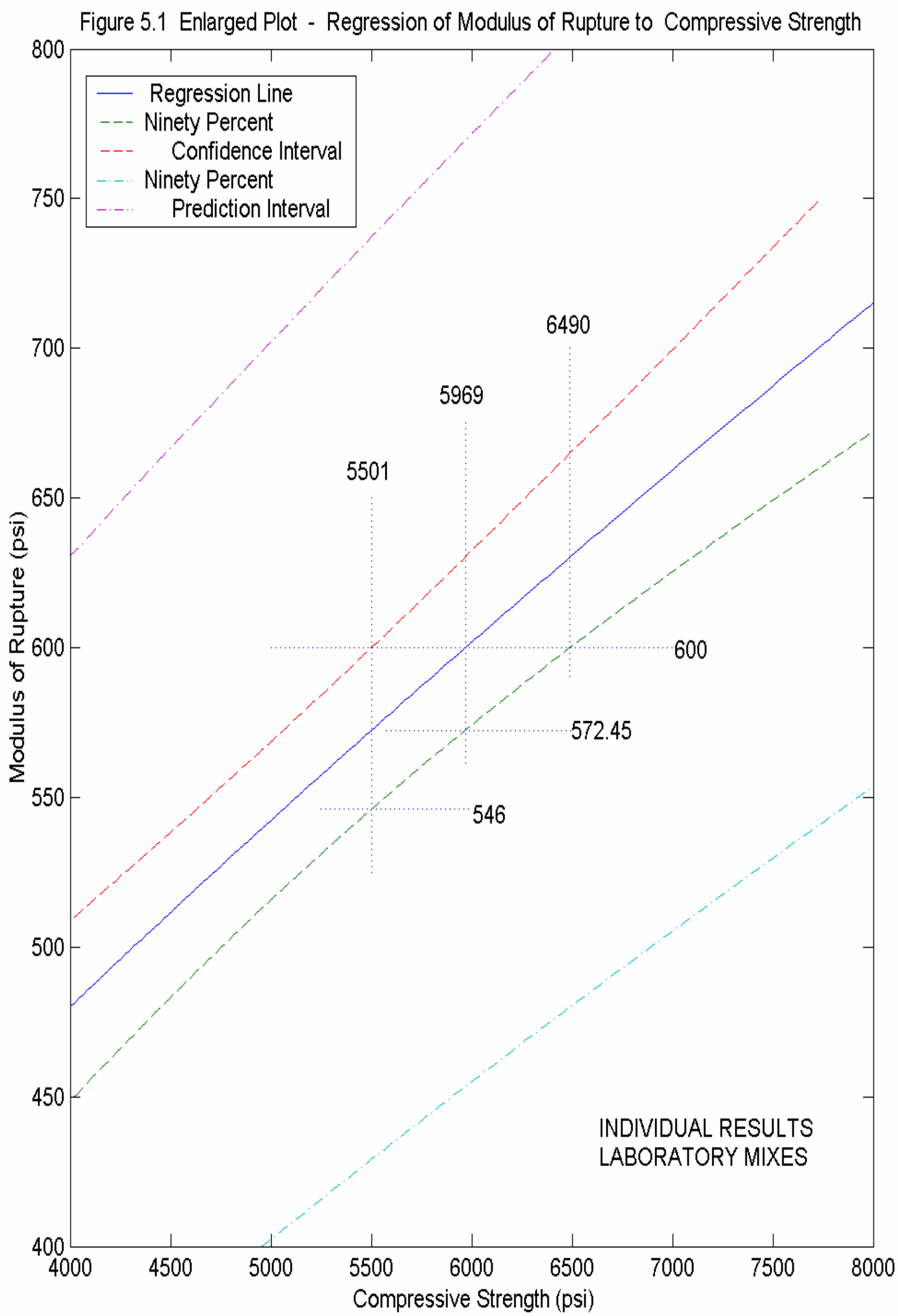


Figure 5.1 Enlarged Plot - Regression of Modulus of Rupture to Compressive Strength
Regression Line
Ninety Percent
Confidence Interval
Ninety Percent
Prediction Interval
6490
5969
5501
600
572.45
546
INDIVIDUAL RESULTS
LABORATORY MIXES
Modulus of Rupture (psi)
Compressive Strength (psi)
800
750
700
650
600
550
500
450
400
4000
4500
5000
5500
6000
6500
7000
7500
8000

regression line would be above the regression line shown in Figure 5.1, and a fifty percent chance that it would be below. If the compressive strength of 5,969 psi was adopted as the second critical value **"μ_t",** there would be a fifty percent chance that the modulus of rupture would be below 600 psi. The intersection of the vertical line drawn at a compressive strength of 5,969 psi intersects the lower bound of the ninety percent confidence interval at a modulus of rupture of 572.45 psi, as indicated in Figure 5.1; thus, there will be a probability of ninety five percent that the modulus of rupture will exceed 572.45 psi. In summary, the most likely condition would be that requiring a compressive strength of 5,969 psi would ensure that the corresponding modulus of rupture would be 600 psi or higher, and in ninety five percent of the cases the modulus of rupture would exceed 572.45 psi. If these considerations represent an acceptable risk to the pavement design engineers of NCDOT, then the second critical parameter could be the following:

$$\boldsymbol{\mu_t = 5{,}969\ \textbf{psi}}$$

These two critical values are used later in this section to select the rejection value and the number of tests to be averaged in a batch.

It is worthwhile pointing out, as indicated in Figure 5.1, that the intersection of the horizontal line at a rupture modulus of 600 psi with the upper bound of the ninety percent confidence interval of the regression line is at 5,501 psi. At this point, that is requiring a compressive strength of 5,501 psi, there is a ninety five percent chance that the modulus of rupture is lower than 600 psi and a five percent chance that it is lower than 546 psi. This third point could allow NCDOT to implement a similar acceptance approach as is being used at the present time. The comparison of the present approach [9] and the proposed new one is the following:

1.) In the present approach, if the batch modulus of rupture average is equal or larger than 600 psi, the lot is accepted. In the new approach, it would be required that the batch compressive strength average would be compared to the rejection value **"R",** that will be selected later in this section, and if the batch average exceeds **"R"** the lot will be accepted;
2.) In the present approach, if the batch modulus of rupture average falls below 600 psi but above 550 psi, the lot is paid at a reduced pay scale depending of the actual modulus of rupture average for the batch. In the new approach, if the batch compressive strength average falls below **"R"** but above the third point described above at a compressive strength of 5,501 psi, the lot could then be paid at a reduced rate in a pay scale similar to the one used for the modulus of rupture; and
3.) In the present approach, if the batch average falls below 550 psi, the lot is rejected and the contractor has to remove and replace the pavement lot. In a similar fashion, in the new approach it could be required that if the compressive strength of the batch falls below 5,501 psi the lot would be rejected and the contractor required to remove and replace the lot.

5.2.2 Second Alternative. The concrete mix used in the research project had been approved by the Materials and Tests group of NCDOT, in the approval document the concrete mix was set for a slump of one and one half inches. Nevertheless, it allowed the contractor to place the concrete with a somewhat higher slump not to exceed three inches. The additional work performed in the present research project using modified mixes indicates that a difference of slump of that magnitude is clearly detected in the correlations of compressive strength versus seismic modulus. The comparison of the standard mix, with the slump of one and one half inch, to MOD2 mix with three inch slump, is shown in Figure 4.12, and a comparison of the correlations of compressive strength to seismic modulus is presented in Figure 5.2. Both figures show that there is a clear difference between the two materials; thus, if the Materials and Tests group approves the use of a larger slump than the slump used when developing the correlations, it might be necessary to allow some flexibility on the acceptance criterion.

The results in Figure 5.2 show clearly that there is no overlap of the ninety five percent confidence intervals of the regression lines for the two concrete mixes. This is equivalent to a hypothesis test of the null hypothesis that the two regression lines are the same. The lack of overlap indicates that for a confidence level of ninety five percent the null hypothesis can be rejected; that is to say that the two populations are clearly different. The results shown in Figure 5.2 are for compressive strength vs. seismic modulus, the actual correlation needed would be modulus of rupture vs. compressive strength. Thus there is some uncertainty of how this last correlation might be affected by the increase in slump of the concrete.

The best approach would be to develop two correlations for the two concrete mixes of different slumps. This would also require testing bending beams prepared with the concrete with the higher slump. These tests were not performed in the present research project; the bending beams were only prepared using the standard mix, which is the mix with one and one half inch slump. The correlation for the higher slump concrete was not established. Thus there is no data to illustrate potential choices of the critical parameters **"μ_a"** and **"μ_t".** An evident potential choice could be to select as **"μ_a"** the intersection of the horizontal line drawn at 600 psi with the regression line of the concrete mix with the lowest slump, in this case for the one and one half inch slump concrete. The value for **"μ_t"** could be the intersection of the same horizontal line at 600 psi with the regression line of the concrete mix with the highest slump, in the present case three inch slump. The discussion of the probabilities of accepting different values of the modulus of rupture cannot be performed in this case, because the second regression line is not available.

Other potential choices can be defined by looking at the intersection of the horizontal line at 600 psi modulus of rupture with the lower and upper bounds of the ninety percent confidence interval of the regression line. However, at this time, these are only speculative considerations since the second regression line is not available.

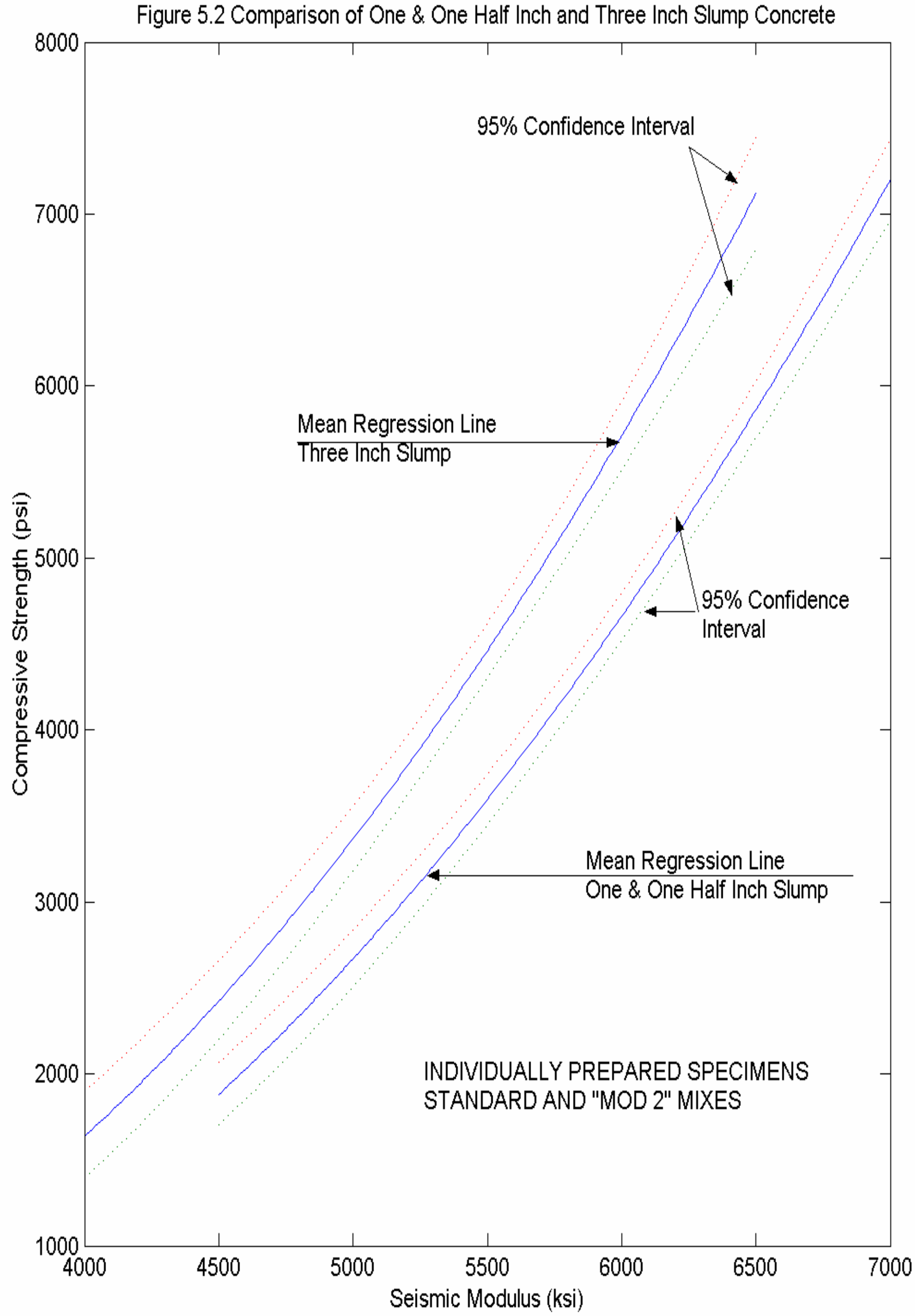


Figure 5.2 Comparison of One & One Half Inch and Three Inch Slump Concrete
95% Confidence Interval
Mean Regression Line
Three Inch Slump
95% Confidence
Interval
Mean Regression Line
One & One Half Inch Slump
INDIVIDUALLY PREPARED SPECIMENS
STANDARD AND "MOD 2" MIXES
Compressive Strength (psi)
Seismic Modulus (ksi)
8000
7000
6000
5000
4000
3000
2000
1000
4000
4500
5000
5500
6000
6500
7000

5.3 Tentative Selection of Acceptable Error Levels

The acceptable error levels are normally small [4, 10] in the range from one percent to five percent. Nevertheless, these error levels should not be selected arbitrarily, since these errors and the critical values should be consistent. For instance, a contractor might be ready to accept a higher **"α error"** if the critical value **"μ_a"** is not too stringent. Conversely, NCDOT could be amenable to accept a higher level of **"β error"** if the second critical value **"μ_t"** is not excessively low.

These considerations again highlight the need to compare the criterion obtained with this approach and the corresponding acceptance/rejection using the modulus of rupture criterion in several pavement construction contracts.

For the purpose of the model being described in this section, the values were arbitrarily chosen to be the following:

Type I or α error ------- 1%
Type II or β error ------- 5%

5.4 Selection of the Standard Deviation of the Compressive Strength

This parameter has to be the standard deviation of individual tests results without any averaging. In a practical application, it would be the standard deviation that can be expected from tests performed by NCDOT's personnel performing the acceptance testing at the construction site. If this experience is not available, it could be developed at the beginning of the project when the test would be performed to develop the correlations. The important aspects to be controlled are the following:

1.) Use results obtained by similarly trained personnel to the personnel that will be performing the field acceptance testing;
2.) Use the same concrete mix that will be used at the construction site;
3.) Use the same size of specimen;
4.) Use the same number of curing days that would be in the contract; and
5.) Use similar sampling techniques, and similar equipment and practices for casting, curing and testing as the ones that will be used in the field.

For the present application the variability is taken to be described by the coefficient of variation published in ASTM C39 for a single operator under field conditions, which is 2.87%. The only caution is that this value is valid for six inch diameter specimens and twelve inches in length. Assuming that this value is applicable to the four inch diameter by eight inch length specimens of the present research project, a concrete with an average compressive strength of 5,969 psi, the compressive strength should have a standard deviation of 171.3 psi. Thus, the value assumed in the rest of this section is the following:

$$\boldsymbol{\sigma = 171.3 \text{ psi}}$$

5.5 Selection of Number of Samples in a Batch and the Rejection Value

The selection process follows the steps described in Appendix M. The following set of values have been selected in the previous subsections:

$$\mu_a = 6{,}490 \text{ psi}$$
$$\mu_t = 5{,}969 \text{ psi}$$
$$\alpha \text{ error} = 1\%$$
$$\beta \text{ error} = 5\%$$
$$\sigma = 171.3 \text{ psi}$$

The first equation to be used is the following:

$$Z_\alpha = (R - \mu_a) / (\sigma / \sqrt{n})$$

the value of Z_α can be found from the tables of probability of the standard normal distribution, as the value of the deviate that leaves an area of 0.01 to the left of it. The value is read as "- 2.323", and thus the equation can be rewritten as follows:

$$R = 6490 - 2.323 * 171.3 / \sqrt{n} \qquad (1)$$

The second equation to be used is the following:

$$Z_\beta = (R - \mu_t) / (\sigma / \sqrt{n})$$

And the value of Z_β can be found from the tables of probability of the standard normal distribution, as the value of the deviate that leaves an area of 0.05 to the right of it. The value is read as "1.645". The equation can now be written as follows:

$$R = 5969 + 1.645 * 171.3 / \sqrt{n} \qquad (2)$$

From the solution of the two simultaneous equations (1) and (2) the following values are found:

$$n = 1.70 \sim 2 \text{ tests and } R = 6{,}135 \text{ psi}$$

Thus the resulting reliability criterion is that per lot of pavement, a batch of two compressive strength tests would be performed. The average of the two tests would be compared to the rejection value. If the average is higher than 6,135 psi, the pavement lot is accepted. If the average is lower than 6,135 psi, the pavement lot is rejected or paid at a decreasing pay scale as suggested in the sub-section 5.2.1.

Although it is only required to average two specimens prepared from a randomly selected batch of concrete, it is advisable to at least cast, cure, and test three specimens to provide some relieve in case that the first two specimens give results that exceed the "Maximum Acceptable Range" for two specimens specified by ASTM C670.

6. Findings and Conclusions

The results of the present research project have shown the very high sensitivity of the free-free resonant column device used. This was illustrated by all the plots shown in Chapter 4. Specifically, the results included in Figure 4.1 show that as the modulus of rupture measured ranged from 300 psi to 800 psi, the seismic modulus ranged from 3,500 ksi to 7,500 ksi. This sensitivity coupled with the very low variability of the seismic modulus in repetitions on the same specimen (giving coefficients of variation on the order of 0.1%) make this device a very reliable tool.

The results of seismic modulus correlate very highly with all three strength tests performed in this project. The lowest determination coefficients (R^2) are 0.890 for the modulus of rupture, 0.896 for the splitting tensile strength, and 0.927 for the compressive strength. Thus these results indicate that the strength test having higher coefficients of variability correspond to the test showing the lower coefficient of determination. When the results for each batch (six for the Ready-Mix and three for the Laboratory-Mixed) are averaged, the coefficients of determination for all the strength tests hover around 0.950. These values of the coefficient of determination are of the same order of magnitude than the values reported by others [8].

The results of the present research program show that the results on specimens of Ready-Mix concrete are not from the same population as the results on specimens of Laboratory-Mixed. The differences between the two regression lines can be attributed to several causes. The most influential appears to be the difference in the slump of the concrete; while the Ready-Mix had a slump of three inches, the Laboratory-Mix was kept at one and one half inches. The next factor has to be found in the problems associated with poor workability of the Ready-Mix concrete, since too many specimens had to be cast at the same time within a limited amount of time. In this manner, the four-inch diameter specimens were the last ones to be cast and, thus, were probably affected the most.

The effect of the lower workability of the concrete is thought to be responsible of an increase of the amount of air trapped in the specimens. This resulted in lowering the unit weight of the specimens. At the same time, the increase in water displaced an equivalent volume of coarse aggregate and mortar. These two effects result in a lowering of the unit weight of the specimens. In this sense, the average unit weight of the four-inch diameter specimens have been calculated and are the following:

1.) Ready-Mix batch 1 . . . 145 pcf,
2.) Ready-Mix batch 2 . . . 140 pcf,
3.) Ready-Mix batch 3 . . . 146 pcf, and
4.) Laboratory-Mixed . . . 152 pcf.

These unit weights permit to advance an explanation of the results presented in Figure 4.7; where batches 1 and 3 show similar patterns, while batch 2 indicates lower strengths and seismic modulus. These results show that a weaker concrete would also have a lower seismic modulus. This is an important observation to understand an apparent incongruence in the results. Specifically, the difference in regression lines for the Ready-Mix and the Laboratory-Mixed shown in Figure 4.8.

Assuming that the regression line is used to predict strength from seismic modulus, it appears that to achieve the same compressive strength, the stronger concrete (Laboratory-Mixed) would require a higher seismic modulus than the weaker concrete (Ready-Mix). However, it is worth noticing that a strength of 4,900 psi could not have been reached with a specimen of batch 2. These considerations indicate that the regression line cannot be extended to higher strengths. Another way of rationalizing the same concept is the fact that the stronger concrete starts at much higher strengths and seismic modulus (for one day curing) that could not be achieved with a weaker concrete.

The underlying conclusion is that the Ready-Mix and the Laboratory-Mixed specimens are data sets for two different concrete mixes. Consistent with this finding, this report treats these two sets of data independently. The above considerations emphasize the need to define the correlation for the exact same concrete mix that will be placed in the field. If there is an allowance for a range of slumps, it might be necessary to develop two regression lines and intervals to determine acceptance. A related consideration is to consider which set of lines to use for acceptance. This is addressed in the following paragraphs.

Assuming that the regression lines and interval developed for the higher slump concrete (weaker concrete) are used to establish the rejection values “R”, and that the actual concrete placed in the field is the lower slump (stronger concrete), then there is a chance of accepting weaker concrete. To illustrate this with an example, continue with Figure 4.8 and consider that the rejection values are given by the regression line. Then, if the compressive strength needed was 3,600 psi, the weaker concrete would require a seismic modulus of 4,893 ksi using the Ready-Mix line; however, for this seismic modulus, the strength of the stronger concrete (Laboratory-Mixed) would only be 2,790 psi. Thus, if the rejection value was 4,893 ksi, there is a chance of accepting concrete with only a 77% of the required strength when the rejection values have been established for the weaker concrete and the concrete placed in the field is the stronger concrete.

An alternative approach is to establish the rejection values for the lower slump concrete (stronger concrete); in this case there is no room for under-estimating the strength. However, if the slump allowance is too large, it might be impossible for the contractor to meet the minimum rejection value specified. Probably the best approach would be to develop the correlations and the rejection values for the exact mix being placed in the field. As an added precaution, it could be worthwhile specifying two rejection values: one for the compressive strength and the other for the seismic modulus. The acceptance would then be based on simultaneously exceeding both rejection values.

The effect of increasing the water and the trapped air in the mix results in displacing coarse aggregate and mortar that would occupy the same volume as occupied by the extra water or air. Since the aggregate and the mortar are heavier than the water or air, the unit weight of the specimen will decrease resulting in a somewhat lower seismic modulus. The technical literature [8] indicates that the type of coarse aggregate has a large effect on the seismic modulus disproportionate to the effect that it would have on the strength. The implication is that the correlations developed can only be used for mixes with coarse aggregates that have similar densities and mechanical properties to those of the coarse aggregate #57M of Pomona Quarry.

To use the same approach on a mix using a coarse aggregate significantly different, would be necessary to develop new correlations from a laboratory program similar to the one implemented in this project. Then a similar process could be followed to choose "R", the reliability based rejection value and the number of specimens to be averaged in a batch.

This process would allow the pavement design engineers to have a high probability that the pavement has the desired modulus of rupture. At the same time, the construction engineers would be able to reduce or eliminate altogether the need to use flexural strength for acceptance testing. The process allows input from both groups and reasonable compromises would have to be reached for the selection of strength parameters and the probability of failure that is to be accepted.

The results of the present research program indicate that there is an effect of the quality of the specimens used to develop the correlations. It appears worthwhile to develop the correlations from specimens cast, cured, and tested by certified technicians of NCDOT. If these tests result in somewhat lower variability, it would reduce the width of the confidence and prediction intervals. These narrower intervals could in turn result in lower rejection values that could be less onerous to be achieved in the field.

7. Recommendations

The strength tests (splitting tension and compressive strength) as well as the seismic modulus determination can be used as alternative tests for the bending beam tests in acceptance testing of concrete pavements. From a technical point of view, the best test would be the test that exhibits the lower variance. The three strength tests used do not let themselves to re-use the specimens for retesting the same specimen; therefore, it is not possible measuring the testing variability alone. The replicate tests always include the specimen variability and the testing variability, thus there is no information about the testing variability alone. The seismic modulus determination is a non-destructive test, and repeated determinations can be performed on the same specimen. In the present research, it was found that the coefficient of variation of repeated tests on the same specimen was on the order of 0.1%.

From this point of view, the seismic modulus would be the best candidate, since it would contribute the least variance to the correlation with modulus of rupture. In this manner, when the correlation is established between modulus of rupture and compressive strength, the variances of these two tests are lumped together resulting in a broader confidence and prediction intervals. However, at the present time, the NCDOT's engineers and technicians, and contractors are not familiar with the seismic modulus measurement and it is believed that a strength test would be much more easily accepted as an alternative to the bending beam tests.

It is believed that a gradual introduction of the seismic modulus determination to the NCDOT's engineers and technicians and contractors would allow this technical community to become familiar with this determination and the predictive capabilities of the test. Consistent with this believe the implementation section includes several implementation levels that would allow for a gradual introduction of the seismic modulus to the technical personnel involved in design and construction of concrete pavements.

For the sake of brevity, the present report only includes one acceptance testing scheme based on the correlations between modulus of rupture and compressive strength. This selection was based on the fact that it is the easiest alternative to be implemented at the present time. Nevertheless, it should not be inferred that it is thought to be the best technical approach to the substitution of bending beam test for acceptance testing of concrete pavements. An acceptance scheme based on splitting tension or on the seismic modulus determination could be designed following the same steps but using the appropriate correlations; that is, modulus of rupture versus splitting tension or the modulus of rupture versus seismic modulus presented in the appendices.

For the initial phase of development of the correlations for new concrete mixes, it is recommended that the specimens for testing are prepared individually to achieve the lowest variability possible. For this purpose, it is recommended that the coarse aggregate is split into size fractions retained on consecutive sieves, and that these fractions are then mixed in the right proportions to adjust to the desired grain size distribution. The need for this step is illustrated in Figure 7.1, which shows the regression lines and the

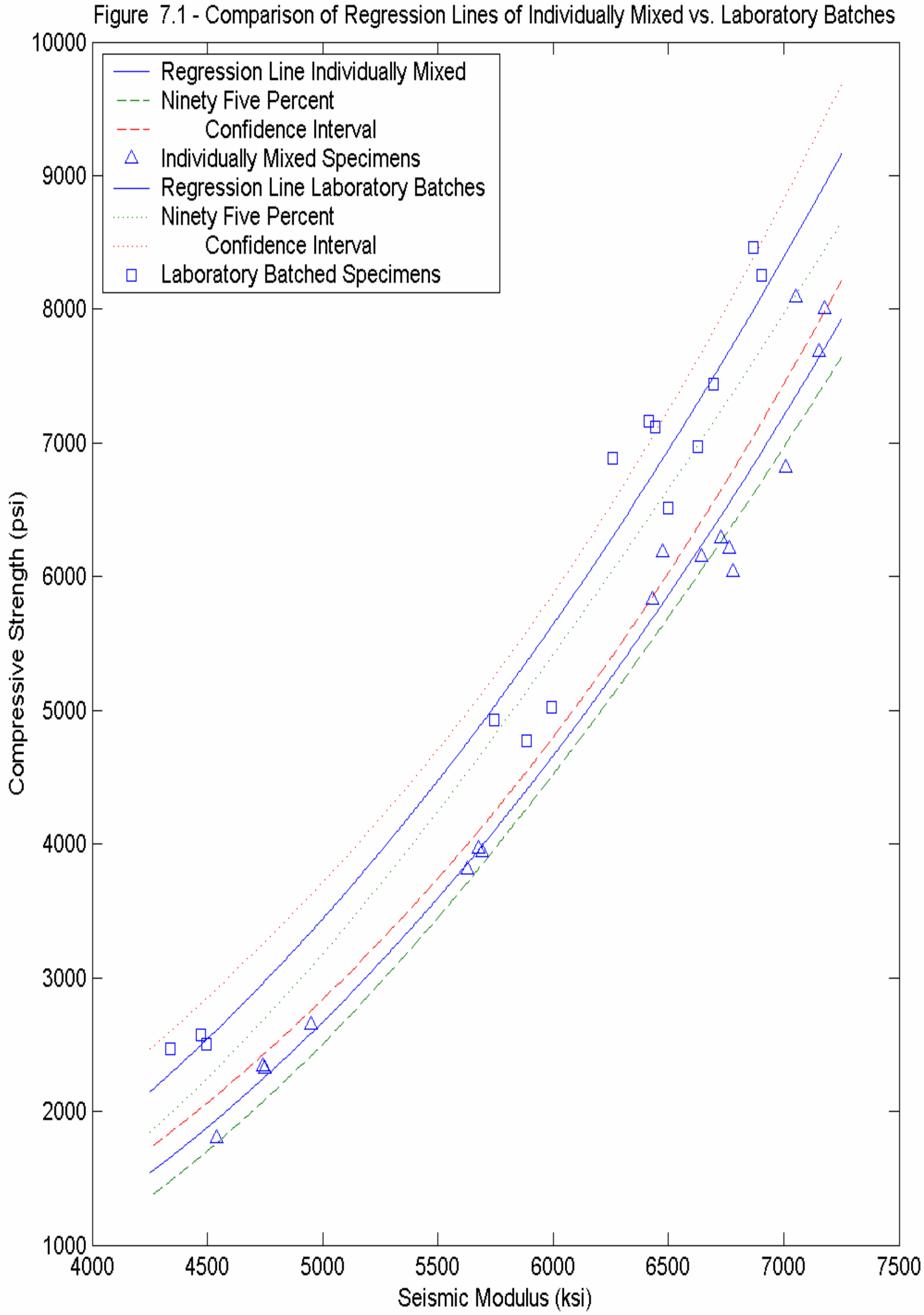


Figure 7.1 - Comparison of Regression Lines of Individually Mixed vs. Laboratory Batches
Regression Line Individually Mixed
Ninety Five Percent
Confidence Interval
Individually Mixed Specimens
Regression Line Laboratory Batches
Ninety Five Percent
Confidence Interval
Laboratory Batched Specimens
Compressive Strength (psi)
Seismic Modulus (ksi)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
4000
4500
5000
5500
6000
6500
7000
7500

corresponding ninety five percent confidence intervals for individually prepared specimens and the specimens cast from laboratory batches.

The results shown in this figure clearly indicate that the two ninety five percent confidence intervals do not overlap. This fact is equivalent to a finding that the hypothesis that the true regression lines for the population are the same can be rejected with a ninety five percent confidence level. Furthermore, the determination coefficient "R^2" is 0.9853 for the individually mixed specimens, and decreases to 0.9725 for the laboratory batched specimens. This is also reflected on the width of the ninety five percent confidence intervals of the regression lines that is larger (more variability) for the laboratory batched specimens. The larger variability in the specimens tested, to define the number of tests to be included in a batch and the corresponding rejection value, could result in an increased number of tests in a batch and somewhat larger rejection values. Both of these two concerns could result in additional work for the acceptance testing and in rejection values that could be more difficult to achieve than necessary. These considerations support the need to use individually mixed specimens in the initial phase to establish the acceptance criterion.

An important aspect is whether the correlations should be developed based on individual tests results or based on batch averages; both approaches were used in the present study and both correlations are presented in the corresponding appendices. To illustrate the relative benefits of these two alternatives, the actual width (in terms of modulus of rupture in psi) of the ninety five percent confidence interval and prediction interval of the regression line of modulus of rupture versus seismic modulus are presented in Table 7.1.

Table 7.1 Vertical Width of Confidence & Prediction Intervals of the Regression Line of Modulus of Rupture vs. Seismic Modulus

	Ninety Five Percent Confidence Interval		Ninety Five Percent Prediction Interval	
	Individual Tests	Batch Average	Individual Tests	Batch Average
Ready- Mix	24 psi (90)	42.2 psi (15)	122.7 psi (90)	98.4 psi (15)
Laboratory Mixed	28.1 psi (32)	37.9 psi (10)	159.4 psi (32)	120.5 psi (10)

Notes: 1. Data extracted from Appendix H at a rupture modulus of 600 psi.
2. The numbers in parenthesis indicate the number of observations.

The individual results include ninety observations for the Ready-Mix specimens and thirty two observations of Laboratory-Mixed (including individually mixed and laboratory batched specimens). The batch of Ready-Mix included six specimens, and the batch of Laboratory-Mixed included three specimens. When the average for the batch is used as a single observation, the number of observations decreased to fifteen observations for the averages of the Ready-Mix batch, and to ten observations for the Laboratory-Mixed batches. The variance **"σ^2"** of the averages of the batches should decrease by a factor that is inversely proportional to the number of specimens in the batch; thus, the variance could be reduced to one-sixth for the Ready-Mix batches and to one-third for the Laboratory-Mixed batches.

The widths of the ninety five percent confidence and prediction intervals depend on the variance of the results as well as the total number of observations used to define the regression line. The effects of these two variables act in opposite directions; namely, a decrease in the variance results in narrower intervals, while a decrease in the number of observations results in an increase of the width of the intervals. The overall effect of these two variables is illustrated in the results shown in Table 7.1. These results show that when using batch averages the width of the ninety five percent confidence interval increases; this trend is consistent for the Ready-Mix and the Laboratory-Mixed batches. The effect on the ninety five percent prediction interval is a consistent decrease of the width of the prediction interval.

In summary, the width of the ninety five percent confidence interval increases when the correlation is established using batch averages in relation to the interval width when the individual tests results are used. Since the proposed acceptance scheme would be affected by an increase of the width of the confidence interval, it is recommended not to use averages. In this manner, it is recommended that the correlations for new concrete mixes be defined using the individual test results, as it was implemented in the present study.

One additional important variable in the proposed acceptance scheme is the expected variance **"σ^2"** of compressive strength tests performed by the NCDOT's field technicians that would be responsible to sample the fresh concrete, cast, cure, and test the specimens for acceptance testing. It is necessary to include in these specimens the normal specimen variability that will be present during the acceptance testing; thus, these specimens should not be reconstituted nor mixed individually.

Several levels of implementation are discussed later in the implementation section. It is recommended that the use of the seismic modulus is gradually introduced to the engineers and technicians of NCDOT and to the contractor's personnel, by implementing the different levels as the confidence in the use and the prediction capabilities of the seismic modulus determination becomes apparent to the technical community involved in the construction of Portland cement concrete pavements. In the not so distance future, if enough confidence is acquired about the use of the seismic modulus, it could be possible to eliminate altogether the systematic need of strength testing for acceptance.

It is recommended that this new methodology of acceptance testing is used, on a trial basis, for a job in which acceptance is controlled with flexural strength tests. So it would be possible to compare the decisions of acceptance or rejection between the two methodologies. Thus providing a means for NCDOT personnel to gain confidence in the new approach before a permanent decision is made.

8. Implementation and Technology Transfer

8.1 General

There are several possible implementation levels depending on how much control is desired to have, by NCDOT engineers, on the constructed pavement. As will be discussed below, the decision to select a certain implementation level does not preclude a later change to a higher implementation level; thus, these levels can be seen as steps for potential improvements with time.

In all the implementation levels, the first step is the development of the appropriate correlations and ninety or ninety five percent intervals. As discussed earlier, the effect of increasing the water and the trapped air in the concrete mass results in displacing coarse aggregate and mortar that would occupy the same volume as occupied by the extra water or air. Since the aggregate and the mortar are heavier than the water or air, the unit weight of the specimen will decrease resulting in a somewhat lower seismic modulus. The technical literature [8] indicates that the type of coarse aggregate has a large effect on the seismic modulus disproportionate to the effect that it would have on the strength. The implication is that the correlation developed in the present research can only be used for mixes with coarse aggregates that have similar densities and mechanical properties to those of the coarse aggregate #57M of Pomona Quarry.

These considerations indicate that if similar aggregates are used in two concrete mixes, there is a chance that the same correlations could be used to control the construction acceptance in both jobs. This fact suggests the need to have a central data base storing all the information develop in previous construction jobs. A data base with correlations and rejection values could be best maintained and managed by a central office, perhaps by the Materials and Tests group. This initial development work for the regression lines and the confidence or prediction intervals would require the direct supervision of a properly trained materials engineer. Probably the best approach would be to place this materials engineer in charge of all the preliminary work for all the pavement construction in the State of North Carolina. This would allow NCDOT personnel to develop confidence on the use of this approach and develop a sense of the need to develop a new set of controlling parameters for a new job. If enough experience is acquired throughout the State of North Carolina, it might be possible some day to divide the state into regions where different correlations and rejection values might be applicable.

The main responsibilities of the materials engineer in charge of the preliminary work would include the selection of the critical values **"μ_a"** and **"μ_t";** the acceptable values for the **"α error"** and **"β error";** and the definition of the variance **"σ^2"** to be expected in the compressive strength measurements of the field technicians. To achieve these goals, it will be necessary to develop the correlations and appropriate ninety or ninety five percent intervals for the specific concrete mix under consideration, discussed earlier and presented in Appendix L. This work will have to be performed in the central laboratory "Materials and Tests" and will be the only part of the project that will require performing bending beam tests. It is imperative that the specimen variability, in this initial phase of the project, be reduced as much as possible. The main concern is that a large variability in this phase could result in harsher specifications, perhaps requiring larger number of tests to be averaged in a batch and rejection values that could be more stringent on the contractor. To minimize the variability, it is recommended that the following precautions are adopted in the initial phase of the project:

1.) The specimens to develop the correlations should be prepared individually. This implies to reconstitute the gradation of coarse aggregate for each specimen, and then mix and cast each specimen individually. In this manner, there is more certainty that the correlations develop are representative of the actual concrete mix approved;
2.) It will be necessary to use experienced technicians that have appropriate training to cast, cure , and test for compressive strength, modulus of rupture, and seismic modulus.
3.) A decision will have to be made as to how many replicate specimens and how many different curing times will have to be included. The values for these numbers should probably be different for the different implementation levels. One general fact should be kept in mind, that by increasing the number of tests included in the correlation, the width of the confidence interval is reduced. Thus, an increase of the number of tests in the initial phase might result in an smaller number of tests in the field and somewhat less strict rejection values.

The same materials engineer will also have to select an appropriate value for the variance **"σ^2"** to be used for the pool of technicians that will perform the sampling and testing in the field. This value is an important and influential variable and the appropriateness of the acceptance criterion depends on choosing a representative value. The main concerns that need to be considered, to develop this value, would be to perform an initial set of measurements, at least thirty, with the following precautions:

1.) Use results obtained by similarly trained personnel to the personnel that will be performing the field acceptance testing;
2.) Use the same concrete mix that will be used at the construction site;
3.) Use the same size of specimen;
4.) Use the same number of curing days that would be in the contract; and
5.) Use similar equipment and practices for sampling fresh concrete, casting, curing and testing as the ones that will be used in the field.

Furthermore, it is important that the concrete used in casting these specimens should be sampled from batches as large as possible/feasible as will be used in the acceptance testing in the field. These specimens should include the normal specimen variability that will be present in the specimens prepared for acceptance testing.

8.2 Implementation Level One

This is the level that would require the least number of changes to be put in place and the least amount of training and expenditures in new equipment.

A central laboratory, such as the Materials and Tests group perhaps, would need to train an engineer to direct the initial phase laboratory program and perform the statistical analyses to select the number of specimens replicates needed to be included in a batch and select the rejection value. Based on this work, when the concrete mix is approved, the number of specimens to be included in a batch and the appropriate rejection value could be specified. Considering the results described in section 5.5, for the present concrete mix, it would be required that for every pavement lot a random batch is sampled and two specimens of compressive strength are prepared and tested. The average compressive strength of these two specimens is then compared to the rejection value of 6,135 psi compressive strength. If the average is equal or exceeds the rejection value, the lot is accepted, otherwise the lot is rejected.

In the present research project, thirty bending beams and thirty compressive strength cylinders of Laboratory-Mixed were cast and were cured for 1, 2, 7, 14, 28 days before strength testing. To develop new correlations in the present "Level One Implementation" is probably not necessary to use so many curing times. The correlations and the statistical analyses could be accomplished by testing a set of thirty bending beams and thirty compressive strength cylinders, ten of each after curing period of 3, 14, and 28 days. Thus a new correlation for a new mix would require about thirty beams to be cast, cured and tested for the whole duration of the paving job. Thus the reduction in number of flexural beam tests would be considerably reduced. If the correlations for the concrete mix and coarse aggregate had been developed for a previous job, the need to perform flexural strength of bending beams would be completely eliminated.

The field technicians performing the acceptance testing will select randomly a batch for each pavement lot and **"n"** compressive strength cylinders will be cast, cured, and tested. The average of the batch will then be compared to the rejection value **"R"**. If the average exceeds the rejection value **"R"**, the lot will be accepted; otherwise, the lot would be rejected. For the case of the concrete mix used in the present research project, the number of compressive strength per batch would be two (or three if some allowance is made for the case of very different specimens results as discussed in section 5.5) and the average of the two tests would then be compared to the rejection value of 6,135 psi.

The level one implementation level would only require training one engineer that should be responsible for all the concrete mixes used in pavement construction in the State of North Carolina. Nobody else in the state would perform flexural tests or seismic modulus determinations. The only additional equipment needed would be a resonant column device for the seismic modulus determinations. The Materials and Tests group already owns one device, thus, there is no need of new expenditures in equipment.

It is highly recommended that the presently proposed approach is used in a job that contractually is supposed to be accepted with flexural strength tests before the new methodology is implemented. From the comparison of the rates of rejection/acceptance decisions using both methodologies, it would be possible to gain confidence on the critical values suggested **"μ_a"** and **"μ_t";** as well as with the appropriate **"α error"** and **"β error".** Furthermore, this exercise can provide some level of confidence or comfort for the contractors, and the NCDOT's construction and pavement design engineers in the new approach of acceptance testing.

8.3 Implementation Level Two

The acceptance scheme for the "level two" implementation would be identical to the "level one" implementation. The main difference between the two levels of implementation would be that some additional compressive strength tests and seismic modulus determinations would be performed in the initial phase, and later at the construction site, to provide some early warning of possible lots with low modulus of rupture.

The first difference would be the need to define the correlations for the whole set of curing times. That is, to prepare specimens and cure these for 1, 2, 7, 14, and 28 days. In this manner, ten specimens for each curing time should be prepared and tested. Thus the tests include fifty bending beams and fifty compressive strength cylinders. Since the specimens for the acceptance criterion will already be available, this will only require producing twenty more bending beams and twenty more compressive cylinders.

The main purpose of this additional work is to define the prediction interval for the ninety five percent confidence level of the regression line between compressive strength and seismic modulus. This prediction interval has a ninety five percent probability of enclosing a future determination. Thus, if some field tests are plotted on the same graph as the prediction interval, if these tests are not included in the prediction interval, there is a ninety five percent probability that the results correspond to a concrete mix different than specified. To illustrate this aspect, the ninety five percent prediction interval for the Laboratory-Mixed specimens obtained in the present research project are presented in Figure 8.1 together with the compressive strength results obtained on Ready-Mixed batch number two for one, two, seven and fourteen days of curing.

In Figure 8.1, the regression line and the ninety five percent prediction interval are plotted limited to the region where actual test results plotted; thus, near the left hand side, a seismic modulus of about 4,250 ksi and compressive strength ranging from 1,000 to about 3,000 psi correspond to the specimens with one day curing. Conversely the specimens cured twenty eight days exhibited seismic modulus of about 7,000 ksi and compressive strengths ranging from 7,000 to about 10,000 psi. The actual specimens of batch number two are also plotted in this figure, all these results plot outside the ninety five percent prediction interval, a clear indication that the two concrete mixes are quite different. If attention is drawn onto the specimens of batch number two cured for two days, it is clear that a set of specimens tested using seismic modulus and compressive strength two days after pouring the slab would provide a clear and early warning that the concrete in the slab will not achieve the expected modulus of rupture.

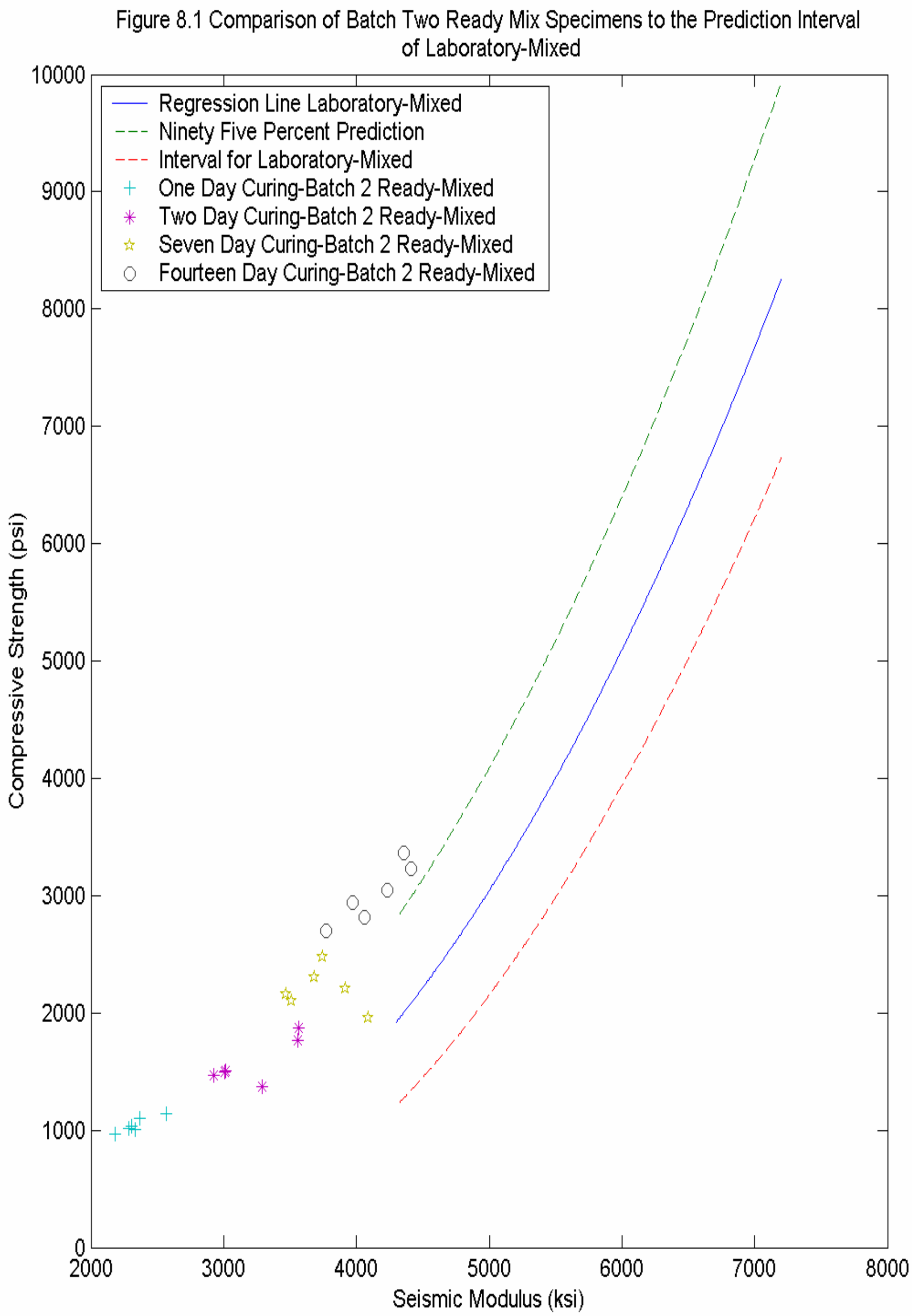


Figure 8.1 Comparison of Batch Two Ready Mix Specimens to the Prediction Interval of Laboratory-Mixed
Regression Line Laboratory-Mixed
Ninety Five Percent Prediction
Interval for Laboratory-Mixed
One Day Curing-Batch 2 Ready-Mixed
Two Day Curing-Batch 2 Ready-Mixed
Seven Day Curing-Batch 2 Ready-Mixed
Fourteen Day Curing-Batch 2 Ready-Mixed
Compressive Strength (psi)
Seismic Modulus (ksi)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
2000
3000
4000
5000
6000
7000
8000

To afford such an early warning, it would be necessary to supplement the initial phase of level one implementation with twenty additional bending beams and twenty additional compressive strength cylinders. Furthermore, the materials engineer would have to produce a plot of the ninety five percent prediction interval such the one shown in Figure 8.1. Then during acceptance testing an additional set of specimens would have to be cast, cured for two days and tested for seismic modulus and compressive strength; these results would then be plotted in the graph with the ninety five percent prediction interval. If the results plot outside the ninety five percent prediction interval, it would indicate that the concrete mix used in the corresponding pavement lot is not the desired concrete mix. In such a case there is a very high probability, at least ninety five percent that the fourteen day compressive strength will be lower than the specification.

The implementation of this level two would require some additional work, training, and additional expenditures in equipment. The major required changes would be the following:

1.) The materials engineer in charge of the initial work phase, would have to perform some additional tests such as twenty bending beam tests and twenty compressive strength tests. These will have to cover the whole range of curing times from one day to twenty eight days. When the concrete mix is approved, the minimum number of specimens to be averaged in a batch and the rejection value will be set as in the previous implementation level one; in the present implementation level two, the regression line and the ninety five percent prediction interval will have to be established for the use of the field personnel performing acceptance testing;
2.) The field technicians performing the acceptance testing will have to prepare for each pavement lot an additional set of compression cylinders to be tested after two days of curing. This early set of specimens would be tested first for the seismic modulus and then tested in compression to failure. The results for each specimen would then be plotted on a chart with the prediction interval; if the points plot outside the expected ninety five percent prediction interval the engineer will be notified of a potential lot with a high probability of not achieving the fourteen day compressive strength specified. In this manner, it is worthwhile to notice that the field technicians would not have to understand any of the statistical considerations involved. These technicians would only perform the two tests and plot the results in a graph, notice whether the points plot outside of the prediction interval supplied by the materials engineer and alert the engineer if appropriate;
3.) The performance of the seismic modulus determination in the field would require some investment in equipment and some training of the NCDOT's field technicians. The cost of an additional resonant column runs on the order of ten thousand dollars, and two or three days might be needed to train a technician to perform the seismic modulus test.

In this implementation level two, the resonant column device will have to be available at the regional testing laboratory; thus, it could be advantageous that the seismic modulus determination is performed on each specimen before the strength test. This additional work on the set of cylinders for the acceptance testing batch will provide some experience for the technicians and the construction engineers allowing them a higher level of confidence on the capabilities of the seismic modulus measurements.

8.4 Potential Future Expansion of Using Seismic Modulus

The gradual implementation of the levels one and two, would permit NCDOT's engineers and technicians, as well as the contractors, to become familiar with the abilities of the seismic modulus determination in acceptance testing.

One of the biggest advantages of the seismic modulus determination is that is non-destructive and that it exhibited the lowest variability of all the techniques used in the present research project. Eventually, if enough confidence is acquired about the use of the seismic modulus, it could be possible to eliminate altogether the need for strength testing for acceptance. The acceptance decision could be based on field surveys of seismic modulus performed on the slab. The coupling of seismic modulus surveys with maturity testing would allow very early testing of the slab after pouring and, then extrapolating to the number of days specified in the contractual documents.

The fact that the seismic modulus can be determined non-destructively on the field slabs, would allow testing the concrete placed, consolidated, and cured under field conditions rather than on the cylinders of record. There is a device the "Portable Seismic Pavement Analyzer" that can measure the seismic modulus in the field. The device can be handled by one technician and the determination can be performed in less than one minute at one point; thus, a single technician can survey a slab fifteen feet by fifteen feet on a three foot grid in less than half an hour. The test can be performed as soon as it is possible to walk on the fresh concrete; therefore, testing and accepting of the pavement lots could be performed with minimal delays after construction.

9. References

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Appendix A

Common Practices on Acceptance Testing
of
Portland-Cement Concrete Pavements
throughout
The United States of America

State	Contact Person	Phone	Email	Policy for Acceptance Testing
Alabama	Sergio Rodriguez		rodriguezs@dot.state.al.us	**Compressive & Flexural Strength (cylinders & beams)**
Alaska	Gregory Christensen		greg_christensen@dot.state.ak.us	**N/A** (Alaska only uses Hot-Mix Asphalt Pavement)
Arizona *				**Compressive Strength (cylinders)** Slump, Air Content, Thickness, Smoothness, Profile Index http://www.dot.state.az.us/HIGHWAYS/cns/C&S_Stored_Specs/2000_Stored_Specs_7-23-04.exe
Arkansas	Wayne H. Casteel		wayne.casteel@arkansashighways.com	**Compressive Strength (cylinders or cores)** Air Content, Slump, Thickness, Smoothness
California	Hector Romero	916-227-1989	hector_romero@dot.ca.gov	**Compressive Strength (cylinders)** Flexural: Modulus of Rupture no less than 3.8 MPa
Colorado	Greg Lowery	303-757-9430	greg.lowery@dot.state.co.us	**Compressive Strength (cylinders)** Flexural Strength (beams - only for contractor's qc) Air Content, Slump, Thickness
Connecticut	John Henault	860-258-0352		**Compressive Strength (cylinders)** Researching Maturity Meters for Future Use
Delaware *		302-760-2371		**Compressive Strength (cylinders)** Cement & Air Content, W/C Ratio, Slump, Thickness http://www.deldot.net/static/pubs_forms/manuals/standard_specifications/division_500.html#SECTION%20501 http://www.deldot.net/static/pubs_forms/manuals/standard_specifications/division_800.html#SECTION%20812
D.C. *		202-645-6140		**Compressive & Flexural Strength (cylinders & beams)** Slump, Air Content, Thickness http://www.ddot.dc.gov/ddot/frames.asp?doc=/ddot/LIB/ddot/information/standards/pdf/divs/div501.pdf&open=|32399|
Florida	David Wang	850-414-4152	david.wang@dot.state.fl.us	**Flexural strength (beams)**
Georgia	Georgene Geary	404-363-7512	georgene.geary@dot.state.ga.us	**Compressive Strength (cylinders)** Slump, Air Content, Thickness, Smoothness
Hawaii *	Casey Abe	808-832-3403		**Compressive & Flexural Strength (cylinders & beams)** Air Content, Slump, Cement Content, Thickness http://www.hawaii.gov/dot/highways/specs94/specs/specspdf/411.pdf
Idaho	Jan Hargrave		jan.hargrave@itd.idaho.gov	**Compressive Strength (cylinders)**
Illinois	Douglas Dirks	217-782-7208	dirksda@dot.il.gov	**Compressive Strength (cylinders) & Flexural Strength (beams using small portable beam breakers)**
Indiana	Rick Yunker	317-610-7251 ext 203	ryunker@indot.state.in.us	**Flexural Strength (beams)** Air Content, Unit Weight, W/C Ratio, Thickness, http://www.ai.org/dot/div/contracts/standards/book/sep06/5-2006.pdf

State	Contact Person	Phone	Email	Policy for Acceptance Testing
Iowa	Kevin Jones	515-239-1237	kevin.jones@dot.iowa.gov	**Flexural Strength (beams)** Slump, Air Content, Unit Weight, Temperature (last 3 on plastic concrete)
Kansas	Rick Kreider	785-296-3711	rickk@ksdot.org	**Compressive Strength (cylinders)** Slump, Air Content, Unit Weight, Aggregate Gradation, Thickness, In-place density as percentage of Unit Weight (on plastic concrete)
Kentucky	Ross Mills	502-564-3160	ross.mills@ky.gov	**Maturity Meter & Compressive Strength (cylinders)**
Louisiana	Khiet Ngo	225-248-4131	khietngo@dotd.louisiana.gov	**Compressive Strength (cores) & Flexural Strength (beams - transitioning all projects to this test)**
Maine	Bruce Yeaton	207-453-7377	bruce.yeaton@maine.gov	**N/A** (Maine only uses Hot-Mix Asphalt Pavement)
Maryland *	Vicki Stewart	410-321-3440	materials@sha.state.md.us	**Compressive Strength (cylinders)** Air Content, Slump, Thickness http://www.sha.state.md.us/businesswithsha/bizStdsSpecs/desManualStdPub/publicationsonline/ohd/PDFS/TRSEC03.PDF
Massachusetts *		617-973-7800	feedback@mhd.state.ma.us	**Flexural Strength (beams)** Slump, Thickness http://166.90.180.162/mhd/downloads/manuals/1995Mspecs.pdf
Michigan	Thomas Woodhouse		woodhouset@michigan.gov	**Compressive Strength (cylinders)**
Minnesota	Maria Masten	651-779-5572	maria.masten@dot.state.mn.us	**Flexural Strength (beams)** Air Content, max W/C ratio of 0.40, Slump, Microwave Oven testing, Thickness (cores also broken for Comp. Strength info)
Mississippi	Mike O'Brien	601-359-1754	mobrien@mdot.state.ms.us	**Compressive Strength (cylinders)**
Missouri *	David Ahlvers	573-751-7455	ahlved@mail.modot.state.mo.us	**Compressive Strength (cylinders)** Slump, Air Content, Smoothness (Profilograph), Thickness http://www.modot.state.mo.us/business/standards_and_specs/nov2004specbook/DIV0500.pdf
Montana *	Rueben Fink	406-444-6285		**Compressive & Flexural Strength (cylinders & beams)** Coarse Agg., Slump, Air, Cement & Water, Thickness http://www.mdt.state.mt.us/contract/net/external/standard_specbook/section501.pdf http://www.mdt.state.mt.us/contract/net/external/standard_specbook/section551.pdf
Nebraska *	Robert Rea	402-479-4677	rrea@dor.state.ne.us	**Compressive Strength (cores or cylinders)** Thickness, Smoothness, Cement Content http://www.nebraskatransportation.org/ref-man/Specsupp/602-Supp.pdf http://www.nebraskatransportation.org/ref-man/Specsupp/603-Supp.pdf

State	Contact Person	Phone	Email	Policy for Acceptance Testing
Nevada *		775-888-7070		**Compressive & Flexural Strength (cylinders & beams)** Slump, Air Content, Thickness, Smoothness http://www.nevadadot.com/business/contractor/standards/documents/2001StandardSpecifications.pdf
New Hampshire	Jim Amero	973-770-5037		**N/A** (NH only uses Hot-Mix Asphalt Pavement)
New Jersey *		973-770-5037 732-308-4022 856-486-6611		**Compressive Strength (cylinders)** Coarse Agg., Slump, Air Content, Thickness, Smoothness http://www.state.nj.us/transportation/eng/specs/english/EnglishStandardSpecifications.htm#_Toc530372711 http://www.state.nj.us/transportation/eng/specs/english/EnglishStandardSpecifications.htm#s914
New Mexico *	Jim Stokes	505-827-5541		**Compressive Strength (cylinders)** Slump, Air Content, Thickness http://www.nmshtd.state.nm.us/upload/images/Spec_for_Highway_and_Bridge_Const/Supplement.pdf
New York	Michael Brinkman	518-457-4584	mbrinkman@dot.state.ny.us	**Compressive Strength (cylinders)** Slump, Air Content, Unit Weight, Smoothness Freeze-Thaw Resistance (cylinders)
North Dakota	Dennis Blasl	701-328-6902	dblasl@state.nd.us	**Flexural Strength (beams)**
Ohio	Roger Green		roger.green@dot.state.oh.us	**Flexural Strength (beams- early opening only)** Yield, Air Content, Thickness, Smoothness Adding Hyperpave Software for determining time to saw contraction joints
Oklahoma	Kenny R. Seward	405-522-4918	kseward@odot.org	**Compressive Strength (cylinders)** Slump, Air Content, W/C Ratio, Cement Substitution
Oregon	Mike Remily		michael.d.remily@odot.state.or.us	**Compressive Strength (cylinders)**
Pennsylvania	Pat Gardiner		jgardiner@state.pa.us	**Compressive Strength (cylinders)** Plastic Air Content, Pavement Depth, Smoothness
Rhode Island *	Mark Felag	401-222-2524 ext. 4130		**Compressive Strength (cylinders)** Air & Cement Content, W/C Ratio, Slump, Temp., http://www.dot.state.ri.us/webproj/engineering/proj/bluebook/CD-Bluebook.pdf
South Carolina	Andy Johnson	803-737-6681	johnsonam@scdot.org	**Flexural Strength (beams)** Slump, Air Content, W/C Ratio http://www.dot.state.sc.us/doing/StandardSpecifications/pdfs/07Division_500-Revised.pdf http://www.dot.state.sc.us/doing/StandardSpecifications/pdfs/09Division_700-Revised.pdf
South Dakota	Darin Hodges		darin.hodges@state.sd.us	**Compressive Strength (cylinders)**
Tennessee	Brian Egan	615-350-4104	brian.egan@state.tn.us	**Compressive Strength (cylinders)** Air Content, Slump, Temp., Thickness, Smoothness
Texas *	Moon Won	512-506-5863	mwon@dot.state.tx.us	**Compressive & Flexural Strength (cylinders & beams)** Temp., Slump, Air Content, Thickness ftp://ftp.dot.state.tx.us/pub/txdot-info/des/specs/specbook.pdf

State	Contact Person	Phone	Email	Policy for Acceptance Testing
Utah	Troy L. Peterson	801-965-3814	tlpeterson@utah.gov	**Compressive Strength (cylinders)** Flexural Strength (early opening only) Thickness, Smoothness
Vermont	Donald H. Lathrop	802-828-6911	don.lathrop@state.vt.us	**Compressive Strength (cylinders)** Slump, Air Content, Temperature, W/C ratio
Virginia	Thomas R. Tate	804-328-3129	thomas.tate@vdot.virginia.gov	**Compressive Strength (cylinders)** Flexural Strength (beams - early opening only) Smoothness (using South Dakota type profiler)
Washington	Jeff Uhlmeyer	360-709-5485	uhlmeyj@wsdot.wa.gov	**Compressive Strength (cylinders)**
West Virginia	Mike Mance		mmance@dot.state.wv.us	**Compressive Strength (random sampled cores)** Thickness
Wisconsin	Sharon Bremser		sharon.bremser@dot.state.wi.us	**Compressive Strength (cylinders or cores)** Concrete Maturity Method, Thickness, Air Content
Wyoming	Andy Freeman	307-777-4476	andy.freeman@dot.state.wy.us	**Compressive Strength (cylinders as related to beam tests) & Flexural Strength (beams)** Cement Substitution limits

States marked with an asterisk (*) are those that we were unable to get a response from the contact. The specifications listed for these are found online (html listed in table) under each state's respective specifications.

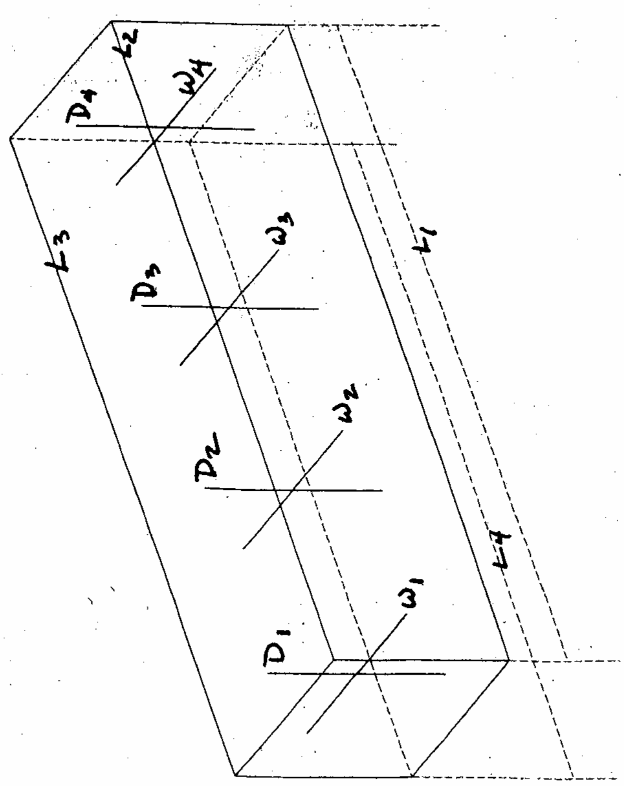
Appendix B

Samples of Laboratory Forms
Used to Record
Observations and Specimen Information
Throughout the Testing Program

Specimen Type	Curing Age	Batch Type	Specimen Number
B0	14	R	044
B0 -20 in Beam B1 –21 in Beam	01 days 02 days 07 days 14 days 28 days	R –Ready Mix L – Lab Mix I – Indiv	Correlative Number B0 –Series B1 -Series

Activity	Date	Time	By who
Pouring	5/10/4	9:00	mf
De-molding	5/11/4	11:15	mf
Curing Tank	5/11/4	11:15	mf.
Testing	5/24/04	16:45	MCw

Weight of Specimen	61.2	Pounds



Length of Specimen (inches)	
L_1	20
L_2	20
L_3	20
L_4	20
Average	20

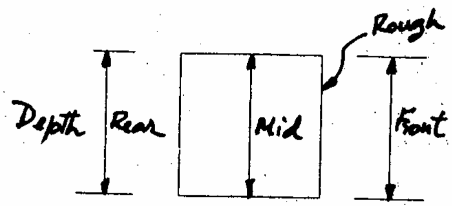
Width of Specimen (inches)	
W_1	6.002
W_2	6.067
W_3	6.053
W_4	6.075
Average	6.049

6.033

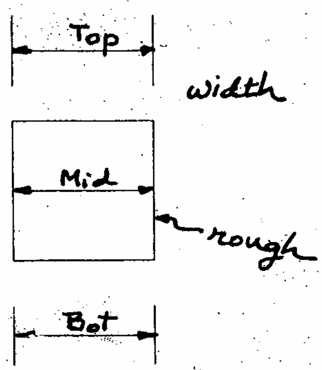
Depth of Specimen (inches)	
D_1	6.017
D_2	5.991
D_3	6.030
D_4	6.035
Average	6.018

Specimen Weight after Curing	61.6 Pounds

Repetition Number	Seismic Young's Modulus (ksi)				
	Trial #1	Trial #2	Trial #3	Trial #4	Trial #5
1	5096	5101	5095		
2	5095	5101	5109		
3	5096	5100	5104		



Measurements of left piece of beam after Failure (inches)	
L_1'	10.591
L_2'	10.298
L_3'	10.718
L_4'	11.486



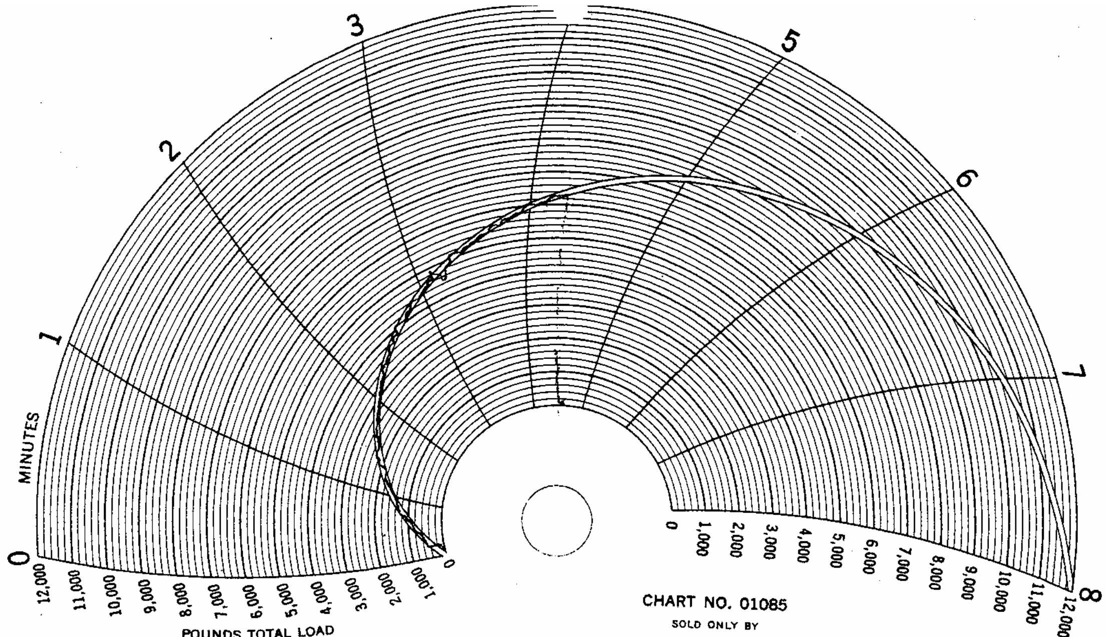
Width at Failure Plane (inches)	
Top	5.957
Mid Point	6.016
Bottom	6.036
Average	6.003

Depth at Failure Plane (inches)	
Front	6.030
Mid Plane	6.003
Rear	6.024
Average	6.019

Weight of left side piece (pounds)	33.0

Number of Coarse Aggregate Particles Split in Tension	28
Number of Coarse Aggregate Particles Crushed in Compression	

R= 521.4300 psi   E= 5,100 ksi



CONCRETE BEAM FLEXURAL STRENGTH TEST - A.S.T.M. PROCEDURE C78

CONTRACTOR________ PROJECT________

BEAM NO. BD-14R-044 MADE 05/10/04 TESTED 05/24/04 AGE 14 days

LOAD 6300 LBS., WIDTH______ IN., DEPTH______ IN., FACTOR______

FLEXURAL STRENGTH______ PSI., SPECIFICATION______ PSI.

REMARKS clock stopped 5 times during flexural test

TESTING AGENCY________

TESTED BY PULE

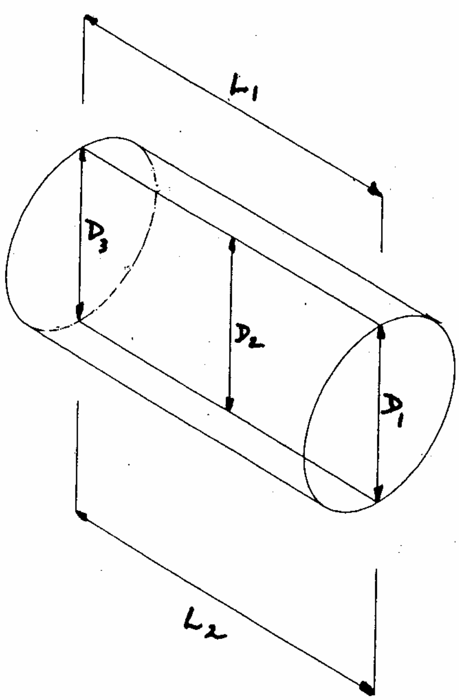
CHECKED BY________

PRINTED IN U.S.A.

Specimen Type	Curing Age	Batch Type	Specimen Number
SC	7	R	069
	01 days 02 days 07 days 14 days 28 days	R – Ready Mix L – Lab Mix I – Indiv	Correlative Number For Split. Tension Cylinders

Activity	Date	Time	By who
Pouring	5/26/4	11: —	MB
De-molding	5/27/4	16:50	Mcw
Curing Tank	5/27/4	17:05	Mcw
Testing	6/2/4	10:40	MB

Weight of Specimen	28.7 Pounds



Length of Specimen (inches)	
L_1	12.214
L_2	12.16
Average	12.187

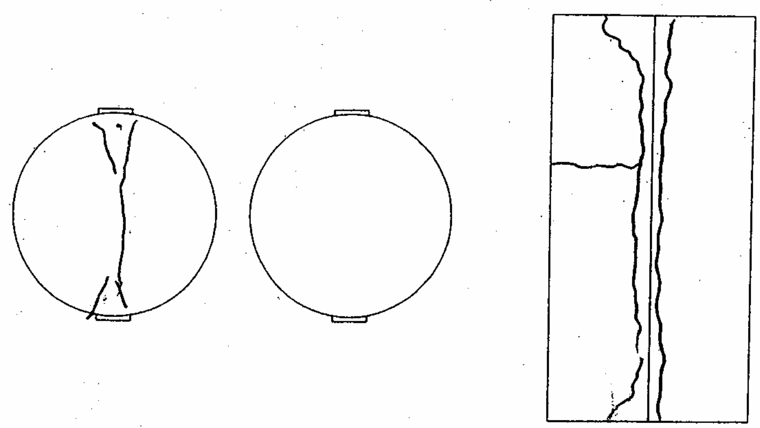
Diameter of Specimen (inches)	
D_1	6.217
D_2	5.983
D_3	6.025
Average	6.075

Specimen Weight after Curing	29.6 Pounds

Repetition Number	Seismic Young's Modulus (ksi)				
	Trial #1	Trial #2	Trial #3	Trial #4	Trial #5
1	4855	4864	4853		
2	4854	4865	4857		
3	4853	4864	4850		

SPLIT TENSION TESTING	
Machine Setting, Number before one Turn	1.5
Sustained Loading Rate (~~pounds~~ Kip/minute)	14
Peak Load Strength (Pounds)	41,488

FAILURE TYPE INTERPRETATION



Burst of Energy Released at Peak Load			yes	no
Magnitude of Burst of Energy Released	Strong	Med.	Weak	None
Weight of Left Half of Split Specimen (pounds)			13.3	
Weight of Right Half of Split Specimen (pounds)			15.6	
Number of Coarse Aggregate Particles Fractured - Left Half			20	
Number of Coarse Aggregate Particles Fractured -Right Half			19	

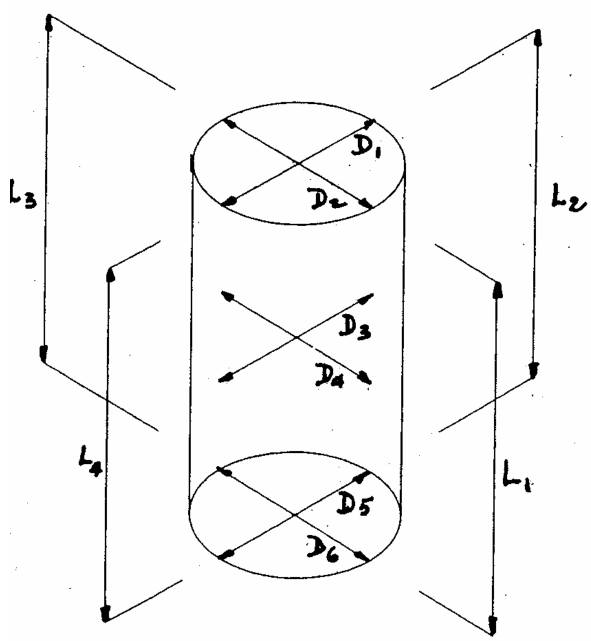
T = 356.746 psi

E = 4,855.67 Ksi

Specimen Type	Curing Age	Batch Type	Specimen Number
C4	7	R	038
	01 days 02 days 07 days 14 days 28 days	R – Ready Mix L – Lab Mix I – Indiv	Correlative Number For 4 in. Compres. Cylinders

Activity	Date	Time	By who
Pouring	5/10/4	9:00	mf
De-molding	5/11/4	14:35	mf
Curing Tank	5/11/4	14:35	mf
Testing	5/17/4	11:30	mf

Weight of Specimen	8.419	Kilograms



Length of Specimen (inches)	
L_1	8.034
L_2	8.018
L_3	8.036
L_4	8.040
Average	8.032

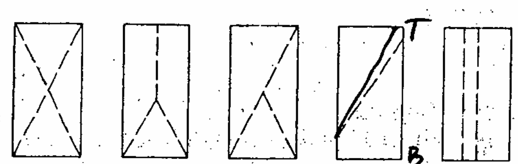
Diameter of Specimen (inches)	
D_1	4.087
D_2	4.083
D_3	4.062
D_4	4.010
D_5	4.033
D_6	4.027
Average	4.050

Specimen Weight after Curing	8.467 lbs ~~Kilograms~~

Repetition Number	Seismic Young's Modulus (ksi)				
	Trial #1	Trial #2	Trial #3	Trial #4	Trial #5
1	3659 ~~NA~~	3641	3696		
2	3673	3675	3705		
3	3668	3679	3700		

COMPRESSION TESTING	
Machine Setting, Number before one Turn	2.0
Sustained Loading Rate (~~pounds~~ kip/minute)	38
Peak Load Strength (Pounds)	29,722

FAILURE TYPE INTERPRETATION (Check the most appropriate)



Cone (a) | Cone and Split (b) | Cone and Shear (c) | Shear (d) | Columnar (e)

Number of Coarse Aggregate Particles Split in Tension	4
Number of Coarse Aggregate Particles Crushed in Compression	—

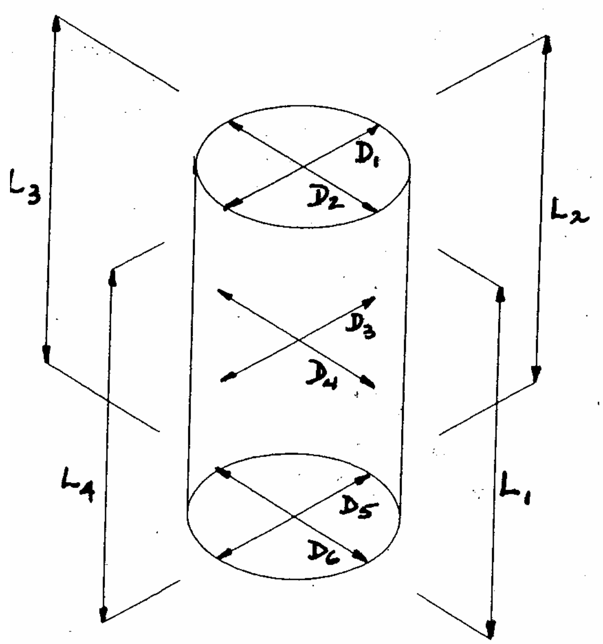
OBSERVATIONS: No Bang
Top cap affected
Bottom cap not
Top cap looked not horizontal
bad capping job ?

C4 = 2,307.2 psi   E = 3,682.3 ksi

Specimen Type	Curing Age	Batch Type	Specimen Number
C6	14	L	110
	01 days 02 days 07 days 14 days 28 days	R – Ready Mix L – Lab Mix I – Indiv	Correlative Number For 6 in. Compres. Cylinders

Activity	Date	Time	By who
Pouring	10/6/04	10:30	MW & MP
De-molding	10/7/04	10:30	MW & MP
Curing Tank	10/7/04	10:30	MW & MP
Testing	10/20/04	14:25	MW & MP

Weight of Specimen	30.5	Pounds



Length of Specimen (inches)	
L_1	12.095
L_2	12.100
L_3	12.118
L_4	12.096
Average	12.1022

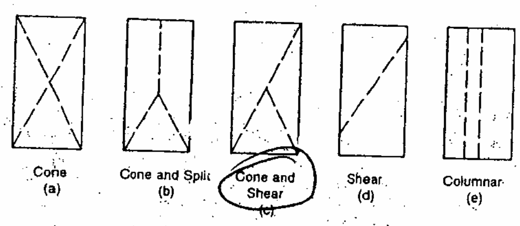
Diameter of Specimen (inches)	
D_1	6.143
D_2	6.008
D_3	6.028
D_4	6.003
D_5	5.981
D_6	5.991
Average	6.0257

Specimen Weight after Curing	30.6	Pounds

Repetition Number	Seismic Young's Modulus (ksi)				
	Trial #1	Trial #2	Trial #3	Trial #4	Trial #5
1	6663	6686	6683	6651	
2	6663	6685	6666	6657	
3	6664	6678	6663.	6656	

COMPRESSION TESTING	
Machine Setting, Number before one Turn	2.0
Sustained Loading Rate (~~pounds~~ kip/minute)	70
Peak Load Strength (Pounds)	191,880

FAILURE TYPE INTERPRETATION (Check the most appropriate)



. 2 Sketches of Types of Fracture

Number of Coarse Aggregate Particles Split in Tension	
Number of Coarse Aggregate Particles Crushed in Compression	

Big bang
Not much affected bottom

E = 6,665.25 Ksi

C6 = 6,728.6 psi

Appendix C

Compressive Strength Results Obtained on Four by Eight Inch Specimens

Specimen ID	Weight (lb)	Diameter (in)	Length (in)	Strength (psi)	Seismic Modulus (ksi)	Break Evaluation
C4-2-R-1	8.566	4.016	8.025	1117.8	3130.7	
C4-2-R-2	8.526	4.025	8.052	1011.7	2963.7	
C4-2-R-3	8.553	4.031	8.066	991.7	2956.7	
C4-2-R-4	8.478	4.017	8.050	919.0	2763.3	
C4-2-R-5	8.500	4.033	7.982	931.9	2795.5	
C4-2-R-6	8.083	4.024	8.009	1018.4	2421.3	Bad Specimen
Average				994.4	2922.0	
C4-7-R-7	8.586	4.055	8.045	2952.2	4523.7	
C4-7-R-8	8.574	4.026	8.060	2479.2	4240.3	
C4-7-R-9	8.525	4.041	8.072	2571.9	4197.0	
C4-7-R-10	8.440	4.036	8.029	2834.9	4239.3	Bad Specimen
C4-7-R-11	8.497	4.040	8.024	3025.1	4458.7	
C4-7-R-12	8.581	4.034	8.091	2664.4	4272.7	
Average				2738.6	4338.5	
C4-14-R-13	8.630	4.016	7.975	4820.8	5651.3	
C4-14-R-14	8.660	4.000	8.000	4972.8	5945.0	
C4-14-R-15	8.570	4.017	8.000	5018.1	5683.7	
C4-14-R-16	8.670	4.000	8.055	4905.1	5854.7	
C4-14-R-17	8.580	4.000	8.000	4881.5	5636.2	
C4-14-R-18	8.650	4.000	8.000	5133.3	5720.7	
Average				4955.3	5748.6	
C4-28-R-19	8.710	4.033	8.100	5712.2	6210.0	
C4-28-R-20	8.680	4.033	8.000	5757.1	6197.0	
C4-28-R-21	8.720	4.033	8.000	5123.9	6209.7	
C4-28-R-22	8.900	4.017	8.100	5478.5	6656.3	
C4-28-R-23	8.770	4.017	8.000	5228.8	6311.3	
C4-28-R-24	8.860	4.033	8.125	5596.1	6266.3	
C4-28-R-25	8.311	4.026	8.050	3291.7	4596.7	
Average				5169.8	6063.9	
C4-1-R-26	8.386	4.035	8.008	1029.9	2307.7	
C4-1-R-27	8.568	4.046	8.139	1138.1	2564.3	
C4-1-R-28	8.390	4.039	8.035	1018.6	2288.0	
C4-1-R-29	8.430	4.037	8.103	1100.8	2371.0	
C4-1-R-30	8.366	4.036	8.035	1001.6	2333.3	
C4-1-R-31	8.462	4.046	8.064	970.5	2182.7	
Average				1043.3	2341.2	

Specimen ID	Weight (lb)	Diameter (in)	Length (in)	Strength (psi)	Seismic Modulus (ksi)	Break Evaluation
C4-2-R-32	8.441	4.061	8.081	1465.7	2928.0	
C4-2-R-33	8.337	4.034	8.034	1496.1	3011.0	
C4-2-R-34	8.379	4.026	8.061	1502.1	3018.0	
C4-2-R-35	8.553	4.054	8.158	1764.9	3560.3	
C4-2-R-36	8.620	4.056	8.189	1868.7	3562.3	
C4-2-R-37	8.141	4.025	8.238	1369.2	3289.7	Bad Specimen
Average				1619.5	3215.9	
C4-7-R-38	8.419	4.050	8.032	2307.2	3682.3	
C4-7-R-39	8.534	4.045	8.074	2479.1	3744.3	
C4-7-R-40	8.346	4.044	8.091	2157.0	3467.0	
C4-7-R-41	8.106	4.034	8.105	2101.1	3510.7	
C4-7-R-42	8.200	4.045	8.134	2205.2	3916.7	Bad Specimen
C4-7-R-43	7.980	4.039	8.173	1961.7	4088.3	Bad Specimen
Average				2261.1	3601.1	
C4-14-R-44	8.393	4.027	8.038	2701.6	3771.5	
C4-14-R-45	8.527	4.045	8.060	3225.4	4411.0	
C4-14-R-46	8.432	4.039	8.071	3366.2	4354.3	
C4-14-R-47	8.582	4.037	8.051	3045.1	4230.0	
C4-14-R-48	8.465	4.045	8.060	2936.1	3969.3	
C4-14-R-49	8.467	4.038	8.034	2813.5	4058.7	
Average				3014.6	4132.5	
C4-28-R-50	8.410	4.014	8.088	3103.5	4223.0	
C4-28-R-51	8.430	4.043	8.087	2959.0	4057.7	
C4-28-R-52	8.419	4.029	8.046	3286.8	4121.0	
C4-28-R-53	8.402	4.029	8.083	3142.5	4130.0	
C4-28-R-54	8.315	4.027	8.045	3356.8	3828.7	
C4-28-R-55	8.436	4.046	8.080	3190.0	4121.3	
Average				3173.1	4080.3	
C4-1-I-56	9.100	4.007	8.097	1803.6	4540.3	Bad Specimen
C4-14-I-57	9.040	4.017	8.004	6034.9	6781.0	
C4-1-R-58	8.544	4.028	7.994	1769.5	3358.7	
C4-1-R-59	8.609	4.019	8.040	1654.1	3085.7	
C4-1-R-60	8.618	4.015	8.027	1689.7	3257.7	
C4-1-R-61	8.639	4.022	8.035	1692.0	3260.3	
C4-1-R-62	8.627	4.035	8.012	1569.7	3271.7	
C4-1-R-63	8.652	4.021	8.042	1717.5	3310.3	
Average				1682.1	3257.4	

Specimen ID	Weight (lb)	Diameter (in)	Length (in)	Strength (psi)	Seismic Modulus (ksi)	Break Evaluation
C4-2-R-64	8.720	4.028	8.015	2563.6	4396.3	
C4-2-R-65	8.790	4.048	8.054	2916.4	4573.3	
C4-2-R-66	8.690	4.020	8.040	2644.0	4274.7	
C4-2-R-67	8.780	4.039	8.104	2679.4	4366.3	
C4-2-R-68	8.797	4.030	8.036	2474.3	4214.0	
C4-2-R-69	8.698	4.030	8.046	2395.2	4114.3	
Average				2612.1	4323.2	
C4-7-R-70	8.729	4.029	8.073	3862.2	4953.7	
C4-7-R-71	8.696	4.019	8.047	3957.8	5013.0	
C4-7-R-72	8.744	4.017	8.115	3590.4	5049.0	
C4-7-R-73	8.671	4.021	8.060	3925.8	4859.7	
C4-7-R-74	8.627	4.027	8.035	3668.9	5361.0	
C4-7-R-75	8.680	4.022	8.074	3505.2	4916.0	
Average				3751.7	5025.4	
C4-14-R-76	8.682	4.017	8.053	4540.7	5528.0	
C4-14-R-77	8.619	4.017	8.019	4280.1	5492.3	
C4-14-R-78	8.717	4.014	8.069	4742.4	5521.7	
C4-14-R-79	8.662	4.014	8.047	4684.2	5512.3	
C4-14-R-80	8.606	4.012	8.043	4724.9	5448.7	
C4-14-R-81	8.723	4.012	8.106	4582.9	5455.0	
Average				4592.5	5493.0	
C4-28-R-82	8.582	4.018	8.031	4789.5	5511.7	
C4-28-R-83	8.536	4.024	8.085	4978.9	5492.0	
C4-28-R-84	8.546	4.016	8.068	4454.0	5525.0	
C4-28-R-85	8.549	4.009	8.034	5130.6	5648.3	
C4-28-R-86	8.525	4.028	8.032	4453.8	5607.3	
C4-28-R-87	8.551	4.026	8.043	4748.8	5462.0	
Average				4759.3	5541.1	
C4-14-I-88	9.000	4.014	8.004	6149.3	6642.7	
C4-14-I-89	8.900	4.016	8.025	6210.3	6761.7	
C4-14-I-90	8.900	4.017	8.011	6285.2	6726.0	
Average				6214.9	6710.1	
C4-28-I-91	8.900	4.037	7.978	7681.5	7152.0	
C4-28-I-92	8.900	4.014	7.994	8089.6	7053.3	
C4-28-I-93	8.800	4.015	8.005	8005.8	7175.0	
Average				7925.7	7126.8	

Specimen ID	Weight (lb)	Diameter (in)	Length (in)	Strength (psi)	Seismic Modulus (ksi)	Break Evaluation
C4-2-I-94	9.000	4.032	8.039	3806.9	5626.7	
C4-2-I-95	9.000	4.031	8.030	3964.7	5677.0	
C4-2-I-96	9.000	4.034	8.004	3940.4	5691.7	
Average				3904.0	5665.1	
C4-7-I-97	9.200	4.035	8.026	6815.4	7007.7	
C4-7-I-98	9.000	4.024	8.048	5826.4	6430.3	
C4-7-I-99	9.100	4.030	8.066	6187.9	6475.0	
Average				6276.6	6637.7	
C4-1-I-100	8.989	4.028	8.008	2324.7	4748.6	
C4-1-I-101	8.981	4.034	7.986	2339.4	4742.3	
C4-1-I-102	9.126	4.034	8.006	2653.5	4947.6	
Average				2439.2	4812.8	
C4-28-L-103	NA	NA	NA	NA	NA	Bad Specimen
C4-28-L-104	8.980	4.027	8.040	8459.9	6868.5	
C4-28-L-105	8.976	4.027	8.043	8257.4	6904.3	
Average				8358.6	6886.4	
C4-2-L-106	9.075	4.019	8.041	4773.1	5884.8	
C4-2-L-107	8.977	4.026	8.005	4932.0	5744.5	
C4-2-L-108	9.095	4.021	8.017	5022.9	5994.5	
Average				4909.4	5874.6	
C4-14-L-109	8.903	4.028	8.029	6974.1	6627.3	
C4-14-L-110	8.795	4.025	8.027	7117.3	6442.5	
C4-14-L-111	8.901	4.021	8.021	7436.3	6695.5	
Average				7175.9	6588.4	
C4-1-L-112	9.014	4.036	8.023	2502.3	4495.5	
C4-1-L-113	8.912	4.031	8.045	2469.6	4338.8	
C4-1-L-114	8.936	4.031	8.010	2567.9	4470.5	
Average				2513.3	4434.9	
C4-7-L-115	9.203	4.017	8.030	6516.7	6498.3	
C4-7-L-116	9.184	4.023	8.096	7167.2	6415.0	
C4-7-L-117	9.129	4.018	8.050	6882.5	6259.0	
Average				6855.5	6390.8	

Appendix D

Compressive Strength Results
Obtained on
Six by Twelve Inch Specimens

Specimen ID	Weight (lb)	Diameter (in)	Length (in)	Strength (psi)	Seismic Modulus (ksi)	Break Evaluation
C6-2-R-1	28.200	6.025	12.125	664.5	2228.0	
C6-2-R-2	28.300	6.017	12.150	799.1	2816.7	
C6-2-R-3	28.400	6.032	12.098	908.6	2872.3	
C6-2-R-4	28.700	6.007	12.160	875.7	2790.3	
C6-2-R-5	28.300	5.997	12.160	624.5	2364.3	
C6-2-R-6	28.700	6.027	12.130	919.8	2807.3	
Average				798.7	2646.5	
C6-7-R-7	29.000	6.032	12.140	2249.0	4200.3	
C6-7-R-8	28.300	6.036	12.090	1787.2	3624.3	
C6-7-R-9	28.400	6.035	12.118	2312.4	3890.7	
C6-7-R-10	28.500	6.024	12.105	1899.8	3880.0	
C6-7-R-11	28.400	6.040	12.075	2185.1	3933.8	
C6-7-R-12	28.500	6.017	12.110	2059.2	3867.0	
Average				2082.1	3899.4	
C6-14-R-13	28.800	6.033	12.100	3922.2	5270.0	
C6-14-R-14	28.900	6.017	12.100	4865.9	5424.7	
C6-14-R-15	28.700	6.050	12.100	4733.3	5286.3	
C6-14-R-16	29.100	6.050	12.175	4922.5	5358.0	
C6-14-R-17	29.300	6.017	12.225	4920.4	5457.7	
C6-14-R-18	28.800	6.033	12.100	4372.0	5348.3	
Average				4622.7	5357.5	
C6-28-R-19	29.600	6.050	12.100	5080.1	6147.7	
C6-28-R-20	29.900	6.017	12.200	5834.8	6308.3	
C6-28-R-21	29.600	6.017	12.100	5476.7	6186.0	
C6-28-R-22	28.800	6.033	12.125	4704.7	5581.3	
C6-28-R-23	29.600	6.017	12.175	5549.5	6399.3	
C6-28-R-24	28.800	6.017	12.150	5208.1	5712.7	
Average				5309.0	6055.9	

Specimen ID	Weight (lb)	Diameter (in)	Length (in)	Strength (psi)	Seismic Modulus (ksi)	Break Evaluation
C6-1-R-25	28.400	6.032	12.086	1729.3	3011.3	
C6-1-R-26	28.700	6.030	12.290	1927.1	3063.3	
C6-1-R-27	28.600	6.016	12.137	1382.3	2853.0	
C6-1-R-28	28.900	6.022	12.299	1502.5	3153.0	
C6-1-R-29	28.700	6.026	12.234	1686.3	2982.3	
C6-1-R-30	28.600	6.018	12.224	1740.8	3019.7	
Average				1661.4	3013.8	
C6-2-R-31	28.600	6.018	12.167	2169.8	3408.3	
C6-2-R-32	28.700	6.020	12.238	2028.7	3297.7	
C6-2-R-33	28.900	6.033	12.198	2594.2	3900.7	
C6-2-R-34	29.000	6.050	12.281	2066.4	3520.0	
C6-2-R-35	29.300	6.018	12.329	2755.9	4051.7	
C6-2-R-36	28.600	6.037	12.271	1804.5	2973.3	
Average				2236.6	3525.3	
C6-7-R-37	28.700	6.045	12.158	3215.7	4165.0	
C6-7-R-38	28.700	6.031	12.204	2332.1	3856.3	
C6-7-R-39	28.700	6.037	12.193	3261.5	4058.7	
C6-7-R-40	28.700	6.006	12.133	3325.3	4419.7	
C6-7-R-41	28.700	6.018	12.159	3116.0	4104.3	
C6-7-R-42	28.900	6.016	12.194	3197.4	4144.0	
Average				3074.7	4124.7	
C6-14-R-43	28.700	6.028	12.244	3484.0	4322.7	
C6-14-R-44	28.500	6.016	12.175	2956.0	4299.7	
C6-14-R-45	28.700	6.021	12.140	3694.8	4774.3	
C6-14-R-46	28.900	6.013	12.210	3821.5	4703.0	
C6-14-R-47	28.800	6.013	12.181	3633.5	4500.7	
C6-14-R-48	28.700	6.000	12.155	3799.6	4698.7	
Average				3564.9	4549.9	

Specimen ID	Weight (lb)	Diameter (in)	Length (in)	Strength (psi)	Seismic Modulus (ksi)	Break Evaluation
C6-28-R-49	28.700	6.028	12.166	3623.8	4407.7	
C6-28-R-50	28.800	6.023	12.142	4584.2	4870.0	
C6-28-R-51	28.700	6.023	12.132	3733.4	4576.3	
C6-28-R-52	28.600	6.028	12.145	4357.6	4817.3	
C6-28-R-53	28.600	6.016	12.155	3812.8	4468.0	
C6-28-R-54	29.000	6.026	12.144	4735.6	5009.0	
Average				4141.2	4691.4	
C6-1-I-55	29.600	5.992	12.066	2290.0	4547.3	
C6-14-I-56	30.500	6.016	12.118	5392.9	6605.3	
C6-1-R-57	29.100	6.021	12.108	1613.2	3175.3	
C6-1-R-58	29.200	6.031	12.127	1994.5	3465.3	
C6-1-R-59	29.200	6.033	12.124	1704.1	3296.0	
C6-1-R-60	29.200	6.031	12.090	2011.7	3574.7	
C6-1-R-61	29.200	6.027	12.121	1669.1	3357.7	
C6-1-R-62	29.100	6.025	12.114	1773.7	3336.3	
Average				1794.4	3367.6	
C6-2-R-63	29.200	6.035	12.085	2815.8	4211.7	
C6-2-R-64	29.500	6.026	12.114	2759.0	4257.0	
C6-2-R-65	29.700	6.024	12.177	2887.8	4397.3	
C6-2-R-66	29.500	6.022	12.172	2925.1	4309.3	
C6-2-R-67	29.300	6.026	12.154	2643.2	4174.7	
C6-2-R-68	29.200	6.028	12.167	2863.9	4378.0	
Average				2815.8	4288.0	
C6-7-R-69	29.000	6.035	12.167	3854.5	4812.7	
C6-7-R-70	29.200	6.027	12.168	3700.7	4829.7	
C6-7-R-71	29.100	6.024	12.190	3976.4	5004.7	
C6-7-R-72	29.400	6.024	12.263	3950.7	4945.3	
C6-7-R-73	29.400	6.025	12.204	3924.9	5012.0	
C6-7-R-74	29.200	6.021	12.182	3780.1	4882.0	
Average				3864.6	4914.4	

Specimen ID	Weight (lb)	Diameter (in)	Length (in)	Strength (psi)	Seismic Modulus (ksi)	Break Evaluation
C6-14-R-75	29.000	6.066	12.138	4212.1	5099.3	
C6-14-R-76	29.200	6.018	12.173	4375.6	5228.0	
C6-14-R-77	29.000	6.032	12.158	4154.9	5207.0	
C6-14-R-78	29.500	6.032	12.185	4297.2	5241.0	
C6-14-R-79	29.000	6.019	12.121	4360.4	5201.0	
C6-14-R-80	29.200	6.029	12.163	4320.7	5280.3	
Average				4286.8	5209.4	
C6-28-R-81	29.500	6.004	12.150	5516.4	5826.3	
C6-28-R-82	29.300	6.039	12.140	4863.7	5699.3	
C6-28-R-83	29.400	6.011	12.165	4337.9	5511.7	
C6-28-R-84	29.200	6.020	12.150	4761.9	5392.7	
C6-28-R-85	29.400	6.011	12.168	5663.9	5850.3	
C6-28-R-86	29.200	6.040	12.146	4782.8	5578.0	
Average				4987.8	5643.1	
C6-14-I-87	30.400	6.013	12.142	6556.3	6523.3	
C6-14-I-88	30.300	6.009	12.086	5159.9	6466.0	
C6-14-I-89	30.300	6.008	12.120	6366.9	6665.5	
Average				6461.6	6594.4	
C6-28-I-90	30.400	6.030	12.161	7889.3	6871.3	
C6-28-I-91	30.400	6.017	12.120	8258.5	6877.8	
C6-28-I-92	30.300	6.021	12.107	8739.3	6960.0	
Average				8295.7	6903.0	
C6-2-I-93	30.400	6.019	12.131	3864.6	5584.7	
C6-2-I-94	30.500	6.023	12.151	3729.2	5652.3	
C6-2-I-95	30.500	6.022	12.172	4010.9	5728.7	
Average				3868.2	5655.2	
C6-7-I-96	30.400	6.015	12.162	5775.3	6262.0	
C6-7-I-97	30.400	6.044	12.131	5991.5	6322.7	
C6-7-I-98	30.500	6.022	12.168	5432.9	6422.3	
Average				5733.2	6335.7	

Specimen ID	Weight (lb)	Diameter (in)	Length (in)	Strength (psi)	Seismic Modulus (ksi)	Break Evaluation
C6-1-I-99	30.400	6.006	12.093	2657.8	4850.6	Bad Specimen
C6-1-I-100	30.400	6.018	12.109	2502.1	4819.6	
C6-1-I-101	30.400	6.021	12.136	2462.4	4742.6	
Average				2540.7	4804.3	
C6-28-L-102	30.600	6.022	12.101	7988.6	6810.5	
C6-28-L-103	30.700	6.023	12.112	8031.6	7003.0	
C6-28-L-104	30.300	6.009	12.103	7886.9	6823.3	
Average				7969.1	6878.9	
C6-2-L-105	30.800	6.027	12.096	4580.2	5791.8	
C6-2-L-106	30.700	6.041	12.102	4663.6	5697.3	
C6-2-L-107	30.700	6.025	12.125	4476.2	5799.8	
Average				4573.3	5762.9	
C6-14-L-108	30.400	6.004	12.117	6256.1	6745.5	
C6-14-L-109	30.400	6.038	12.114	6849.6	6581.5	
C6-14-L-110	30.500	6.026	12.102	6728.6	6665.3	
Average				6611.4	6664.1	
C6-1-L-111	30.300	6.020	12.086	2621.5	4513.0	
C6-1-L-112	30.400	6.020	12.110	2707.9	4641.5	
C6-1-L-113	30.300	6.023	12.086	2618.9	4421.8	
Average				2649.5	4525.4	
C6-7-L-114	30.500	6.023	12.106	6322.9	6175.0	
C6-7-L-115	30.600	6.023	12.108	6601.3	6346.0	
C6-7-L-116	30.400	6.020	12.080	6466.6	6203.8	
Average				6463.6	6241.6	

Appendix E

Results of Modulus of Rupture Obtained by One Third Point Loading In Bending Beam Tests

Specimen ID	Unit Weight (lb/ft^3)	Width (in)	Depth (in)	Seismic Modulus (ksi)	Modulus of Rupture (psi)
B0-1-R-001	147.1	5.972	5.991	4445.5	419.9
B0-1-R-002	146.5	6.117	6.091	4359.3	404.5
B0-1-R-003	142.7	6.098	6.070	4246.5	404.6
B0-1-R-004	143.1	6.091	6.058	4183.0	406.6
B0-1-R-005	146.5	6.088	6.057	4540.0	467.4
B1-1-R-001	143.7	6.151	5.951	4333.0	355.3
Average				4351.2	409.7
B0-2-R-006	147.2	6.058	6.008	4561.7	403.3
B0-2-R-007	150.0	6.122	5.970	5379.3	511.4
B0-2-R-008	148.1	6.083	5.999	5135.0	468.6
B0-2-R-009	148.4	5.991	5.994	5034.3	468.3
B0-2-R-010	149.7	5.962	6.002	5137.0	494.4
B1-2-R-002	142.4	6.153	5.980	4422.0	449.9
Average				4944.9	466.0
B0-28-R-011	144.5	5.938	6.013	5937.3	603.6
B0-28-R-012	144.3	5.953	6.017	5887.0	584.7
B0-28-R-013	144.4	5.933	5.993	5876.3	633.4
B0-28-R-014	145.4	5.947	5.973	5960.3	593.8
B0-28-R-015	146.1	6.103	6.047	5890.3	596.9
B1-28-R-003	146.1	6.146	6.010	6009.3	624.3
Average				5926.8	606.1
B0-14-R-016	145.5	6.040	6.053	5499.7	573.4
B0-14-R-017	147.5	6.133	6.077	5772.0	560.3
B0-14-R-018	145.7	6.150	6.057	5815.7	590.4
B0-14-R-019	146.7	6.017	5.963	5806.3	593.1
B0-14-R-020	146.8	6.047	5.953	5784.7	587.9
B1-14-R-004	144.7	6.163	5.990	5758.3	602.4
Average				5739.5	584.6

Note: No bad specimen found during testing

Specimen ID	Unit Weight (lb/ft^3)	Width (in)	Depth (in)	Seismic Modulus (ksi)	Modulus of Rupture (psi)
B0-7-R-021	150.2	6.030	5.990	5939.3	561.6
B0-7-R-022	149.7	6.013	5.977	5922.3	603.3
B0-7-R-023	149.1	6.030	5.967	5904.0	545.0
B0-7-R-024	149.5	6.013	5.973	5828.0	583.1
B0-7-R-025	148.9	5.953	6.007	5809.3	553.1
B1-7-R-005	147.8	6.223	6.003	5876.7	577.8
Average				5879.9	570.7
B0-1-R-026	143.7	6.056	6.000	3647.7	363.3
B0-1-R-027	145.8	6.226	6.083	3694.0	375.0
B0-1-R-028	144.1	6.128	6.015	3759.0	389.7
B0-1-R-029	145.9	6.128	6.045	3731.3	369.8
B0-1-R-030	143.6	6.074	6.025	3745.3	383.7
B1-1-R-006	145.0	6.000	6.000	3488.0	354.2
Average				3677.6	372.6
B0-2-R-031	142.6	6.161	6.072	3946.0	412.1
B0-2-R-032	144.2	6.143	6.095	4112.7	414.1
B0-2-R-033	145.6	5.975	6.051	4016.7	412.4
B0-2-R-034	143.3	6.228	6.018	3836.3	415.0
B0-2-R-035	146.1	6.136	6.055	4026.3	414.1
B1-2-R-007	151.0	6.263	6.020	4672.3	452.0
Average				4101.7	419.9
B0-7-R-036	144.7	6.203	6.115	4756.7	504.4
B0-7-R-037	146.0	6.006	6.019	4862.7	512.9
B0-7-R-038	145.8	6.212	6.074	4816.0	487.0
B0-7-R-039	145.6	6.135	6.071	4761.3	525.4
B0-7-R-040	143.9	6.011	6.008	4781.7	530.9
B1-7-R-008	146.3	6.238	5.984	4725.3	491.6
Average				4784.0	508.7

Note: No bad specimen found during testing

Specimen ID	Unit Weight (lb/ft^3)	Width (in)	Depth (in)	Seismic Modulus (ksi)	Modulus of Rupture (psi)
B0-14-R-041	144.0	5.972	5.945	4908.7	511.7
B0-14-R-042	143.9	6.039	5.963	5011.7	494.6
B0-14-R-043	143.9	5.976	5.984	5034.0	487.9
B0-14-R-044	146.2	6.003	6.019	5100.0	521.4
B0-14-R-045	145.9	6.010	5.960	5022.0	505.9
B1-14-R-009	143.6	6.245	5.966	4959.3	502.1
Average				5006.0	503.9
B0-28-R-046	146.6	6.047	6.020	5269.7	509.3
B0-28-R-047	145.5	6.099	5.989	5256.3	543.1
B0-28-R-048	148.7	6.149	6.043	5288.3	537.1
B0-28-R-049	147.7	6.096	6.024	5312.7	471.9
B0-28-R-050	148.3	6.150	6.071	5303.0	484.4
B0-28-R-051	145.3	6.066	6.014	5244.7	443.0
B1-28-R-010	147.1	6.188	5.989	5367.7	510.9
Average				5291.8	500.0
B0-1-R-052	143.6	6.042	5.958	3988.7	398.6
B0-1-R-053	144.8	5.938	5.997	3949.3	387.7
B0-1-R-054	147.5	6.189	6.043	4103.0	382.3
B0-1-R-055	144.8	6.048	5.979	3989.3	349.7
B0-1-R-056	145.5	6.114	6.001	4116.7	372.0
B1-1-R-014	147.3	6.097	5.966	4149.3	393.7
Average				4049.4	380.7
B0-2-R-057	144.5	6.071	6.017	4363.3	429.9
B0-2-R-058	146.6	6.156	6.079	4277.0	411.4
B0-2-R-059	147.0	6.187	6.081	4404.7	397.3
B0-2-R-060	145.1	6.121	6.019	4331.3	454.6
B0-2-R-061	145.1	6.089	5.987	4376.0	445.4
B1-2-R-015	145.0	6.013	5.976	4432.3	463.9
Average				4364.1	433.7

Note: No bad specimens found during testing

Specimen ID	Unit Weight (lb/ft^3)	Width (in)	Depth (in)	Seismic Modulus (ksi)	Modulus of Rupture (psi)
B0-7-R-062	144.0	5.990	5.993	5014.0	468.5
B0-7-R-063	146.1	6.120	6.115	5154.0	491.6
B0-7-R-064	144.3	6.117	6.009	4990.3	472.7
B0-7-R-065	147.1	6.132	6.055	4966.3	520.4
B0-7-R-066	144.4	5.952	5.979	4961.0	482.2
B1-7-R-016	144.5	6.137	5.967	4858.7	475.0
Average				4990.7	485.1
B0-14-R-067	144.7	6.060	6.019	5160.0	467.4
B0-14-R-068	146.9	6.182	6.060	5272.3	444.0
B0-14-R-069	142.4	5.998	5.955	5109.7	524.7
B0-14-R-070	142.4	5.979	5.965	5041.0	507.6
B0-14-R-071	146.2	6.109	6.039	5246.0	492.9
B1-14-R-017	146.4	6.100	5.998	5347.7	505.8
Average				5196.1	490.4
B0-28-R-072	145.5	6.017	5.964	5762.0	563.5
B0-28-R-073	149.7	6.210	6.061	6001.3	568.0
B0-28-R-074	146.2	6.039	5.969	5856.0	610.7
B0-28-R-075	149.1	6.249	6.119	5949.7	623.2
B0-28-R-076	148.2	6.142	6.076	5835.7	571.6
B1-28R-018	149.9	6.078	5.979	6010.7	599.8
Average				5902.6	589.5
B1-1-L-011	152.2	6.279	5.967	4761.3	389.8
B1-1-L-012	149.6	6.236	6.043	4607.3	406.6
Average				4684.3	398.2
B1-14-I-013	153.6	6.269	5.992	6686.5	659.0
B1-14-I-019	152.4	6.187	5.995	6589.7	599.0
B1-14-I-020	153.1	6.152	5.961	6764.0	658.7
B1-14-I-021	151.9	6.175	6.019	6761.0	635.6
Average				6700.3	638.1

Note: No bad specimen found during testing

Specimen ID	Unit Weight (lb/ft^3)	Width (in)	Depth (in)	Seismic Modulus (ksi)	Modulus of Rupture (psi)
B1-28-I-022	152.7	6.137	5.958	6958.7	751.9
B1-28-I-023	152.8	6.156	5.969	7065.0	689.5
B1-28-I-024	153.3	6.166	5.994	7106.7	731.3
Average				7043.4	724.2
B1-2-I-025	152.3	6.177	6.050	5982.0	493.6
B1-2-I-026	151.7	6.201	6.033	5777.0	470.5
B1-2-I-027	152.3	6.177	6.031	5905.7	504.7
Average				5888.2	489.6
B1-7-I-028	151.2	6.142	5.996	6309.0	611.4
B1-7-I-029	151.9	6.160	5.933	6389.7	618.4
B1-7-I-030	152.9	6.148	6.050	6496.3	599.9
Average				6398.3	609.9
B1-1-I-031	152.1	6.149	5.944	4912.0	389.4
B1-1-I-032	152.1	6.168	5.962	4787.6	328.4
B1-1-I-033	154.4	6.190	5.970	5385.5	522.2
Average				5028.4	413.3
B1-28-L-034	153.1	6.146	5.946	6941.8	745.5
B1-28-L-035	153.7	6.068	5.932	6970.3	657.5
B1-28-L-036	153.2	6.184	5.960	7028.8	704.7
Average				6980.3	702.6
B1-14-L-037	151.7	6.138	5.997	6592.0	636.1
B1-14-L-038	153.1	6.222	5.938	6759.0	631.8
B1-14-L-039	155.2	6.114	5.944	6910.0	637.5
Average				6753.7	635.1

Note: No bad specimen found during testing

Specimen ID	Unit Weight (lb/ft^3)	Width (in)	Depth (in)	Seismic Modulus (ksi)	Modulus of Rupture (psi)
B1-1-L-040	151.8	6.152	5.976	4932.7	434.2
B1-1-L-041	151.9	6.198	5.955	4989.6	413.5
B1-1-L-042	154.4	6.152	5.946	5178.5	413.8
Average				5033.6	420.5
B1-2-L-043	152.4	6.182	5.938	5580.5	528.4
B1-2-L-044	154.3	6.170	5.967	5858.8	565.4
B1-2-L-045	155.8	6.084	5.933	5732.3	538.0
Average				5723.8	543.9
B1-7-L-046	154.2	6.067	5.949	6382.3	561.6
B1-7-L-047	154.2	6.146	5.944	6424.0	663.3
B1-7-L-048	151.9	6.130	5.957	6246.5	629.0
Average				6350.9	618.0

Note: No bad specimen found during testing

Appendix F

Split Tensile Strength Results Obtained on Six by Twelve Inch Specimens

Specimen ID	Weight (lb)	Diameter (in)	Length (in)	Seismic Modulus (ksi)	Strength (psi)	Break Evaluation
SC-2-R-001	28.7	6.036	12.157	2761.0	114.4	
SC-2-R-002	28.6	6.053	12.155	2781.3	137.7	
SC-2-R-003	28.4	6.058	12.100	2284.3	108.9	
SC-2-R-004	28.8	6.008	12.160	3222.7	147.2	
SC-2-R-005	28.9	6.008	12.140	3179.8	150.9	
SC-2-R-006	28.8	5.992	12.095	3190.0	178.6	
Average				2903.2	139.6	
SC-7-R-007	28.9	6.053	12.120	4038.7	299.3	
SC-7-R-008	28.5	6.053	12.084	3711.3	271.1	
SC-7-R-009	28.7	5.957	12.113	4159.3	201.9	
SC-7-R-010	28.7	6.077	12.125	3651.0	222.1	
SC-7-R-011	28.9	5.983	12.135	4125.0	272.2	
SC-7-R-012	28.6	5.991	12.125	3984.3	257.9	
Average				3944.9	254.1	
SC-14-R-013	29.3	6.000	12.139	5553.3	455.8	
SC-14-R-014	28.9	5.978	12.127	5537.3	455.8	
SC-14-R-015	29.2	5.996	12.214	5541.0	459.3	
SC-14-R-016	28.7	6.011	12.112	5392.7	396.8	
SC-14-R-017	29.1	6.011	12.115	5436.7	389.0	
SC-14-R-018	29.5	6.026	12.288	5455.3	405.7	
Average				5486.1	427.1	
SC-28-R-019	30	5.990	12.200	6320.7	475.8	
SC-28-R-020	30	6.010	12.130	6354.7	489.6	
SC-28-R-021	30.1	6.040	12.180	6455.7	448.2	
SC-28-R-022	29	6.040	12.120	5597.3	435.4	
SC-28-R-023	29.8	6.020	12.100	6302.0	480.1	
SC-28-R-024	29.2	6.010	12.150	5728.3	422.9	
Average				6126.5	458.7	

Specimen ID	Weight (lb)	Diameter (in)	Length (in)	Seismic Modulus (ksi)	Strength (psi)	Break Evaluation
SC-1-R-025	28.5	6.153	12.125	3399.0	245.0	
SC-1-R-026	28.5	6.048	12.111	3023.7	197.5	
SC-1-R-027	28.5	6.073	12.249	2955.0	154.3	
SC-1-R-028	28.7	6.024	12.197	3007.3	201.3	
SC-1-R-029	28.2	6.074	12.110	2972.0	188.8	
SC-1-R-030	28.6	5.984	12.139	3540.0	213.5	
Average				3149.5	200.1	
SC-2-R-031	29.3	5.960	12.207	4037.0	266.1	
SC-2-R-032	28.1	6.016	12.137	3190.3	179.1	Bad Specimen
SC-2-R-033	29.1	6.057	12.196	4095.3	218.3	
SC-2-R-034	28.6	6.058	12.344	3459.3	188.0	
SC-2-R-035	28.7	5.994	12.162	3636.0	302.4	
SC-2-R-036	29	5.945	12.190		0.0	Bad Specimen
Average				3806.9	243.7	
SC-7-R-037	28.7	6.040	12.138	4162.7	293.1	
SC-7-R-038	28.7	5.988	12.175	3942.7	301.8	
SC-7-R-039	29	6.079	12.196	4481.3	250.5	
SC-7-R-040	28.4	6.067	12.315	3975.7	296.9	
SC-7-R-041	28.7	6.041	12.153	4121.0	310.7	
SC-7-R-042	29.4	5.987	12.258	4710.0	329.5	
Average				4232.2	297.1	
SC-14-R-043	29.1	6.076	12.198	4306.3	315.9	
SC-14-R-044	28.7	6.080	12.136	4469.0	296.4	
SC-14-R-045	29.1	6.197	12.186	4103.3	348.3	
SC-14-R-046	29.1	6.047	12.274	4386.0	316.0	
SC-14-R-047	29.1	6.150	12.173	4506.0	367.1	
SC-14-R-048	28.4	6.148	12.138	4211.0	287.5	
Average				4330.3	321.9	

Specimen ID	Weight (lb)	Diameter (in)	Length (in)	Seismic Modulus (ksi)	Strength (psi)	Break Evaluation
SC-28-R-049	29	6.007	12.102	5029.0	436.9	
SC-28-R-050	28.9	5.998	12.159	4459.7	343.0	
SC-28-R-051	29	6.037	12.140	4861.3	416.9	
SC-28-R-052	29	6.029	12.140	4892.0	396.6	
SC-28-R-053	29.2	6.011	12.131	4990.7	364.6	
SC-28-R-054	28.9	6.043	12.175	4650.0	332.0	
Average				4813.8	381.7	
SC-1-I-055	29.7	6.000	12.023	4452.3	239.3	
SC-14-I-056	30.6	6.065	12.119	6492.6	489.5	
SC-1-R-057	28.9	6.056	12.138	3080.8	181.9	
SC-1-R-058	29.1	6.037	12.111	3448.3	203.5	
SC-1-R-059	29.1	6.064	12.091	3340.0	223.1	
SC-1-R-060	29.3	6.035	12.127	3503.0	204.4	
SC-1-R-061	29.4	6.022	12.104	3600.7	225.9	
SC-1-R-062	29.4	6.076	12.130	3547.7	211.7	
Average				3420.1	208.4	
SC-2-R-063	29.8	6.055	12.189	4291.7	319.5	
SC-2-R-064	29.5	6.005	12.156	4185.3	322.3	
SC-2-R-065	29.6	6.025	12.126	4299.3	263.5	
SC-2-R-066	29.5	6.059	12.145	4256.3	304.0	
SC-2-R-067	29.8	6.044	12.156	4377.3	327.4	
SC-2-R-068	29.8	6.037	12.173	4344.7	303.9	
Average				4292.4	306.8	
SC-7-R-069	29.6	6.075	12.187	4855.7	356.7	
SC-7-R-070	29.8	6.051	12.218	4875.7	331.9	
SC-7-R-071	29.6	6.044	12.171	5048.7	372.4	
SC-7-R-072	29.4	6.023	12.119	5003.3	362.9	
SC-7-R-073	29.5	6.084	12.140	4874.7	393.2	
SC-7-R-074	29.8	6.088	12.268	4793.3	387.5	
Average				4908.5	367.4	

Specimen ID	Weight (lb)	Diameter (in)	Length (in)	Seismic Modulus (ksi)	Strength (psi)	Break Evaluation
SC-14-R-075	29.3	6.016	12.135	5141.3	405.4	
SC-14-R-076	29.4	6.007	12.184	5147.7	404.2	
SC-14-R-077	29.3	6.054	12.121	5183.7	402.5	
SC-14-R-078	29.4	6.045	12.131	5202.8	403.6	
SC-14-R-079	29.3	6.064	12.106	5102.0	402.3	
SC-14-R-080	29.2	6.038	12.110	5126.3	359.8	
Average				5150.6	396.3	
SC-28-R-081	29.5	6.034	12.130	5638.2	446.3	
SC-28-R-082	29.7	6.031	12.176	5762.5	426.4	
SC-28-R-083	29.5	6.052	12.122	5719.0	426.9	
SC-28-R-084	29.5	6.022	12.163	5965.3	450.7	
SC-28-R-085	29.7	6.041	12.141	5677.0	466.2	
SC-28-R-086	29.4	6.020	12.143	5669.3	459.3	
Average				5738.6	446.0	
SC-14-I-087	30.7	6.103	12.152	6362.0	536.6	
SC-14-I-088	30.6	6.042	12.142	6550.0	476.0	
SC-14-I-089	30.7	6.075	12.119	6543.3	484.3	
Average				6485.1	499.0	
SC-28-I-090	30.2	5.960	12.121	6846.3	532.4	
SC-28-I-091	30.5	6.074	12.128	6654.3	532.5	
SC-28-I-092	30.3	6.052	12.137	6702.7	513.5	
Average				6734.4	526.1	
SC-2-I-093	30.5	6.042	12.133	5579.3	412.7	
SC-2-I-094	30.5	6.020	12.136	5619.3	370.1	
SC-2-I-095	30.5	6.006	12.145	5531.3	401.8	
Average				5576.6	394.9	
SC-7-I-096	30.5	6.069	12.103	6165.0	462.2	
SC-7-I-097	30.5	6.048	12.094	6234.7	457.0	
SC-7-I-098	30.6	6.032	12.134	6239.0	474.9	
Average				6212.9	464.7	

Specimen ID	Weight (lb)	Diameter (in)	Length (in)	Seismic Modulus (ksi)	Strength (psi)	Break Evaluation
SC-1-I-099	30.1	5.996	12.073	4771.0	257.0	
SC-1-I-100	30.1	6.047	12.083	4287.7	180.4	
SC-1-I-101	30.5	6.066	12.114	4695.0	239.0	
Average				4584.6	225.5	
SC-28-L-102	30.5	6.030	12.131	6829.5	497.7	
SC-28-L-103	30.4	6.029	12.087	6883.0	566.1	
SC-28-L-104	30.6	6.038	12.138	6903.3	540.8	
Average				6871.9	534.9	
SC-2-L-105	30.6	6.038	12.101	5717.5	423.7	
SC-2-L-106	30.7	6.065	12.101	5797.5	388.6	
SC-2-L-107	30.6	6.050	12.079	5835.0	406.6	
Average				5783.3	406.3	
SC-14-L-108	30.6	6.053	12.076	6607.8	488.6	
SC-14-L-109	30.5	6.038	12.063	6600.5	536.3	
SC-14-L-110	30.6	6.041	12.069	6559.5	553.1	
Average				6589.3	526.0	
SC-1-L-111	30.2	6.038	12.041	4600.3	272.1	
SC-1-L-112	30.3	6.074	12.111	4545.0	301.2	
SC-1-L-113	30.3	6.041	12.091	4561.5	234.8	
Average				4568.9	269.3	
SC-7-L-114	30.6	6.058	12.073	6211.8	511.1	
SC-7-L-115	30.7	6.035	12.120	6365.3	499.3	
SC-7-L-116	30.5	6.084	12.092	6100.0	494.6	
Average				6225.7	501.7	

Appendix G

Additional Compressive Strength Results
Obtained on
Four by Eight Inch Specimens
of
Modified Concrete Mixes

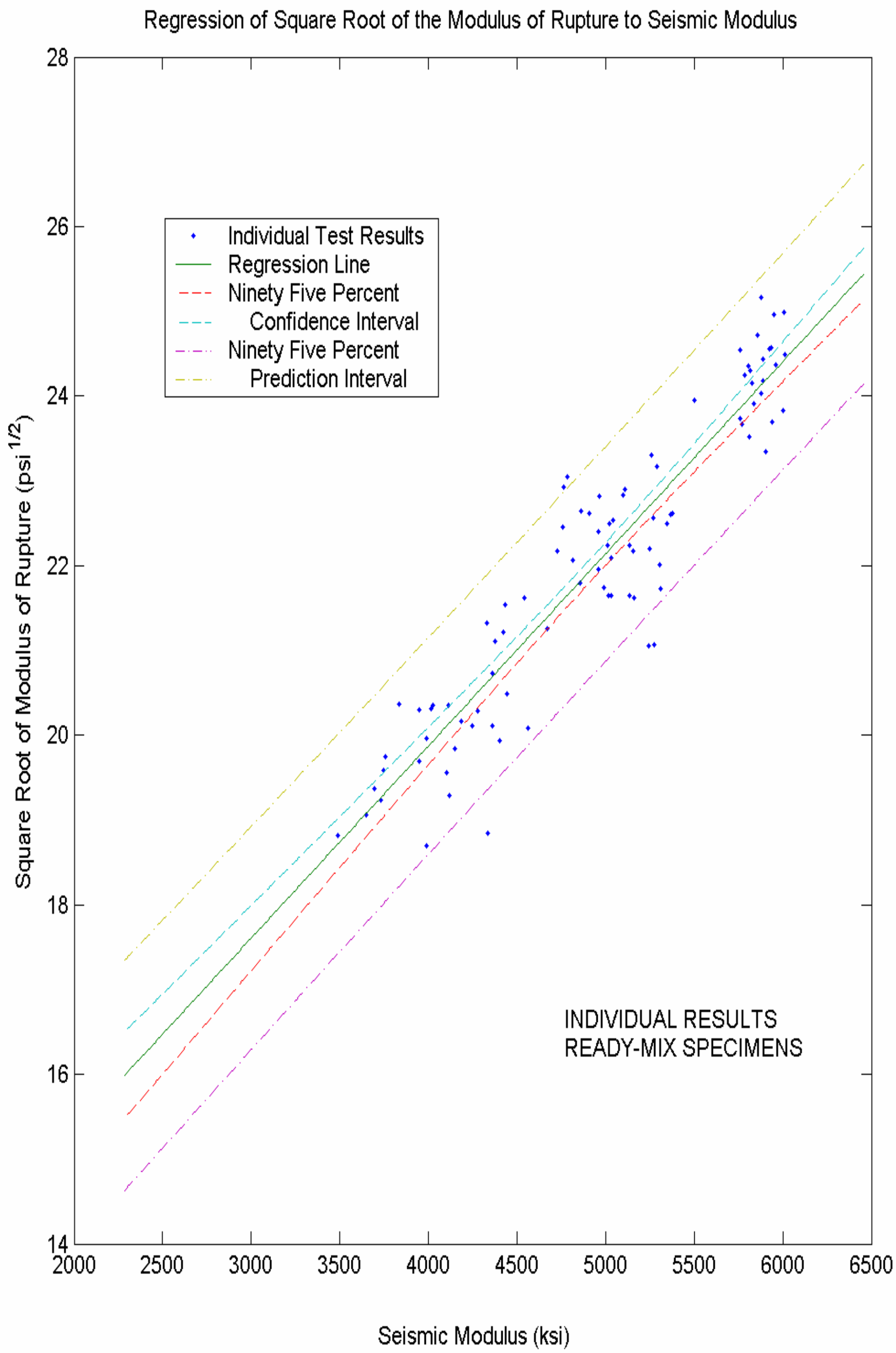
Specimen ID	Weight (lb)	Length (in)	Diameter (in)	Seismic Modulus (ksi)	Strength (psi)	Break Evaluation
C4-28-MD1-1	8.952	7.975	4.025	7500.8	7032.1	
C4-28-MD1-2	8.966	7.991	4.023	7058.5	8350.8	
C4-28-MD1-3	9.016	8.015	4.020	7256.3	8371.2	
Average				7271.8	7918.0	
C4-14-MD1-4	8.928	8.005	4.028	6709.3	6430.9	
C4-14-MD1-5	8.961	8.011	4.024	6768.5	6555.7	
C4-14-MD1-6	9.000	8.030	4.030	6758.3	7353.2	
Average				6745.3	6779.9	
C4-1-MD1-7	8.986	8.063	4.023	4636.0	2364.7	
C4-1-MD1-8	8.958	7.987	4.005	4822.0	2510.0	
C4-1-MD1-9	8.949	8.053	4.027	3529.5	1176.8	
Average				4329.2	2017.2	
C4-7-MD1-10	8.930	8.014	4.015	6270.0	6314.8	
C4-7-MD1-11	9.030	8.024	4.017	6836.0	7452.4	
C4-7-MD1-12	8.950	8.039	4.040	6279.0	5883.7	
Average				6461.7	6550.3	
C4-?-MD1-13						
C4-?-MD1-14	8.947	7.970	4.024	5766.8	4771.0	
C4-?-MD1-15	8.953	8.037	4.014	5830.5	4649.0	
Average				5798.6	4710.0	
C4-?-MD1-16	8.914	8.006	4.015	5756.3	4792.4	
C4-?-MD1-17	8.887	8.018	4.019	5573.3	4271.6	
C4-?-MD1-18	8.786	7.967	4.015	5826.8	4664.4	
Average				5700.0	4468.0	
C4-2-MD1-19	10.490	8.026	4.026	5652.8	2316.1	
C4-2-MD1-20	9.920	7.997	4.017	3872.0	1073.5	
C4-2-MD1-21	10.140	8.044	4.025	2702.5	618.6	
Average				4075.8	1336.1	

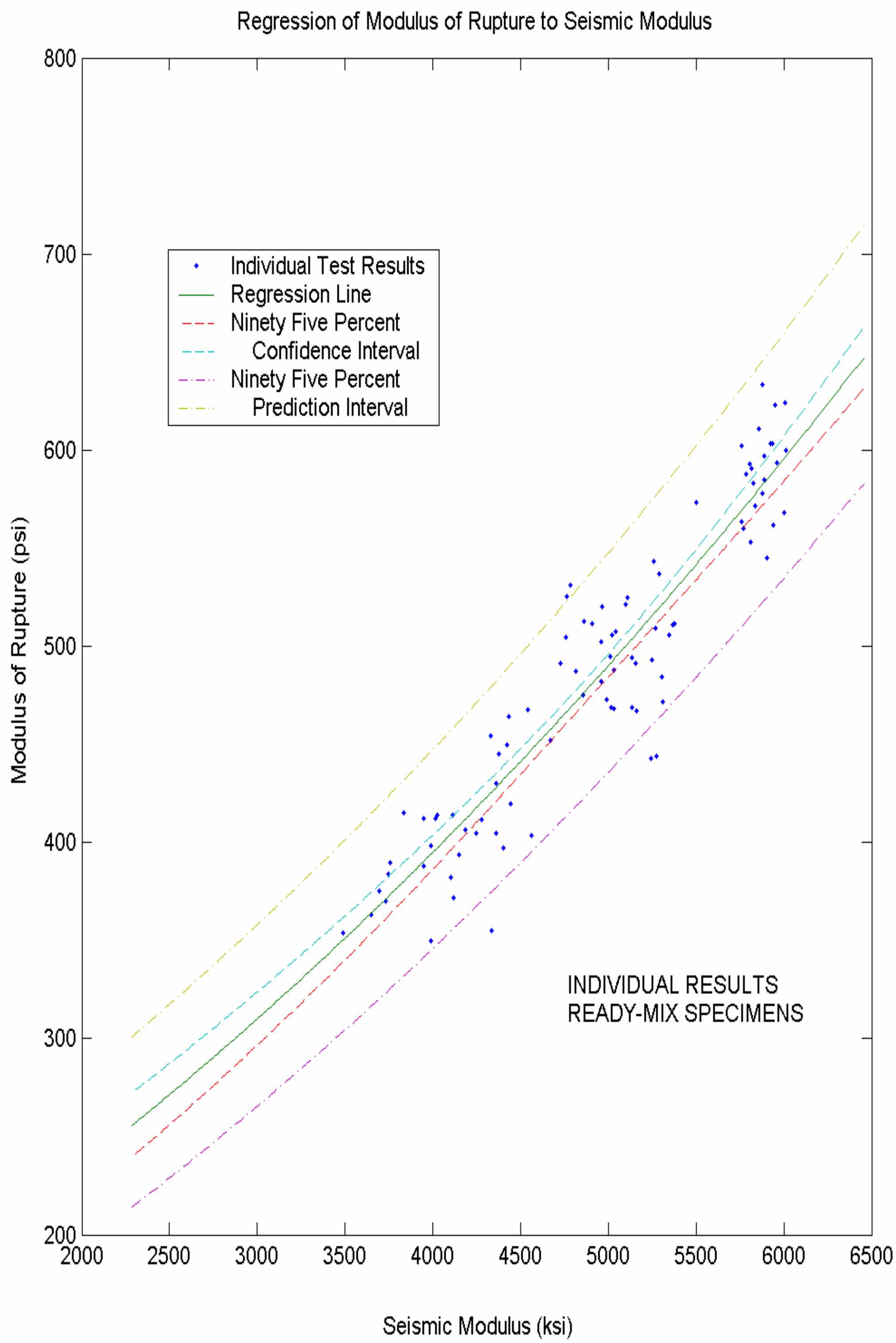
Specimen ID	Weight (lb)	Length (in)	Diameter (in)	Seismic Modulus (ksi)	Strength (psi)	Break Evaluation
C4-20-MD2-1	8.811	8.009	4.027	6616.0	5853.3	
C4-20-MD2-2	8.822	7.975	4.019	6678.8	6502.4	
C4-20-MD2-3	8.800	7.961	4.022	6705.0	6419.6	
Average				6666.6	6258.4	
C4-2-MD2-4	8.731	7.945	4.009	4410.0	1847.5	
C4-2-MD2-5	8.664	7.946	4.011	4348.8	1838.9	
C4-2-MD2-6	8.706	7.905	4.016	4470.5	1753.4	
Average				4409.8	1813.3	
C4-14-MD2-7	8.650	8.051	4.015	5752.3	4121.9	
C4-14-MD2-8	8.703	8.054	4.026	5708.0	5029.2	
C4-14-MD2-9	8.778	7.911	4.021	6350.8	6055.3	
Average				5937.0	5068.8	
C4-28-MD2-10	8.144	8.006	4.021	4461.6	2996.4	
C4-28-MD2-11	8.312	7.978	3.991	4287.7	2503.9	
C4-28-MD2-12	8.052	8.021	4.010	4223.6	2654.1	
Average				4324.3	2718.2	
C4-28-MD2-13	8.624	7.996	4.026	6088.1	5721.2	
C4-28-MD2-14	7.920	8.010	4.024	3678.4	2301.3	
C4-28-MD2-15	8.294	7.991	4.001	4630.4	3043.8	
Average				4799.0	3688.8	
C4-28-MD2-16	8.750	7.914	4.039	6454.5	6429.9	
C4-28-MD2-17	8.780	7.992	4.026	6201.0	6577.2	
C4-28-MD2-18	8.750	7.934	4.029	6168.5	6117.5	
Average				6274.7	6374.9	
C4-14-MD2-19	8.723	7.930	4.031	6103.8	5833.5	
C4-14-MD2-20	8.735	7.932	4.037	5963.1	5815.1	
C4-14-MD2-21	8.742	7.956	4.034	6057.6	5871.7	
Average				6041.5	5840.1	
C4-7-MD2-22	8.789	7.949	4.029	5589.8	4785.1	
C4-7-MD2-23	8.735	7.944	4.035	5657.0	4731.8	
C4-7-MD2-24	8.720	7.955	4.029	5574.3	4894.2	
Average				5607.0	4803.7	
C4-3-MD2-25	8.791	7.956	4.032	4749.0	3093.4	
C4-3-MD2-26	8.795	7.982	4.028	5075.1	3523.7	
C4-3-MD2-27	8.731	8.014	4.023	4085.2	1558.9	
Average				4636.4	2725.3	

Specimen ID	Weight (lb)	Length (in)	Diameter (in)	Seismic Modulus (ksi)	Strength (psi)	Break Evaluation
C4-28-MD3-1	9.112	8.030	4.042	7158.5	7118.0	
C4-28-MD3-2	9.101	8.007	4.034	7304.0	7729.3	
C4-28-MD3-3	9.095	8.017	4.027	7203.8	7635.9	
Average				7222.1	7494.4	
C4-14-MD3-4	9.064	8.036	4.027	6821.5	6111.2	
C4-14-MD3-5	9.053	8.031	4.029	6738.8	6686.2	
C4-14-MD3-6	9.075	8.009	4.024	6862.3	7134.6	
Average				6807.5	6644.0	
C4-7-MD3-7	9.011	8.045	3.989	6679.5	6472.8	
C4-7-MD3-8	8.996	8.052	4.004	6551.0	6321.3	
C4-7-MD3-9	8.996	8.065	4.005	6455.0	6362.1	
Average				6561.8	6385.4	
C4-2-MD3-10	9.026	8.005	4.026	5737.7	4355.8	
C4-2-MD3-11	9.064	8.013	4.024	5756.5	4243.5	
C4-2-MD3-12	9.116	8.039	4.030	6000.3	4754.9	
Average				5831.5	4451.4	
C4-1-MD3-13	9.013	8.027	4.028	4775.3	2309.1	
C4-1-MD3-14	9.002	8.017	4.031	4559.9	1997.4	
C4-1-MD3-15	8.997	8.018	4.033	4490.8	1984.6	
Average				4608.6	2097.0	

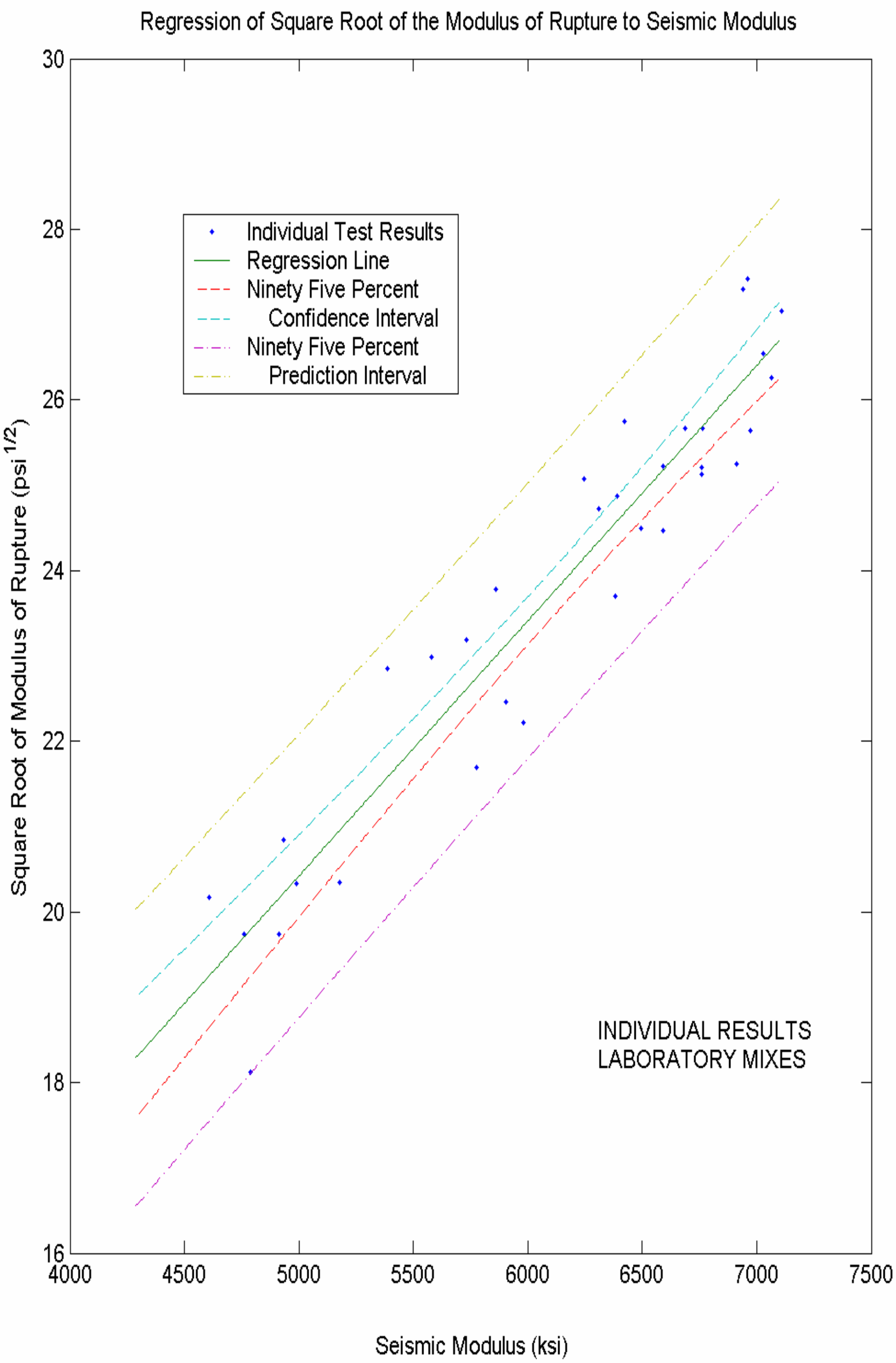
Appendix H

Regression Results
of
Modulus of Rupture versus Seismic Modulus

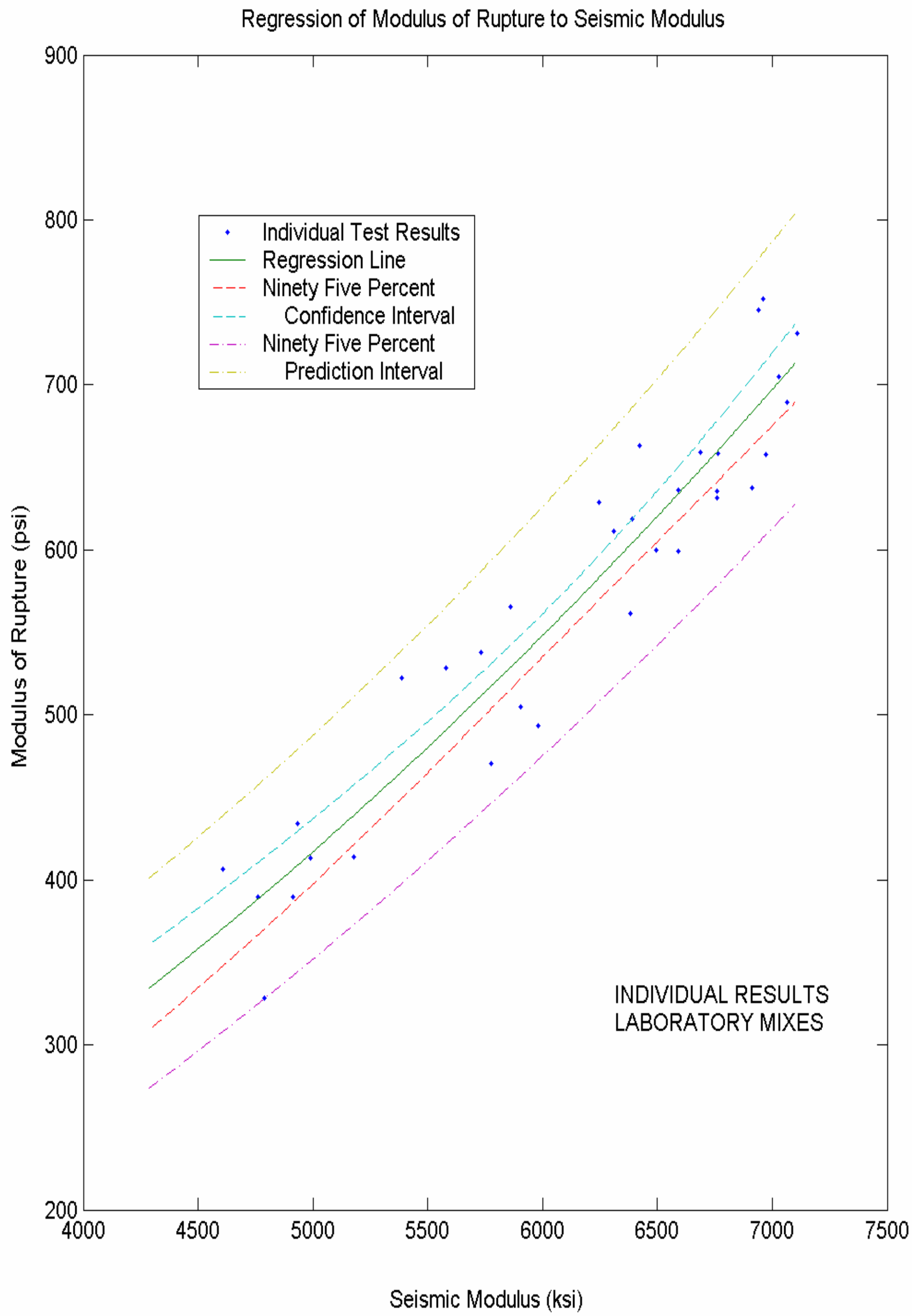

Regression of Square Root of the Modulus of Rupture to Seismic Modulus
Individual Test Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
INDIVIDUAL RESULTS
READY-MIX SPECIMENS
Square Root of Modulus of Rupture (psi 1/2)
Seismic Modulus (ksi)
28
26
24
22
20
18
16
14
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500

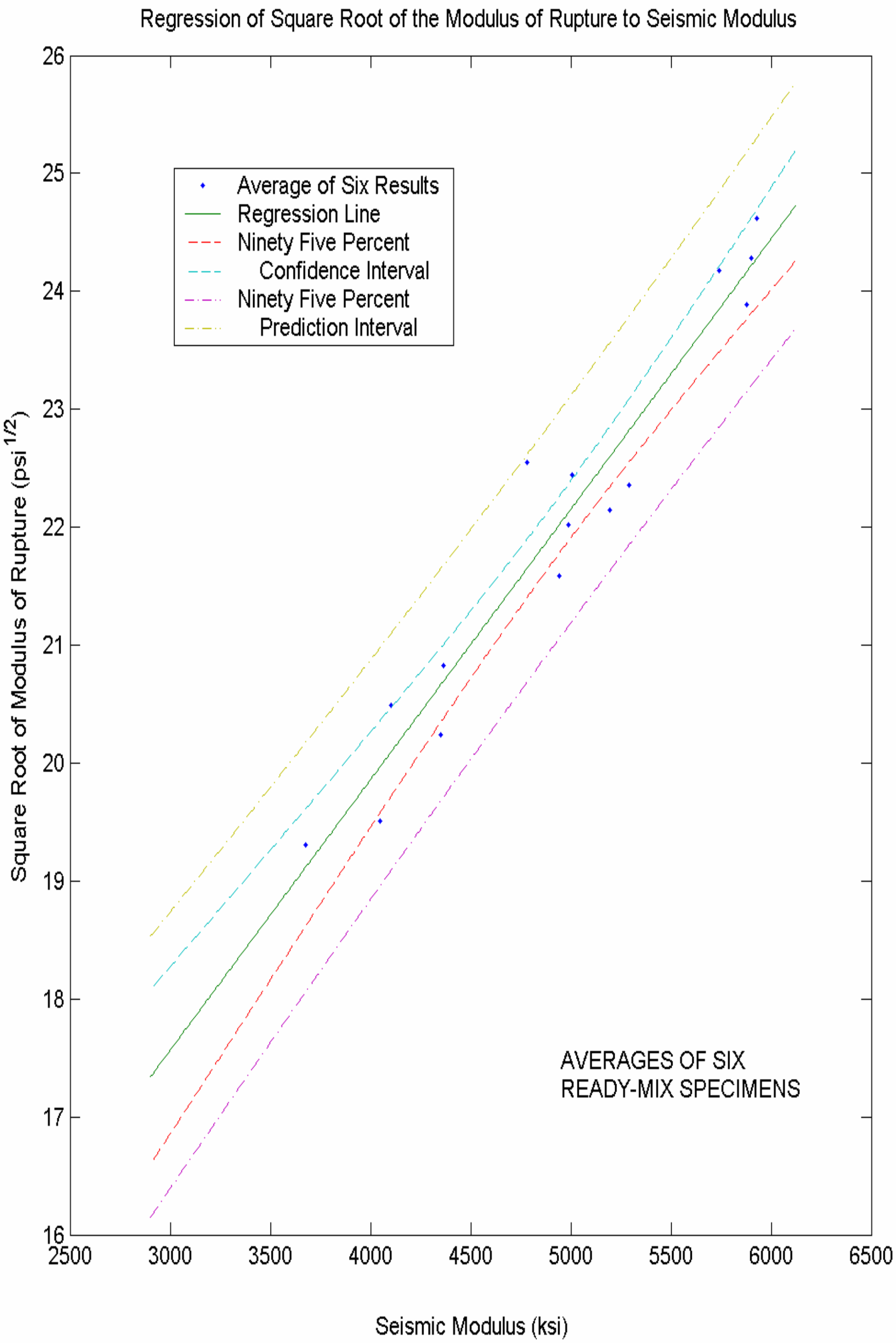


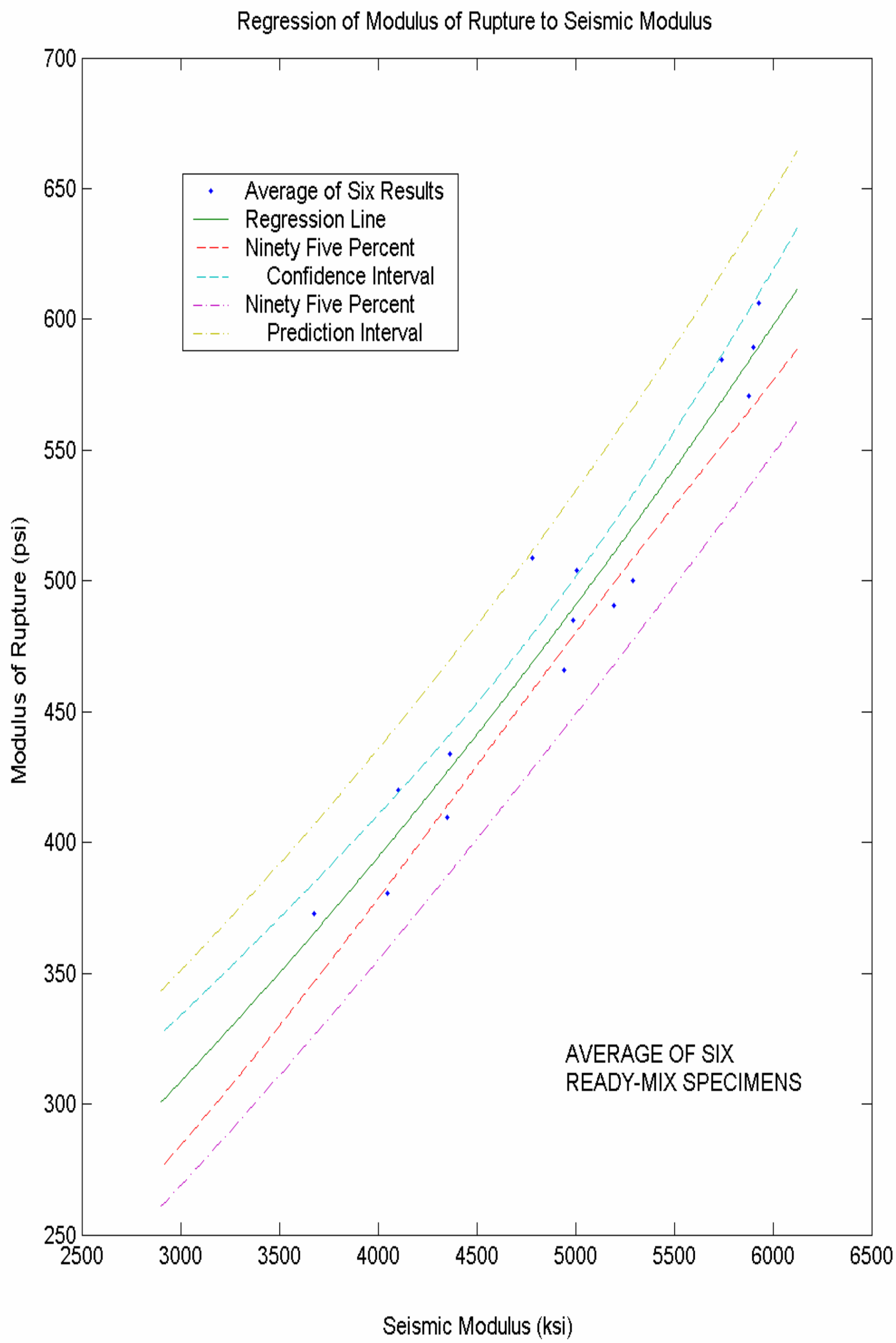
Regression of Modulus of Rupture to Seismic Modulus
800
700
600
500
400
300
200
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
Modulus of Rupture (psi)
Seismic Modulus (ksi)
Individual Test Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
INDIVIDUAL RESULTS
READY-MIX SPECIMENS



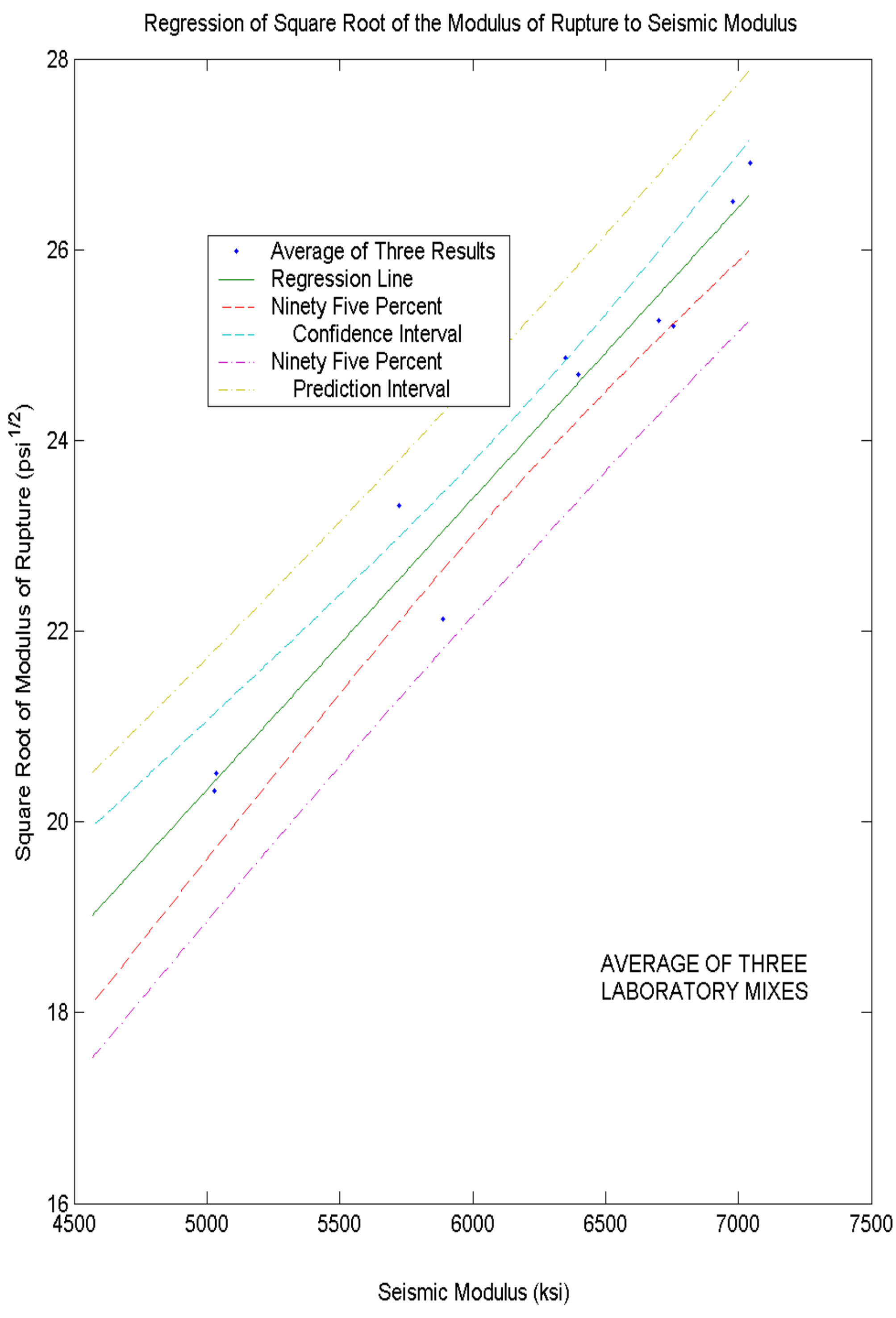
Regression of Square Root of the Modulus of Rupture to Seismic Modulus
Individual Test Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
INDIVIDUAL RESULTS
LABORATORY MIXES
Square Root of Modulus of Rupture (psi 1/2)
Seismic Modulus (ksi)
30
28
26
24
22
20
18
16
4000
4500
5000
5500
6000
6500
7000
7500


Regression of Modulus of Rupture to Seismic Modulus
Modulus of Rupture (psi)
Seismic Modulus (ksi)
900
800
700
600
500
400
300
200
4000
4500
5000
5500
6000
6500
7000
7500
Individual Test Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
INDIVIDUAL RESULTS
LABORATORY MIXES

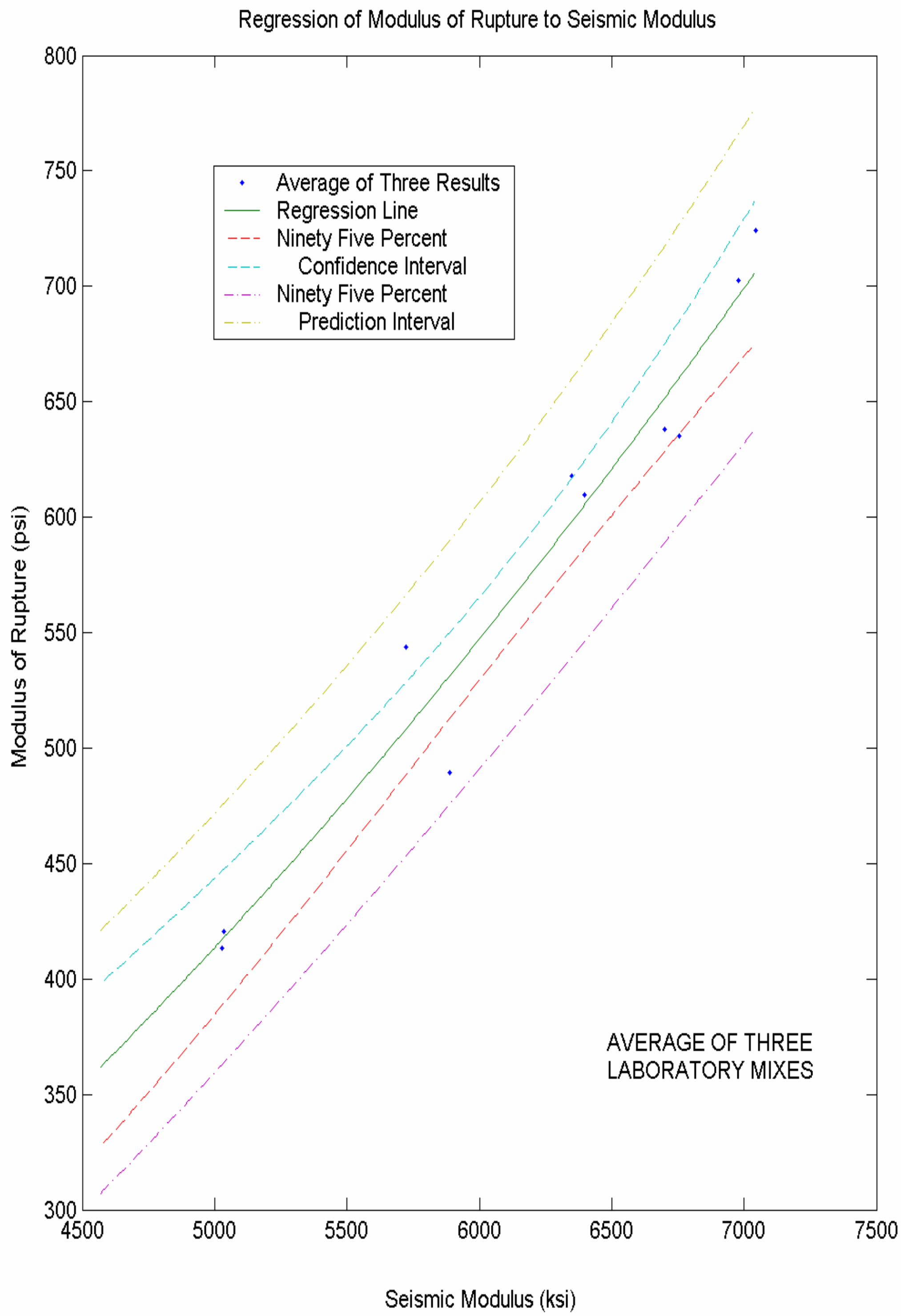

Regression of Square Root of the Modulus of Rupture to Seismic Modulus
Average of Six Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
AVERAGES OF SIX
READY-MIX SPECIMENS
Square Root of Modulus of Rupture (psi 1/2)
Seismic Modulus (ksi)
26
25
24
23
22
21
20
19
18
17
16
2500
3000
3500
4000
4500
5000
5500
6000
6500



Regression of Modulus of Rupture to Seismic Modulus
Average of Six Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
AVERAGE OF SIX
READY-MIX SPECIMENS
Modulus of Rupture (psi)
Seismic Modulus (ksi)
700
650
600
550
500
450
400
350
300
250
2500
3000
3500
4000
4500
5000
5500
6000
6500



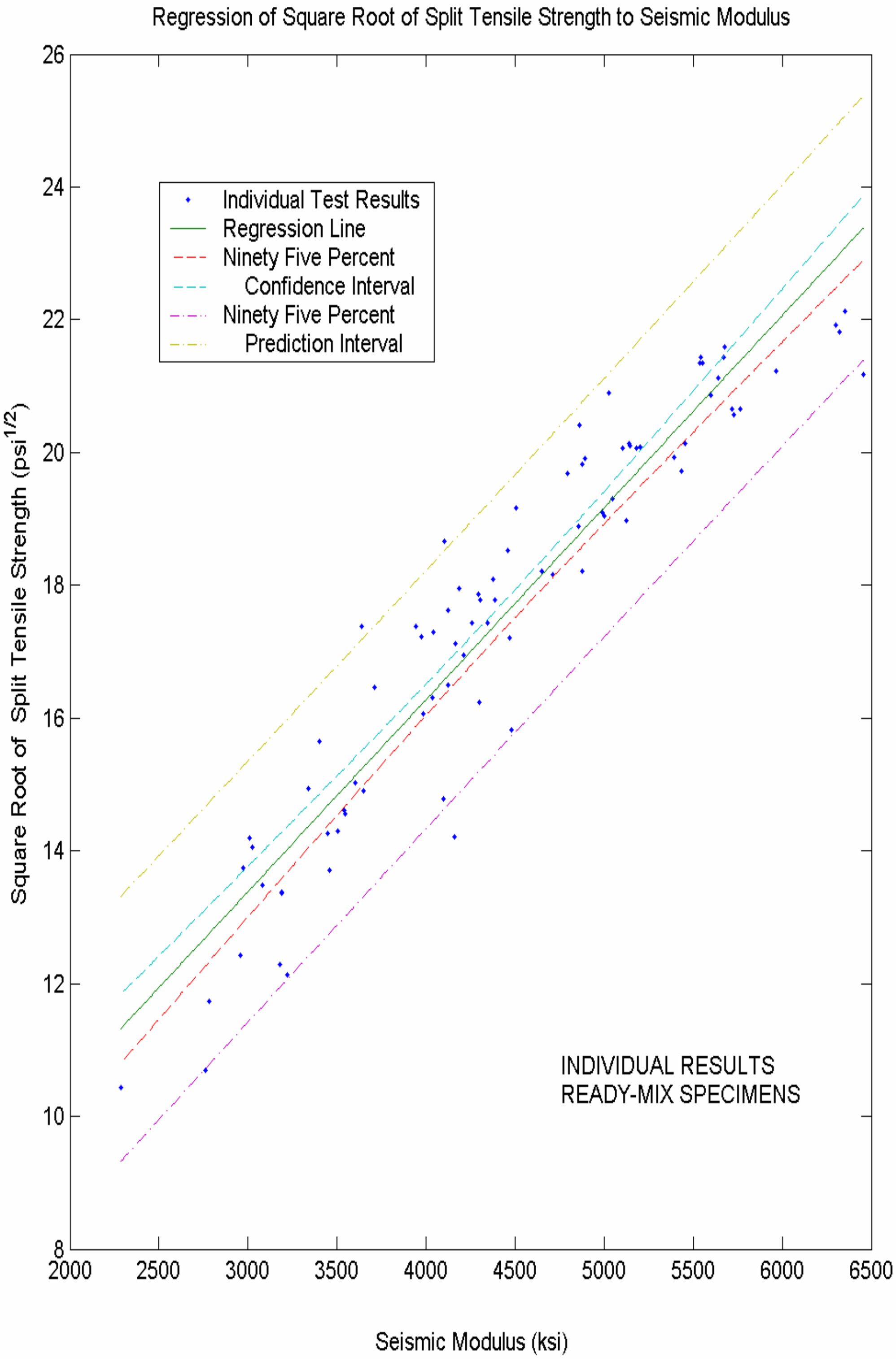
Regression of Square Root of the Modulus of Rupture to Seismic Modulus
Average of Three Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
AVERAGE OF THREE
LABORATORY MIXES
Square Root of Modulus of Rupture (psi 1/2)
Seismic Modulus (ksi)
28
26
24
22
20
18
16
4500
5000
5500
6000
6500
7000
7500

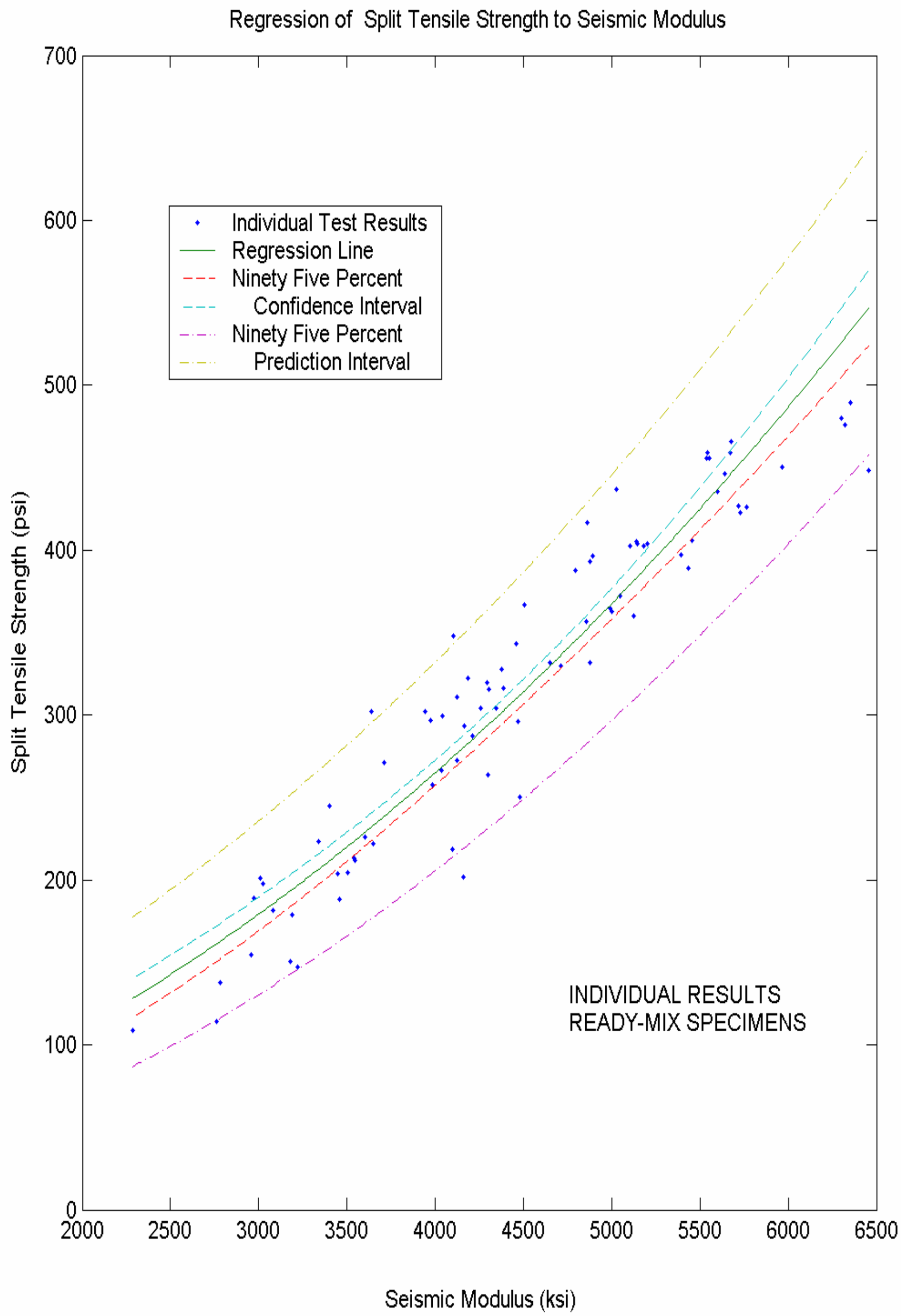


Regression of Modulus of Rupture to Seismic Modulus
Average of Three Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
AVERAGE OF THREE
LABORATORY MIXES
Modulus of Rupture (psi)
Seismic Modulus (ksi)
800
750
700
650
600
550
500
450
400
350
300
4500
5000
5500
6000
6500
7000
7500

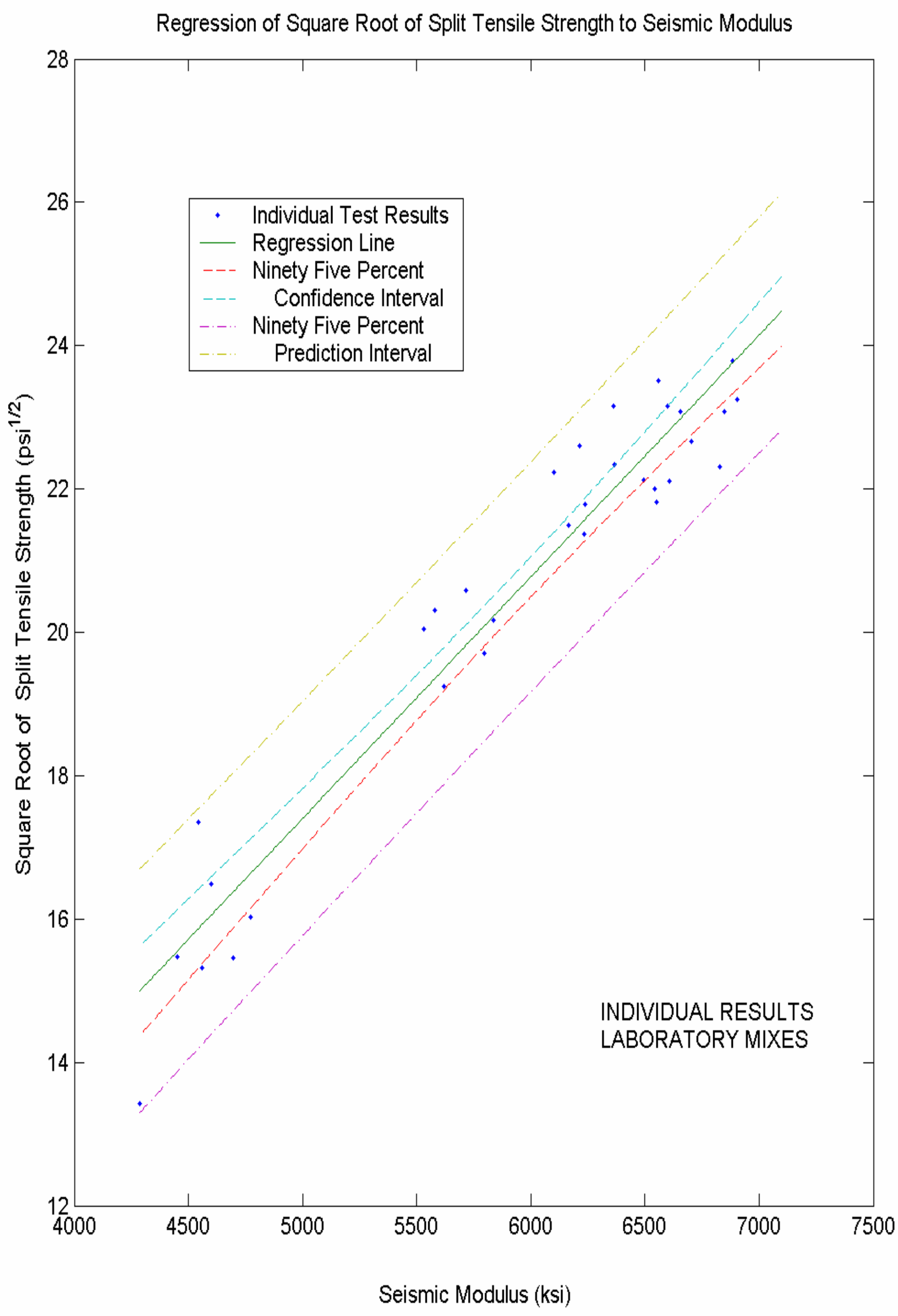
Appendix I

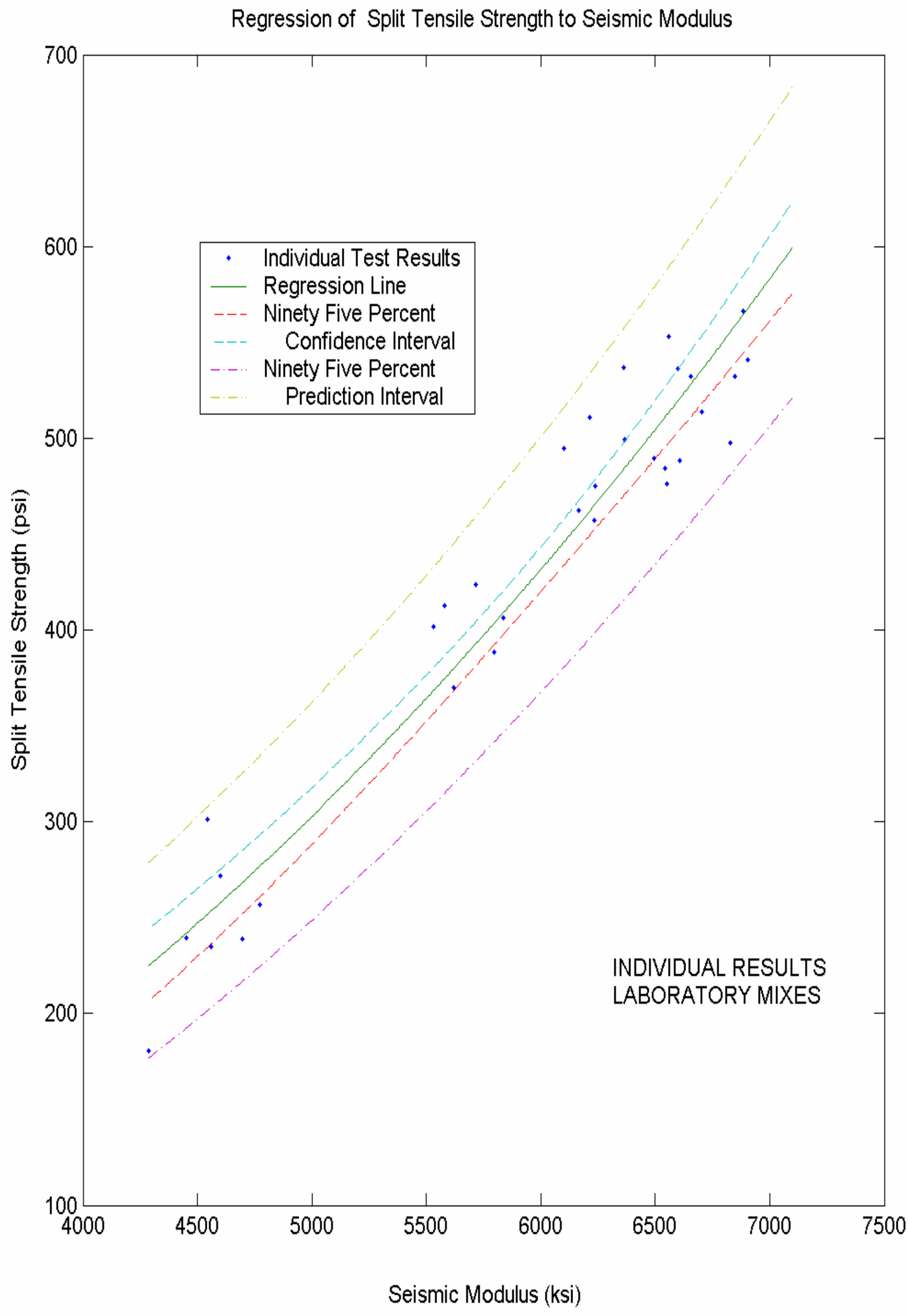
Regression Results
of
Split Tensile Strength versus Seismic Modulus

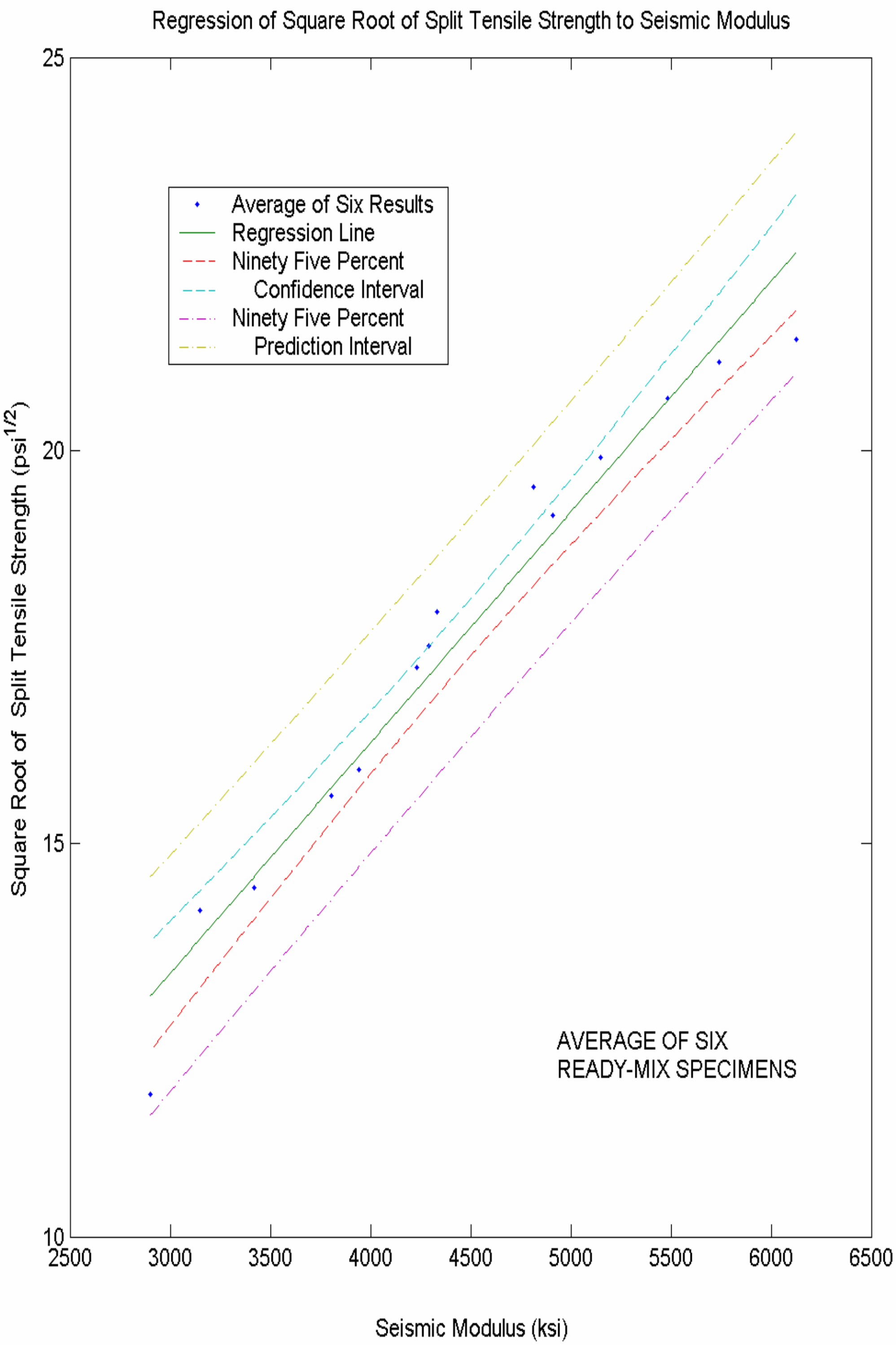

Regression of Square Root of Split Tensile Strength to Seismic Modulus
Individual Test Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
INDIVIDUAL RESULTS
READY-MIX SPECIMENS
Square Root of Split Tensile Strength (psi^1/2)
Seismic Modulus (ksi)
26
24
22
20
18
16
14
12
10
8
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500



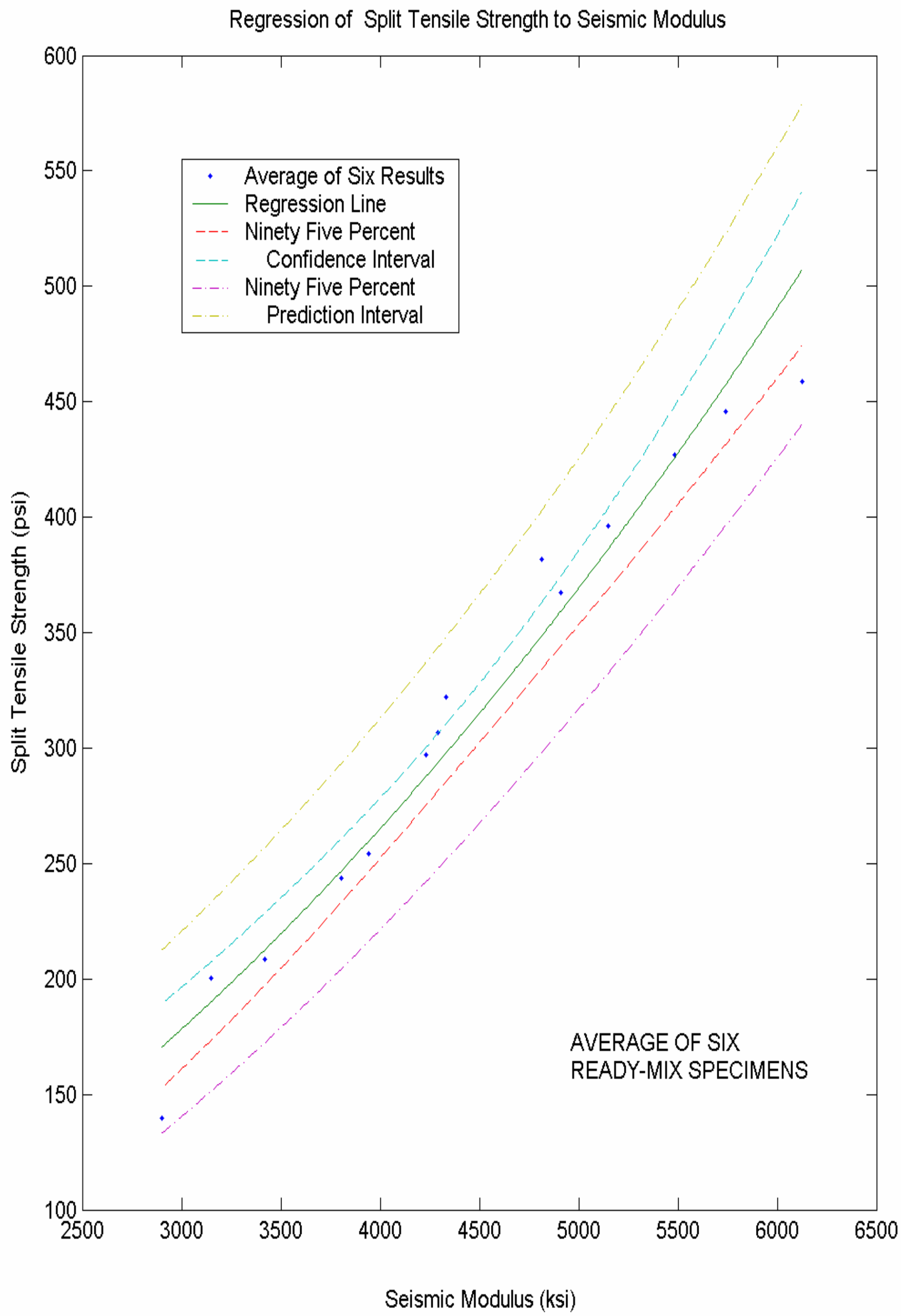
Regression of Split Tensile Strength to Seismic Modulus
Split Tensile Strength (psi)
Seismic Modulus (ksi)
0
100
200
300
400
500
600
700
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
Individual Test Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
INDIVIDUAL RESULTS
READY-MIX SPECIMENS

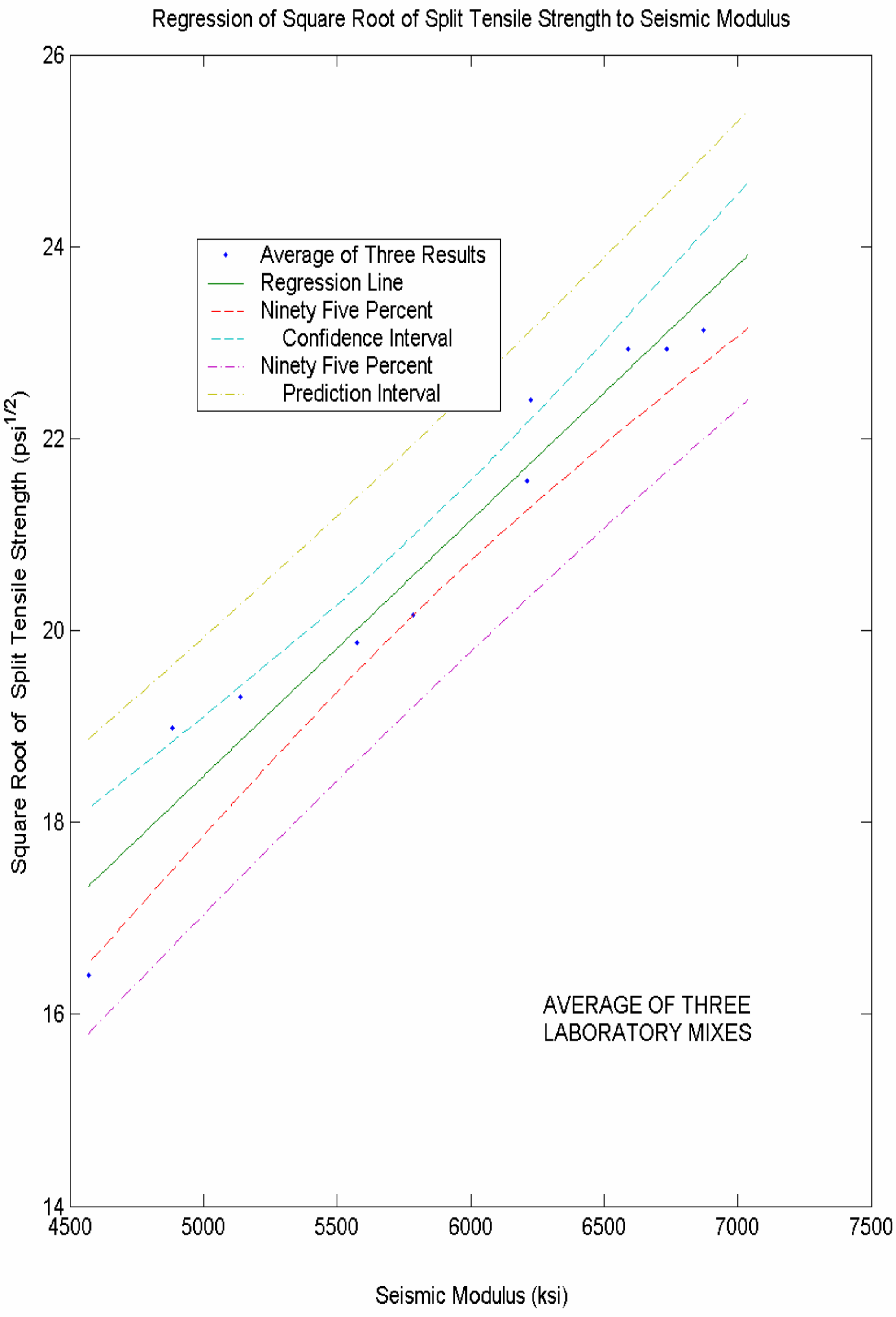

Regression of Square Root of Split Tensile Strength to Seismic Modulus
Individual Test Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
INDIVIDUAL RESULTS
LABORATORY MIXES
Square Root of Split Tensile Strength (psi^1/2)
Seismic Modulus (ksi)
28
26
24
22
20
18
16
14
12
4000
4500
5000
5500
6000
6500
7000
7500

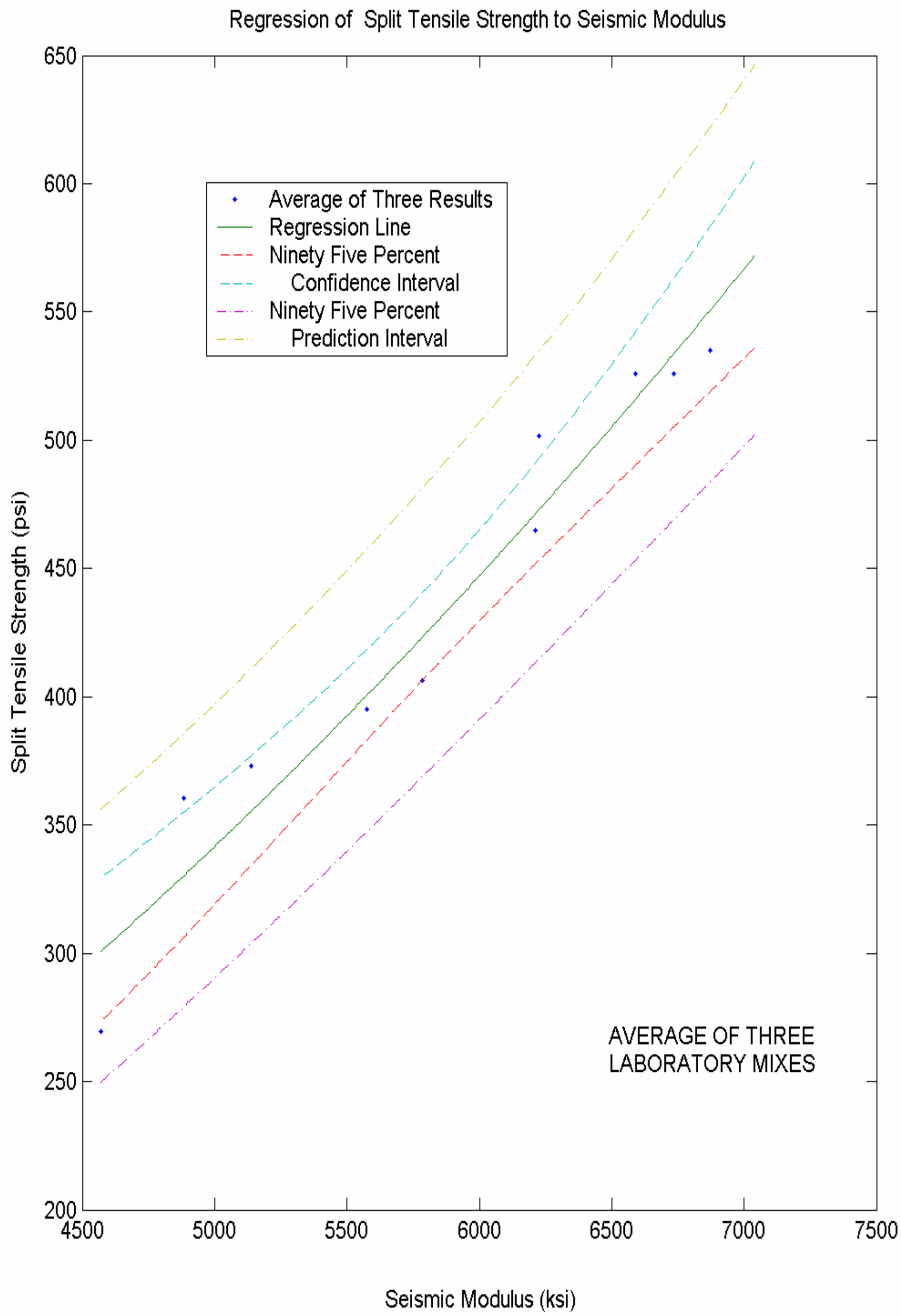

Regression of Split Tensile Strength to Seismic Modulus
Individual Test Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
INDIVIDUAL RESULTS
LABORATORY MIXES
Split Tensile Strength (psi)
Seismic Modulus (ksi)
700
600
500
400
300
200
100
4000
4500
5000
5500
6000
6500
7000
7500



Regression of Square Root of Split Tensile Strength to Seismic Modulus
Average of Six Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
AVERAGE OF SIX
READY-MIX SPECIMENS
Square Root of Split Tensile Strength (psi^1/2)
Seismic Modulus (ksi)
25
20
15
10
2500
3000
3500
4000
4500
5000
5500
6000
6500

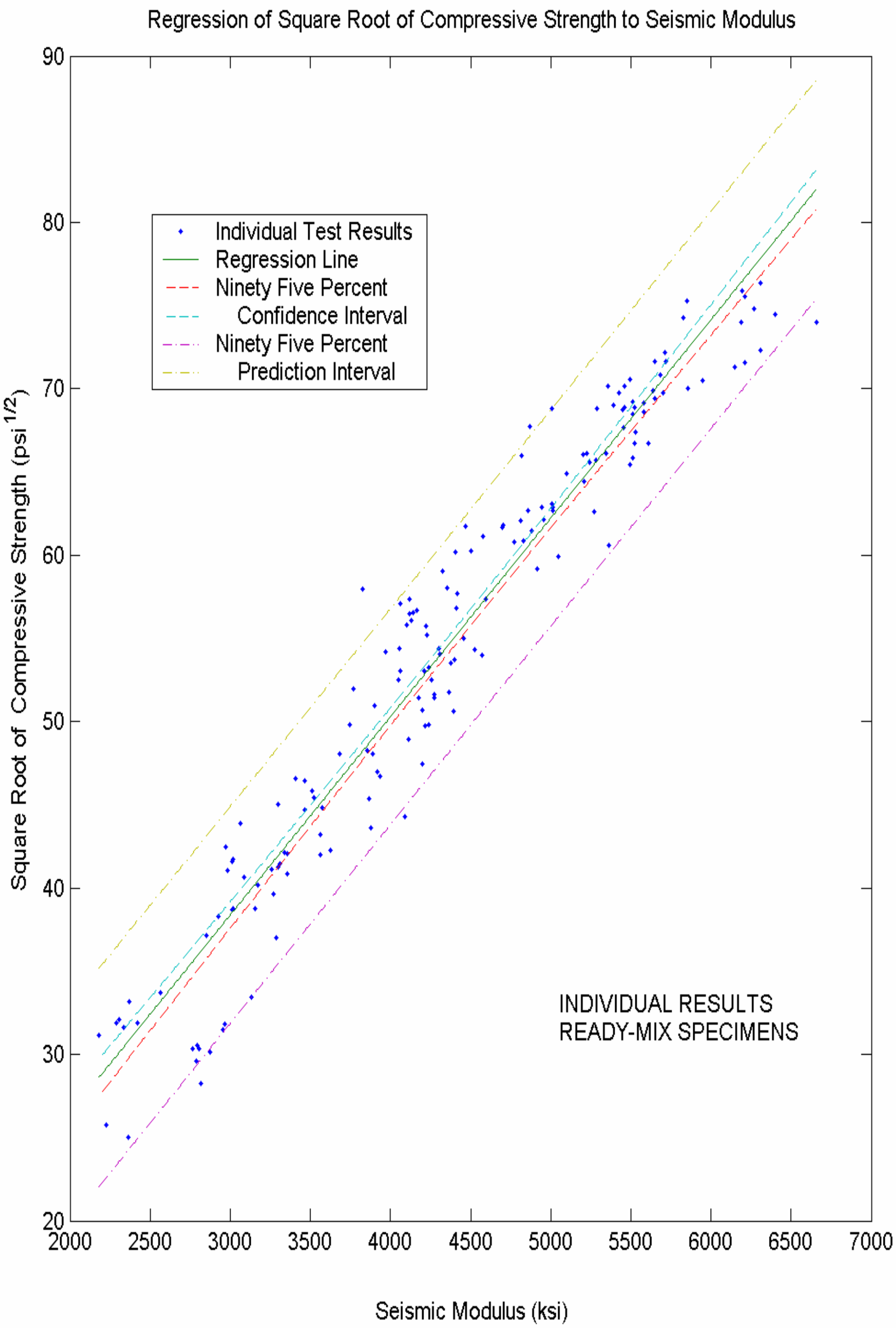

Regression of Split Tensile Strength to Seismic Modulus
Average of Six Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
AVERAGE OF SIX
READY-MIX SPECIMENS
Split Tensile Strength (psi)
Seismic Modulus (ksi)
600
550
500
450
400
350
300
250
200
150
100
2500
3000
3500
4000
4500
5000
5500
6000
6500

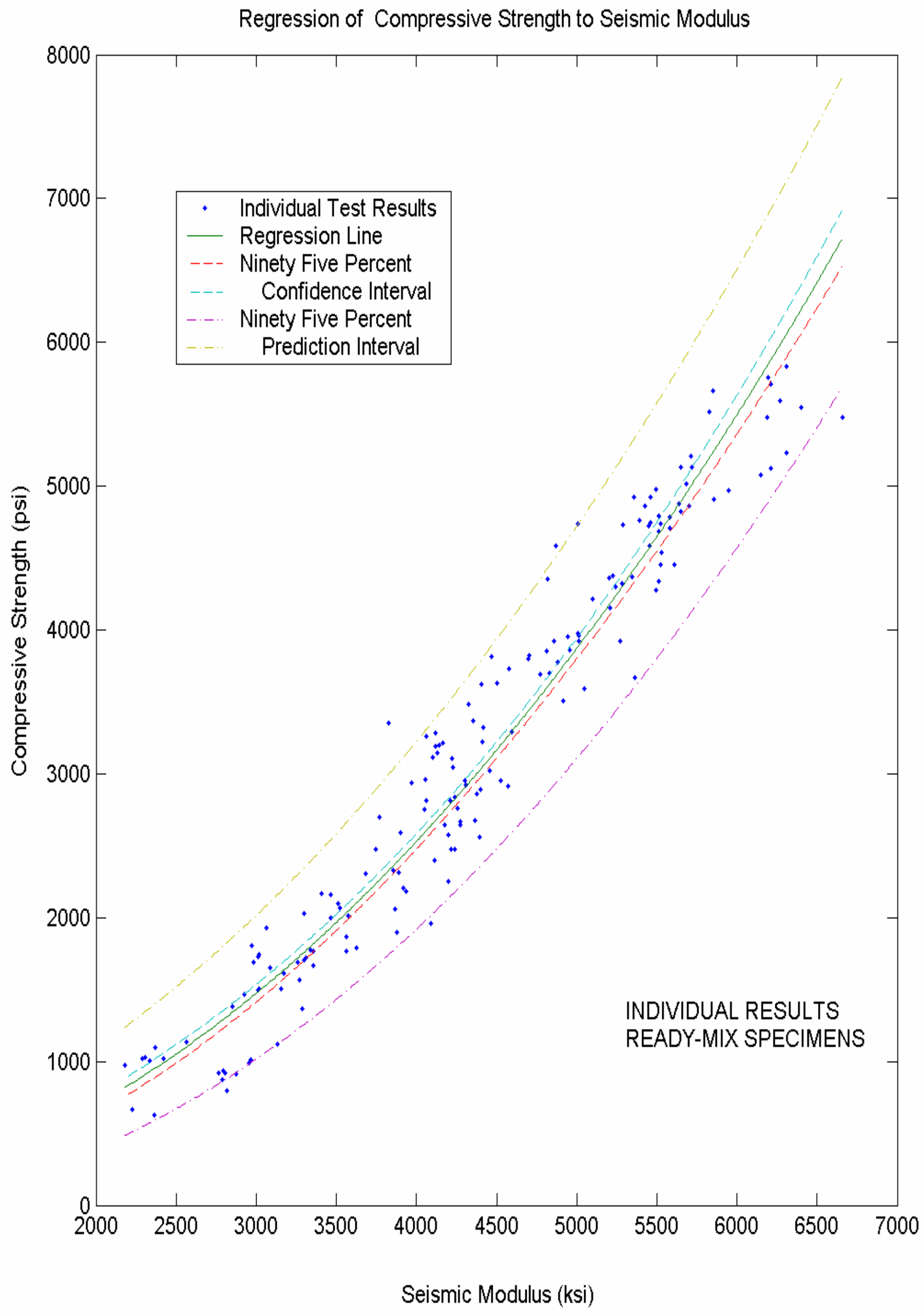

Regression of Square Root of Split Tensile Strength to Seismic Modulus
Average of Three Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
AVERAGE OF THREE
LABORATORY MIXES
Square Root of Split Tensile Strength ($psi^{1/2}$)
Seismic Modulus (ksi)
26
24
22
20
18
16
14
4500
5000
5500
6000
6500
7000
7500

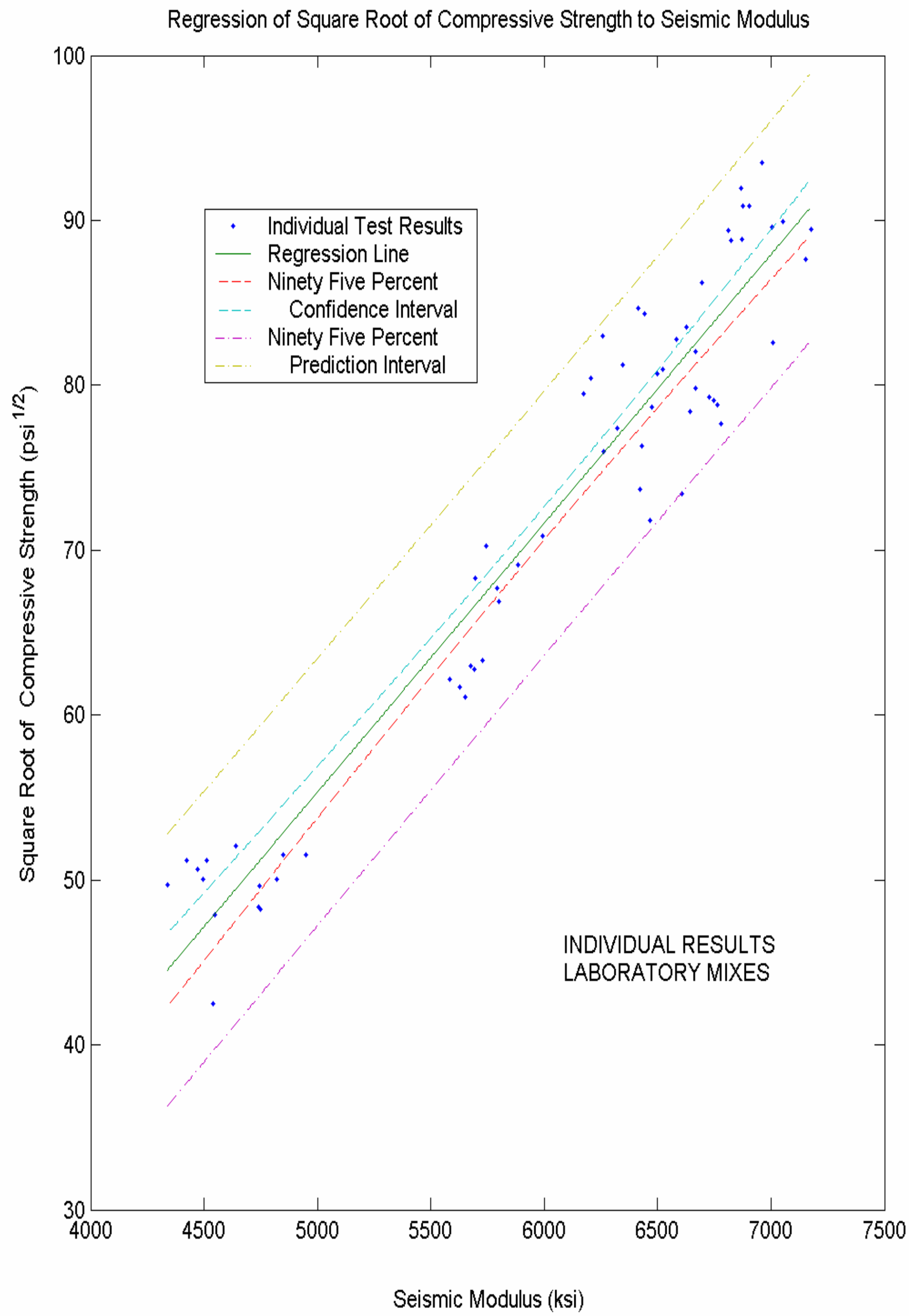

Regression of Split Tensile Strength to Seismic Modulus
Average of Three Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
AVERAGE OF THREE
LABORATORY MIXES
Split Tensile Strength (psi)
Seismic Modulus (ksi)
650
600
550
500
450
400
350
300
250
200
4500
5000
5500
6000
6500
7000
7500

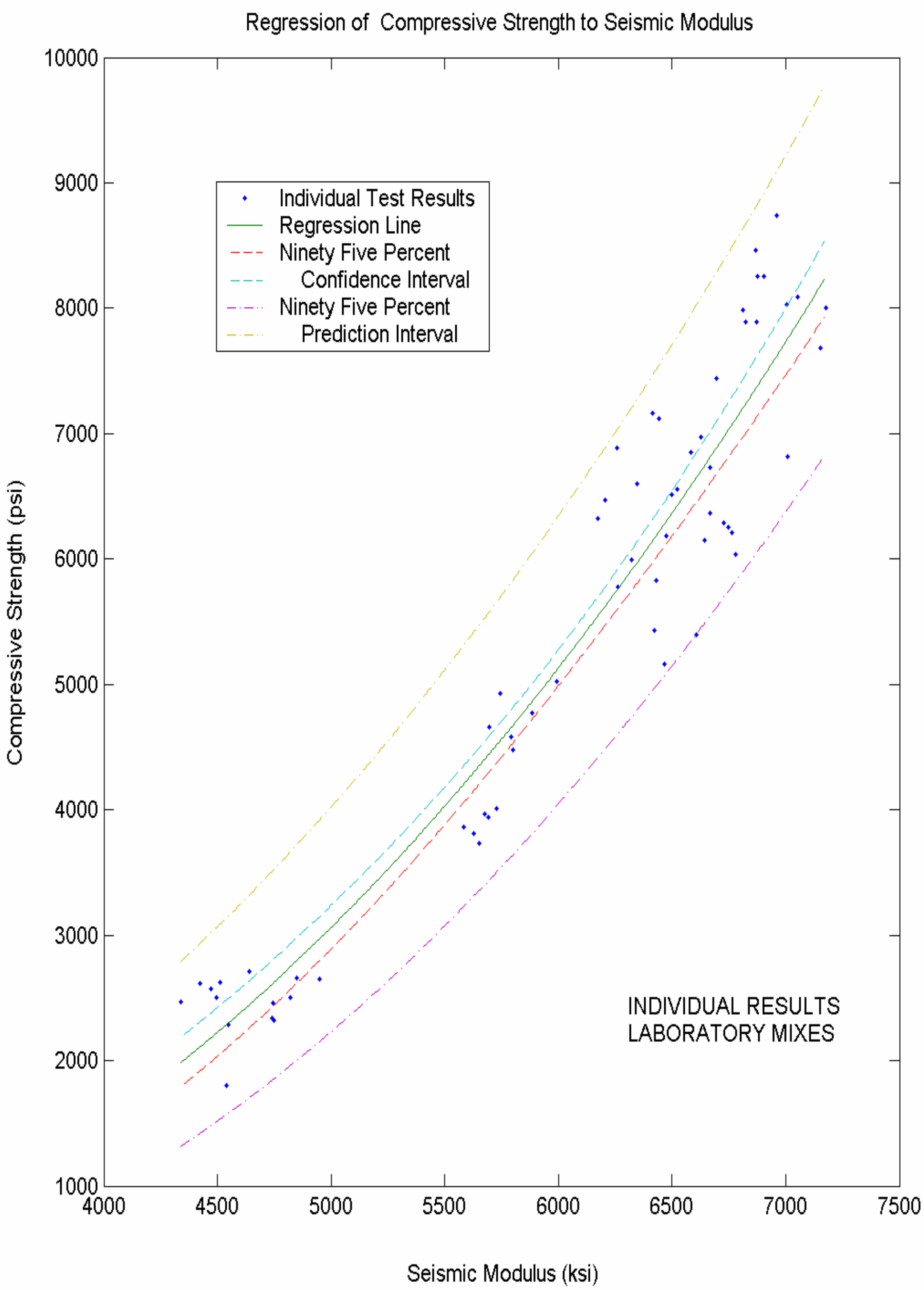
Appendix J

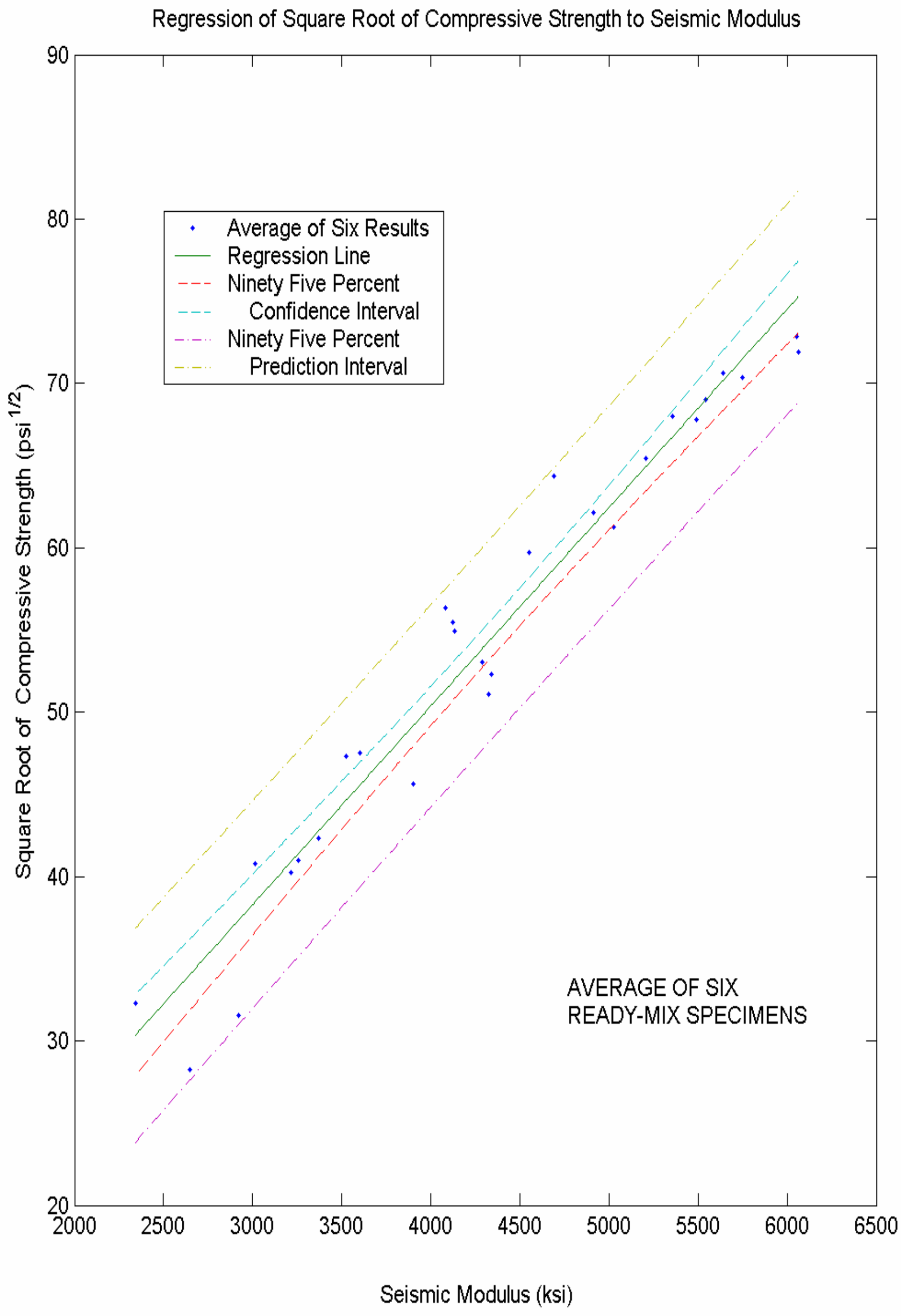
Regression Results
of
Compressive Strength versus Seismic Modulus

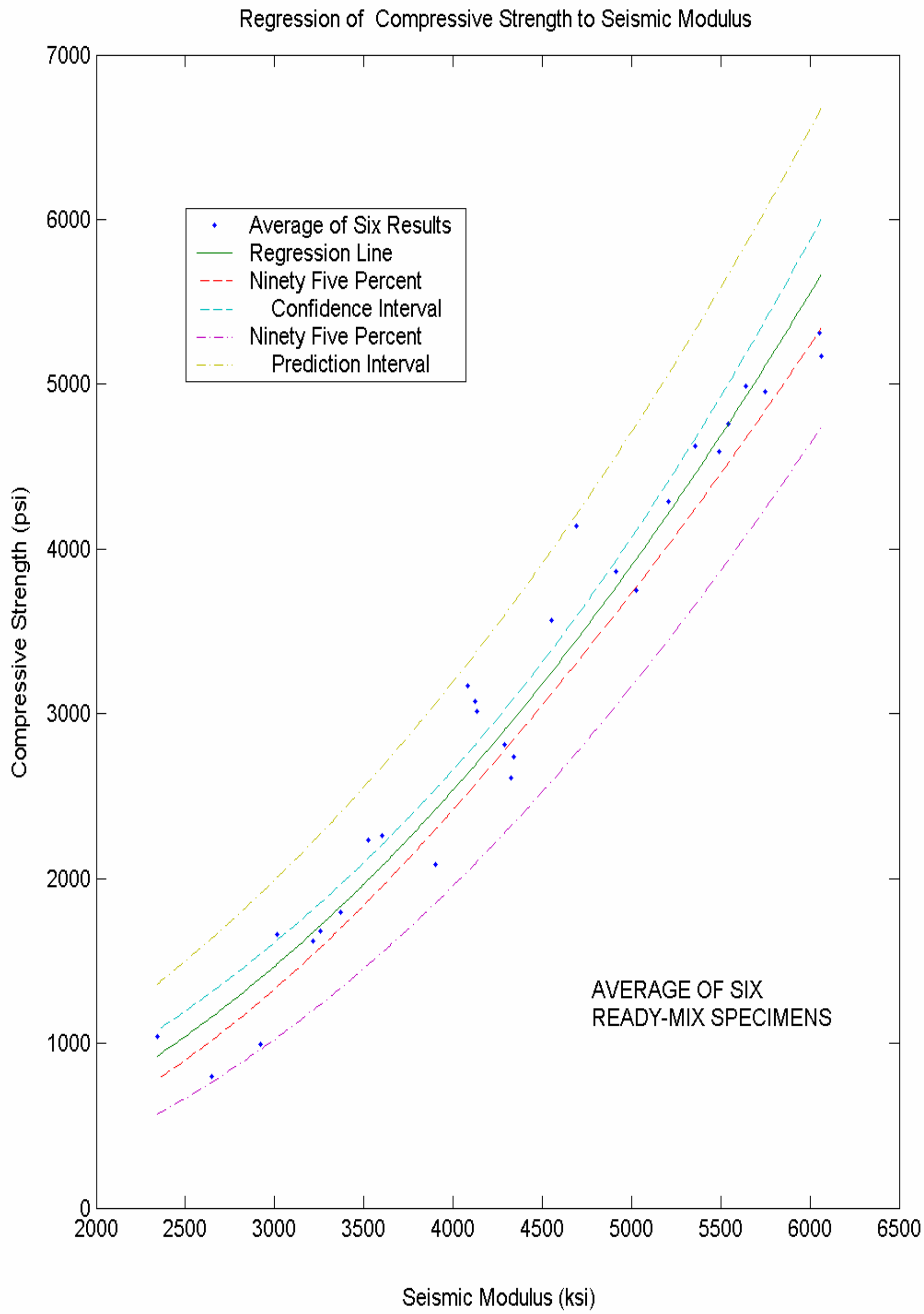

Regression of Square Root of Compressive Strength to Seismic Modulus
Individual Test Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
INDIVIDUAL RESULTS
READY-MIX SPECIMENS
Square Root of Compressive Strength (psi 1/2)
Seismic Modulus (ksi)
90
80
70
60
50
40
30
20
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000

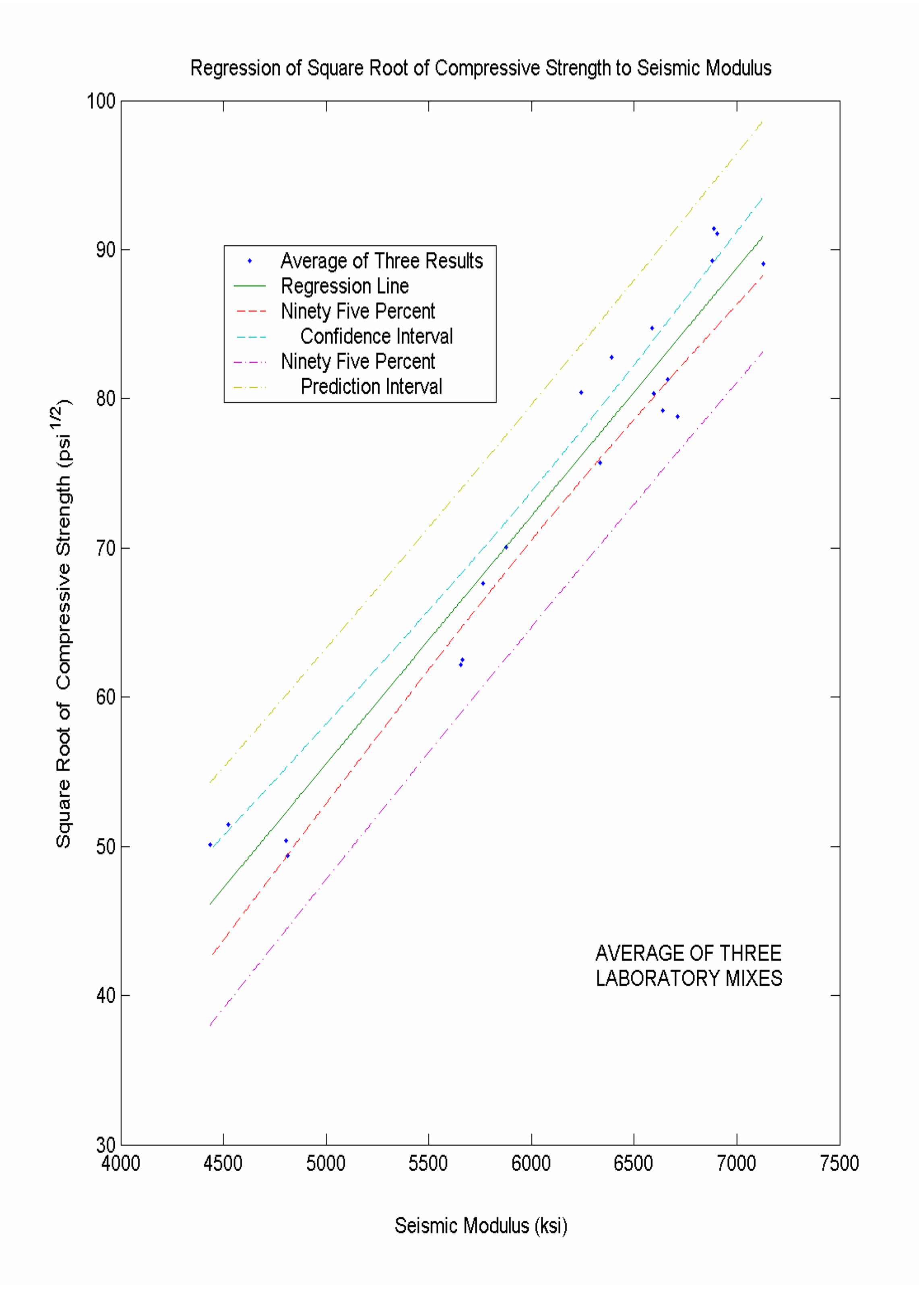

Regression of Compressive Strength to Seismic Modulus
8000
7000
6000
5000
4000
3000
2000
1000
0
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
Compressive Strength (psi)
Seismic Modulus (ksi)
Individual Test Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
INDIVIDUAL RESULTS
READY-MIX SPECIMENS

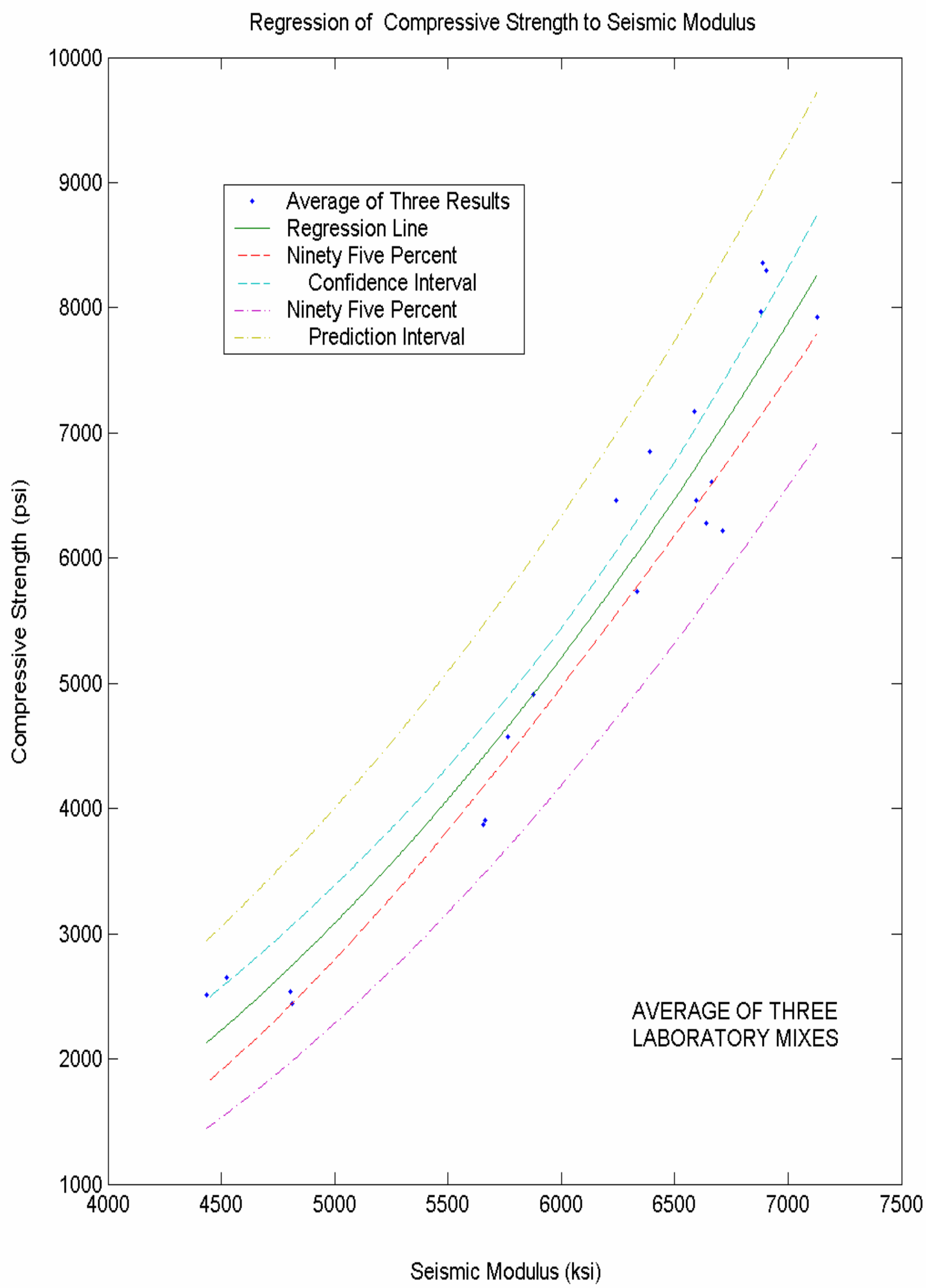

Regression of Square Root of Compressive Strength to Seismic Modulus
Individual Test Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
INDIVIDUAL RESULTS
LABORATORY MIXES
Square Root of Compressive Strength (psi $^{1/2}$)
Seismic Modulus (ksi)
100
90
80
70
60
50
40
30
4000
4500
5000
5500
6000
6500
7000
7500


Regression of Compressive Strength to Seismic Modulus
Individual Test Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
INDIVIDUAL RESULTS
LABORATORY MIXES
Compressive Strength (psi)
Seismic Modulus (ksi)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
4000
4500
5000
5500
6000
6500
7000
7500


Regression of Square Root of Compressive Strength to Seismic Modulus
Average of Six Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
AVERAGE OF SIX
READY-MIX SPECIMENS
Square Root of Compressive Strength (psi 1/2)
Seismic Modulus (ksi)
90
80
70
60
50
40
30
20
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500

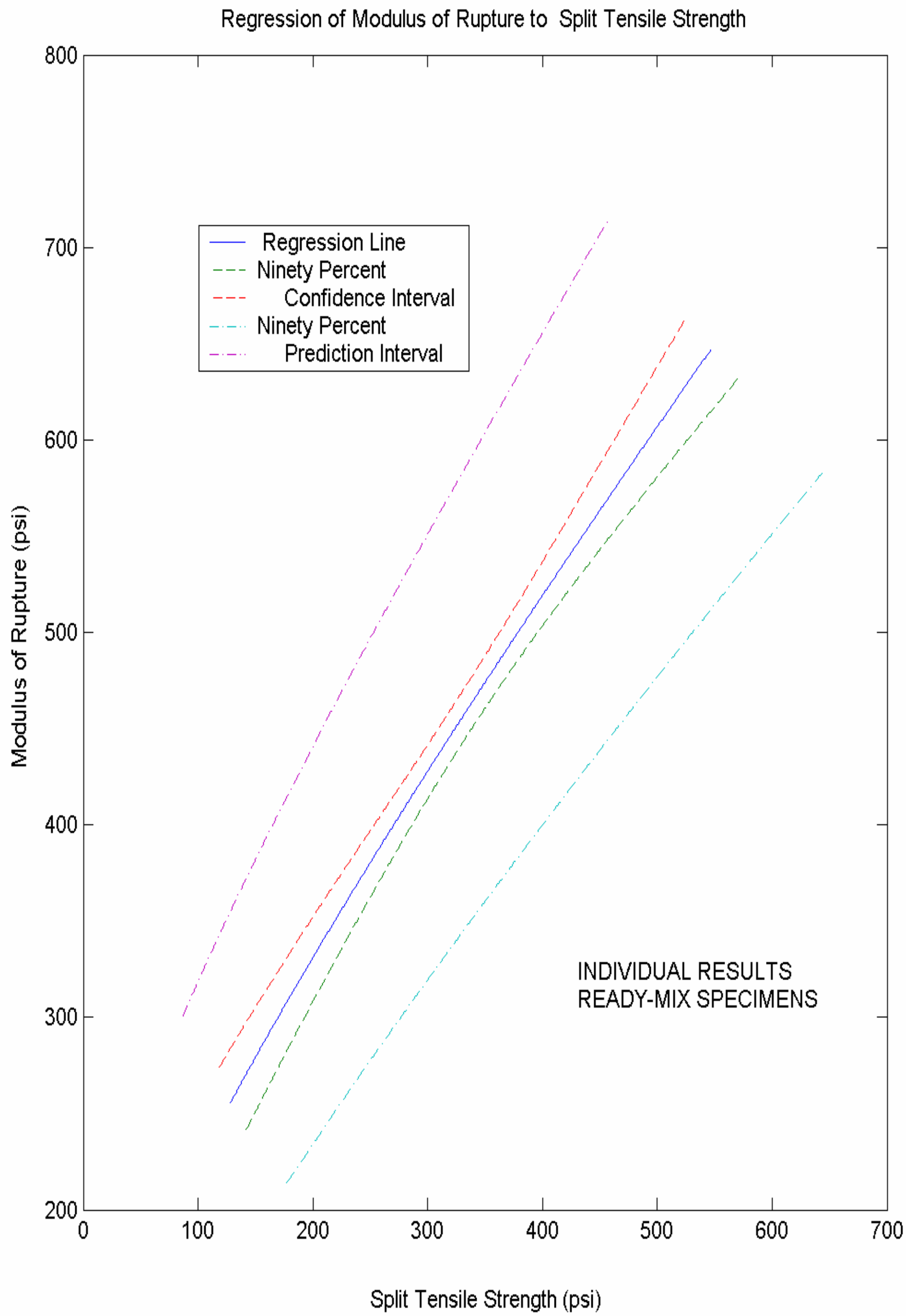

Regression of Compressive Strength to Seismic Modulus
Compressive Strength (psi)
Seismic Modulus (ksi)
0
1000
2000
3000
4000
5000
6000
7000
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
Average of Six Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
AVERAGE OF SIX
READY-MIX SPECIMENS

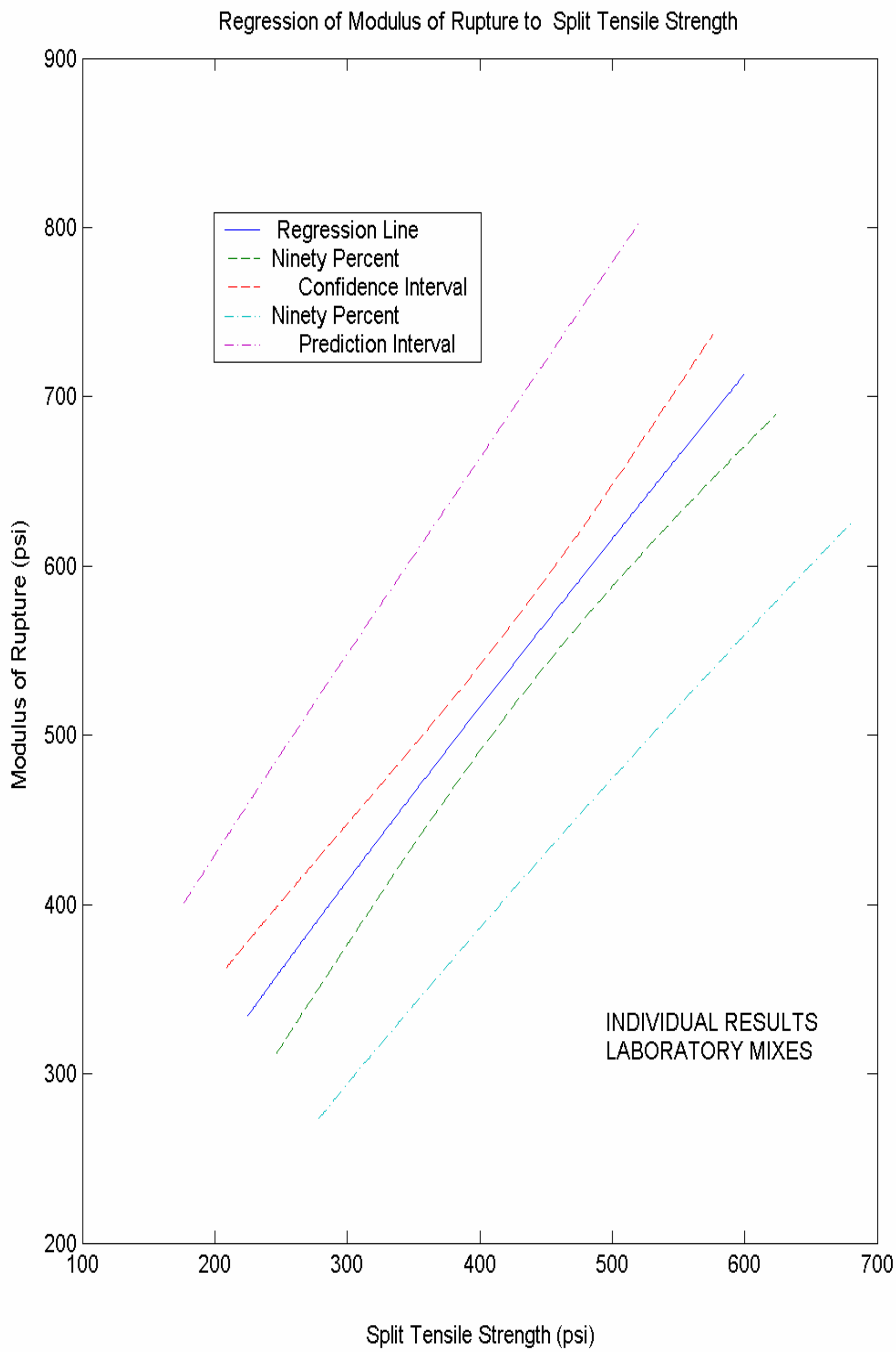

Regression of Square Root of Compressive Strength to Seismic Modulus
Average of Three Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
AVERAGE OF THREE
LABORATORY MIXES
Square Root of Compressive Strength (psi 1/2)
Seismic Modulus (ksi)
100
90
80
70
60
50
40
30
4000
4500
5000
5500
6000
6500
7000
7500


Regression of Compressive Strength to Seismic Modulus
Compressive Strength (psi)
Seismic Modulus (ksi)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
4000
4500
5000
5500
6000
6500
7000
7500
Average of Three Results
Regression Line
Ninety Five Percent
Confidence Interval
Ninety Five Percent
Prediction Interval
AVERAGE OF THREE
LABORATORY MIXES

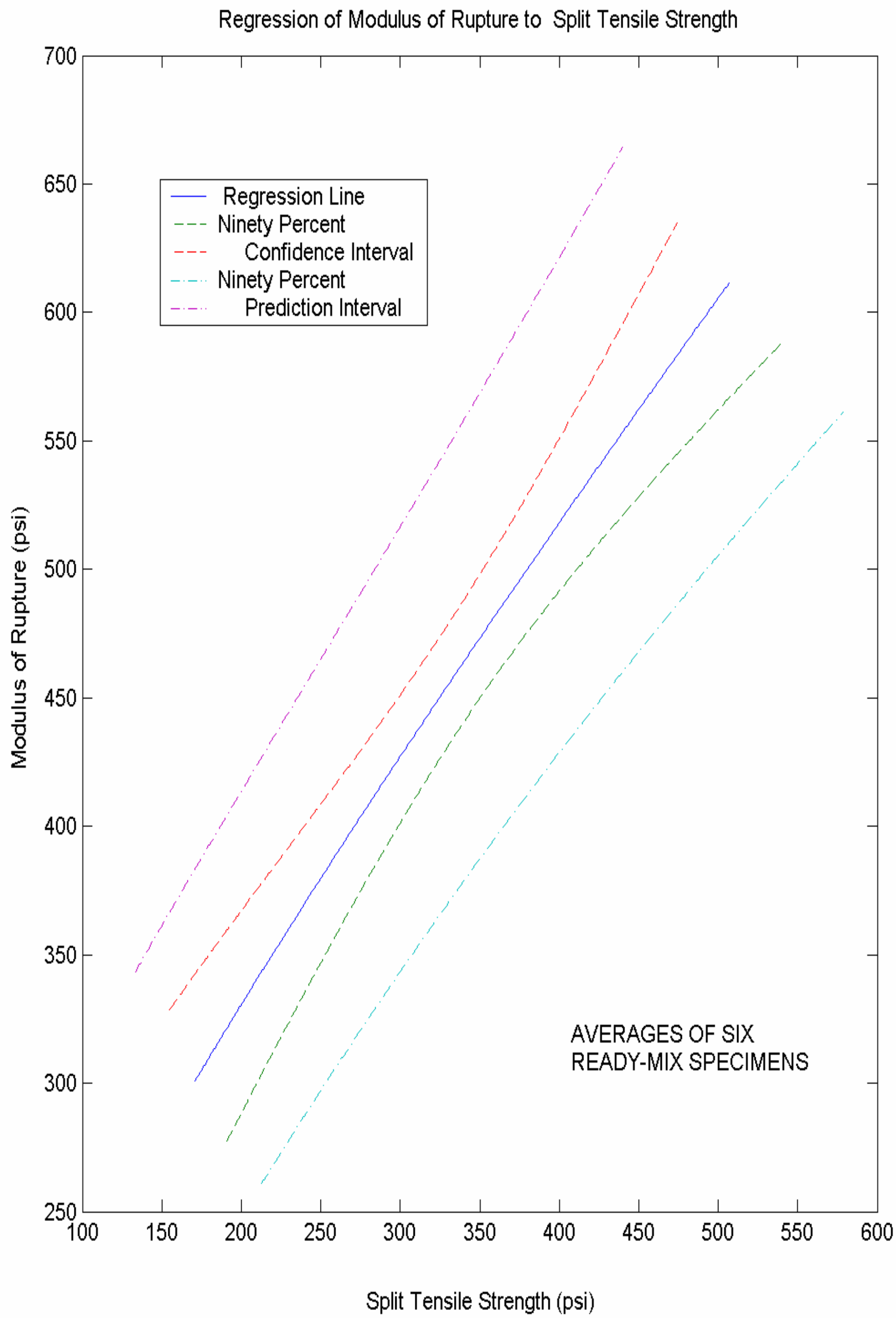
Appendix K

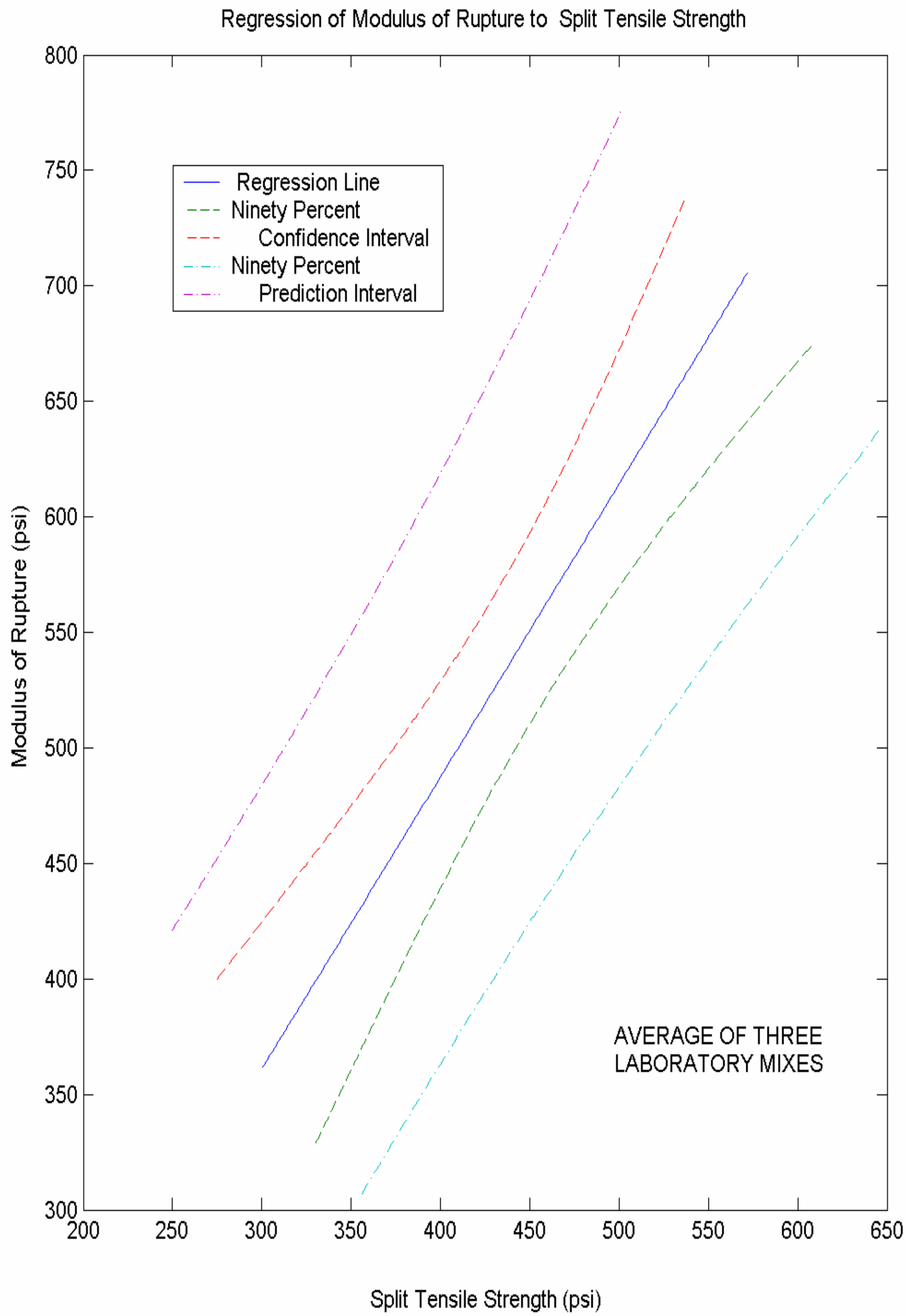
Regression Results
of
Modulus of Rupture versus Split Tensile Strength


Regression of Modulus of Rupture to Split Tensile Strength
Regression Line
Ninety Percent
Confidence Interval
Ninety Percent
Prediction Interval
INDIVIDUAL RESULTS
READY-MIX SPECIMENS
Modulus of Rupture (psi)
Split Tensile Strength (psi)
800
700
600
500
400
300
200
0
100
200
300
400
500
600
700



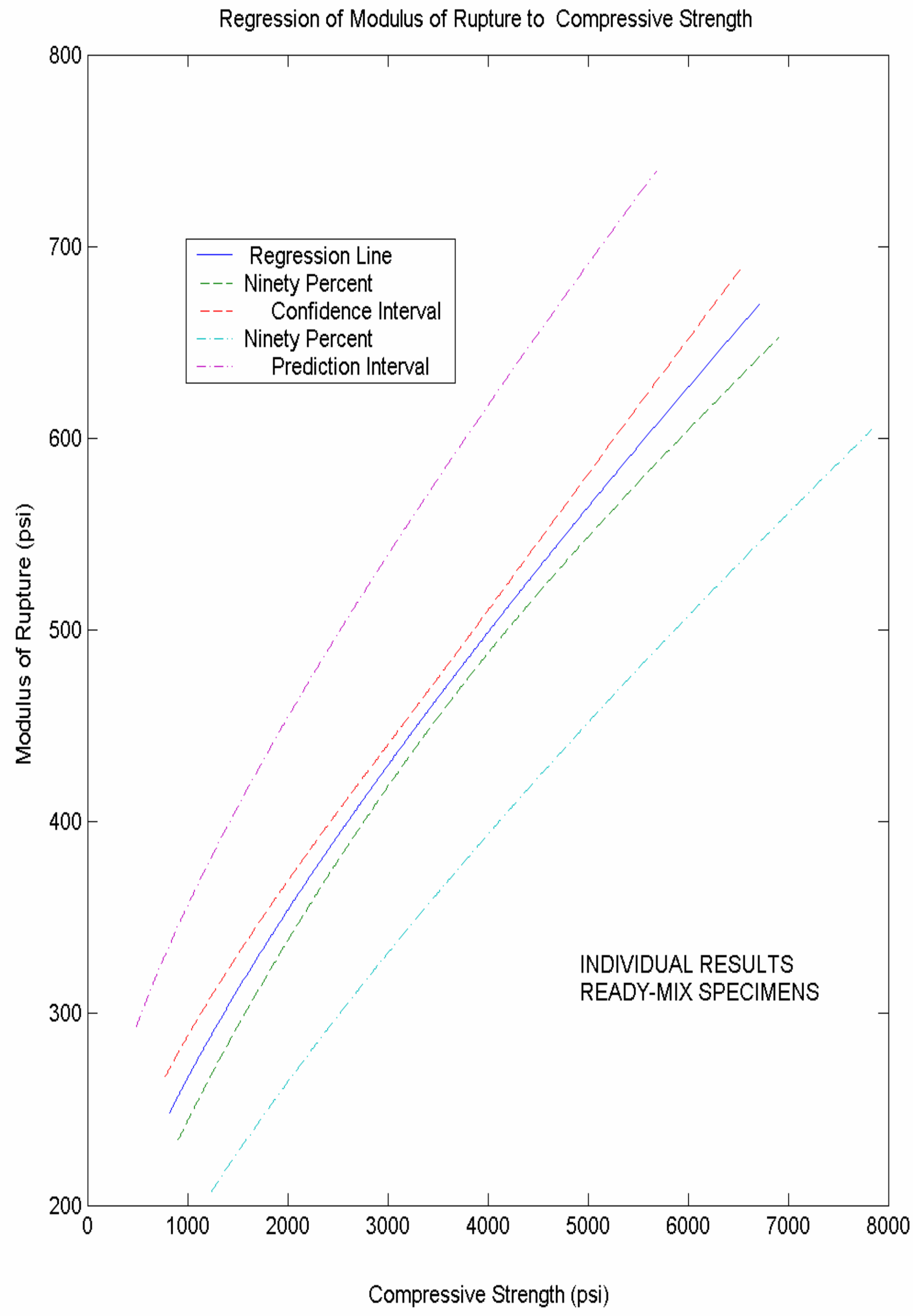
Regression of Modulus of Rupture to Split Tensile Strength
Regression Line
Ninety Percent
Confidence Interval
Ninety Percent
Prediction Interval
INDIVIDUAL RESULTS
LABORATORY MIXES
Modulus of Rupture (psi)
Split Tensile Strength (psi)
900
800
700
600
500
400
300
200
100
200
300
400
500
600
700


Regression of Modulus of Rupture to Split Tensile Strength
Regression Line
Ninety Percent
Confidence Interval
Ninety Percent
Prediction Interval
AVERAGES OF SIX
READY-MIX SPECIMENS
Modulus of Rupture (psi)
Split Tensile Strength (psi)
700
650
600
550
500
450
400
350
300
250
100
150
200
250
300
350
400
450
500
550
600

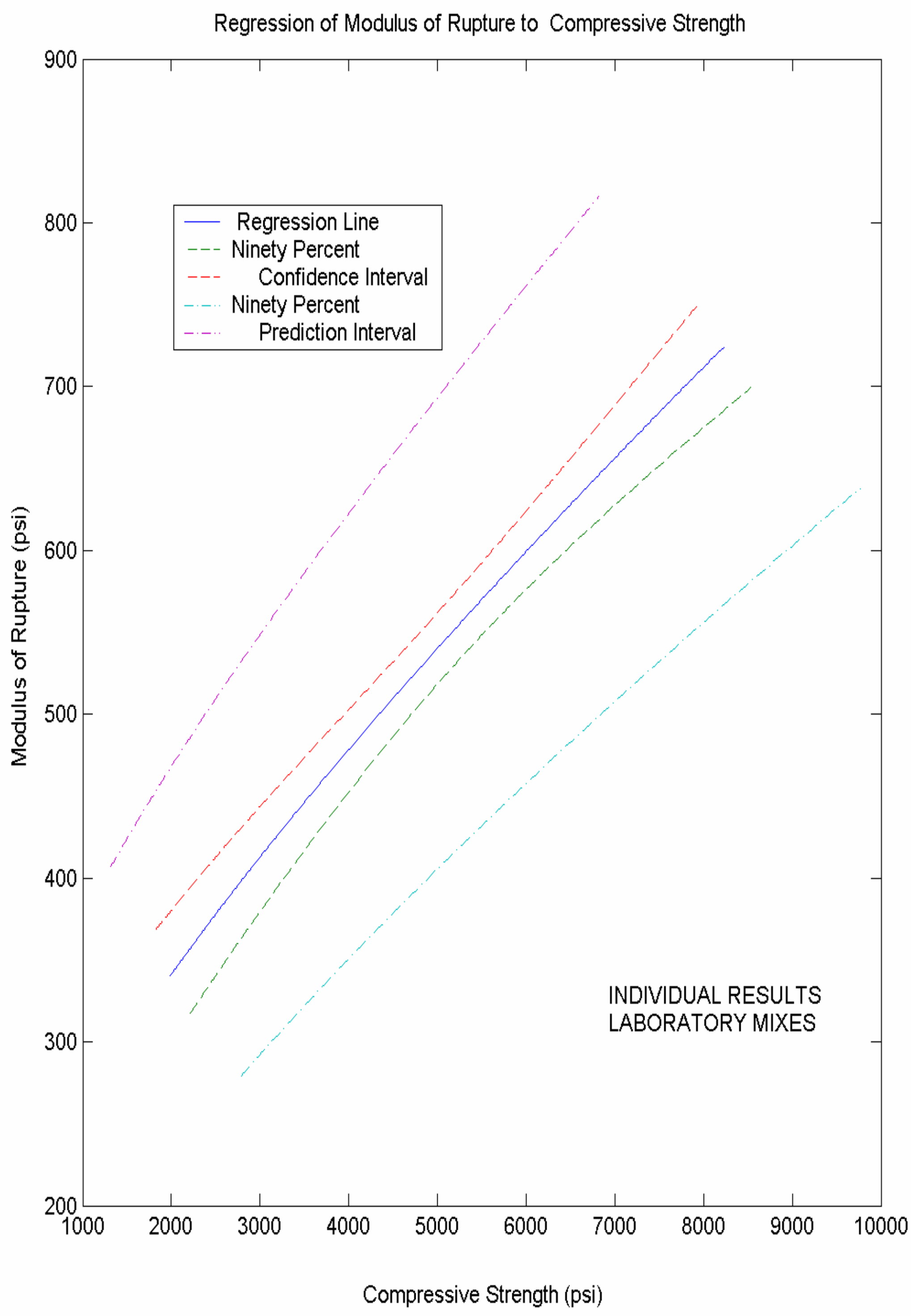

Regression of Modulus of Rupture to Split Tensile Strength
Modulus of Rupture (psi)
Split Tensile Strength (psi)
Regression Line
Ninety Percent
Confidence Interval
Ninety Percent
Prediction Interval
AVERAGE OF THREE
LABORATORY MIXES
800
750
700
650
600
550
500
450
400
350
300
200
250
300
350
400
450
500
550
600
650

Appendix L

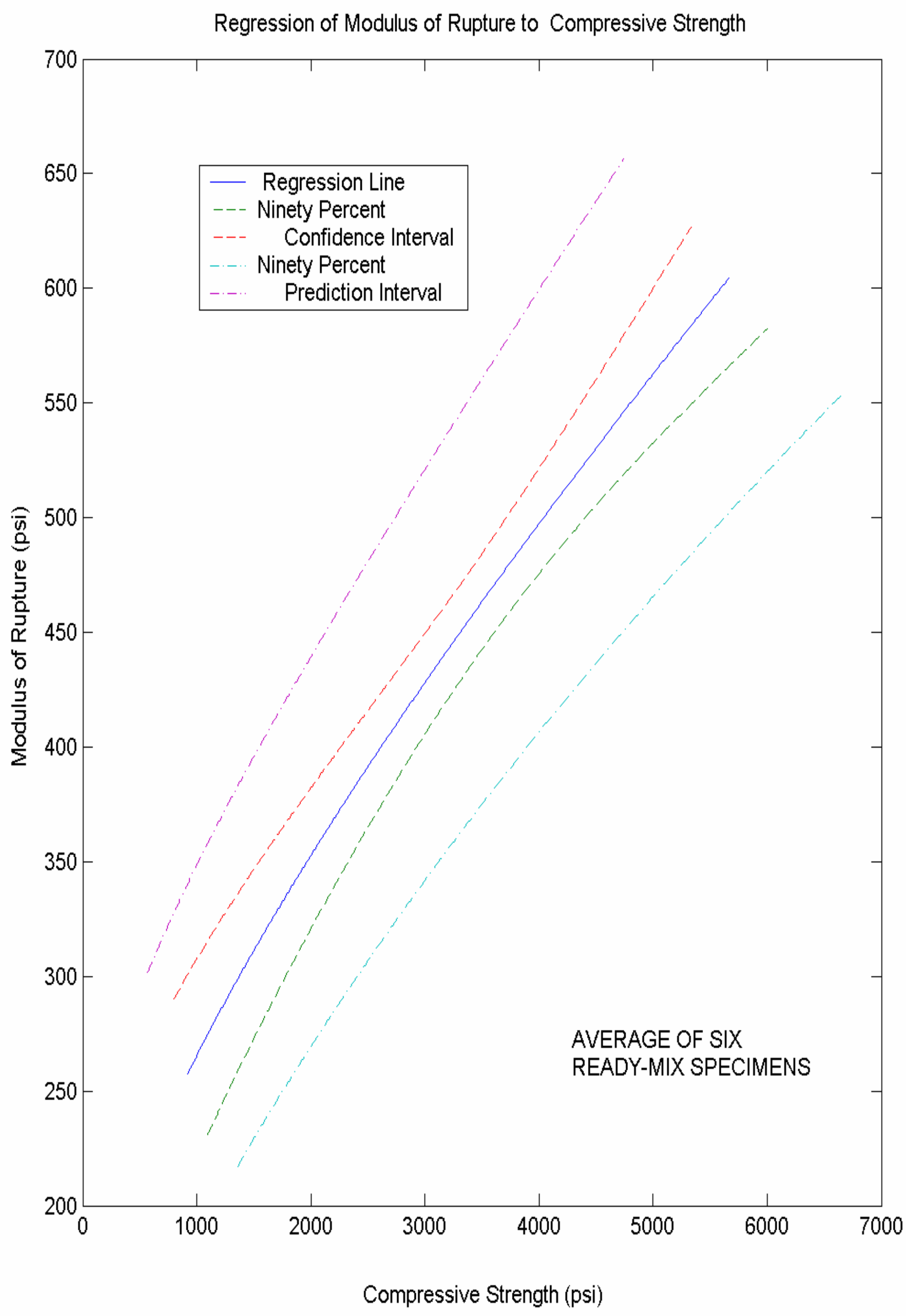
Regression Results
of
Modulus of Rupture versus Compressive Strength

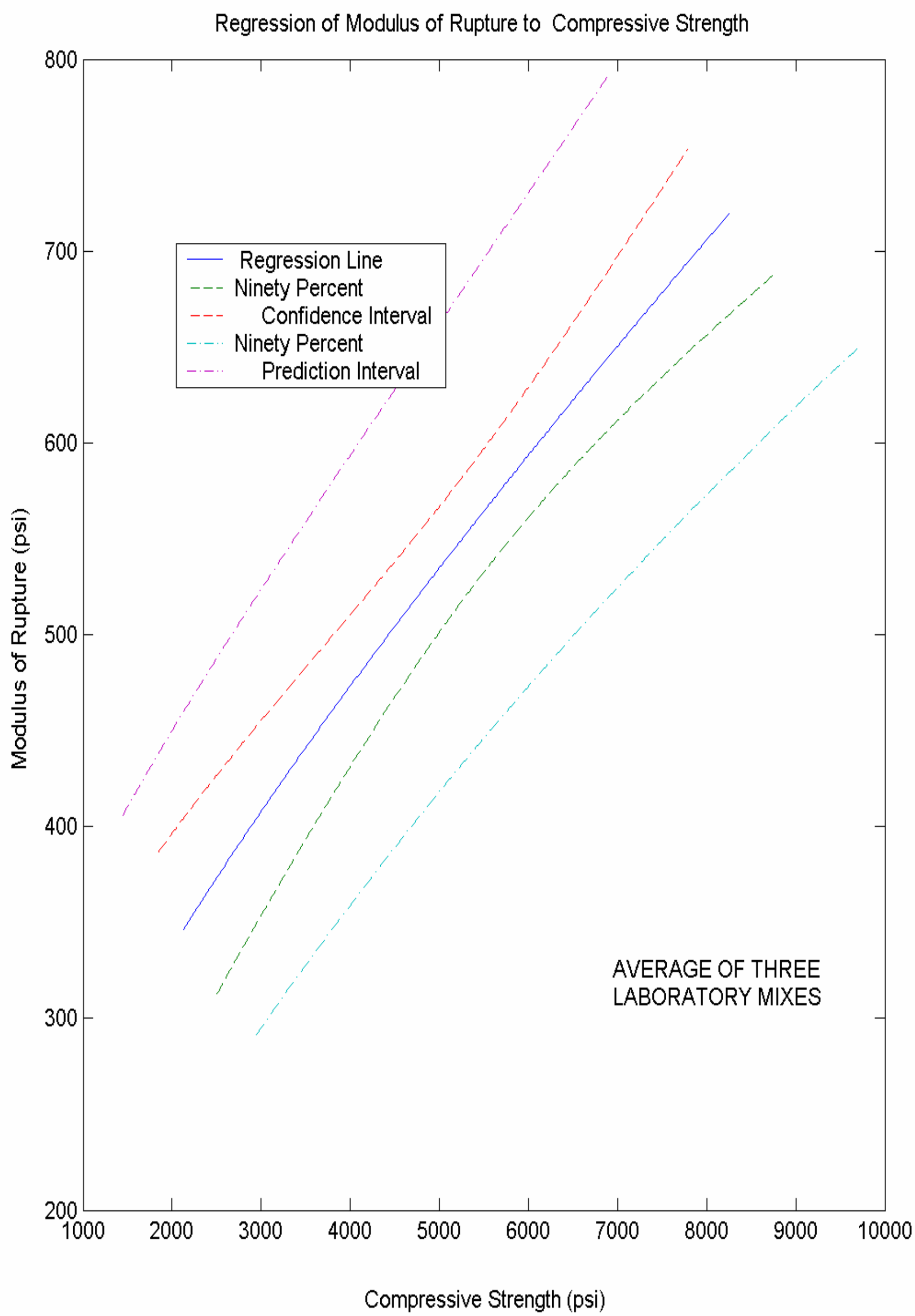


Regression of Modulus of Rupture to Compressive Strength
800
700
600
500
400
300
200
0
1000
2000
3000
4000
5000
6000
7000
8000
Modulus of Rupture (psi)
Compressive Strength (psi)
Regression Line
Ninety Percent
Confidence Interval
Ninety Percent
Prediction Interval
INDIVIDUAL RESULTS
READY-MIX SPECIMENS



Regression of Modulus of Rupture to Compressive Strength
900
800
700
600
500
400
300
200
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Modulus of Rupture (psi)
Compressive Strength (psi)
Regression Line
Ninety Percent
Confidence Interval
Ninety Percent
Prediction Interval
INDIVIDUAL RESULTS
LABORATORY MIXES


Regression of Modulus of Rupture to Compressive Strength
Modulus of Rupture (psi)
Compressive Strength (psi)
700
650
600
550
500
450
400
350
300
250
200
0
1000
2000
3000
4000
5000
6000
7000
Regression Line
Ninety Percent
Confidence Interval
Ninety Percent
Prediction Interval
AVERAGE OF SIX
READY-MIX SPECIMENS


Regression of Modulus of Rupture to Compressive Strength
Modulus of Rupture (psi)
Compressive Strength (psi)
200
300
400
500
600
700
800
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Regression Line
Ninety Percent
Confidence Interval
Ninety Percent
Prediction Interval
AVERAGE OF THREE
LABORATORY MIXES

Appendix M

Summary Review of Statistical Concepts for Acceptance Sampling by Attributes

Appendix M

Acceptance criteria based on acceptance sampling and testing programs have the ultimate objective to provide evidence of the compliance of the built pavement with construction specifications. Due to the variability of the specimens of record and the testing variability, probabilistic concepts and statistical techniques are useful in making decisions and establishing criteria for quality assurance.

One of the first steps is the definition of the acceptance lot. For concrete pavements, NCDOT Standard Specification [9] establishes 1,333.33 square yards of pavement placed within fourteen days as the largest lot possible for acceptance testing. The minimum testing is one set of two bending beams (6 in. x 6 in. x 20 in.) from a randomly selected batch of concrete. The standard specification indicates that the average of these two specimens is to be considered as one test. These considerations suggest that NCDOT is presently using an acceptance scheme based on acceptance sampling by attributes. In these type of schemes, a sample statistic (such as the batch mean **"$\bar{E}$"**) is compared to some rejection value **"R"**. Based on this comparison, the quality of the lot (and, thus, the pay scale or the acceptance/rejection) is determined.

This specification is of the type that states that if as follows:

$$\bar{\mathbf{E}} \text{ (based on } \mathbf{n} \text{ specimens)} >= \mathbf{R} \tag{1}$$

Where:

- **$\bar{E}$** is the batch average flexural strength;
- **n** is the number of specimens in a batch, at least two bending beams;
- **R** is the rejection value, corresponding to a flexural modulus of 600 psi at fourteen days.

Then the corresponding pavement lot is accepted. If the batch average falls below the rejection value **"R,"** a diminished pay rate is defined based on the actual value of the batch average **"$\bar{E}$."**

Clearly NCDOT, at the present time, uses an average quality criterion, since the assurance of quality is based on the average modulus of rupture of the lot.

This type of criterion implies that the lot is of acceptable quality if the average quality of the batch exceeds a predefined mark. In order to include reliability in this approach, it is necessary to select a mean modulus of rupture of the population of the lot **"μ_a"** such that if the population mean is equal to or exceeds **"μ_a"** the lot is clearly of acceptable quality. At the same time it is also necessary to select a mean value of the modulus of rupture of the population of the lot **"μ_t"** such that if the population mean is equal to or less than **"μ_t"** the lot is of bad or unacceptable quality.

The selection of these two critical values: **"μ_a"** and **"μ_t"** for practical applications is a difficult and involved decision for most pavements applications [4]. The appropriate definition of these parameters would require large amounts of data from new research or historical data from typical pavement construction that are known to have performed appropriately. One possible approach could be to implement the new reliability approach in one or several pavement construction contracts that contractually are specified using the present acceptance testing criterion. From the comparison of the simultaneous acceptance/rejection decisions using the two methods, it could be possible to fine tune appropriate values of the critical parameters **"μ_a"** and **"μ_t".**

This approach assumes that a lot is acceptable if the population mean **"μ_{lot}"** for the lot is equal to or larger than the critical limit **"μ_a".** The population mean of the lot **"μ_{lot}"** is not known, an estimator for that value is the batch average "**$\bar{E}$".** However, this estimator is a random variable with a normal distribution, the mean of this distribution is equal to **"μ_{lot}"** and the variance is **"σ^2/n",** where **"n"** is the number of samples averaged in a batch.

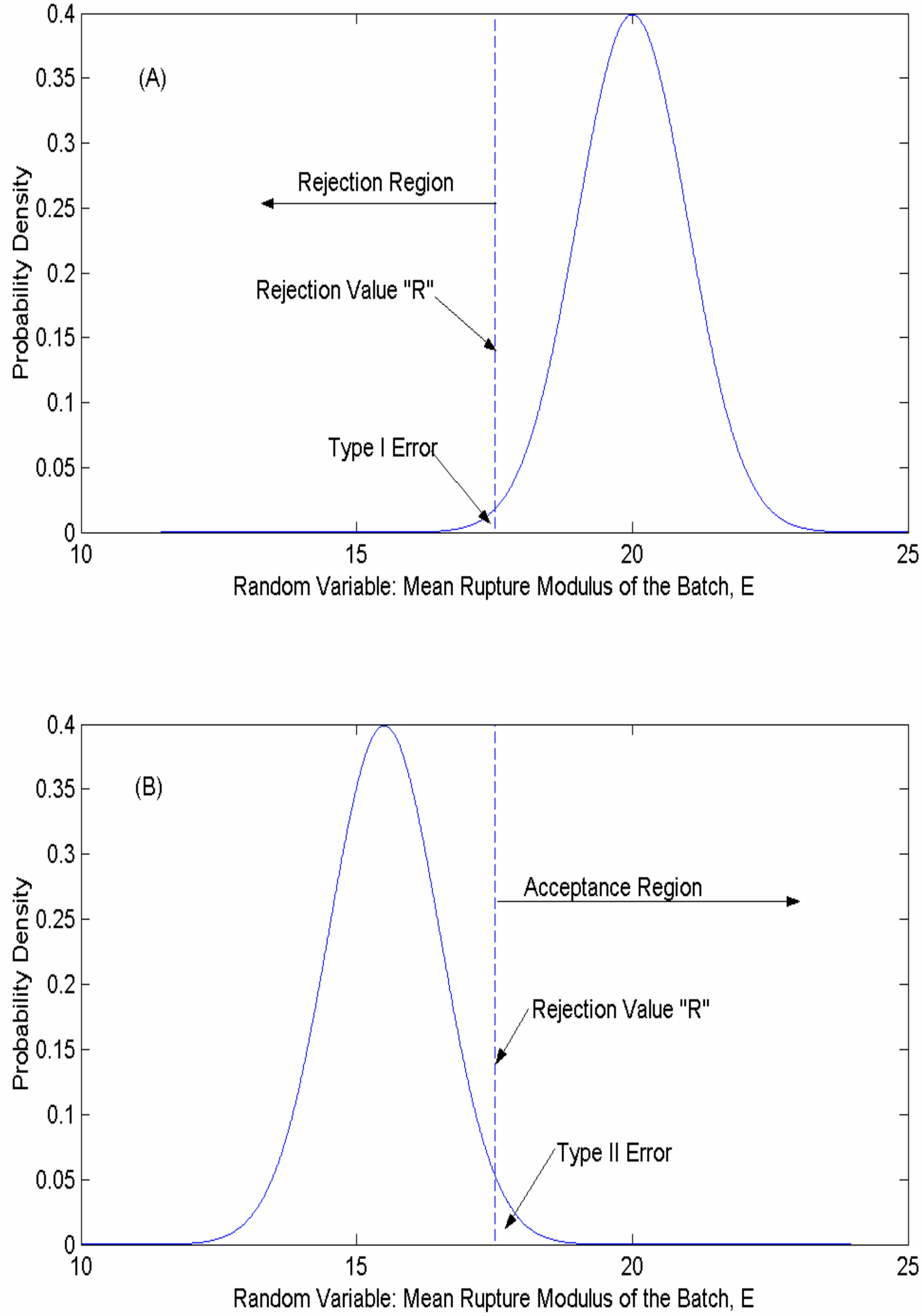
An important observation from statistics [4] is that if a random variable has a normal distribution **"N (μ,σ^2)"** with a mean "**μ"** and a variance "**σ^2"** ; then, if batches of **"n"** realizations of this random variable are averaged and the average treated as a single observation (the average modulus of rupture of the batch **"$\bar{E}$"**), the average will also be a random variable with a normal distribution **"N ($\mu,\sigma^2/n$)"** with the same mean "**μ",** but the variance would be reduced to **"σ^2/n".** In this manner, using averages for the number of tests in a batch it is possible to reduce the variance of the distribution of the averages of a batch.

It is expected that the batch average **"$\bar{E}$"** will approximate **"μ_{lot}"**; however, the batch average is a random variable with a normal distribution **"N ($\mu_{lot},\sigma^2/n$)".** Thus, it is possible that a realization of the batch average **"$\bar{E}$"** could be lower than a previously chosen rejection limit **"R"** (the method of selection of **"R"** is discussed later in this Appendix). To illustrate the concepts of error types, a fictitious example has been presented in Figure M.1. The following assumptions have been made to prepare this figure:

"μ_a" is equal to twenty;
"μ_t" is equal to fifteen and one half;
"σ^2/n" the variance of the batch average is equal to one; and
"R" the rejection value equal to seventeen and one half.

Figure M.1 (A) shows a graphical representation of the probability density function of a normal distribution of batch averages **"$\bar{E}$"** for a "**μ_{lot}"** equal to twenty. Since the "**μ_{lot}"** is equal to the critical value **"μ_a"**, the lot is of an acceptable quality. However, as indicated by the distribution there is a possibility that one realization of the batch average **"$\bar{E}$"** could be lower than the rejection value **"R";** and, thus, according to (1) the lot would be rejected. The probability of such an occurrence is given by the area enclosed below the normal distribution, the horizontal **"$\bar{E}$"** axes, and to the left of the vertical line at the rejection value **"R"**. This probability is known as the **"α error"** or **"Type I error"** and is the probability, or risk, that the contractor is accepting that a truly acceptable lot would be rejected or paid at some reduced rate. It is obvious from the above discussion that by

Figure M.1 Conceptual Illustrations of the Type I and the Type II Errors



increasing the number of tests **"n"** in a batch, it would be possible to reduce the variance of the distribution **"σ^2/n"** of the batch average. The resulting distribution would be more packed around the mean and would, thus, result in lower **"α or Type I error".** Seemingly, the error level could be reduced to any desired level; however, there are practical and economical limits to increasing the number of tests **"n"** in a batch.

Figure M.1 (B) shows a graphical representation of the probability density function of a normal distribution of batch averages **"$\bar{E}$"** for a "**μ_{lot}**" equal to fifteen and a half. Since the "**μ_{lot}**" is equal to the critical value **"μ_t"**, the lot is of a poor quality. However, as indicated by the distribution there is a possibility that one realization of the batch average **"$\bar{E}$"** could be higher than the rejection value **"R";** and, thus, according to (1) the lot would be accepted. The probability of such an occurrence is given by the area enclosed below the normal distribution, the horizontal **"$\bar{E}$"** axes, and to the right of vertical line at the rejection value **"R"**. This probability is known as the **"β error"** or **"Type II error"** and is the probability, or risk, that NCDOT would accept, or pay at full price, a truly poor or unacceptable lot. It is also clear that it would be possible to reduce this error by increasing the number of specimens **"n"** averaged for every batch. In any practical application there are physical and economical limits that prevent the large number of specimens that could be required for very low error levels. In practical applications these errors are commonly limited to be between one percent and five percent.

The selection of the **"Type I"** error acceptable to the contractor and **"Type II"** error acceptable to NCDOT are also difficult decisions [4 &10] as much as the selection of the critical values **"μ_a"** and **"μ_t".** If the selected values of these parameters are not based on ample experience of well performing pavements under field conditions, there is always the possibility of a specification that is too strict. That could result in a specification that the contractor cannot comply with.

The selection of the number of specimens to be included in a batch **"n"** and the appropriate rejection value **"R"** are determined based on the two critical values **"μ_a"** and **"μ_t"** ,as well as the **"Type I"** and **"Type II"** acceptable error levels and the variance **"σ^2"** of the population of individual test without any averaging. To illustrate this selection process, an example is solved for the following assumed conditions:

"μ_a"	is equal to twenty;
"μ_t"	is equal to fifteen and one half;
"Type I"	the acceptable error is two percent;
"Type II"	the acceptable error is five percent; and
"σ^2"	the variance of the population of individual test results is assumed to be equal to four.

For this selection, it is necessary to use a normal distribution **"N (μ_a,σ^2/n)"** where **"n"** is an unknown. It is needed to select **"R"** (also unknown) in such a manner that the area below the distribution to the left of **"R"** is the accepted **"Type I"** error level. This can be accomplished by transforming the distribution to the standard normal distribution N (0,1).

The transformation is given by the following expression:

$$\mathbf{Z_\alpha = (R - \mu_a) / (\sigma / \sqrt{n})}$$

Where **"Z_α"** is the standard normal deviate. For the values assumed above, this equation reduces to the following:

$$\mathbf{Z_\alpha = (R - 20) / (2 / \sqrt{n})} \qquad (2)$$

Given that the accepted value of the **"Type I"** error is two percent, the value of **"Z_α"** can be found from the Standard Normal Probability Tables [10]. This value is the value of the standard normal deviate that encloses an area to the left of two percent. The value of **"Z_α"** is -2.056. Thus equation (2) reduces to the following:

$$\mathbf{R = 20 - (2 * 2.056) / \sqrt{n}} \qquad (3)$$

This is an equation with the two unknowns. In a similar manner, another equation can be derived from the case illustrated in Figure M.1 (B). The transformation needed to reduce the distribution **"$N (\mu_t, \sigma^2/n)$"** to the standard normal distribution is the following:

$$\mathbf{Z_\beta = (R - \mu_t) / (\sigma / \sqrt{n})}$$

And for the particular values assumed in this example, it reduces to the following:

$$\mathbf{Z_\beta = (R - 15.5) / (2 / \sqrt{n})} \qquad (4)$$

Given that the accepted value of the **"Type II"** error is five percent, the value of **"Z_β"** can be found from the standard normal probability tables [10]. This value is the value of the standard normal deviate that encloses an area to the right of five percent. The value of **"Z_β"** is 1.645. Thus equation (4) reduces to the following:

$$\mathbf{R = 15.5 + (2 * 1.645) / \sqrt{n}} \qquad (5)$$

Equations (3) and (5) are two simultaneous equations with two unknowns. Thus the solution provides the values of **"R"** and **"n".** Since the two equations are solved for **"R"**, equating the two right hand sides provides one equation in **"n"** as follows:

$$\mathbf{20 - 4.112 / \sqrt{n} = 15.5 + 3.290 / \sqrt{n}}$$

The result is a value for **"n"** of 2.71 and substituting this value of **"n"** into equation (3) or (5) the value of **"R"** is calculated to be 17.50. Thus **"n"** would be rounded up to three tests in a batch. The results of this example indicates that the acceptance testing would consists of testing batches of three specimen per lot, and the average for the batch **"$\bar{E}$"** would then be compared to the rejection value **"R"** of 17.50. The two possible outcomes would then be the following:

1.) if **"$\bar{E}$"** is larger than or equal of 17.50, the lot would be accepted, and
2.) if **"$\bar{E}$"** is smaller than 17.50, the lot would be rejected.

In all the discussion in this appendix, it has been assumed that the variance **"σ^2"** of the population of the individual strength test is known from previous experience. If this assumption is not appropriate, then the sample variance **"s^2"** can be used. However, the use of the normal distribution would not be appropriate, it would be necessary to use the Student's t-distribution [10]. In this case, an additional complication would arise, since the Student's t-distribution is different depending on the degrees of freedom **"v".** The degrees of freedom are the number of test, minus one, on which the calculation of the variance **"s^2"** is based.

The equations set up for the normal distribution for the values of the standard normal deviate **"Z_α"** and **"Z_β"** would have to be replaced by the Student's t-distribution deviates such as the following:

$$\mathbf{t_{\alpha;n-1} = (R - \mu_a) / (s / \sqrt{n})} \qquad (6)$$
$$\mathbf{t_{\beta;n-1} = (R - \mu_t) / (s / \sqrt{n})} \qquad (7)$$

both of the Student's t-distribution deviates depend on the number of individual test averaged to find the batch average. To solve the system of equations, it would be necessary to solve using a trial and error process, such as the following:

1.) an initial value of the number of test **"n_o"** would be arbitrarily selected;
2.) with this value of **"n_o"** the tables of probability for the Student's t-distribution would be used to find **"$t_{\alpha;n-1}$"** and **"$t_{\beta;n-1}$"** for the **"Type I"** and **"Type II"** errors selected;
3.) the set of equations (6) and (7) would then be solved for **"R"** and **"n";**
4.) if the calculated value for **"n"** is different than the assumed value of **"n_o",** a new guess for **"n_o"** would be selected, and steps 2) and 3) repeated;
5.) this process would be repeated until the value assumed to set the system of equations is equal to the calculated value found from the solution of the system of equations.

One point that is important to realize is that the Student's t-distributions are much flatter than the normal distribution; thus, to achieve comparable alpha and beta errors, the Student's t-distribution would require much larger numbers of individual tests to obtain the batch average. A rule of thumb is that when the number of tests in a batch reaches about thirty, the Student's t-distribution is very close to the normal distribution. Typically, when the sample includes more than thirty observations, the large sample statistics considers that there is enough information about the variance to consider that **"σ^2"** is known. Based on this observation, if there is no previous information as to the variance of the strength test intended of being used in the acceptance testing of a project, it might be preferable to implement an statistical evaluation of the repeatability of the operators that would be performing the testing, for the size of specimen that will be used, the same number of curing days, the same equipment (to cast, cure, and tests the specimens), and for concrete of the same strength as to the concrete mix to be used in the pavement construction. This extra work needed to define the variance of the field personnel at the beginning of the construction program, could reduce considerably the number of tests that would later be needed to implement the acceptance testing of the pavement lots.