SHRP-P-636

Portland Cement Concrete Core Proficiency Sample Program

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Strategic Highway Research Program
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350/NAP/593

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Contents

Abstract

This document provides a description and process of the Portland Cement Concrete Core Proficiency Sample Program.

Executive Summary

One element of Quality Assurance (QA) for laboratory testing that was deemed to be of key importance by SHRP, as a result of Expert Task Group (ETG) recommendations, is the American Association of State Highway and Transportation Officials (AASHTO) accreditation program (AAP) for laboratories. All laboratories providing long-term pavement performance (LTPP) testing services were required to be accredited by AAP. Most of the laboratory tests on LTPP field samples were addressed by the AAP, which includes on-site inspections of equipment and procedures, and participation in applicable proficiency sample series. However, a few critical tests in the SHRP LTPP studies were not fully addressed. After extensive consultation and careful study, it was determined that supplemental programs should be designed to provide assurance that quality test data would be obtained by using approaches similar to those provided by AAP for other tests.

One supplemental program approved for implementation was the Portland Cement Concrete (PCC) Core Proficiency Sample Program. The program was designed to provide precision data concerning the static modulus of elasticity, poisson's ratio, splitting tensile strength, and compressive strength.

The PCC core program was modeled after the familiar Cement and Concrete Reference laboratory (CCRL) proficiency sample programs at the National Institute of Standards and Technology (NIST). The core samples were prepared and distributed to participants, the raw test data was collected and entered into a matrix for analysis, and an interim report to participants was distributed for SHRP by the Iowa Department of Transportation's Office of Materials.

Two different PCC mixes were prepared by the Iowa Materials Laboratory and cast into forms that would allow 4 in. diameter by approximately 9 in. length cores to be obtained for testing. All cores were taken, cured and shipped in accordance with standard practice. Twelve cores were sent to each participating laboratory for testing at age 56 days, six from each mix.

Instructions to the laboratories directed that two cores from each mix be tested in compression, two from each mix be tested for splitting tensile strength, and two be tested for static modulus of elasticity and poisson's ratio. A single operator was to perform the same test on both samples. Different operators could be used for different tests. Explicit directions were included concerning procedures to be followed for each test.

Raw test data were returned to Iowa for matrix entry and preliminary reports to participants. Subsequently, preliminary scatter diagrams and individualized tables of results were distributed to the cooperating laboratories.

A 3 ½ in. floppy disk containing the raw test data along with the core sample identification key was prepared by the Iowa Materials Office and forwarded to the SHRP Quality Assurance Engineer when all data had been received. The floppy disk was then transmitted to the SHRP Statistician for final analysis and determination of test precision.

The statistician's initial report indicated that potential outliers existed in the data which should be investigated. An investigation was conducted by the Quality Assurance Engineer. It was determined that the outliers should be set aside in the final analysis.

The SHRP authorization to proceed with tests of LTPP field samples was issued based on results of the proficiency sample tests.

Precision statements were derived and drafted in the standard AASHTO/ASTM format for use by standards writing committees as they deem appropriate.

Appendices to this report contain the complete set of supporting documents for this program as listed in the table of contents.

Thirteen (13) laboratories participated in this program. Each participant has made a substantial contribution to the successful completion of SHRP research in the LTPP program. Participants were:

Florida Department of Transportation, Gainesville, Florida
Iowa Department of Transportation, Ames, Iowa
Federal Highway Administration, Denver, Colorado
California Department of Transportation, Sacramento, California
West Virginia Department of Transportation, Charleston, West Virginia
Law Engineering, Atlanta, Georgia
National Aggregates Association/National Ready Mix Concrete Association, Silver Spring, Maryland
Bureau of Reclamation, Denver, Colorado
Waterways Experiment Station, Vicksburg, Mississippi
Concrete Materials and Technical Services, Skokie, Illinois
CANMET, Ottawa, Ontario, Canada
Wiss, Janey and Elsner, Northbrook, Illinois
New York Department of Transportation, Albany, New York

APPENDIX I

K. [illegible]

Form 000032
3-86 H-8687

IOWA DEPARTMENT OF TRANSPORTATION

800 Lincoln Way, Ames, Iowa 50010 515/239-1649

Ref. No. 435.24

November 2, 1989

Garland W. Steele
President, Steele Engineering, Inc.
Box 173
Tornado, West Virginia 25202

Dear Garland:

Attached is information on the "Precision and Accuracy Determination for P.C. Concrete Core Testing". The concrete was poured on October 19 and cored on October 26 and 27. Iowa's B-4 mix is commonly used for low traffic county roads. The C-4 mix is used on primary and interstate paving.

We will be sending you a draft of "instructions for testing" for your review in the next week or two. Please let me know if you have any questions about our plans.

Sincerely,

Kevin Jones
Cement & Concrete
Engineer

KJ:sh
Attach.
cc: B. Brown

COPY

MLR-89-11

Concrete Pour

October 19, 1989   8:00 a.m.   Special Investigations Lab

Materials

Cement - Northwestern Type I
Coarse Aggregate - Martin Marietta Ferguson
Fine Aggregate - Halletts Materials, Ames
Air Entraining Agent - Protex AES

Mix No.	Cement lbs.	Coarse Agg. lbs.	Fine Agg. lbs.	Air Entraining Agent Oz.
B-4	492	1558	1558	5.33
C-4	624	1499	1495	5.75

Test Results

Mix No.	W/C	Slump	Air
B-4	.60	2.0"	4.8%
C-4	.49	1.5"	4.9%

APPENDIX II

Iowa Department of Transportation
Materials Office
Cement and Concrete Laboratory
800 Lincoln Way
Ames, Iowa 50010
(515) 239-1649

Sponsored by
Strategic Highway
Research Program
(SHRP)

November 8, 1989

TO: Participating Laboratories

SUBJECT: P.C.C. Core Samples for Testing

The samples for precision and accuracy determination for P.C.C. core testing are being shipped to you the week of November 27th. Shipment will consist of two boxes each containing six p.c.c. cores. The samples are packaged in plastic bags to retain the moisture and are identified as No. 1 and No. 2. The core samples upon arrival should be cured in lime water as per ASTM C-192 until the test date of December 14, 1989.

If you do not receive the samples or if the samples you receive are seriously damaged, notify us immediately and the necessary replacement will be sent.

The tests should be conducted on December 14 if possible and the test results sent to me. After receiving the test results from each participating laboratory, the results will be sent to AMRL for analysis. The results of the AMRL analysis will be sent to each participating laboratory.

Instructions for testing and the necessary sheets for reporting the test results are enclosed. Please read these instructions carefully before proceeding with the tests.

Sincerely,

Kevin B. Jones
Cement & Concrete Engineer
Materials Office
Iowa Department of Transportation

Enclosures

IOWA DEPARTMENT OF TRANSPORTATION
P.C.C. Core Samples for Testing

A total of twelve P.C.C. Core samples will be sent to each participating laboratory. Six cores will be from each mix. Two concrete cores from each mix will be tested by each participating laboratory for (a) compressive strength, (b) splitting tensile strength and (c) static modulus of elasticity. It is recommended that one operator make the same test on both samples

APPLICABLE DOCUMENTS

AASHTO T22-88I	Compressive Strength of Cylindrical Concrete Specimens
AASHTO T24-86	Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
AASHTO T198-88I	Splitting Tensile Strength of Cylindrical Concrete Specimens
AASHTO T67-85	Load Verification of Testing Machine
AASHTO T231-87I	Capping Cylindrical Concrete Specimens
ASTM C469-87	Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression

INSTRUCTIONS

- COMPRESSIVE STRENGTH TESTING -

This test shall be conducted as per AASHTO T22-88I except for the following modifications:

- The diameter (D) of the test specimen shall be determined to the nearest 0.01 inch by averaging two diameters measured by a caliper at right angles to each other at about the mid-height of the specimen.

- Measure the length of specimen before capping (LO) and after capping (L) to the nearest 0.1 inch prior to testing. The length shall be determined by averaging four measurements equally spaced around the specimen. The length of the specimen when capped, shall be as nearly as practicable twice its diameter. Section 6.2 of AASHTO T24-86 for specimen end preparation shall be followed.

- Test specimens shall be sawed on both the top and bottom ends of the core to achieve the desired L/D ratio of approximately 2.00. (Use the length of the capped specimen to compute the L/D ratio).

- AASHTO T231-87I procedure for capping hardened concrete specimens shall be followed for capping both ends of specimen. Neither end of test specimens when tested shall depart from perpendicularity to the axis by more than 0.5^{o} (equivalent to 1/8 inch in 12 inches).

- Type of fracture should be reported (Refer to Fig. 2 of AASHTO T22-88I).

- SPLITTING TENSILE STRENGTH TESTING -

This test shall be carried out in accordance with AASHTO T198-88I except for the following modifications:

- Measure the diameter (D) and the length (L) of the test specimens to the nearest 0.01 inch following section 5.2 of AASHTO T198-88I.

- The test specimen shall be sawed or ground to achieve a uniform length, and the end surfaces shall conform to section 6.2 of AASHTO T24-86. The L/D ratio shall be nearly as possible to 2. Test specimens shall be trimmed as not to exceed 1-1/4 inch at the bottom of the specimen and up to 1 inch at the top of the specimen. (The finished ends are not to be capped).

- Type of fracture should be reported (Refer to Fig. 2 of AASHTO T22-88I).

- STATIC MODULUS OF ELASTICITY TESTING -

This test shall be performed in accordance with ASTM C469-87 except for the following modifications:

- The diameter (D) and the length (L) of the test specimen shall be determined in the same manner as described for compressive strength testing.

- L/D ratio of the specimen shall be determined in the same manner as described for compressive strength testing.

- Ends of the test specimen shall be capped as per AASHTO T231-87I.

- The test specimen shall be weighed prior to testing and the weight recorded to the nearest gram. The unit weight (CW) shall be calculated to the nearest 1 pcf by dividing the weight of the specimen by its volume using the dimensions determined above.

- Deformation should be measured by a linear variable differential transformer (LVDT).

- The value of S_2 for the modulus of elasticity testing shall correspond to 40% of the ultimate load determined in the compressive strength testing.

- Calculate the modulus of elasticity to the nearest 50,000 psi and poisson's ratio to the nearest 0.01.

- REPORTING -

The test results shall be reported on the attached forms and returned to the Iowa Department of Transportation as soon as possible.

P.C.C. CORE TESTING PROGRAM
REPORT FORM

TO: Mr. Kevin B. Jones
Cement & Concrete Engineer
Materials Office
Iowa Department of Transportation
800 Lincoln Way
Ames, Iowa 50010

FROM: ____________________

Compressive Strength of P.C.C. Cores

Test Date ________

Type of Capping System: ____________________

Sample	Diameter (D) (Inches)	Length Before Capping (LO) (Inches)	Length of Capped Specimen (L) (Inches)	L/D Ratio	Cross-Sectional Area (A) (Sq. In.)	Maximum Load (LBF)	Compressive Strength (CS) (PSI)	Type of Fracture (FR)	Comments
No. 1									
No. 2									

Average Compressive Strength: __________ PSI

Remarks: ____________________

Tests Performed by ____________________ Date __________

Tests Reported by ____________________ Title __________

//

P.C.C. CORE TESTING PROGRAM
REPORT FORM

TO: Mr. Kevin B. Jones
Cement & Concrete Engineer
Materials Office
Iowa Department of Transportation
800 Lincoln Way
Ames, Iowa 50010

FROM: ______________________

Splitting Tensile Strength of P.C.C. Cores

Test Date ____________

Sample	Diameter (D) (Inches)	Specimen Length (L) (Inches)	L/D Ratio	Maximum Load (LBF)	Splitting Tensile Strength (STS) (PSI)	Type of Fracture (FR)	Bearing Surface of Specimen Capped or Ground		Comments
							Yes	No	
No. 1									
No. 2									

Average Splitting Tensile Strength: ____________ PSI

Remarks: ______________________

Tests Performed by ______________________ Date ____________

Tests Reported by ______________________ Tile ____________

P.C.C. CORE TESTING PROGRAM
REPORT FORM

TO: Mr. Kevin B. Jones
Cement & Concrete Engineer
Materials Office
Iowa Department of Transportation
800 Lincoln Way
Ames, Iowa 50010

FROM: ______________________

Static Modulus of Elasticity of P.C.C. Cores

Test Date ____________

Type of Capping System: ______________________

Sample	Diameter (D) (Inches)	Specimen Length (L) (Inches)	L/D Ratio	Unit Wt. (CW) (PCF)	Modulus of Elasticity (EC) PSI	Poisson's Ratio (U)	Stress Strain Plots Made		Comments
							Yes	No	
No. 1									
No. 2									

Average Static Modulus of Elasticity: __________ PSI

Remarks: ______________________

Tests Performed by: ______________________ Date ____________

Tests Reported by: ______________________ Title ____________

RESULTS OF PCC CORE TESTING

MLR-89-11

FEBRUARY 1990

IOWA DEPARTMENT OF TRANSPORTATION
HIGHWAY DIVISION
OFFICE OF MATERIALS
AMES, IOWA 50010
(515) 239-1649

Summary of Results - General

In most cases, averages, standard deviations, and coefficients of variation are given with all results reported, and then with one or more outlying results omitted. In some cases two or more recalculations, with laboratories omitted, have been done for the same test; and in these cases, all of the laboratories omitted in previous recalculations are also omitted in subsequent ones. Results omitted are values which are more than three standard deviations from the mean of one or both samples. In most cases, elimination of these outlying results has little effect on the average, but may have a more pronounced effect on the standard deviation and coefficient of variation.

Scatter Diagrams

A set of scatter diagrams is supplied with the report.

The manner of preparing scatter diagrams, and their interpretation, is described in the Crandall and Blaine paper, published in the 1959 ASTM Proceedings. Each of the laboratories will receive a complete set of diagrams. In those instances where the laboratory was unable to report results, diagrams will still be furnished.

A scatter diagram is plotted for each test method by taking the results received from each laboratory and plotting the value for the odd numbered samples on the X, or horizontal axis, against the value for the even numbered samples on the Y, or vertical axis. To locate your point, just plot as you would when plotting any scatter diagram. The vertical and horizontal lines of dashes, which divide the diagrams into samples respectively. The first line of print under the diagram includes the test number, as given on the data sheet, the test title, and the number of data points on the diagrams. The number of plotted points may not agree with the total number of data pairs included in the analysis because a few points may be off the diagram, and some points may represent several data pairs, which are identical. Laboratories whose points are off the diagram will have a rating of $\pm$ 1 for that particular test.

As described in Crandall and Blaine, a tight circular pattern of points around the intersection of the median lines is the ideal situation. A stretching out of the pattern into the first (upper right) and third (lower left) quadrants indicates some kind of bias or tendency for laboratories to get high or low results on both samples. Examination of the scatter diagrams indicates strong evidence of bias on almost all tests.

Each laboratory receives an individualized Table of Results. The Table of Results shows the test number, test title and the reporting unit in the first three columns. Thereafter, it lists in order, the laboratory's results for the odd and even numbered samples, overall averages for the odd and even numbered samples and the laboratory's ratings for the odd and even samples. (See reverse for an explanation of the scatter diagrams.)

The laboratory ratings, shown in the Table of Results for the individual laboratory, were determined in the manner described by Crandall and Blaine, using a rating scale of 1 to 5 instead of 0 to 4. The ratings have no valid standing beyond indicating the difference between the individual laboratory result and the average for a particular test.

The table which follows, details the relationship between the ratings and the averages.

Ratings	Range (Number of Standard Deviations)	Number (Per 1000 of Laboratories) that might have greater variation
5	Less than 1	317
4	1 to 1.5	134
3	1.5 to 2	45
2	2 to 2.5	12
1	Greater than 2.5	--

The sign of the rating merely indicates whether the result reported was greated or less than the average obtained.

In cases where some of the laboratories' results are eliminated, averages, standard deviations, coefficients of variation, and the ratings of the other laboratories' results, are recalculated, using the data remaining after the elimination.

P.C.C. CORE SAMPLES NO. 1 AND NO. 2

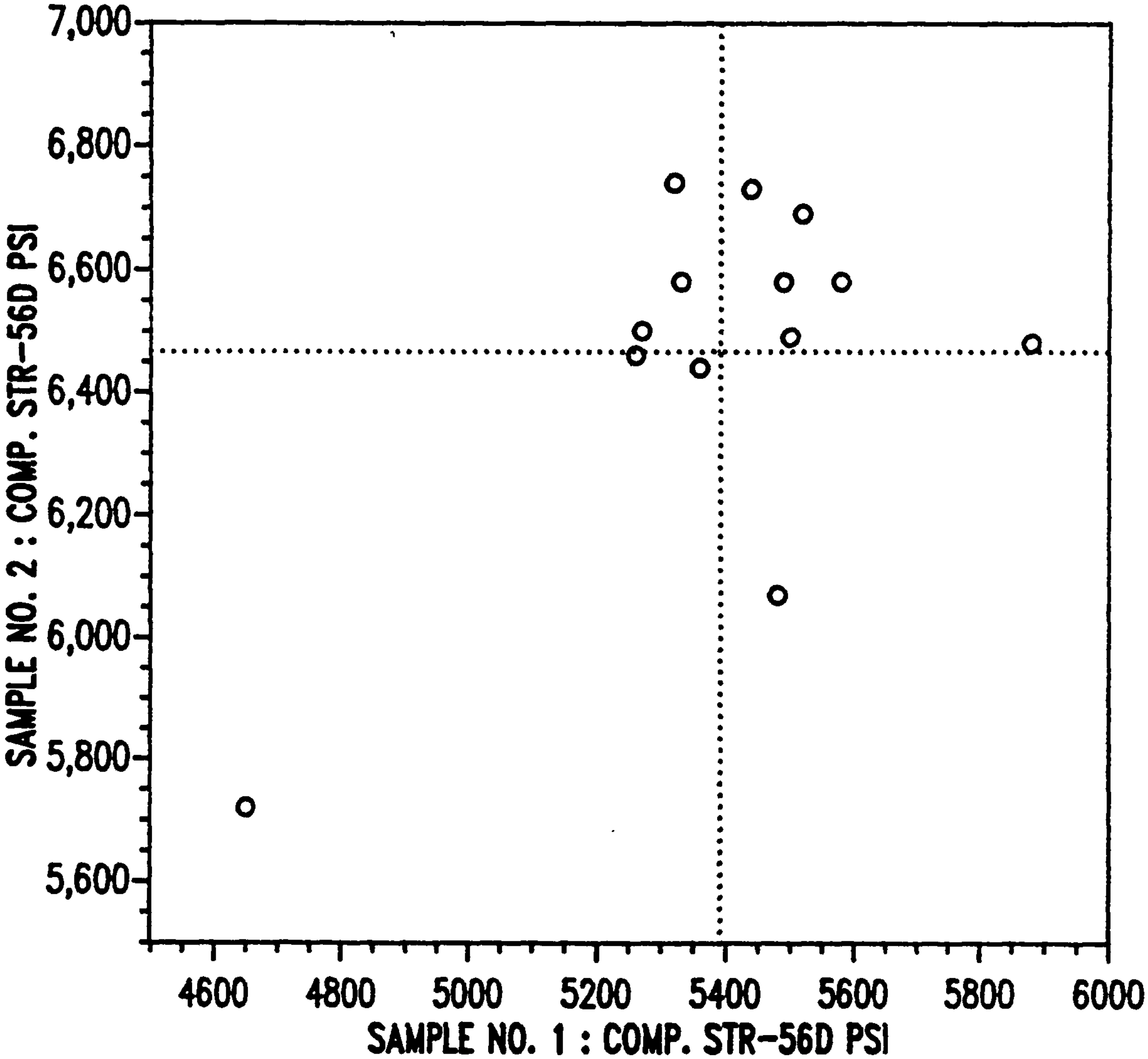
SUMMARY OF RESULTS

			SAMPLE NO. 1			SAMPLE NO. 2		
TEST	UNIT	#LABS	AVERAGE	S.D.	C.V.	AVERAGE	S.D.	C.V.
COMPRESSIVE STRENGTH	PSI	13	5390.8	265.2	4.92	6466.2	270.3	4.18
SPLITTING TENSILE STRENGTH	PSI	12	521.2	63.3	12.15	589.5	91.7	15.55
MODULUS OF ELASTICITY	KSI	10	4145	459	11.08	4400	402	9.15
POISSON'S RATIO		7	0.207	0.039	18.74	0.206	0.046	22.33

RESULTS FOR
P.C.C. CORE SAMPLES NO. 1 AND NO. 2

TEST	UNIT	LAB DATA		AVERAGES		RATINGS	
		1	2	1	2	1	2
COMPRESSIVE STRENGTH	PSI			5391	6466		
SPLITTING TENSILE STRENGTH	PSI			521	590		
MODULUS OF ELASTICITY	KSI			4145	4400		
POISSON'S RATIO				0.21	0.21		

COMPRESSIVE STRENGTH RESULTS
CONCRETE SAMPLE NOS. 1 & 2

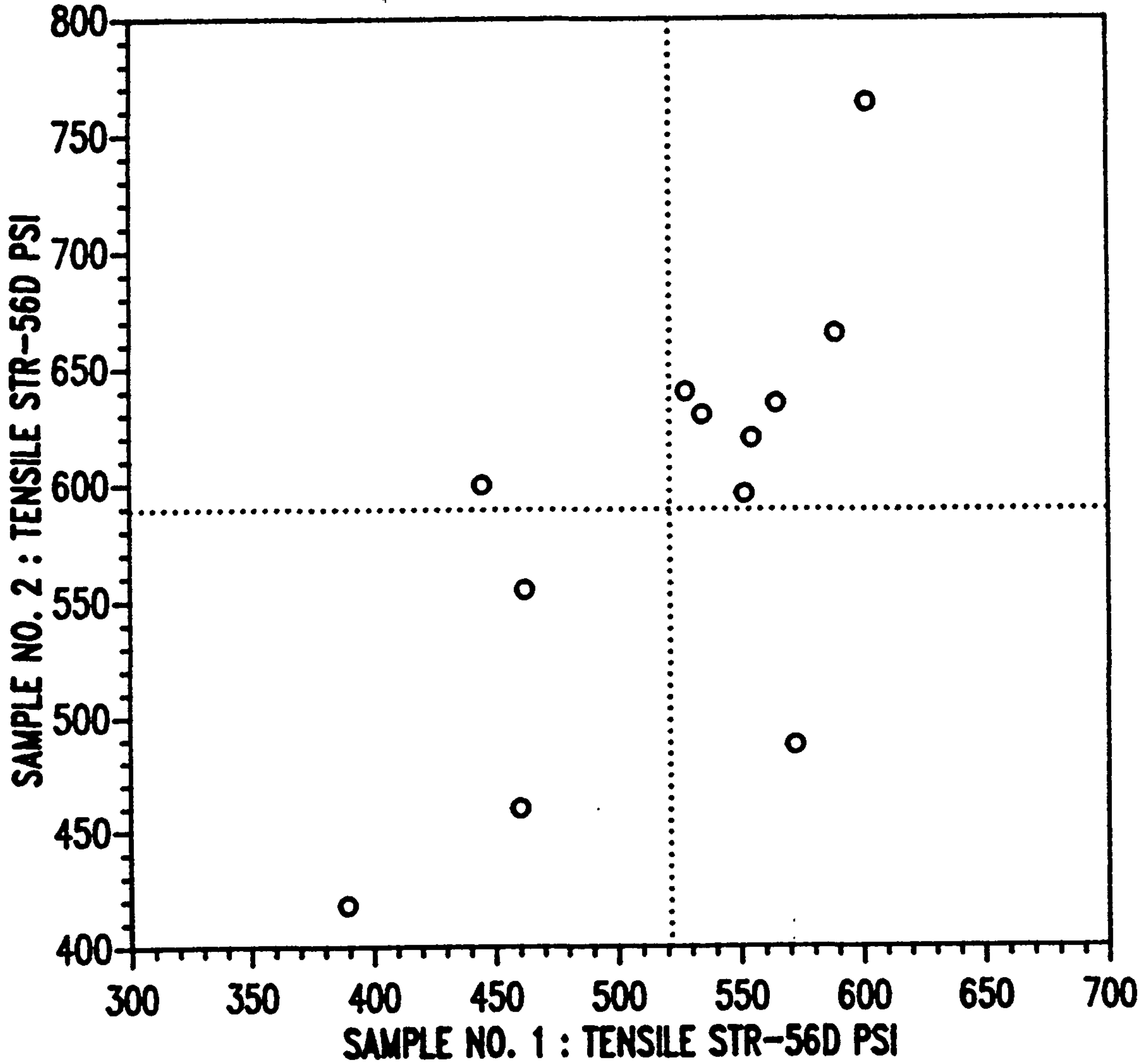


TEST NO. 1 COMP STR-56D 13 POINTS

SAMPLE NO. 1 AVG 5390.8 S.D. 265.2 C.V. 4.92

SAMPLE NO. 2 AVG 6466.2 S.D. 270.3 C.V. 4.18

SPLITTING TENSILE STRENGTH RESULTS
CONCRETE SAMPLE NOS. 1 & 2

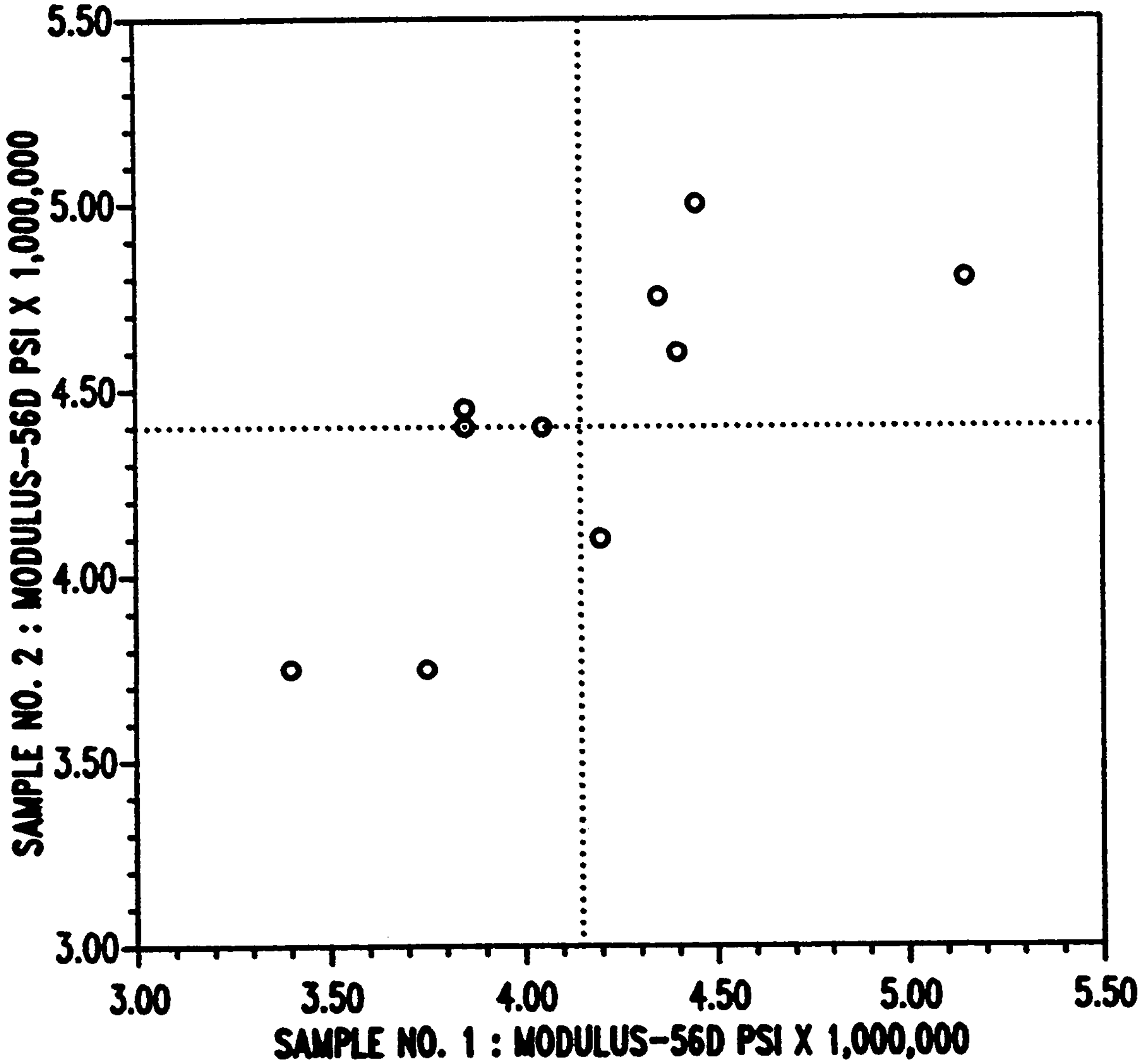


TEST NO. 2 TENSILE STR-56D 12 POINTS

SAMPLE NO. 1 AVG 521.2 S.D. 63.3 C.V. 12.15

SAMPLE NO. 2 AVG 589.5 S.D. 91.7 C.V. 15.55

STATIC MODULUS RESULTS
CONCRETE SAMPLE NOS. 1 & 2

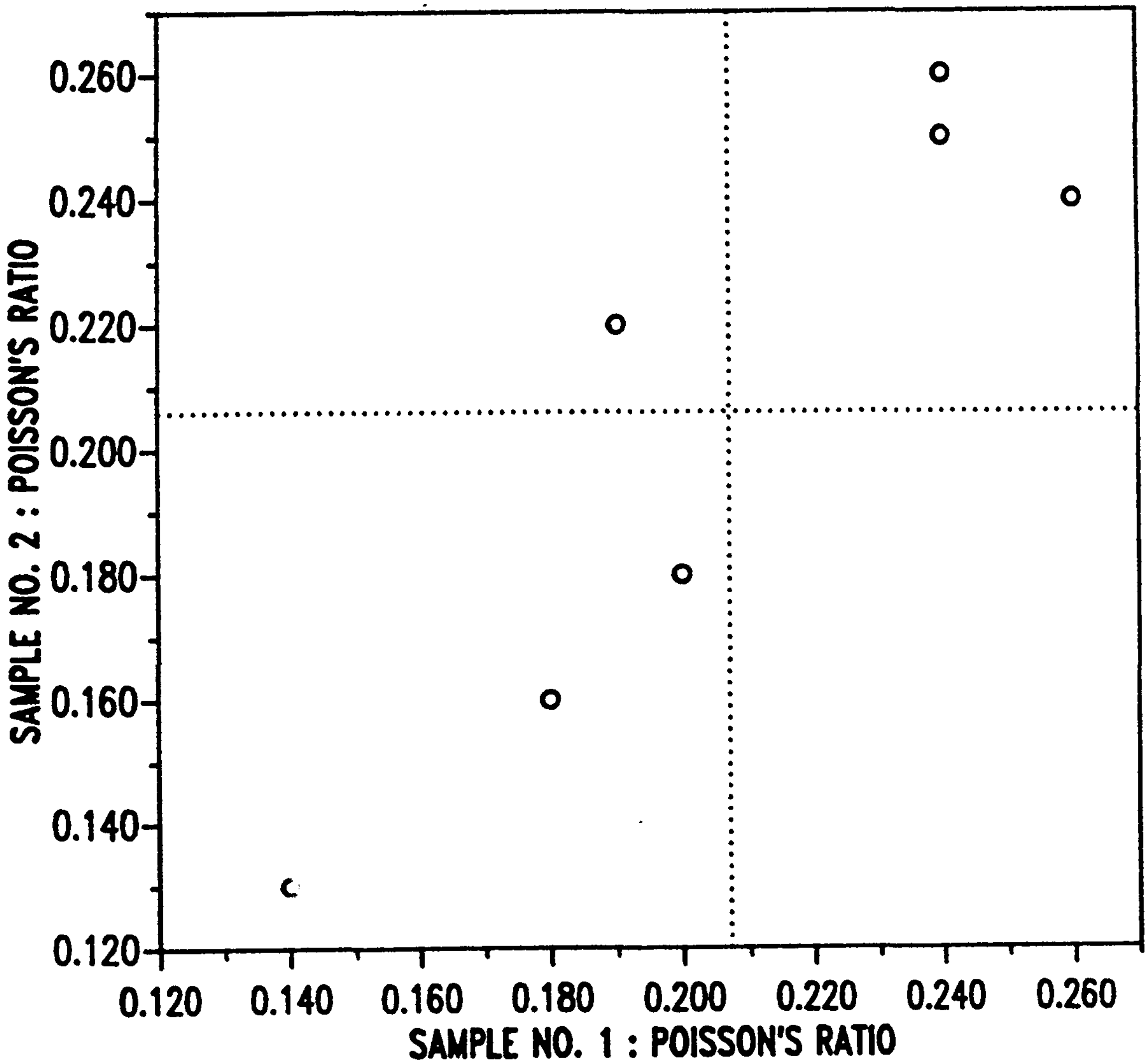


TEST NO. 3 STATIC MOD-56D 10 POINTS

SAMPLE NO. 1 AVG 4.145 S.D. 0.459 C.V. 11.08

SAMPLE NO. 2 AVG 4.400 S.D. 0.402 C.V. 9.15

POISSON'S RATIO RESULTS
CONCRETE SAMPLE NOS. 1 & 2



TEST NO. 4 POISSON'S RATIO–56D 7 POINTS

SAMPLE NO. 1 AVG 0.207 S.D. 0.039 C.V. 18.74

SAMPLE NO. 2 AVG 0.206 S.D. 0.046 C.V. 22.33

APPENDIX IV

Steele Engineering, Inc.

February 27, 1990

Robin High
TRDF
2602 Dellana Lane
Austin, TX 78746

Dear Robin:

Subject: SHRP Portland Cement Concrete Core Proficiency Sample Program.

Enclosed is a floppy disk with the raw data gathered from the subject program. Three pairs of cores for each of two mixes were distributed to participating laboratories. One pair from each mix was to be tested in compression, one in split tension, and one pair in static modulus including poisson's ratio.

Replicate sets of values for each of the four properties for each mix were obtained. However, all values were not determined by all laboratories. Therefore, the degrees of freedom available differs for each of the properties to be evaluated.

Please review the data and I will be in contact with you concerning the analyses you feel would be most appropriate. I am sure that Virgil could provide some valuable guidance also.

Yours very truly

Garland W. Steele, P.E.
President, Steele Engineering, Inc.

enclosure: floppy disk

Box 173 • Tornado, West Virginia 25202 • Tele. (304) 727-8719

APPENDIX V

Steele Engineering, Inc.

October 5, 1990

Robin High
TRDF
2602 Dellana Lane
Austin, TX 78746

Dear Robin:

Subject: SHRP Portland Cement Concrete Core Proficiency Sample Program.

The report, dated 5/21/90, on components of variance analysis of data gathered in the subject program has been carefully reviewed. As suggested on page 4, the two possible outlier values in compressive strength data have been investigated.

Both the laboratories involved in the performance of the tests and the laboratory responsible for preparation of the samples were queried concerning possible assignable causes that may have affected the two values. The final conclusions are based on the recollections and comments of the participating parties. Each felt that the values were the result of an assignable cause, however there was not agreement (and there was no objective information) that would lead to the positive identification of same. The first possible outlier (page 2, figure 2) in the compressive strength data was likely the result of mis-identification of a specimen or cross-identification of two specimens. The second possible outlier in the compressive strength data was likely the result of an error in recording the dial reading or mis-identification of specimens.

Based upon the above, it is recommended that the data be retained and placed in the SHRP data bank. However, the two values in question should be identified in the data bank as probable outliers, and the components of variance analysis placed in the data bank and used by SHRP should exclude these two values.

The suggestions on page 10 of the report concerning tensile strength values were of greater concern, since it was felt that their implementation would be quite time consuming and relatively costly. Careful review of the presentation of data in the report then revealed that replicate columns 2 and 3 under tensile strength in figure 2 on page 2 have been transposed. Investigation of the original worksheets verifies that column 2 data should be moved to column 3 and column 3 data should be moved to column 2. This will substantially change the end results. It should be noted that lab 1 will likely still present a problem (ie reporting mix 1 strength greater than mix 2 strength). However, the possible cross-identification of specimens noted previously would involve one or more of these cores.

Box 173 • Tornado, West Virginia 25202 • Tele. (304) 727-8719

The aforementioned review also revealed that the same transposition of values has ocurred for the modulus of elasticity and Poisson's ratio in figure 2 on page 2. Columns 2 and 3 should be interchanged in each case.

It is probable that these transpositions resulted from a computer glitch when the data was transferred from one system to another.

Please call after completion of the analysis for tensile strength, modulus, and Poisson's ration at which time we can determine the appropriate course of action based upon the results obtained therefrom.

Let me know if you have any questions concerning the above items.

Yours very truly

Garland W. Steele, P.E.
President, Steele Engineering, Inc.

cc: Adrian Pelzner

TRDF

SHRP • LONG TERM PAVEMENT PERFORMANCE PROGRAM

TECH MEMO:	AU-127	DATE:	December 21, 1990
AUTHORS:	Robin High RH	FILE:	P-001
DISTRIBUTION:	Garland Steele, Bill Hadley		
SUBJECT:	Variance Component Analysis of SHRP Portland Cement Concrete Core Proficiency Sample Program		

A proficiency test program was undertaken in SHRP-LTPP to establish the variance components assciated with testing various properties of Portland cement concrete cores. The test program involved the determination of four engineering material properties (compressive strength, tensile strength, modulus of elasticity, and Poisson's ratio) for two mixes (medium and high strength) at thirteen different laboratories. The tensile strength was determined by the indirect tension test, while compressive strength, modulus of elasticity, and Poisson's ratio were estimated from an unconfined compression test. The scope of the proficiency test program as well as the data from the material tests are presented in Figure 1.

The analysis phase of the Portland cement concrete core sample proficiency program first performs an analysis of the variance (ANOVA) observed in the four materials. It will then assess the magnitudes of the between and within laboratory testing variations (σ^2_{LAB} and σ^2 respectively) for each property.

Two replicate sets of concrete cores were provided to each of the laboratories for the two mixes and four material tests. Several laboratories did not have the capability to conduct the test procedures required to estimate modulus of elasticity and Poisson's ratio; therefore, some of the cells in the design were not filled (see Figure 1). Since the data summarizing the various material properties will not be compared with one another, this is not a major limitation. However, fewer degrees of freedom are available to estimate the sources of variability for the modulus of elasticity and Poisson's ratio than for the compressive and tensile strengths.

2602 Dellana Lane Austin, Texas • Telephone 512 / 327-4211 • Fax 512 / 328-7246

TEST	COMPRESSIVE STRENGTH				TENSILE STRENGTH				MODULUS				POISSON'S RATIO			
MIX																
REPLICATE	1		2		1		2		1		2		1		2	
LAB	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	4920	4380	6350	5090*	594	550	474	501								
2	5540	5330	6600	6860	480	575	635	645	3.7	3.8	3.75	3.75				
3	5150	5580	6280	6595	584	593	708	622								
4	5300	5240	6470	6520	462		543	566								
5	5500	5480	6650	6500	460	430	605	595	4.4	4.3	4.75		0.23	0.24	0.26	
6	5470	5680	6740	6430	475	450	455	470	4.3	4.6	5.0	5.0	0.26	0.21	0.25	0.25
7	5330	5190	6400	6520					3.4	3.47	3.74	3.74				
8	5110	5550	6660	6500	555	555	615	630								
9	6335*	5423	6640	6325	538	567	575	618	4.23	4.14	4.2	4.1	0.21	0.19	0.17	0.18
10	5750	5290	6790	6590	398	380	419	417	4.1	4.0	4.5	4.25	0.2	0.18	0.23	0.22
11	5410	5240	7040	6450	545	525	605	655	4.0	3.7	4.5	4.45				
12	5210	5790	6530	6450	560	570	610	660	3.8	3.9	4.5	4.3	0.18	0.17	0.14	0.17
13	5540	5430	6050	6090	560	644	789	740	5.25	5.1	4.9	4.75	0.25	0.27	0.24	0.25

Figure 1. Concrete core proficiency sample test data.

ESTIMATION OF VARIANCE COMPONENTS

The experimental design under which the data were collected has a direct impact on how the statistical analysis should properly proceed. The statistical concepts behind the analysis approach used in this memorandum are explained briefly in Appendix A and summarize the procedure which determined the results presented in the following sections. An analysis of variance table along with expected mean squares are provided for each material property. From these summary statistics the variance components for between (σ^2_{LAB}) and within laboratories (σ^2) can be estimated. Details about their computation are explained in Appendix A. Analyses to check the similarity of variances across laboratories were performed for each material property with the results reported in Appendix B.

Compressive Strength

Four compressive strength tests were obtained from all thirteen laboratories. The factorial shown in Figure 1 is completely balanced. A preliminary review of the data revealed two possible outliers in the data. These values have been designated with an * in Figure 1 and occur in laboratories 1 and 9. The possible causes behind these potential outliers remain unknown; these two compressive strength values appear to deviate substantially when compared with the other compressive strengths of the same mix from different laboratories.

The following alternatives are likely to be possible causes of the two outliers. First, they may be an extreme manifestation of the random variability inherent in the test procedure which occurs when tests are performed using different operators in different laboratories. If this were true, these values should be retained and processed in the same manner as the other observations within the test program. Removing these data without justification would result in lower estimates of the process variability than should be reported.

On the other hand, the outlying values could be the result of deviations from the prescribed experimental procedures or may represent an error in calculating or recording numerical values. It is essential to investigate the actual reasons for these outlying values and to correct any error(s) that are found. Only in this manner should the observations be confidently identified as erroneous data and eliminated. Contact with the responsible testing laboratory is necessary to establish an appropriate action.

The analysis of variance table for all 52 compressive strength values are presented in Table 1. As explained in Appendix A, a commonly used method for calculating the respective variance components for laboratory and error consists of equating the mean square from each source of variation to its expected mean square and solving for σ^2_{LAB} and σ^2. These numbers are reported as the variance component estimates in Table 1.

The lower portion of Table 1 indicates the effect of the difference between the two levels of the factor MIX is significant at the $\alpha = 0.01$ level. This result implies the difference between average compressive strength values, which are expected to vary from the medium and high strength levels, have been verified. The interaction between LAB and MIX was not found to be significant and therefore has been combined with the estimate for ERROR. The estimated standard deviation within laboratories for all compressive strength data is $\sigma = (79630)^{1/2} = 281$ psi which is considered to be an excellent measure of repeatability for compressive strength.

The estimated within laboratory variation, σ^2, is larger than the between laboratory variation, $\sigma^2_{LAB} = 42748.9$. A small value of σ^2_{LAB} is desirable since it implies similar average test values are found at each of the 13 laboratories. From Table 1 the F-ratio for testing the significance of variation between labs is F=3.15. Although this value is not extremely large, it does indicate some variation between laboratories exists. Table 7 indicates the difference in average values across laboratories. The difference will be shown to be due to the possible outlier from laboratory 1.

Since there has been no determination at this time concerning the final status of the potential outliers, two additional analyses of variance were investigated. The first considers the results when omitting the presumed

Table 1. Analysis of variance for compressive strength, all data.

SOURCE	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	EXPECTED MEAN SQUARE
LAB	12	3007508.81	250625.73	$\sigma^2 + 4\ \sigma^2_{LAB}$
MIX	1	15025275.08	15025275.08	$\sigma^2 + \phi(MIX)$
ERROR	38	3025940.42	79630.01	σ^2

Variance Component	Estimate
σ^2_{LAB}	42748.9
σ^2	79630.0

SOURCE	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	F-RATIO
MODEL	13	18032783.88	1387137.22	17.42 *
LAB	12	3007508.81	250625.73	3.15 *
MIX	1	15025275.08	15025275.08	188.69 *
ERROR	38	3025940.42	79630.01	
CORRECTED TOTAL	51	21058724.31		

* Significant at the 0.01 level.

outlier from laboratory 1, while the second analysis summarizes the results when omitting the presumed outliers from laboratories 1 and 9.

The analysis of variance table derived from omitting the value 5090 of MIX 2 from the laboratory 1 results is presented in Table 2. The estimate of the within laboratory variance has been reduced to $\sigma^2 = 66984.55$. This result gives an estimated testing standard deviation of $\sigma = 258.8$ psi. The estimate of the between laboratory variance has been reduced to $\sigma^2_{LAB} = 16616.8$. The impact of this one omitted data value has made a large reduction in both estimates of the two components of variance.

The analysis of variance table derived when omitting the values of 5090 from MIX 2 (laboratory 1) and 6335 from Mix 1 (laboratory 9) is presented in Table 3. The estimates of the variance component and significance level for between laboratories, σ^2_{LAB}, remain nearly the same as the results for the previous case. The within laboratory variance, $\sigma^2 = 49754.7$, has been further reduced and now lies below what may be considered normal testing variation since the estimated standard deviation of $\sigma = (49754.7)^{1/2} = 223$ psi is less than the expected number for concrete core tests.

Based on the results from Tables 2 and 3 it is likely the value from laboratory 1 is an outlier whereas the value from laboratory 9 is less certain. These status of the outlying data values needs to be further established before accepting the analysis of variance results in either Table 2 or Table 3.

Tensile Strength

The analysis of variance and variance component estimates for the tensile strength from twelve laboratories are presented in Table 4. The significance of the factor MIX on tensile strength is indicated in Table 4 by the large F-ratio ($F=26.08$). These variance components were estimated after removing the effect of the difference in tensile strength due to the factor MIX.

The between laboratory variation, $\sigma^2_{LAB} = 5167.96$, indicates the variation in the test results across laboratories is greater than the variation within

Table 2. Analysis of variance for compressive strength with one possible outlier removed.

SOURCE	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	EXPECTED MEAN SQUARE
LAB	12	1585469.40	132122.45	$\sigma^2 + 3.92\ \sigma^2_{LAB}$
MIX	1	15560753.72	15560753.72	$\sigma^2 + \phi(MIX)$
ERROR	37	2478428.45	66984.55	σ^2

Variance Component	Estimate
σ^2_{LAB}	16616.8
σ^2	66984.55

SOURCE	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	F-RATIO
MODEL	13	17863230.37	1374094.64	20.51 *
LAB	12	1585469.40	132122.45	1.97
MIX	1	15560753.72	15560753.72	232.30 *
ERROR	37	2478428.45	66984.55	
CORRECTED TOTAL	50	20341658.82		

* Significant at the 0.01 level.

Table 3. Analysis of variance for compressive strength with two possible outliers removed.

SOURCE	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	EXPECTED MEAN SQUARE
LAB	12	1346096.76	112174.73	$\sigma^2 + 3.84\ \sigma^2_{LAB}$
MIX	1	16216287.41	16216287.41	$\sigma^2 +$ Q(MIX)
ERROR	36	1791170.68	49754.74	σ^2

Variance Component	Estimate
σ^2_{LAB}	16255.2
σ^2	49754.7

SOURCE	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	F-RATIO
MODEL	13	18395392.94	1415030.23	28.44 *
LAB	12	1346096.76	112174.73	2.25
MIX	1	16216287.41	16216287.41	325.92 *
ERROR	36	1791170.68	49754.74	
CORRECTED TOTAL	49	20186563.62		

* Significant at the 0.01 level.

laboratories (σ^2 = 2046.59) by a factor of 2 1/2. From this data the testing standard deviation is estimated to be σ = 45.24. This feature is also indicated by the significant F-ratio for LAB (F=10.88) in Table 4. Therefore, the average test scores when compared across laboratories will be different for subsets of the laboratories grouped together. Table 7 summarizes the differences in average test results for tensile strength.

Modulus of Elasticity and Poisson's Ratio

The values reported for modulus of elasticity and Poisson's ratio given in Figure 1 were reported to only one or two significant digits and lie in a relatively narrow range when compared across all laboratories and mixes. In this analysis the data assume only a small number of values. Since analysis of variance techniques work most efficiently with response data on a continuous scale, roundoff errors and a very small range of data may not give very accurate estimates of these variance estimates.

Results found from the analysis of variance are reported in Table 5 for modulus of elasticity. The F-ratio for MIX indicates that a significant difference was found for the factor modulus of elasticity (F=13.82). Including this factor in the model removes the effect of the two types of mixes before the variation due to laboratories or testing are estimated. The between laboratory variance component (σ^2_{LAB} = 0.19077) is nearly five times larger than the within laboratory variance component (σ^2 = 0.04176). This result indicates a lack of uniformity of measurements across laboratories. This difference is also indicated in Table 5 by the large F-ratio for LAB (F=18.74). The differences in average test results across laboratories for modulus are summarized in Table 7.

Results are give from the analyses of variance reported in Table 6 for Poisson's ratio. The small F-ratio for MIX indicates that no significant difference was found for this factor on Poisson's ratio (F=0.02). The between laboratory variance component (σ^2_{LAB} = 0.0011805) is more than three times larger than the within laboratory variance component (σ^2 = 0.0003537). This result indicates a lack of uniformity of measurement across laboratories and is also indicated in the analysis of variance table for the factor LAB (F =

Table 4. Analysis of variance for tensile strength.

SOURCE	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	EXPECTED MEAN SQUARE
LAB	11	244959.23	22269.02	$\sigma^2 + 3.913\ \sigma^2_{LAB}$
MIX	1	50778.59	50778.59	$\sigma^2 + \phi(MIX)$
ERROR	34	69583.93	2046.59	σ^2

Variance Component	Estimate
σ^2_{LAB}	5167.96
σ^2	2046.59

SOURCE	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	F-RATIO
MODEL	12	295737.82	24644.82	12.04 *
LAB	11	244959.23	22269.02	10.88 *
MIX	1	53381.49	53381.49	26.08
ERROR	34	69583.93	2046.59	
CORRECTED TOTAL	46	365321.74		

* Significant at the 0.01 level.

Table 5. Analysis of variance for modulus.

SOURCE	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	EXPECTED MEAN SQUARE
LAB	8	6.2591	0.78239	$\sigma^2 + 3.8824\ \sigma^2_{LAB}$
MIX	1	0.5114	0.51144	$\sigma^2 + \phi(MIX)$
ERROR	25	1.0439	0.04176	σ^2

Variance Component	Estimate
σ^2_{LAB}	0.19077
σ^2	0.04176

SOURCE	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	F-RATIO
MODEL	9	6.7705	0.7523	18.02 *
LAB	8	6.2591	0.7824	18.74 *
MIX	1	0.5772	0.5772	13.82 *
ERROR	25	1.0439	0.04176	
CORRECTED TOTAL	34	7.8145		

* Significant at the 0.01 level.

Table 6. Analysis of variance for Poisson's ratio.

SOURCE	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	EXPECTED MEAN SQUARE
LAB	5	0.024306	0.004861	$\sigma^2 + 3.8182\ \sigma^2_{LAB}$
MIX	1	0.00000952	0.00000952	$\sigma^2 + \phi(MIX)$
ERROR	16	0.005659	0.0003537	σ^2

Variance Component	Estimate
σ^2_{LAB}	0.0011805
σ^2	0.0003537

SOURCE	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARE	F-RATIO
MODEL	6	0.024315	0.0040525	11.46 *
LAB	5	0.243056	0.048611	13.74 *
MIX	1	0.00000784	0.00000784	0.02
ERROR	16	0.005659	0.0003537	
CORRECTED TOTAL	22	0.029974		

* Significant at the 0.01 level.

Table 7. Analysis of laboratory means.

Compressive Strength

LAB:	9	10	2	6	11	5	12	8	3	4	7	13	1
MEAN:	6181	6105	6082	6080	6035	6032	5995	5955	5901	5882	5860	5778	5185
GROUP:	—	—	—	—	—	—	—	—	—	—	—	—	
													—

Tensile Strength

LAB:	13	3	12	8	2	11	9	1	4	5	6	10
MEAN:	683	627	600	589	584	582	574	530	524	522	462	404
GROUP:	—	—										
		—	—	—	—	—	—	—	—	—		
								—	—	—	—	
											—	—

Modulus

LAB:	13	6	5	10	9	11	12	2	7
MEAN:	5.00	4.72	4.48	4.21	4.17	4.16	4.12	3.75	3.59
GROUP:	—	—							
		—	—						
			—	—	—	—	—		
								—	—

Poisson's Ratio

LAB:	13	5	6	10	9	12
MEAN:	0.2525	0.2433	0.2425	0.2075	0.1875	0.1650
GROUP:	—	—	—			
				—	—	
					—	—

ratio equals 13.74). Differences in average test results across laboratories for Poisson's ratio are summarized in Table 7.

ILLUSTRATING DIFFERENCES AMONG MEANS: MULTIPLE COMPARISONS

If two sample means and their standard deviations are computed from the test results from two laboratories, then inferences about whether the true population means of each laboratory are equal to one another is tested with the two-sample t-test or by constructing a confidence interval. If data are available from more than two laboratories, a confidence interval for each laboratory can just as easily be constructed, each giving the probability of including its corresponding true population mean. What then is the probability that all intervals will simultaneously contain their respective true means? If each test has the significance level α, then the probability all tests have significance α is less than all of them having significance level α alone. The goal of multiple comparisons is to control this probability. The procedure reaches the conclusion that either the means are the same versus the alternative that they are the different. Probability statements needs to be stronger than for a single comparison of two means and therefore require special types of tests.

Table 7 is to be used to make interpretations concerning which laboratories are producing statistically different results. The average test results from each laboratory are presented in a row and ranked from largest to smallest. Groups of laboratory means are underlined to indicate which ones are not statistically different from one another. The averages to be most concerned with are those which lie on either end of the row. If one continuous line does not appear underneath these averages, there is evidence to suggest the true means from that laboratory exceed the two or three standard deviation control limits and do not conform to the rest of the data.

When interpreting these confidence intervals, means which are underlined do not imply the population means are necessarily equal to one another equal; rather it indicates that an insufficient sample size was used to detect a difference. Nontransitive results occur also. For example, if the row contains seven values, the three largest means and the three smallest means may be significantly different from one another, yet the four means in the middle may not be significantly different from each other even though some of these means belong to both groups which are different.

SUMMARY

Test results for compressive strength were found to be nearly the same across all laboratories and that the within laboratory variation was nearly equal to the value expected. Large variations in test results across laboratories were found for tensile strength, the modulus of elasticity, and Poisson's ratio. One possible cause for these results are differences in laboratory procedures when using specialized tests to estimate these material properties. A query of the cooperating laboratories to further evaluate the extent of the differences in estimating these material properties should be a direct consequence from the analysis of variance presented here.

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APPENDIX A

EXPERIMENTAL DESIGN

The design of the experiment includes two classification variables which were controlled and are assumed to account for variations in the test results. The layout of the factors and their levels is shown in Figure 1. The two primary variables, laboratories (LAB) and mixes (MIX), represent the inference space relative to this study and serve as the independent variables in the statistical analysis. Inconclusive results from this experiment are likely to occur if other variables, which were not measured or controlled, influenced the results.

FACTOR CLASSIFICATIONS

The experimental design used to relate these factors requires explanation since the data collection plan implies what inferences can be made and requires the application of specific analysis methods. Each primary variable is classified as either fixed or random. The decision to designate an effect in one of these two ways is based on the inferential objectives of the study and also by the definition of the factor.

A variable is defined to be fixed if all levels of interest are included in the test plan. In this analysis only two levels of MIX were defined. They were chosen as either medium or high strength which implies two specific levels. The factor MIX is designated to be fixed and an effect summarizing the average difference between the two levels can be computed.

A factor is designated as random whenever only a few elements from the entire population of interest are included in the design, and the ones included are chosen at random. The laboratories chosen for this design are considered to be a random sample of all possible laboratories. They are designated as having random effects and the variance component σ^2_{LAB} will be computed.

Factors whose levels appear with every level of the remaining factors are defined as crossed with one another. For this reason, in the proposed design the levels of MIX and LAB are all crossed with one another since it is possible to find any combination of the levels of these two factors.

The type of replication used in this test plan determines how the error term for the within laboratory is estimated. Two measurements were made within each laboratory for each mix. The method used in the analysis of variance provides an estimate of the pure error, σ^2, which summarizes the ability of the tests to repeat themselves for the same laboratory and mix.

VARIANCE COMPONENTS

The objective of variance component analysis is to deduce values of variances which cannot be measured directly. The total variation is to be separated into parts assignable to different sources (between and within laboratories). The model of interest is the two-factor model with mixed effects (one random and one fixed). The form of the model is:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \epsilon_{ijk}$$

where μ = mean
α_i = effect of the i^{th} laboratory (random)
β_j = effect of the j^{th} mix (fixed)
ϵ_{ijk} = residual (random)

One of the most commonly used methods for calculating the respective variance components for between and within laboratory consists of equating the mean square from each source of variation to its expected mean square and then solving for σ^2_{LAB} and σ^2. These two numbers are reported in the set of variance component estimates provided in Tables 1 through 5.

Let $T_{i..} = \Sigma\Sigma\, Y_{ijk}$, the sum of all measurements made in the i^{th} laboratory ($i=1,\ldots,13$) and T be their average. Then it can be shown that for balanced data the expected of the mean squares for laboratories and for the residual components have the following values:

$$E\ [MS_{LABS}] = E\ [\ \Sigma\ (T_{i..} - T)^2\ ] \quad = \sigma^2 + bn\ \sigma^2_{LAB}$$

$$E\ [MS_{RESD}] = E\ [\ \Sigma\Sigma\Sigma\ (Y_{ijk} - Y)^2\ ] = \sigma^2$$

To calculate the variance components σ^2 and σ^2_{LAB}, compute the analysis of variance as given in Tables 1 through 6, set these two expressions equal to their expected mean squares, and solve the two equations simultaneously.

For unbalanced data the factor bn in the first of the two equations is slightly different. This situation occurred in the analyses summarized in Tables 2 through 6. The variance components will loose some of their optimal properties; however, if the number of missing data points is small they will still be reasonable good estimates of the true values.

APPENDIX B

An important part of a thorough analysis of this data is to investigate the similarity of measurement variances (homogeneity) within laboratories. The investigation initially assumes the hypothesis that all measurement variations within different laboratories are the same. The objective is to determine if there is sufficient evidence to reject this hypothesis based on the observed data.

Estimated variances within each of the laboratories were calculated using the following formula for all four material tests:

$$\sigma_{ij}^2 = \Sigma\ (Y_{ijk} - Y_{ij})^2 \ /\ (N_{ij} - 1)$$

$$= [\ \Sigma\ Y_{ijk}^2 - N_{ij}Y_{ij}^2\ ]\ /\ (N_{ij} - 1)$$

where Y_{ijk} = the k^{th} observation from the i^{th} laboratory and the j^{th} mix

N_{ij} = the number of test results from the i^{th} laboratory and the j^{th} mix

The data used for these calculations are given in Figure 1. The subscript i refers to the i^{th} laboratory ($i = 1,\ldots, 13$) and the subscript j refers to either MIX 1 ($j = 1$) or MIX 2 ($j = 2$).

The estimated variances within each laboratory and mix are listed in Tables B-1 through B-4 from which are observed wide ranges of values. Since these computations are based on one degree of freedom (i.e., $(N_{ij} - 1) = 1$), these values should not be considered accurate estimates. For example, in Table B-1 the variances of compressive strength from MIX 1 range from a low of 200 in laboratory 5 to a high of 415,872 in laboratory 9. An even wider range for MIX 2 of 800 to 793,800 is observed. This large variance from MIX 2 is the consequence of a possible outlier. The second largest variance 174,050 in MIX 2 is considerable larger than the remaining variances. Based on the visual observations of these numbers alone some major differences in within laboratory variation most likely exist.

Although not nearly as severe, wide ranges in variances also exist in the determination of the other three material properties as well. Whenever only one observation was available from any cell for any of these three properties (N_{ij} = 1) it was not possible to calculate an estimated variance. This deficiency is indicated in Tables B-2, B-3, and B-4 by a blank.

Most statistical tests for the homogeneity of variances require at least three observations, do not have sufficient power when working with small sample sizes, or do not work well with nonnormal data. In this study, a maximum of two replicates were available from each cell. The wide range of values already observed leads to the conclusion that the assumption of normality may not be justified. Therefore, tests for homogeneity of variances based on these statistical methods are not feasible.

Since two cores from different mixes were sent to each laboratory, it is possible compute a pooled estimate of the within laboratory variance which makes more efficient use of the data. This method assumes the testing variation will be the same for both MIX 1 and MIX 2. Combining the data from the two mixes in each laboratory, the formula to compute this pooled estimate is:

$$\sigma_{ip}^2 = [(n_{i1} - 1) * \sigma_{i1}^2 + (n_{i1} - 1) * \sigma_{i2}^2] / NS$$

where NS = ($n_{i1} + n_{i2} - 2$). This estimate is a weighted average of the two previous estimates where the weights are the number of tests performed on each mix. In this analysis the sample sizes are the same for each mix so the pooled estimate is the sum of the two previous estimates within each laboratory divided by 2. They are based on two degrees of freedom (NS = 2) rather than one and have much greater efficiency.

For compressive strength, the pooled estimates appear to be more homogeneous and are more reasonable than the individual estimates for all laboratories. Values for laboratories 1 and 9, where the potential outliers were identified, are still quite large. Estimates from the other three material tests are much more comparable to one another.

Table B-1. Within laboratory variances - Compressive Strength.

COMPRESSIVE STRENGTH

	MIX 1		MIX 2		POOLED	
LAB_i	$N_{i1}-1$	σ_{i11}^2	$N_{i2}-1$	σ_{i12}^2	NS	σ_{ip}^2
1	1	145800.0	1	793800.0	2	469800.00
2	1	22050.0	1	33800.0	2	27925.00
3	1	92450.0	1	49612.5	2	71031.25
4	1	1800.0	1	1250.0	2	1525.00
5	1	200.0	1	11250.0	2	5725.00
6	1	22050.0	1	48050.0	2	35050.00
7	1	9800.0	1	7200.0	2	8500.00
8	1	96800.0	1	12800.0	2	54800.00
9	1	415872.0	1	49612.5	2	232742.25
10	1	105800.0	1	20000.0	2	62900.00
11	1	14450.0	1	174050.0	2	94250.00
12	1	168200.0	1	3200.0	2	85700.00
13	1	6050.0	1	800.0	2	3425.00

Table B-2. Within laboratory variances - Tensile Strength.

TENSILE STRENGTH

	MIX 1		MIX 2		POOLED	
LAB_i	$N_{i1}-1$	σ_{i11}^2	$N_{i2}-1$	σ_{i12}^2	NS	σ_{ip}^2
1	1	968.0	1	364.5	2	666.25
2	1	4512.5	1	50.0	2	2281.25
3	1	40.5	1	3698.0	2	1869.25
4	0		1	264.5	1	264.50
5	1	450.0	1	50.0	2	250.00
6	1	312.5	1	112.5	2	212.50
8	1	0.0	1	112.5	2	56.25
9	1	420.5	1	924.5	2	672.50
10	1	162.5	1	2.0	2	82.00
11	1	200.0	1	1250.0	2	725.00
12	1	50.0	1	1250.0	2	650.00
13	1	3528.0	1	1200.5	2	2364.25

Table B-3. Within laboratory variances - Modulus of Elasticity.

MODULUS OF ELASTICITY

	MIX 1		MIX 2		POOLED	
LAB_i	$N_{i1}-1$	σ_{i11}^2	$N_{i2}-1$	σ_{i12}^2	NS	σ_{ip}^2
2	1	0.005	1	0.0	2	0.0025
5	1	0.005	0		1	0.005
6	1	0.045	1	0.0	2	0.0225
7	1	0.0025	1	0.0	2	0.01225
9	1	0.0041	1	0.005	2	0.0045
10	1	0.005	1	0.0313	2	0.0181
11	1	0.045	1	0.0013	2	0.0231
12	1	0.005	1	0.02	2	0.0125
13	1	0.0113	1	0.0113	2	0.0113

Table B-4. Within laboratory variances - Poisson's Ratio.

POISSON'S RATIO

	MIX 1		MIX 2		POOLED	
LAB_i	$N_{i1}-1$	σ_{i11}^2	$N_{i2}-1$	σ_{i12}^2	NS	σ_{ip}^2
5	1	.00005	0		1	.00005
6	1	.00125	1	.0	2	.00063
9	1	.0002	1	.00005	2	.000125
10	1	.0002	1	.00005	2	.000125
12	1	.00005	1	.00045	2	.000400
13	1	.0002	1	.00005	2	.00025

APPENDIX VII

TECH MEMO: AU-127 (Addendum - Precision Statements)

DATE: March 19, 1991

AUTHORS: Robin High, Virgil Anderson

SUBJECT: Precision Statements for SHRP Portland Cement Concrete Core Proficiency Samples

The within and between laboratory variance components for the concrete core proficiency samples were given in Technical Memorandum AU-127 dated December 21, 1990. This addendum provides precision statements, based on the results presented in that report, for compressive stength, tensile strength, modulus of elasticity, and Poisson's ratio.

WITHIN-LABORTORY PRECISION STATEMENTS FOR SHRP CONCRETE CORE SAMPLES

The within-laboratory precision statements are based on the results for SHRP concrete proficiency sample cores. The standard deviation of an individual measurement and the two standard deviations limits for the difference between two observations from the same laboratory are given. This latter value implies that the difference between one measurement selected at random from each laboratory will differ from another measurement made on the same type of concrete core by more than 2 2 σ only 5% the time.

Compressive Strength

Precision - The within-laboratory single operator standard deviation for compressive strength has been found to be $\sigma = 258.8$. Therefore, results of two properly conducted tests by the same operator in the same laboratory on the same concrete sample should not differ by more than $2\sqrt{2}\,\sigma = 732.0$.

These numbers represent, respectively, the 1S and D2S limits as described in ASTM Practice C670, for Preparing Precision Statements for Test Methods for Construction Materials.

Tensil Strength

Precision - The within-laboratory single operator standard deviation for tensile strength has been found to be $\sigma = 45.24$. Therefore, results of two properly conducted tests by the same operator in the same laboratory on the same concrete sample should not differ by more than $2\sqrt{2}\,\sigma = 128.0$.

These numbers represent, respectively, the 1S and D2S limits as described in ASTM Practice C670, for Preparing Precision Statements for Test Methods for Construction Materials.

Modulus of Elasticity

Precision - The within-laboratory single operator standard deviation for modulus of elasticity has been found to be $\sigma = 0.204$. Therefore, results of two properly conducted tests by the same operator in the same laboratory on the same concrete sample should not differ by more than $2\sqrt{2}\,\sigma = 0.578$.

These numbers represent, respectively, the 1S and D2S limits as described in ASTM Practice C670, for Preparing Precision Statements for Test Methods for Construction Materials.

Poisson's Ratio

Precision - The within-laboratory single operator standard deviation for Poisson's Ratio has been found to be $\sigma = 0.0188$. Therefore, results of two properly conducted tests by the same operator in the same laboratory on the same concrete sample should not differ by more than $2\sqrt{2}\,\sigma = 0.0532$.

These numbers represent, respectively, the 1S and D2S limits as described in ASTM Practice C670, for Preparing Precision Statements for Test Methods for Construction Materials.

BETWEEN-LABORTORY PRECISION STATEMENTS FOR SHRP CONCRETE CORE SAMPLES

The between-laboratory variance components for the concrete core samples, given in Technical Memorandum AU-127, are derived in this section. The two standard deviations limits for the difference between two observations from different laboratories are given. These values imply that the difference between one measurement selected at random from each of two laboratories will differ from each other by more than $2\sqrt{2(\sigma^2_{LAB} + \sigma^2)}$ only 5% the time.

Compressive Strength

Precision - The between-laboratory single operator standard deviation for compressive strength has been found to be $\sqrt{\sigma^2_{LAB} + \sigma^2}$ = 289.14. Therefore, the results of properly conducted tests from one concrete sample in each of two laboratories should not differ by more than $2\sqrt{2\ (\sigma^2_{LAB} + \sigma^2)}$ = 817.81 from each other.

These numbers represent, respectively, the 1S and D2S limits as described in ASTM Practice C670, for Preparing Precision Statements for Test Methods for Construction Materials.

Tensil Strength

Precision - The between-laboratory single operator standard deviation for tensile strength has been found to be $\sqrt{\sigma^2_{LAB} + \sigma^2}$ = 84.94. Therefore, the results of properly conducted tests from one concrete sample in each of two laboratories should not differ by more than $2\sqrt{2\ (\sigma^2_{LAB} + \sigma^2)}$ = 240.24 from each other.

These numbers represent, respectively, the 1S and D2S limits as described in ASTM Practice C670, for Preparing Precision Statements for Test Methods for Construction Materials.

Modulus of Elasticity

Precision - The between-laboratory single operator standard deviation for modulus of elasticity has been found to be $\sqrt{\sigma^2_{LAB} + \sigma^2} = 0.482$. Therefore, the results of properly conducted tests from one concrete sample in each of two laboratories should not differ by more than $2\sqrt{2(\sigma^2_{LAB} + \sigma^2)} = 1.364$ from each other.

These numbers represent, respectively, the 1S and D2S limits as described in ASTM Practice C670, for Preparing Precision Statements for Test Methods for Construction Materials.

Poisson's Ratio

Precision - The between-laboratory single operator standard deviation for Poisson's ratio has been found to be $\sqrt{\sigma^2_{LAB} + \sigma^2} = 0.0392$. Therefore, the results of properly conducted tests from one concrete sample in each of two laboratories should not differ by more than $2\sqrt{2(\sigma^2_{LAB} + \sigma^2)} = 0.1108$ from each other.

These numbers represent, respectively, the 1S and D2S limits as described in ASTM Practice C670, for Preparing Precision Statements for Test Methods for Construction Materials.

APPENDIX VIII

Steele Engineering, Inc.

March 26, 1990

W. Charles Greer, Jr.
Law Engineering
396 Plasters Avenue NE
Atlanta, GA 30324

Dear Charles:

Subject: SHRP PCC Core Proficiency Sample Program.

I am pleased to advise that SHRP, based upon test results from the subject program, has authorized your laboratory to proceed with the testing of portland cement concrete (PCC) cores from field sections of the LTPP project in accordance with required protocols.

It was noted that your laboratory achieved a rating of five, using the Cement and Concrete Reference Laboratory (CCRL) approach to analysis, on all tests included in the subject program. This was indeed an excellent performance. As you proceed with these tests on SHRP field samples, the same internal quality control practices should be followed that were used when testing the PCC proficiency samples, thus providing confidence in the data generated.

Yours very truly

Garland W. Steele, P.E.
President, Steele Engineering, Inc.

cc: Adrian Pelzner

Box 173 • Tornado, West Virginia 25202 • Tele. (304) 727-8719

13 LABS PARTICIPATE IN SHRP PCC CORE PROFICIENCY SAMPLE PROGRAM

Final results of the Portland Cement Concrete Core Proficiency Sample Program were recently forwarded to the 13 participating laboratories by the Iowa Department of Transportation Office of Materials. Over 150 4" by 8" cores were shipped for determining the precision of tests to be performed on concrete pavement cores from the LTPP study.

The program was designed to obtain data on the static modulus of elasticity, poissons ratio, splitting tensile strength, and compressive strength. Detailed data analysis is now under way by statiscal consultants at TRDF. However, preliminary data analysis and laboratory ratings were determined using the widely recognized Cement and Concrete Reference Laboratory (CCRL) approach[1]. The best laboratory rating under this proceedure is a 5, indicating that a laboratory's test result is less than one standard deviation from the mean of all results.

The preliminary analysis indicated that the SHRP laboratory for concrete testing (Law Engineering, Atlanta) achieved a 5 rating in each category of the program. Based upon this performance, SHRP has directed Law to proceed with the concrete core tests on LTPP field samples.

Laboratories participating in this program were:

Florida Department of Transportation, Gainesville, FL

Iowa Department of Transportation, Ames IA

Federal Highway Administration, Denver, CO

California Department of Transportation, Sacramento, CA

West Virginia Department of Transportation, Charleston, WV

Law Engineering, Atlanta, GA

National Aggregates Association/National Ready Mix Concrete Association, Silver Springs, MD

Bureau of Reclamation, Denver, Co

Waterways Experiment Station, Vicksburg, MI

Concrete Materials and Technical Services, Skokie, IL

CANMET, Ottawa, Ontario, Canada

Wiss, Janey and Elsner, Northbrook, IL

New York Department of Transportation, Albany, NY

W. Charles Greer, Jr.
Law Engineering
396 Plasters Avenue NE
Atlanta, GA 30324

1 1959 ASTM Proceedings, Crandall and Blaine paper.

Compressive Strength

Precision

The within-laboratory single operator standard deviation for compressive strength of PCC cores has been found to be σ = [A]258.8. Therefore, results of two properly conducted tests by the same operator in the same laboratory on the same concrete sample should not differ by more than $2\sqrt{2}\ \sigma$ = [B]732.0.

The between-laboratory single operator standard deviation for compressive strength of PCC cores has been found to be $\sqrt{(\sigma^2_{lab}+\sigma^2)}$ = [A]289.14. Therefore, results of properly conducted tests from one concrete sample in each of two laboratories should not differ by more than $2\sqrt{(2(\sigma^2_{lab}+\sigma^2))}$ = [B]817.81 from each other.

These numbers represent, respectively, the [A]D1S and [B]D2S limits as described in ASTM Practice C670, Preparing Precision Statements for Test Methods for Construction Materials.

Splitting Tensile Strength

Precision

The within-laboratory single operator standard deviation for splitting tensile strength of PCC cores has been found to be σ = [A]45.24. Therefore, results of two properly conducted tests by the same operator in the same laboratory on the same concrete sample should not differ by more than $2\sqrt{2}\ \sigma$ = [B]128.0.

The between-laboratory single operator standard deviation for splitting tensile strength of PCC cores has been found to be $\sqrt{(\sigma^2_{lab}+\sigma^2)}$ = [A]84.94. Therefore, results of properly conducted tests from one concrete sample in each of two laboratories should not differ by more than $2\sqrt{(2(\sigma^2_{lab}+\sigma^2))}$ = [B]240.24 from each other.

These numbers represent, respectively, the [A]D1S and [B]D2S limits as described in ASTM Practice C670, Preparing Precision Statements for Test Methods for Construction Materials.

Modulus of Elasticity

Precision

The within-laboratory single operator standard deviation for modulus of elasticity of PCC cores has been found to be σ = [A]0.204. Therefore, results of two properly conducted tests by the same operator in the same laboratory on the same concrete sample should not differ by more than $2\sqrt{2}\,\sigma$ = [B]0.578.

The between-laboratory single operator standard deviation for modulus of elasticity of PCC cores has been found to be $\sqrt{(\sigma^2_{lab}+\sigma^2)}$ = [A]0.482. Therefore, results of properly conducted tests from one concrete sample in each of two laboratories should not differ by more than $2\sqrt{(2(\sigma^2_{lab}+\sigma^2))}$ = [B]1.364 from each other.

These numbers represent, respectively, the [A]D1S and [B]D2S limits as described in ASTM Practice C670, Preparing Precision Statements for Test Methods for Construction Materials.

Poisson's Ratio

Precision

The within-laboratory single operator standard deviation for Poisson's ratio of PCC cores has been found to be σ = [A]0.0188. Therefore, results of two properly conducted tests by the same operator in the same laboratory on the same concrete sample should not differ by more than $2\sqrt{2}\,\sigma$ = [B]0.0532.

The between-laboratory single operator standard deviation for Poisson's ratio of PCC cores has been found to be $\sqrt{(\sigma^2_{lab}+\sigma^2)}$ = [A]0.0392. Therefore, results of properly conducted tests from one concrete sample in each of two laboratories should not differ by more than $2\sqrt{(2(\sigma^2_{lab}+\sigma^2))}$ = [B]0.1108 from each other.

These numbers represent, respectively, the [A]D1S and [B]D2S limits as described in ASTM Practice C670, Preparing Precision Statements for Test Methods for Construction Materials.

Long-Term Pavement Performance Advisory Committee

Expert Task Group