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16. Abstract

In order to improve the quality of concrete construction in the state of Texas, the SDHPT must always search for better and improved ways to ensure the quality of the concrete used in construction. Traditionally, SDHPT has used the center point flexural load test as its main test procedure for determining the strength of concrete. However, due to the large scatter in the test results obtained using this procedure, it is often not clear what the actual strength of the concrete is, thus rendering the test procedure inadequate. As a result, there is an urgent need to develop the necessary information to allow the use of a different quality control procedure by resident engineers in the field. The test procedure adopted must be one which provides for more consistent test results while being easy to perform, low cost, and sensitive to variations in the strength of the concrete.

This study investigated the use of center point loading versus third point loading in determining the flexural strength of concrete. A total of over seven hundred beam specimens were cast from fourteen different mixes. Factors investigated to determine their effect on flexural strength test results included specimen size, coarse aggregate size and type, and concrete strength. Statistical analyses were performed to determine standard deviations, coefficients of variation, and acceptable between-laboratory variations for each flexural strength test method.

Current Texas highway specifications should be modified to incorporate the use of flexural strength testing by third point loading. Flexural strength requirements need to be made compatible with third point testing, using the correlation determined herein.

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IMPROVED CONCRETE QUALITY CONTROL PROCEDURES INCLUDING THIRD POINT LOADING

by

P.M. Carrasquillo and R.L. Carrasquillo

Research Report 1119-1F

"Improved Concrete Quality Control Procedures
Including Third Point Loading"

Conducted for

Texas
State Department of Highways and Public Transportation

In Cooperation with the
U.S. Department of Transportation
Federal Highway Administration

by

CENTER FOR TRANSPORTATION RESEARCH
BUREAU OF ENGINEERING RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

November 1987

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

PREFACE

This report summarizes a detailed study on test procedures used to determine the flexural strength of concrete. Various factors were investigated to determine if and to what extent they affect flexural strength test results.

This research study, Project 3-9-87-1119, entitled "Improved Concrete Quality Control Procedures Including Third Point Loading," was conducted at the Phil M. Ferguson Structural Engineering Laboratory as part of the overall research program of the Center for Transportation Research, Bureau of Engineering Research, of The University of Texas at Austin. The work was sponsored jointly by the Texas State Department of Highways and Public Transportation and the Federal Highway Administration.

The overall study was directed by Dr. Ramon L. Carrasquillo, Associate Professor of Civil Engineering. The detailed work was carried out under the direct supervision of Peggy M. Carrasquillo, M.S., Research Engineer, Center for Transportation Research.

S U M M A R Y

In order to improve the quality of concrete construction in the state of Texas, the SDHPT must always search for better and improved ways to ensure the quality of the concrete used in construction. Traditionally, SDHPT has used the center point flexural load test as its main test procedure for determining the strength of concrete. However, due to the large scatter in the test results obtained using this procedure, it is often not clear what the actual strength of the concrete is, thus rendering the test procedure inadequate. As a result, there is an urgent need to develop the necessary information to allow the use of a different quality control procedure by resident engineers in the field. The test procedure adopted must be one which provides for more consistent test results while being easy to perform, low cost, and sensitive to variations in the strength of the concrete.

This study investigated the use of center point loading versus third point loading in determining the flexural strength of concrete. A total of over seven hundred beam specimens were cast from fourteen different mixes. Factors investigated to determine their effect on flexural strength test results included specimen size, coarse aggregate size and type, and concrete strength. Statistical analyses were performed to determine standard deviations, coefficient of variations, and acceptable between-laboratory variations for each flexural strength test method.

Current Texas highway specifications should be modified to incorporate the use of flexural strength testing by third point loading. Flexural strength requirements need to be made compatible with third point testing, using the correlation determined herein.

I M P L E M E N T A T I O N

This report summarizes an experimental study aimed at developing sufficient data to provide guidelines for the adoption of an improved method for testing flexural strength of concrete. The results of this study should be considered by the Texas State Department of Highways and Public Transportation in the modification of concrete flexural strength requirements and the adoption of flexural strength testing of concrete by third point loading.

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CHAPTER 1

INTRODUCTION

1.1 General

A brief overview of the research program presented herein will be given in this chapter. This will include a description of the topics which will be addressed and their importance in the development of specifications to ensure quality concrete construction. Basic terms will be defined.

1.2 Definitions

Flexural strength test results depend on the test method used. In general, flexural strength test results obtained using center point loading will be higher than those obtained from third point loading.

The two test methods are represented schematically in Fig. 1.1. Assuming conformance with elastic theory, when a beam is tested in center point loading (CPL) the cross section of the beam subjected to maximum moment, and therefore maximum stress, is located at the point where load is applied, as shown in Fig. 1.1a. Therefore, if failure occurs at that location, then the result reflects the flexural capacity of the concrete along that plane only. If failure occurs at some point along the beam other than where the load is applied, the actual flexural capacity of the concrete at the plane of failure is lower than that measured, because the moment and stress at the point of failure are lower than at the point of loading. Therefore, for failure at a cross section other than at mid-span, the actual maximum stress at the plane of failure should be calculated based on the actual moment at that cross section.

When beams are tested using third point loading (TPL), there is a region of the beam equal to 1/3 of its span length which is subjected to uniform maximum moment, as shown in Fig. 1.1b. Therefore, failure could occur at any cross section within that region and no correction would be needed since the failure surface would have been subjected to maximum stress.

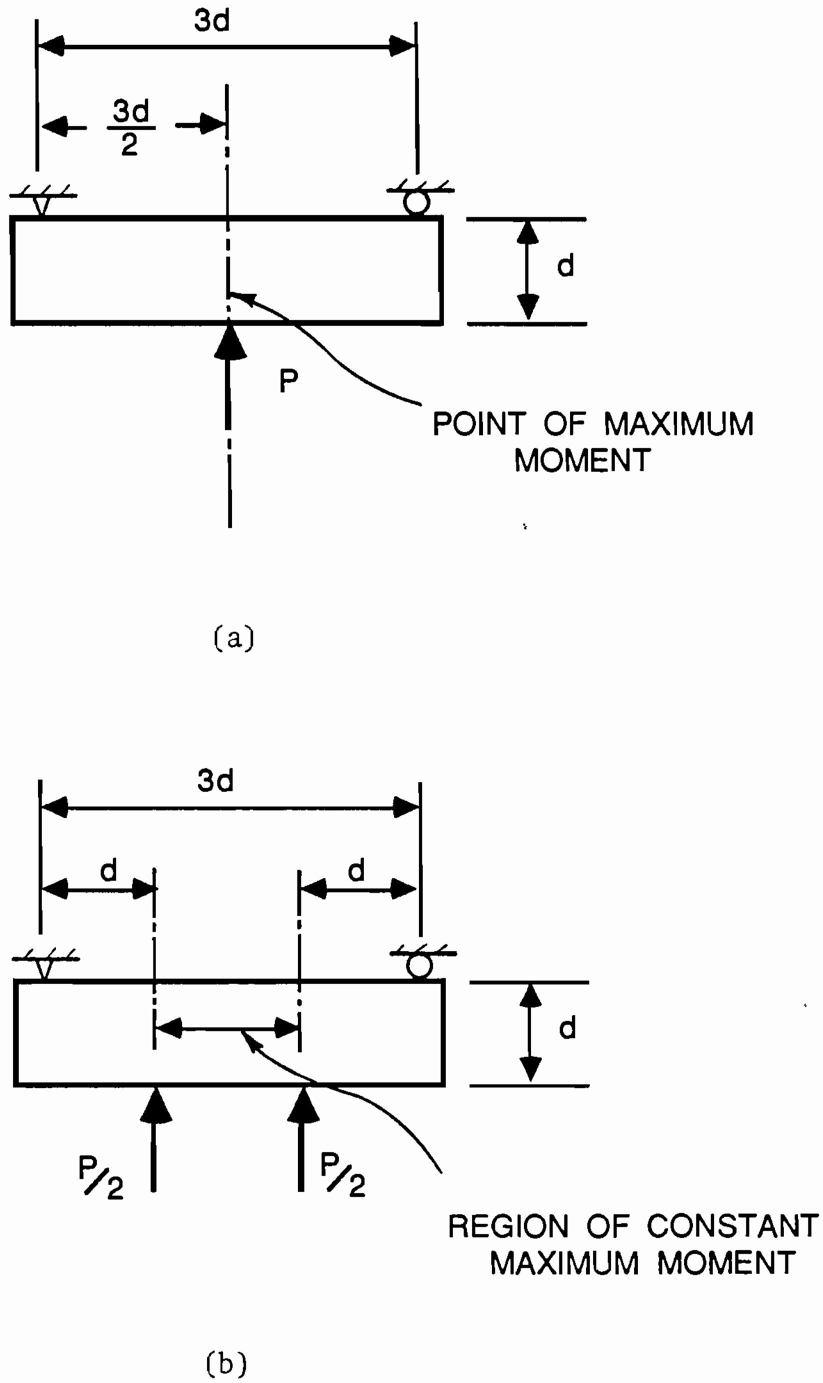


Fig. 1.1 Schematic representation of test set-up for (a) center point loading, and (b) third point loading.

1.3 Justification of Research

In order to improve the quality of concrete construction in the state of Texas, the SDHPT must always search for better and improved ways to ensure the quality of the concrete used in construction. Traditionally, the SDHPT has used the center point flexural load test as its main test procedure for determining the strength of concrete. Due to the large scatter in the test results using this procedure, it is often not clear what the actual strength of the concrete is, rendering the test procedure inadequate. As a result, there is an urgent need to develop the necessary information to allow the use of a different quality control procedure by resident engineers in the field. The test procedure developed must be one which provides for more consistent test results while being easy to perform, low cost, and sensitive to variations in the strength of the concrete.

Since the SDHPT is mostly concerned with the strength of concrete in flexure, it makes sense that the most widely used quality control test procedure for strength in the field is the flexural beam test. Among the advantages of using this test over compressive strength cylinders and indirect tensile tests is that the flexural beam strength of concrete is more sensitive than those other test procedures to variations in materials and types of aggregates which also affect the performance of pavements. In addition, the equipment required is less expensive and requires less maintenance. One disadvantage is the size and weight of the specimens used, making them heavy (60-70 lbs.) and difficult to handle.

However, a major disadvantage in the current practice is the use of the center point flexural test procedure which produces inconsistent test results due to the test conditions. Other test layouts, such as the third point load test, produce much more consistent test results while measuring the flexural strength of the concrete. In order to use a different strength test procedure, a correlation must be made between the measured strength value of the same concrete using each test procedure. This would allow for introducing the necessary modifications to the existing concrete specifications to account for the use of the different test procedure.

Another possible improvement to the current practice is the use of smaller size specimens; i.e., 4-1/2 in. x 4-1/2 in. x 15-1/2 in. beam specimens tested on a 13-1/2 in. span. This size specimen should be adequate as long as maximum size coarse aggregates less than 1-1/2 in. are used.

1.4 Objectives of Research

The overall objectives of this project are as follows:

1. Determine the advantages and disadvantages of changing current SDHPT strength testing practice from center point loading (CPL) flexural test to third point loading (TPL) flexural test.

2. Develop a correlation between the measured concrete strength using each test procedure for all classes of concrete.

3. Develop the necessary changes in existing concrete specifications when using the TPL test.

4. Study the feasibility of using a smaller size flexural beam specimen as an improvement in the current quality control procedures.

5. Gather information and test data in order to develop a recommended precision statement for the proposed test procedure.

1.5 Research Plan

A research program was conducted which allowed the study of the use of the third point loading flexural test procedure in place of center point loading, as well as the feasibility of using 4-1/2 in. x 4-1/2 in. x 15-1/2 in. beam specimens instead of the traditional 6-in. x 6-in. x 20-in. beam specimens. Specimens were cast and tested from concrete mixtures representing various classes of concrete. The effects of coarse aggregate type and size, specimen size, and concrete strength on the variability of each test method were investigated. Guidelines were prepared for expected within-laboratory and between-laboratory variations for each test method and specimen size, based on the data from this study.

1.6 Report Format

This report is divided into seven chapters and two appendices. A review of the technical literature relevant to the present study is presented in Chapter 2. Details of the experimental program are given in Chapter 3 and the results from the experimental program are presented in Chapters 4 and 5, and discussed in Chapter 6.

Chapter 7 contains the summary and conclusions resulting from the experimental program and recommendations for further research. Individual test results and details of data reduction are given in Appendices A and B.

This study was conducted at the Phil M. Ferguson Structural Engineering Laboratory at The University of Texas Balcones Research Center.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The following is a review of information regarding factors which are of major importance in the testing of plain concrete beams in flexure. Topics covered include the method of loading, specimen dimensions, the nominal maximum size of the coarse aggregate used and its amount in the concrete mixture.

2.2 Method of Loading

Flexural strength test results obtained from concrete specimens loaded at their third points differ from results of specimens loaded at their center point. This was first addressed in a paper written by Gonnerman and Shuman [3] in which they stated that, with third point loading, the probability of locating the weakest section in the specimen was greater than with center point loading.

Kellermann [5] conducted research in which he subjected beams to third point and center point loading. Since beams loaded at their center point do not always fail at midspan, which is the plane of maximum moment, he calculated the failure stress of these beams both at midspan and at the point of fracture. As shown in Fig. 2.1, results obtained from third point loading were lowest, while those calculated at midspan for center point loading were highest. For all 6-in. x 6-in. x 21-in. beams tested (18-in. span), the results obtained from beams loaded at midspan with the stress calculated at midspan were, on the average, approximately 14 percent higher than results obtained from third point loading. When theoretical statistics were applied to Kellermann's data [14], the results predicted that the two test methods should differ by approximately 12 percent.

The average percent variation of Kellermann's test results for each loading method are shown in Fig. 2.2. In general, the variation of test results obtained from third point loading was slightly lower than that for center point loading calculated at midspan. However, when the stress was calculated at the point of fracture for specimens loaded at their center point, the variation of the test results was significantly higher than for either of the other two methods. Kellermann attributed this to the problem of determining exactly the location of the failure plane. For example, for a 6-in. x 6-in. x 21-in. beam which fails at 4800 lbs. load, taking the point of fracture as being 1/2-in. from midspan yields a stress of 567 psi, whereas at an inch from midspan the stress would be only 533 psi as

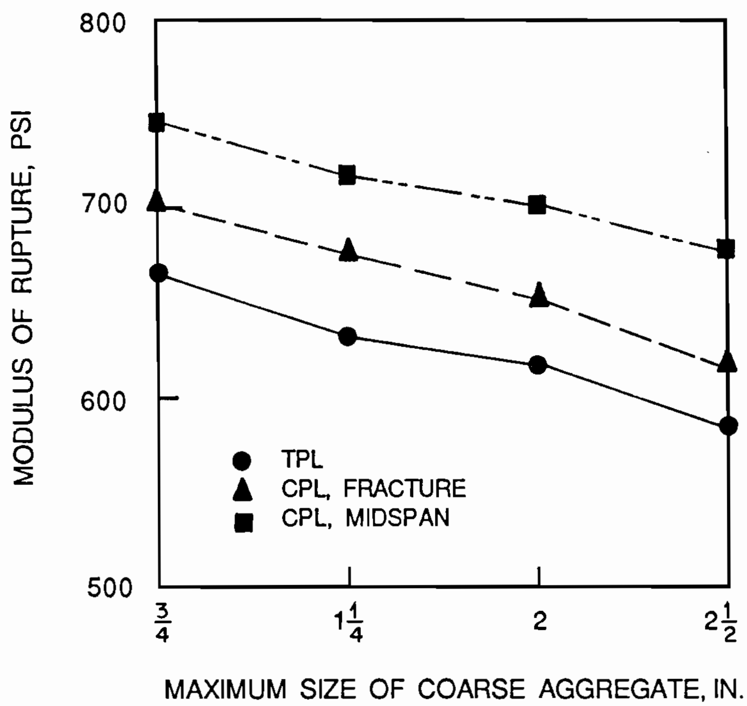


Fig. 2.1 Effect of method of loading and maximum size of coarse aggregate on average value of modulus of rupture of 6-in. x 6-in. x 21-in. beams (after Kellerman [5]).

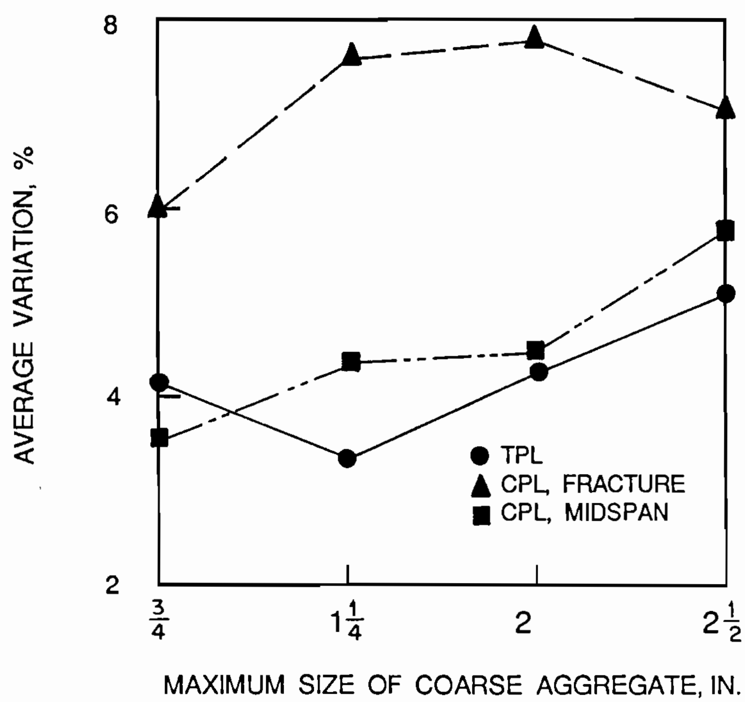


Fig. 2.2 Effect of method of loading and maximum size of coarse aggregate on average percentage variation of test results from 6-in. x 6-in. x 21-in. beams (after Kellerman [5]).

shown in Fig. 2.3. Thus, an error of 1/2-in. in locating the point of fracture would result in a variation in the test results of six percent due to this cause alone. As larger coarse aggregate is used, determining the location of the failure plane becomes more difficult.

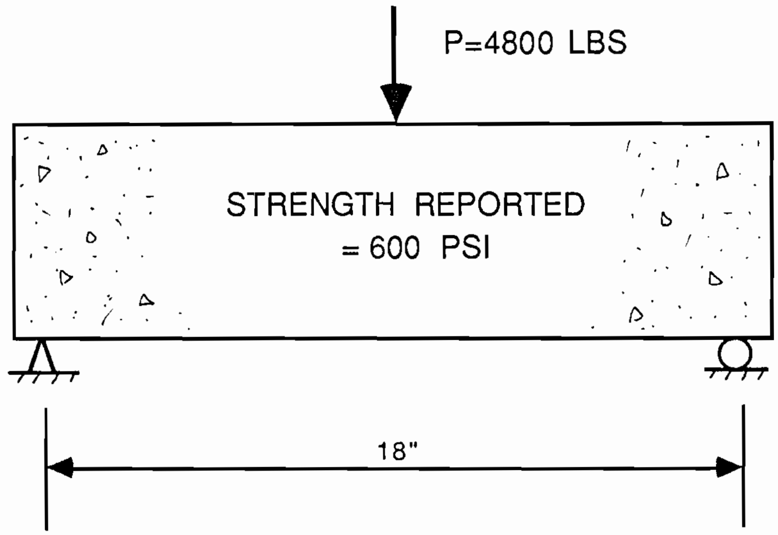
2.3 Specimen Dimensions

The effects of beam width and depth and length of span on flexural strength test results were investigated by several authors [5, 6, 14]. Generally, all authors concluded that the average flexural strength of test specimens was unaffected by changes in specimen width. The data of Reagel and Willis [6] is shown in Fig. 2.4. In addition, Tucker [14] and Reagel and Willis found that as the beam width was increased, the percentage variation of the test results decreased.

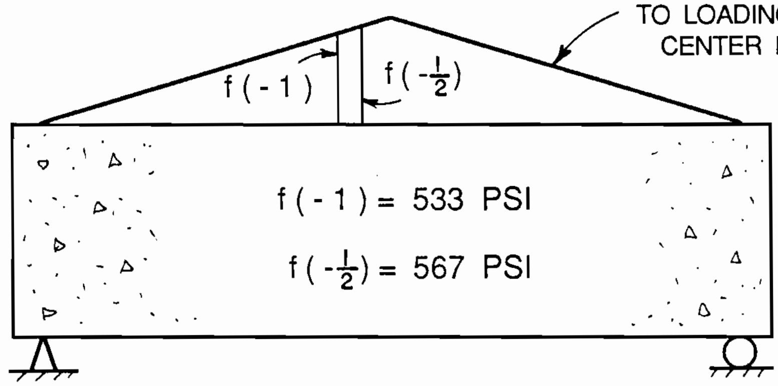
The above authors [6, 14] found that the modulus of rupture was affected significantly by the depth of the beam, however. As shown in Fig. 2.5, for each laboratory used in Reagel and Willis' study, increasing the beam depth caused a decrease in the modulus of rupture. The average of all laboratories combined is plotted in Fig. 2.6. On the average, increasing the beam depth from four inches to ten inches caused a decrease in the flexural strength of 100 psi. This is equivalent to approximately 17 psi per inch increase in depth, or two percent. In addition, the percentage variation of the test results decreased as the beam depth was increased.

Kellermann [5], on the other hand, did not vary the beam width and depth independently. Instead, he tested beams having cross sections of 6-in. x 6-in. and 8-in. x 8-in., and found that, in agreement with Tucker [14] and Reagel and Willis [6], the average modulus of rupture was lower for the larger cross section. However, unlike the preceding authors, Kellermann found that the variation of his test results was lower for beams having the smaller cross section. His results are shown in Fig. 2.7 for different sizes of coarse aggregate.

When the effect of length of span on the modulus of rupture was investigated, it was found by Kellermann [5] that as the length of span was increased, the average flexural strength of the specimens decreased. These results are shown in Fig. 2.8, and are in agreement with statistical theory [14]. Reagel and Willis [6], on the other hand, found that increasing the span from 18 inches to 36 inches resulted in a decrease of only 9 psi in the average flexural strength of the beams. Thus, they concluded that the modulus of rupture was independent of span length.



(a)



(b)

Fig. 2.3 For center point loading, effect of a difference of 1/2-inch in the location of the failure plane on the resulting flexural strength: a) strength reported based on midspan stress; b) stresses at 1/2-in. and 1-in. from midspan.

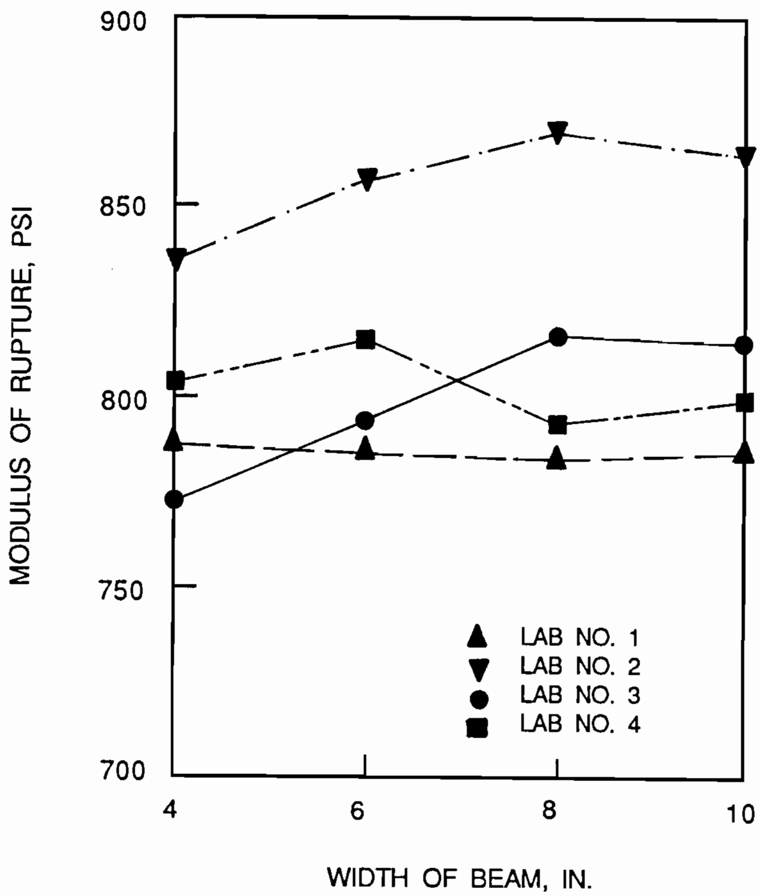


Fig. 2.4 Effect of width of beam on the average modulus of rupture of concrete test specimens tested in four different laboratories using third point loading (after Reagel and Willis [6]).

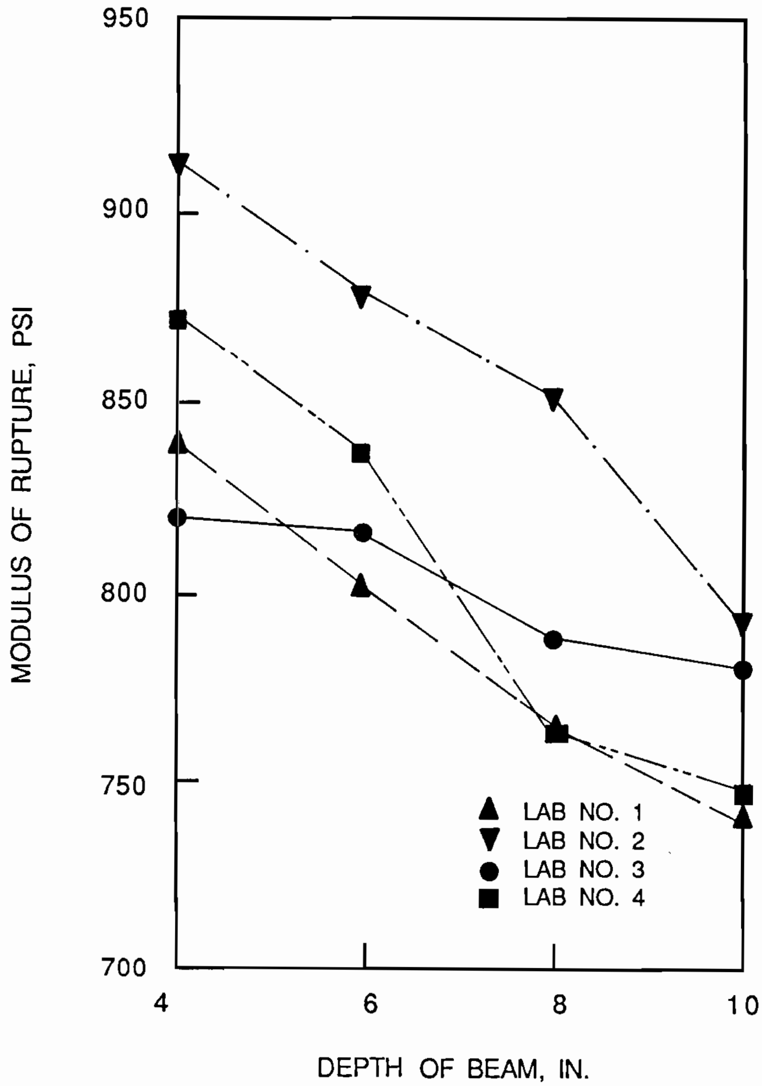


Fig. 2.5 Effect of depth of beam on the average modulus of rupture of concrete test specimens tested in four different laboratories using third point loading (after Reagel and Willis [6]).

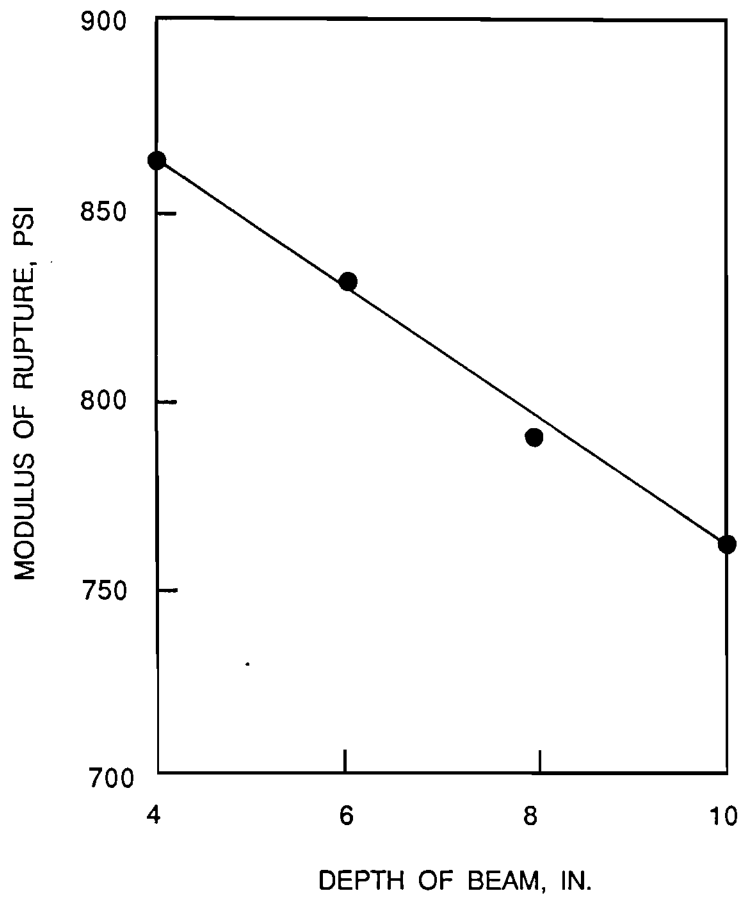


Fig. 2.6 Effect of depth of beam on the average modulus of rupture of concrete test specimens tested in third point loading, all laboratories combined (after Reagel and Willis [6]).

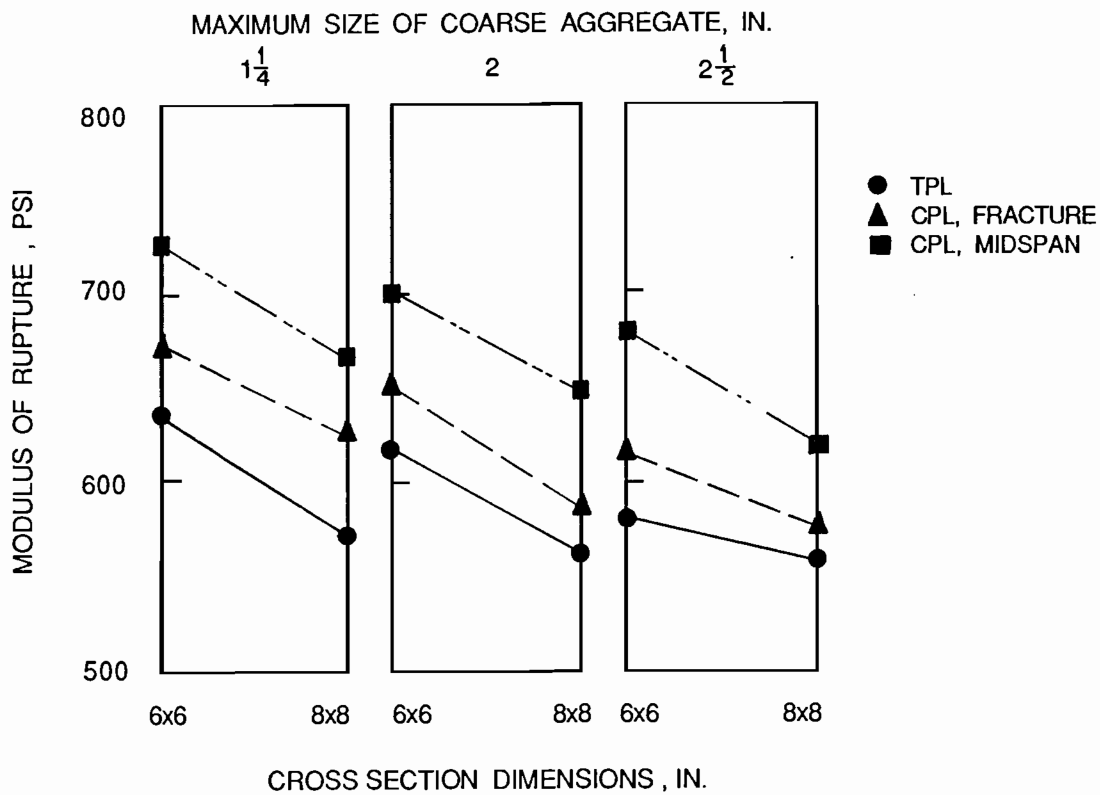


Fig. 2.7 Effect of cross section of beam on the average modulus of rupture of concrete test specimens. Span length is three times depth (after Kellermann [5]).

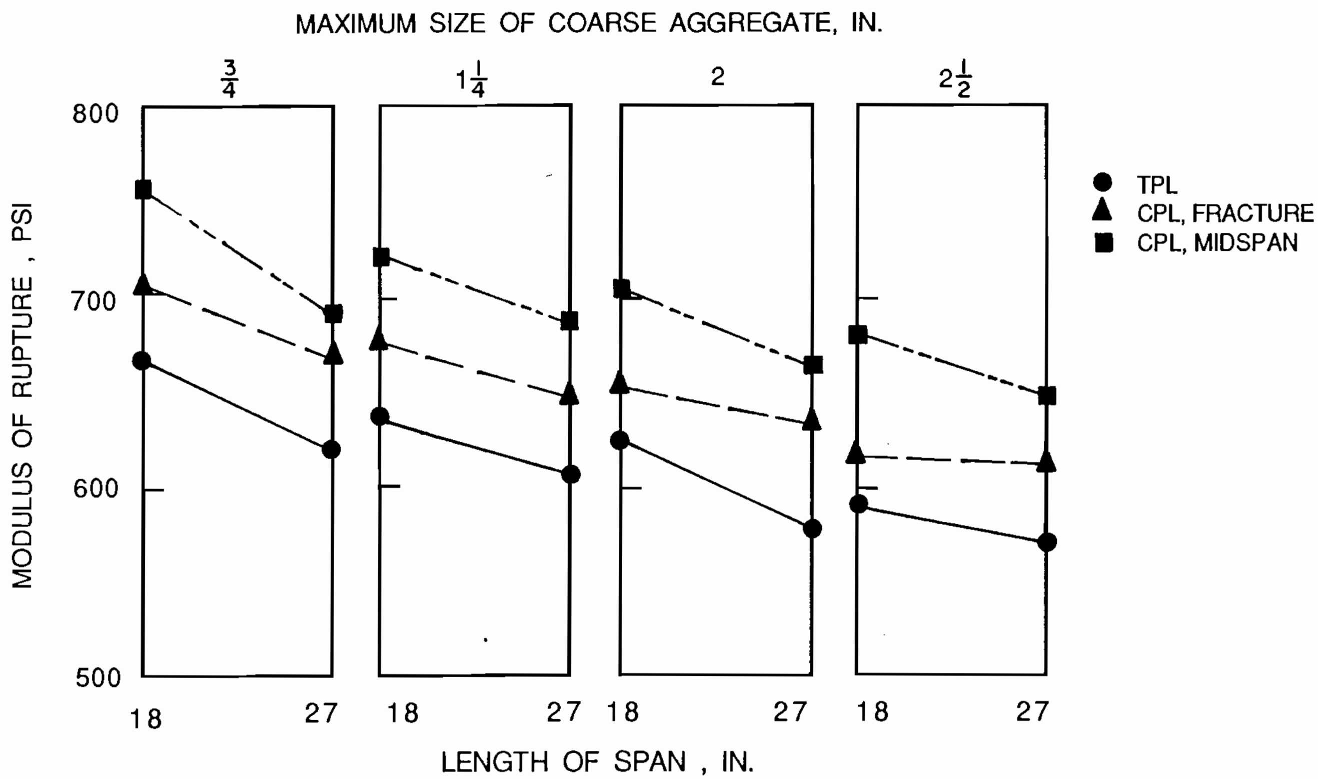


Fig. 2.8 Effect of length of span on the average modulus of rupture of concrete test specimens having a cross section of 6-in. x 6-in. (after Kellermann [5]).

With regards to variation of test results, Kellermann's [5] results showed lower variation for the shorter length of span (except for the case of calculating the stress at the point of fracture for center point loading), as shown in Fig. 2.9. This is not in agreement with statistical theory [14].

2.4 Coarse Aggregate

2.4.1 Nominal Maximum Size. Kellermann [5] conducted tests on concrete beams made using limestone coarse aggregate. In order to study the effect of coarse aggregate size on average flexural strength and variation of test results, he used four different nominal maximum sizes, ranging from 3/4-in. to 2-1/2 in. Results of these tests can be seen in Figs. 2.1 and 2.2. In general, higher flexural strengths and lower variations of test results were obtained with the use of smaller-sized coarse aggregate.

2.4.2 Volume. Jackson and Kellermann [4] investigated the effect of the volume of coarse aggregate in a concrete mixture on the percentage variation of flexural strength test results. The concrete beams were loaded at their third points. As shown in Fig. 2.10, for both gravel and limestone coarse aggregates, the variation of test results increased as the volume of coarse aggregate increased.

2.5 Summary

Test results obtained from beams loaded at their center point are higher than those obtained from beams loaded at their third points. Based on the literature reviewed, the difference is, on the average, approximately 14 percent.

Although flexural strength test results were found to be independent of beam width, they were affected by changes in the beam depth and length of span. In general, as the beam depth and length of span increased, the average modulus of rupture decreased, as did the percentage variation of test results.

A concrete containing smaller-size coarse aggregate will produce higher flexural strengths and more uniform test results than will a concrete containing larger-size coarse aggregate. In addition, the variation of the test results will increase as the volume of coarse aggregate in the concrete is increased, for a given nominal maximum size.

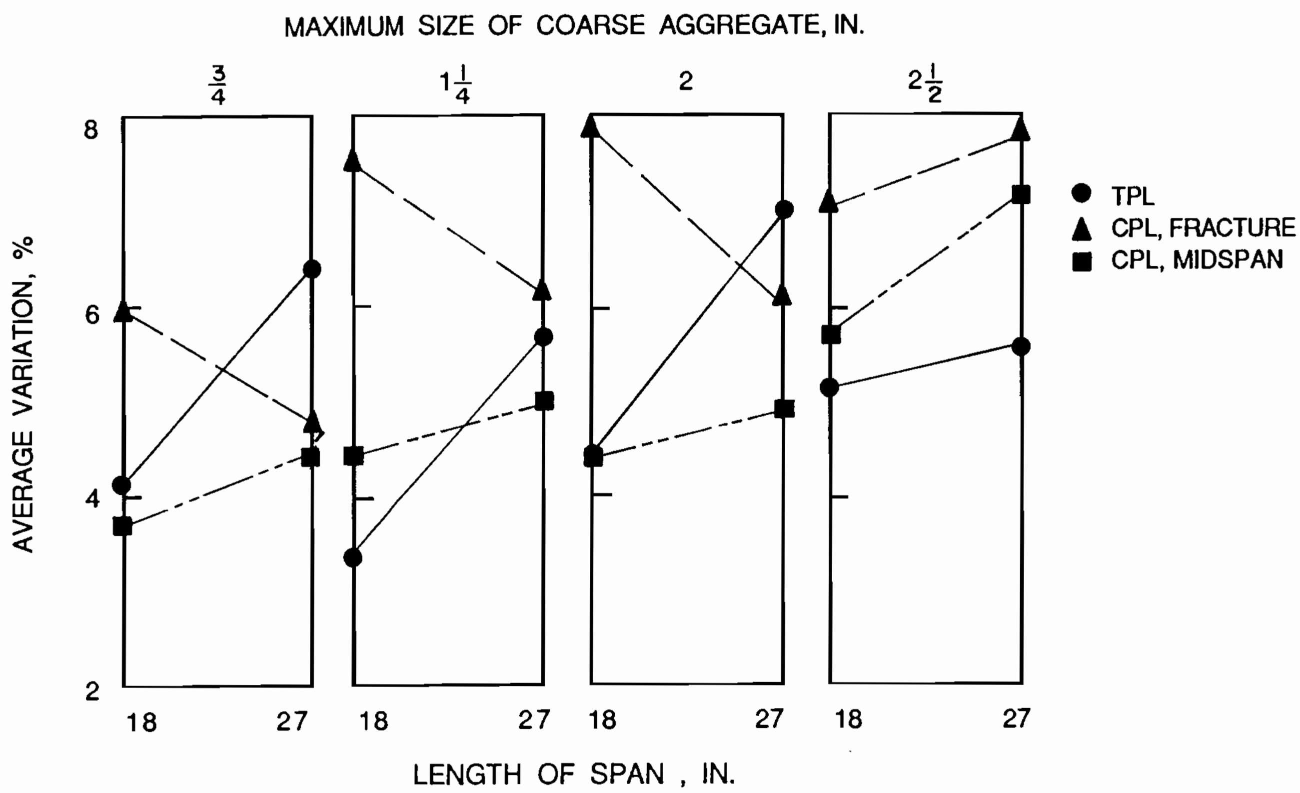


Fig. 2.9 Effect of length of span on average percentage variation of test results from 6-in. x 6-in. concrete beams (after Kellermann [5]).

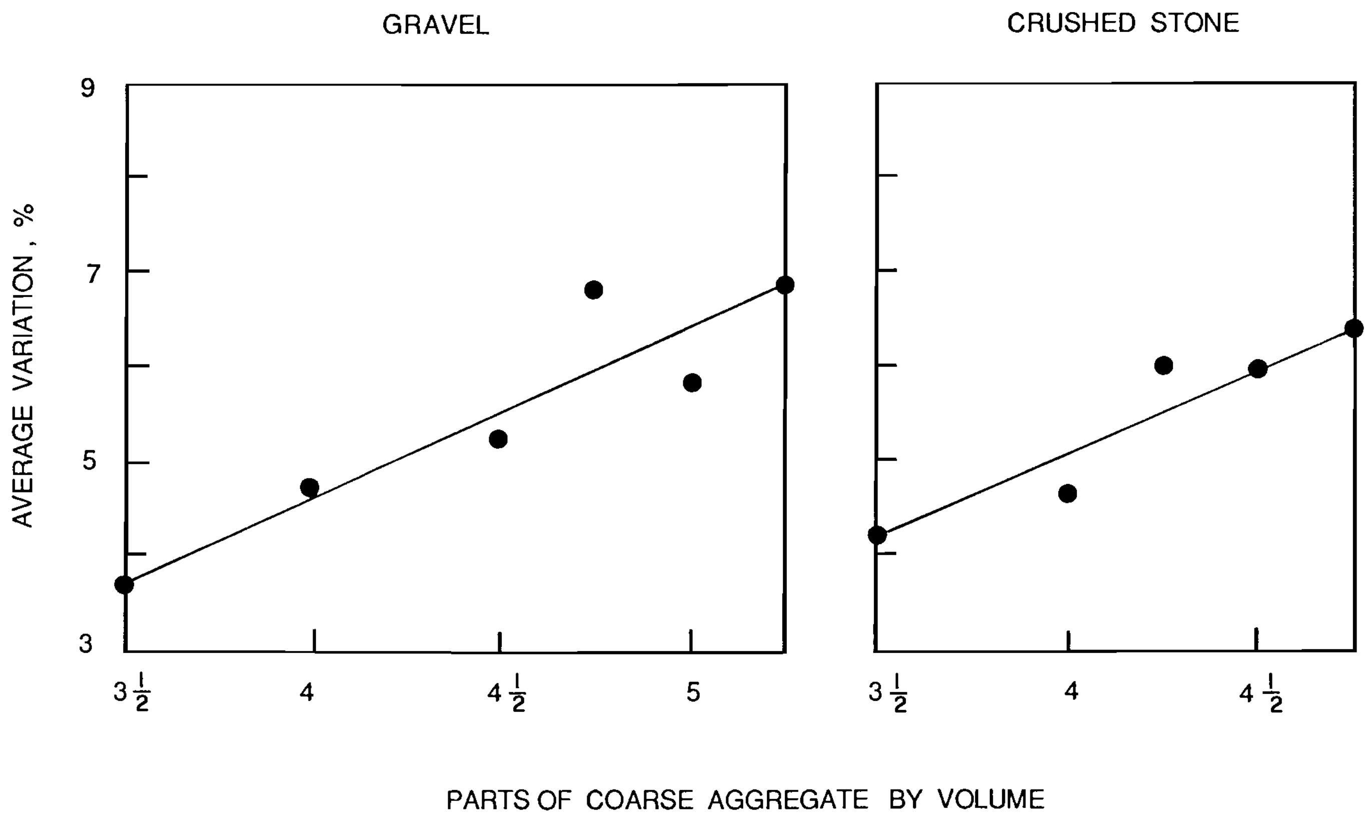


Fig. 2.10 Effect of volume of coarse aggregate on average percentage variation of test results from concrete beams loaded at their third points (after Jackson and Kellermann [4]).

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 Introduction

In all, nearly 800 beam specimens were cast from concrete mixtures selected to represent various classifications of concrete from the Texas Standard Specifications [15]. Strength of concrete beams tested according to Test Method TEX-420-A [2] ranged from 625 to 990 psi at seven days. The following variables were studied:

a. method of loading;
b. specimen dimensions;
c. coarse aggregate size.

The research program was conducted in two distinct stages. In the first stage, specimens were cast from concrete mixtures having different mixture proportions, coarse aggregate types, and coarse aggregate nominal maximum sizes in order to determine the effect of these factors on flexural strength test results. For the second stage two concrete mixtures were chosen, based on the results of the first stage tests, for use in an interlaboratory testing program to determine the precision of the test procedures. In this chapter, details from each stage in the experimental program will be given. These will include casting procedure, testing procedure, mixture proportions, and material properties.

3.2 First Stage Tests

The purpose of the first stage tests was to determine the effects of various properties of the concrete mixture on flexural strength test results. In all, 480 beams and 100 cylinders were cast from a total of ten concrete mixtures.

3.2.1 Material Properties. All concrete was produced at a commercial ready-mix plant and transported to the laboratory in transit mixers. The cement used met the requirements for ASTM C150 Type I [12]. Several of the concrete mixtures contained fly ash. The fly ash used was from an approved source, meeting Texas Specifications for Type B fly ash, and had a specific gravity of 2.56. All mixtures used natural river sand.

Both crushed limestone and siliceous river gravel were used as coarse aggregate. The river gravel was available in various nominal maximum sizes. Those maximum sizes used in this study included the following: 3/8-in., 3/4-in., and 1-1/2-in. Two gradations of the crushed limestone coarse aggregate were used. These had nominal maximum sizes of 1/2-in. and 1-in.

3.2.2 Mixture Proportions. Ten different concrete mixtures were chosen to represent flexural strengths of different classifications of concrete used by the TSDHPT. Details of each of these mixes, numbered one through ten, are given in Tables 3.1 and 3.2. Various combinations of coarse aggregate type, size, and concrete strength were obtained.

3.2.3 Specimen Preparation. For each mix, a batch of three cubic yards of ready-mix concrete was ordered. The casting procedure for each of the ten mixes was the same. Upon arrival of the ready-mix truck at the laboratory, the concrete was sampled and, if necessary, the slump was adjusted through the addition of water to the truck. Once the desired slump had been achieved, two wheelbarrows were filled and this concrete was discarded as being non-representative.

A total of 48 beam specimens were cast from each mix, being comprised of twenty-four 6-in. x 6-in. x 20-in. beams and twenty-four 4.5-in. x 4.5-in. x 15.5-in. beams. The smaller beam molds were constructed similarly to the larger beam molds, as shown in Fig. 3.1. In addition to the beam specimens, ten 6-in. x 12-in. cylinders were cast from each mix. The beams and cylinders were prepared in accordance with the procedures outlined in TEX 420 A [2] and TEX 418 A [1].

Two crews of workers were used in the preparation and testing of the specimens. In casting the specimens for each mix, the molds were divided so that each crew was responsible for the preparation of 12 large beams, 12 small beams, and five cylinders. Thus, in the reporting of specimen test results, each mix number will be followed by either an "A" or "B" to indicate the crew which prepared those specimens. To help control the material variability within these groups of specimens, all specimens prepared by each crew for a given mix were compacted by the same person. After finishing, the specimens were kept moist under wet burlap and plastic. After approximately 24 hours, the specimens were demolded and placed in saturated lime water until being tested.

3.2.4 Test Procedure. When the concrete beam specimens reached the age of seven days, they were tested in either center or third point loading, as diagrammed in Fig. 3.2. The test procedures followed were TEX 420 A [2] and ASTM C78 [13], respectively. All beams were tested on a Rainhart Series 416 Recording Beam Tester. In order to test the smaller beams, the machine was modified so that the

Table 3.1 Mixture proportions of mixes for first stage tests.

Mix Number	Coarse Aggregate Used	Mixture Proportions, per cubic yard: Cement, lbs.	Fly Ash, lbs.	Sand, lbs. (SSD)	Coarse Agg., lbs. (SSD)	Water,[1] lbs.	WR-R,[2] oz.	WR,[3] oz.	AEA,[4] oz.
1	1 1/2-in. SRG[5]	344	95	1438	1754	228	---	14.6	---
2	1-in. CS[6]	351	99	1453	1845	224	15.3	---	---
3	3/4-in. SRG	585	--	1316	1952	148	25.0	---	6.2
4	1-in. CS	584	--	1390	1794	189	24.6	---	6.2
5	3/4-in. SRG	338	--	1511	1723	260	---	10.1	---
6	3/8-in. SRG	424	--	1710	1721	182	---	12.7	---
7	3/4-in. SRG	531	--	1463	1742	250	---	20.8	---
8	1/2-in. CS	536	227	1130	1827	257	---	23.3	---
9	1 1/2-in. SRG	523	--	1313	1873	242	---	16.8	2.7
10	1-in. CS	519	--	1202	1963	195	---	16.6	2.9

1 Water value does not include water added by driver to adjust concrete slump before leaving batch plant, since this information was not available.

2 ASTM C494 [11] Type D, water-reducing and retarding admixture

3 ASTM C494 Type A, water-reducing admixture

4 ASTM C260 [10], air entraining admixture

5 Siliceous river gravel

6 Crushed limestone

Table 3.2 Concrete properties for mixes used in first stage tests.

Mix Number	Cementitious Material, sks/cubic yard[1] Cement	Fly Ash	Total	W/C + FA Ratio[2], Gal./Sk.	Concrete slump, in.	Air Content, %
1	3.66	1.22	4.88	5.6	4.75	5.0
2	3.74	1.28	5.02	5.4	2.75	2.25
3	6.23	----	6.23	2.9	4.75	5.5
4	6.22	----	6.22	3.7	2.25	4.75
5	3.60	----	3.60	8.7	2.5	4.5
6	4.51	----	4.51	4.9	2.0	3.0
7	5.65	----	5.65	5.3	2.5	2.0
8	5.70	2.93	8.63	3.6	8.25	1.5
9	5.57	----	5.57	5.2	7.0	3.0
10	5.52	----	5.52	4.2	4.5	6.0

[1] 1 sk = 0.485 ft^3

[2] Values may be low since water added to truck by driver at the batch plant to adjust concrete slump is not included.

Fig. 3.1 Beam mold construction for both 4.5-in. x 4.5-in. x 15.5-in. beams and 6-in. x 6-in. x 20-in. beams.

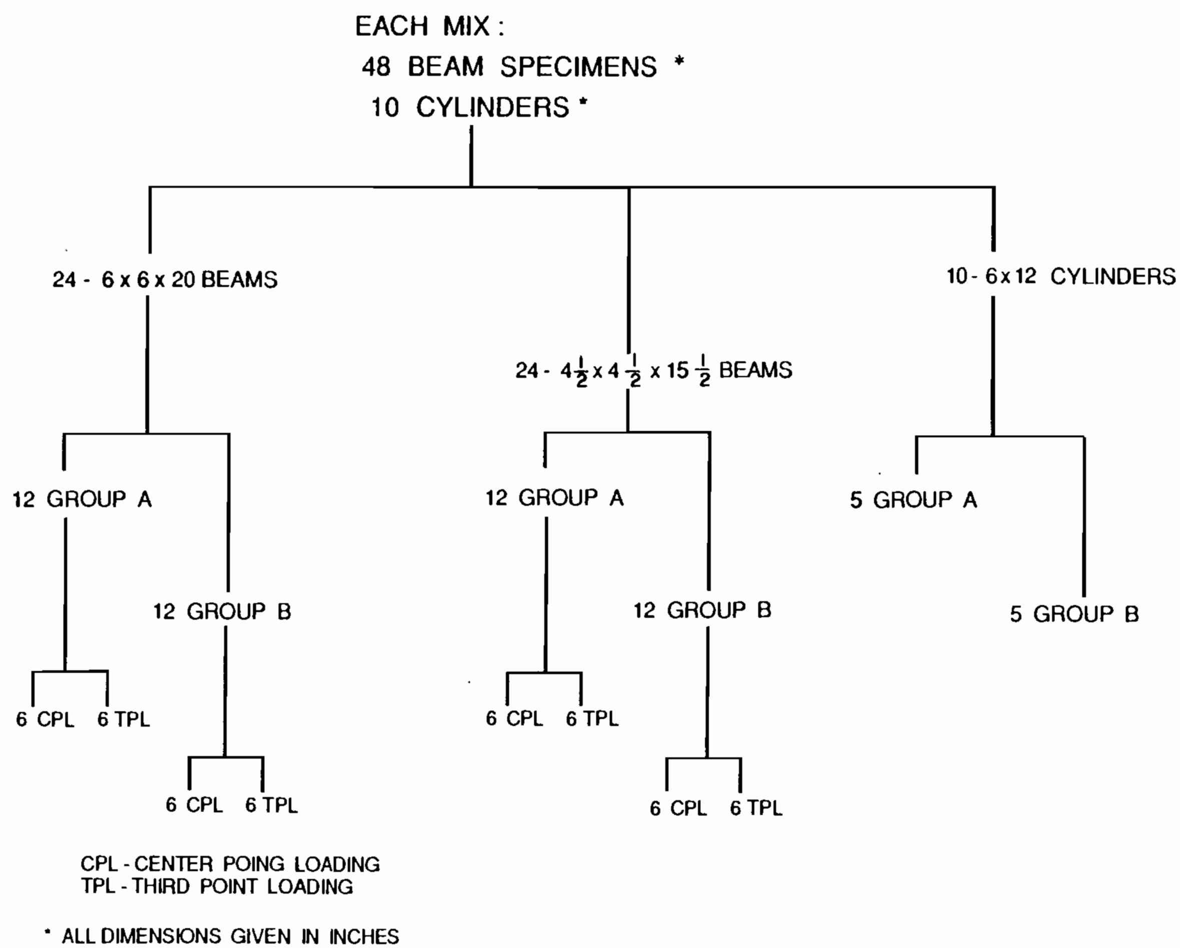


Fig. 3.2 Preparation and testing diagram of specimens for each mix from the first stage of testing.

span length and loading points were appropriate for the beam dimensions, as shown in Fig. 3.3. Also, recording charts having the proper "load tracking" spiral for the smaller beams were prepared. Samples of these are shown in Figs. 3.4 and 3.5.

The concrete cylinders were capped and tested according to Test Method TEX 418 A [1].

3.3 Second Stage Tests

The purpose of the second stage tests was to generate sufficient data to develop a between-laboratory precision statement for each test method. For this purpose, 140 beam specimens were cast from each of two different mix designs which were selected on the basis of those used in the first stage tests.

3.3.1 Mixture Proportions. Two concrete mixtures were chosen based on the performance of the mixes used during the first stage tests, and 140 beams were cast from each. However, due to the difficulty encountered in casting 140 strength specimens at one time, it was decided to order the same mix on two different days and cast half of the specimens on each day. Thus, Mix Nos. 11 and 12 represent one basic mix design, and Mix Nos. 13 and 14 represent the other.

Mix Nos. 11 and 12 were designed to contain four sacks of cement per cubic yard with 1-1/2 in. nominal maximum size gravel. This low cement content was used in order to limit the strength of the concrete. Mix Nos. 13 and 14 were designed to contain 5-1/2 sacks of cement per cubic yard with 3/4-in. gravel. This design was chosen to yield a higher flexural strength level. Thus, Mix Nos. 11 and 12 will be referred to as the "low" mix design, and Mix Nos. 13 and 14 will be the "high" mix design. Corrected mixture proportions for each mix are given in Table 3.3.

3.3.2 Specimen Preparation. For the second stage tests, 70 specimens were cast from each of four batches. The 70 specimens were comprised of thirty-five 6-in. x 6-in. x 20-in. beams and thirty-five 4.5-in. x 4.5-in. x 15.5-in. beams. The first two batches cast, totalling 140 specimens, were from concrete representing the "low" mix design, while the second two batches represented the "high" mix design.

The specimens were molded and cured for the first 24 hours according to ASTM C31 [7], with the exception that internal vibration was used for consolidation. This was done in an effort to achieve more uniform compaction for the large number of specimens being cast.

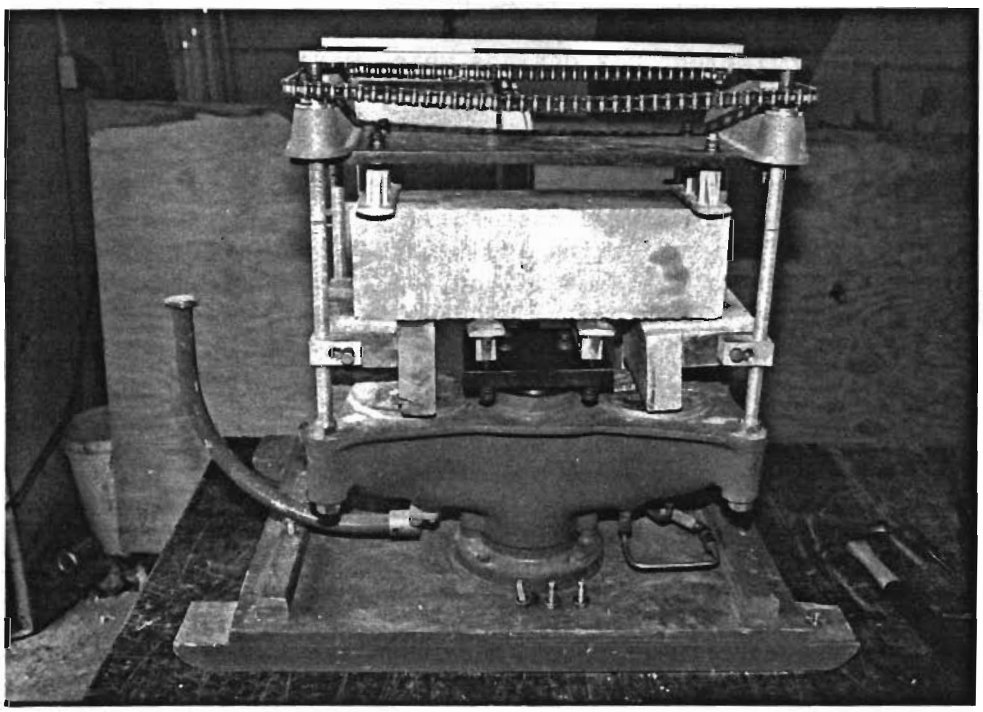


Fig. 3.3 Modification of Rainhart Beam Tester to accommodate 4.5-in. x 4.5-in. x 15.5-in. beams; third point loading head shown.

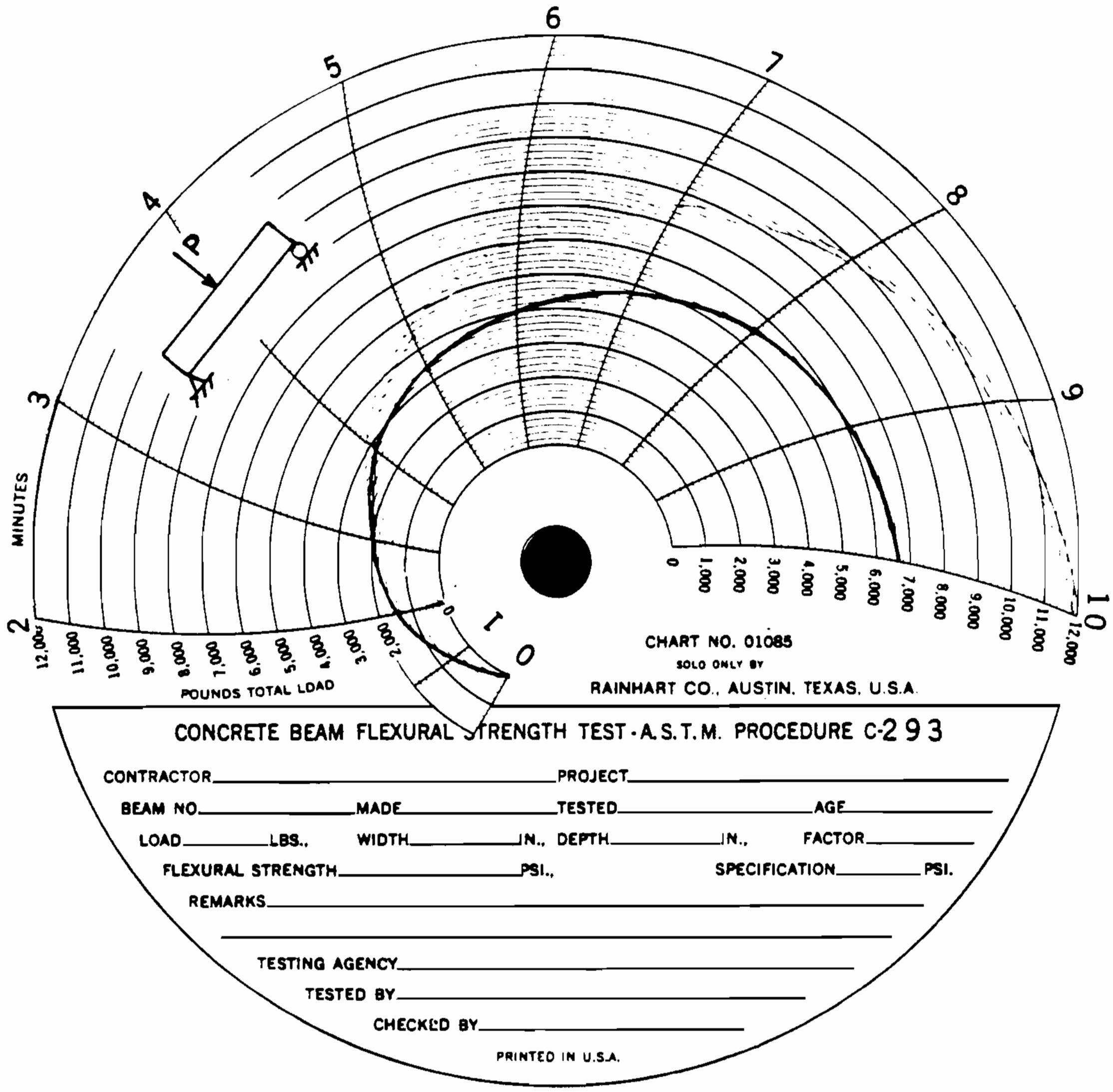


Fig. 3.4 Recording chart used for testing 4.5-in. x 4.5-in. x 15.5-in. beams in center point loading.

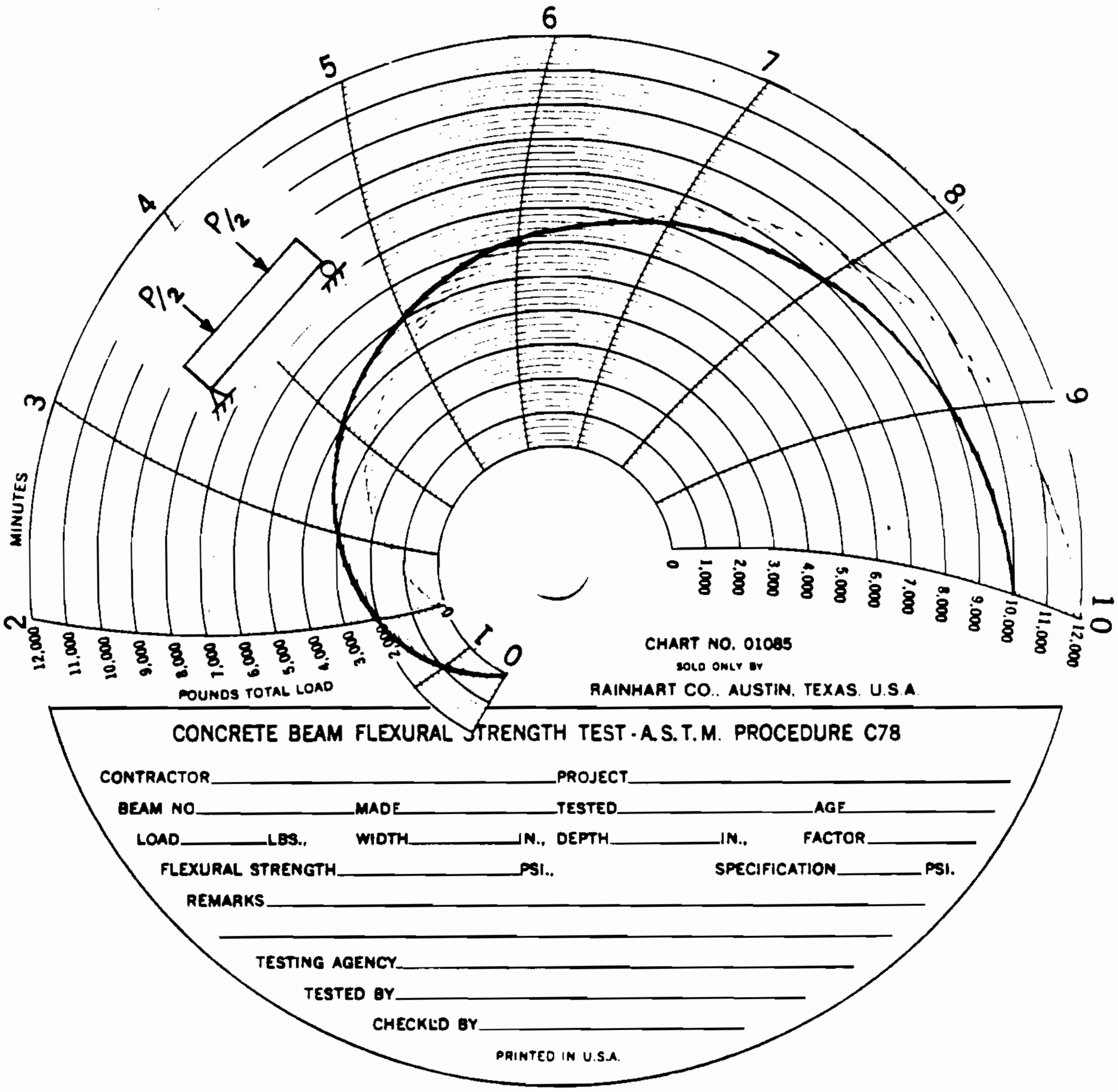


Fig. 3.5 Recording chart used for testing 4.5-in. x 4.5-in. x 15.5-in. beams in third point loading.

Table 3.3 Mixture proportions of mixes used for second stage tests.

Mix No.	Coarse Aggregate Used	Mixture Proportions, per cubic yard							
		Cement, lbs.	Sand, lbs. (SSD)	Coarse Agg., lbs. (SSD)	Water,[1] lbs.	WR-R,[2] oz.	WR,[3] oz.	AEA,[4] oz.	Slump, in.
11 (low)	1-1/2 in. SRG[5]	386	1410	1815	239	16.4	---	2.0	8
12 (low)	1-1/2 in. SRG	424	1532	1590	266	----	15.8	2.3	6.5
13 (high)	3/4-in. SRG	527	1579	1755	202	----	21.4	---	2.5
14 (high)	3/4-in. SRG	528	1387	1910	215	21.1	----	---	---

1 Water content does not include water added at batch plant by driver to adjust slump.

2 ASTM C494 Type D

3 ASTM C494 Type A

4 ASTM C260

5 Siliceous River Gravel

A 3/4-in. diameter head vibrator was inserted into the concrete and slowly withdrawn so that the length of time of each insertion was approximately three seconds. The number of insertions per layer for each specimen was four for the larger beams and three for the smaller beams. Upon demolding, the specimens were placed in saturated lime water until the time of testing.

3.3.3 Testing Procedure. In order to prepare a precision statement for interlaboratory precision, it was necessary, based on the procedure outlined in ASTM C802 [8], to obtain data from a minimum of ten different testing laboratories. Since this statement is being prepared for Texas SDHPT use, it seemed appropriate that, as much as possible, the data should be obtained from tests conducted by the SDHPT. To this end, assistance was provided by the main headquarters and field offices of District 14 in testing the beam specimens. In addition to the seven testing facilities provided by District 14, the SDHPT Materials and Tests Division provided an additional testing facility. To bring the number of testing sites to ten, specimens were also tested at the Ferguson Structural Engineering Laboratory at Balcones Research Center, and at the Civil Engineering Department on the University of Texas at Austin campus. The beams were stored in saturated lime water for between 75 to 90 days, at which time they were removed and transported to the various testing sites for testing. Precautions were taken so that the specimens were not damaged and remained moist during transit.

The testing sites, numbered one through ten, correspond to the following locations:

Lab No.	
1	TSDHPT District 14 Field Office #1
2	TSDHPT District 14 Field Office #2
3	TSDHPT District 14 Field Office #3
4	TSDHPT District 14 Field Office #4
5	TSDHPT District 14 Field Office #5
6	TSDHPT Materials and Tests Division
7	TSDHPT District 14 Field Office #6
8	Ferguson Laboratory
9	TSDHPT District 14 Headquarters
10	Civil Engineering Department, University of Texas

Distribution of the "low" specimens to the various testing facilities is diagrammed in Fig. 3.6. The distribution of the "high" specimens was similar, with specimens from Mix No. 13 being tested in center

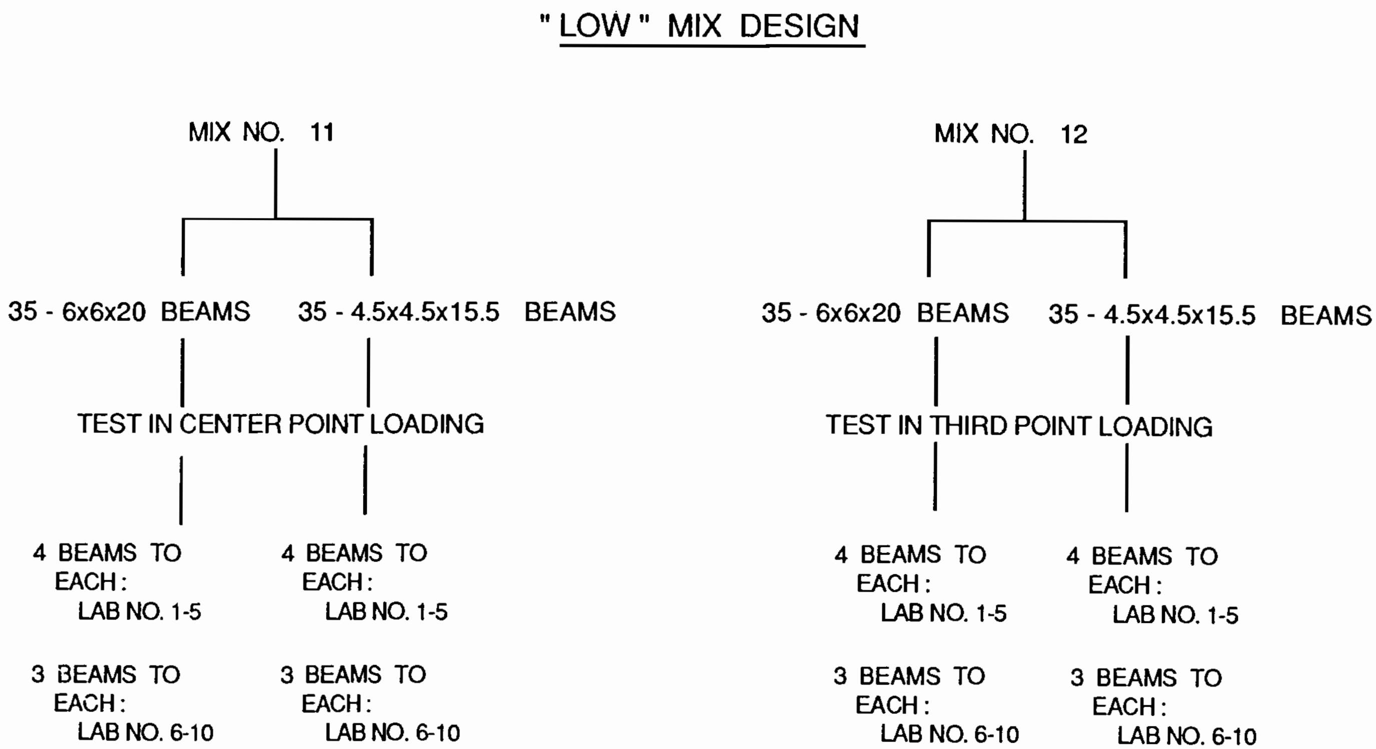


Fig. 3.6 Distribution of beams for testing in the interlaboratory study.

point loading and those from Mix No. 14 being tested in third point loading.

At each testing site, the specimens were tested by personnel from that site normally responsible for testing beams in flexure, and thus familiar with the test method, TEX 420A [2], for center point loading. All accessories required for testing the beams in third point loading and for testing the 4.5-in. x 4.5-in. x 15.5-in. beams were provided by the researchers and transported with the beams to the testing location. The beams subjected to third point loading were tested according to ASTM C78 [13]. In all cases, the beams were tested using a Rainhart Series 416 Recording Beam Tester. The calibration of each machine had been verified within two weeks preceding the tests being conducted for the interlaboratory study.

CHAPTER 4

FIRST STAGE TEST RESULTS

4.1 Introduction

In this chapter, the experimental results obtained from the first stage tests are presented. These include the effects of specimen dimensions, coarse aggregate type and nominal maximum size, and loading method on flexural strength test results, as well as the relationship between flexural and compressive strength at seven days. Individual test results are given in Appendix A, along with equations used in reducing this data. In general, data points for flexural strength represent the average of 12 specimens tested, whereas data points for compressive strength represent the average of ten specimens tested. Modulus of rupture of beams loaded in center point loading is calculated at midspan and at the point of fracture. Center point loading test results presented are based on the stress at midspan as per the standard test procedure, unless specifically stated that the stress at fracture is used. The discrepency between the actual stress (at fracture) and the reported stress (at midspan) will be presented in Section 4.5.

4.2 Specimen Dimensions

The effect of specimen dimensions on the average modulus of rupture, standard deviation, and coefficient of variation of test results is studied. Results from both center point loading and third point loading are presented.

4.2.1 Center Point Loading. The effect of beam dimensions on the average modulus of rupture of specimens tested in center point loading is shown graphically in Fig. 4.1 versus coarse aggregate size for each of the ten concrete mixtures used in the first stage tests. In general, no trend is evident with regards to specimen size and average modulus of rupture results. The standard deviation of the test results, however, is affected by specimen dimensions, as shown in Fig. 4.2. In all cases except those mixes using 1-1/2-in. siliceous river gravel, the standard deviation of test results was higher for the smaller beams. The same trend can be seen in Fig. 4.3 for the coefficient of variation of the test results.

The ratio of the modulus of rupture of the 4.5-in. x 4.5-in. x 15.5-in. beams to the 6-in. x 6-in. x 20-in. beams is given in Table 4.1 for each mix. As shown in the table, the average ratio is

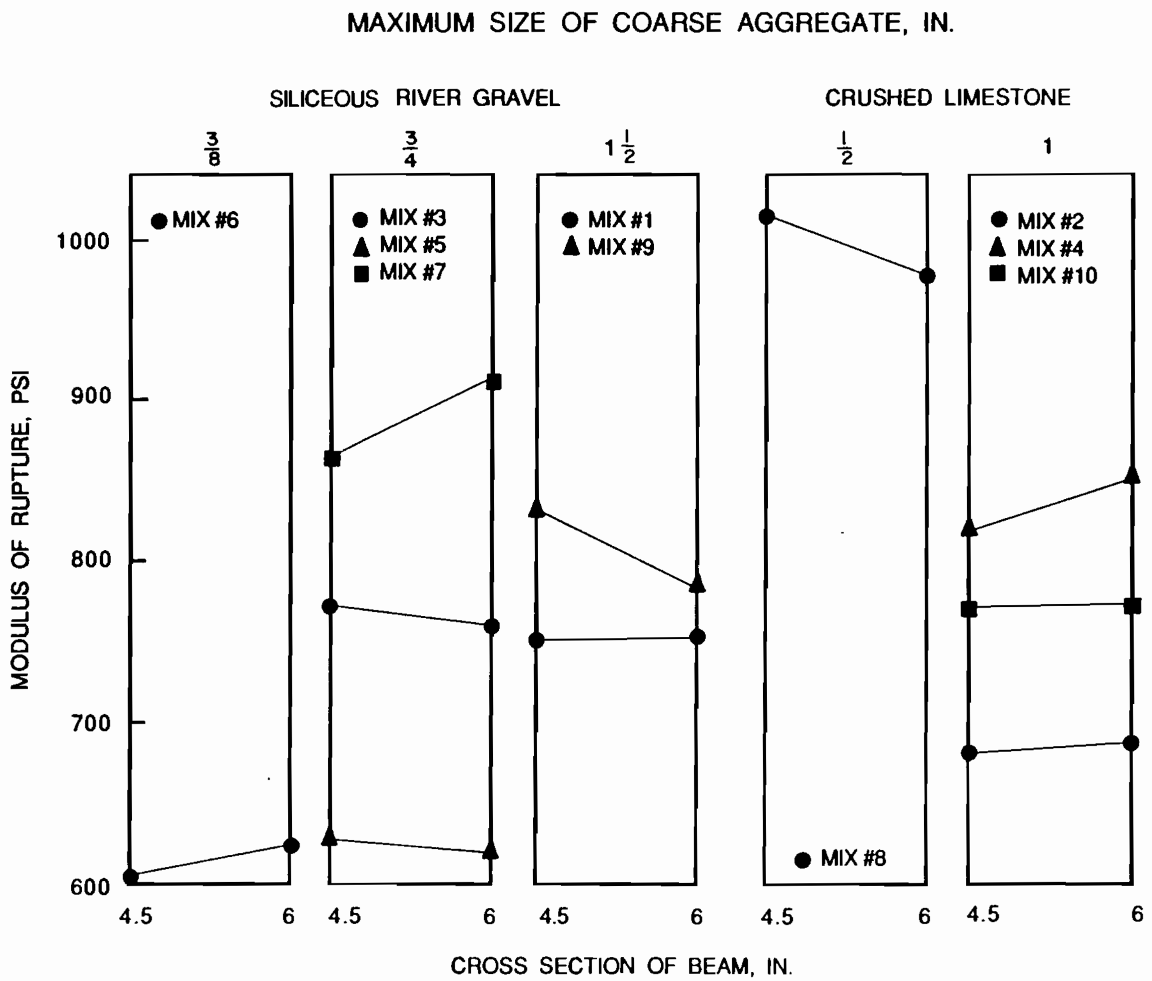


Figure 4.1 Effect of specimen dimensions on the modulus of rupture of beams loaded at their center point.

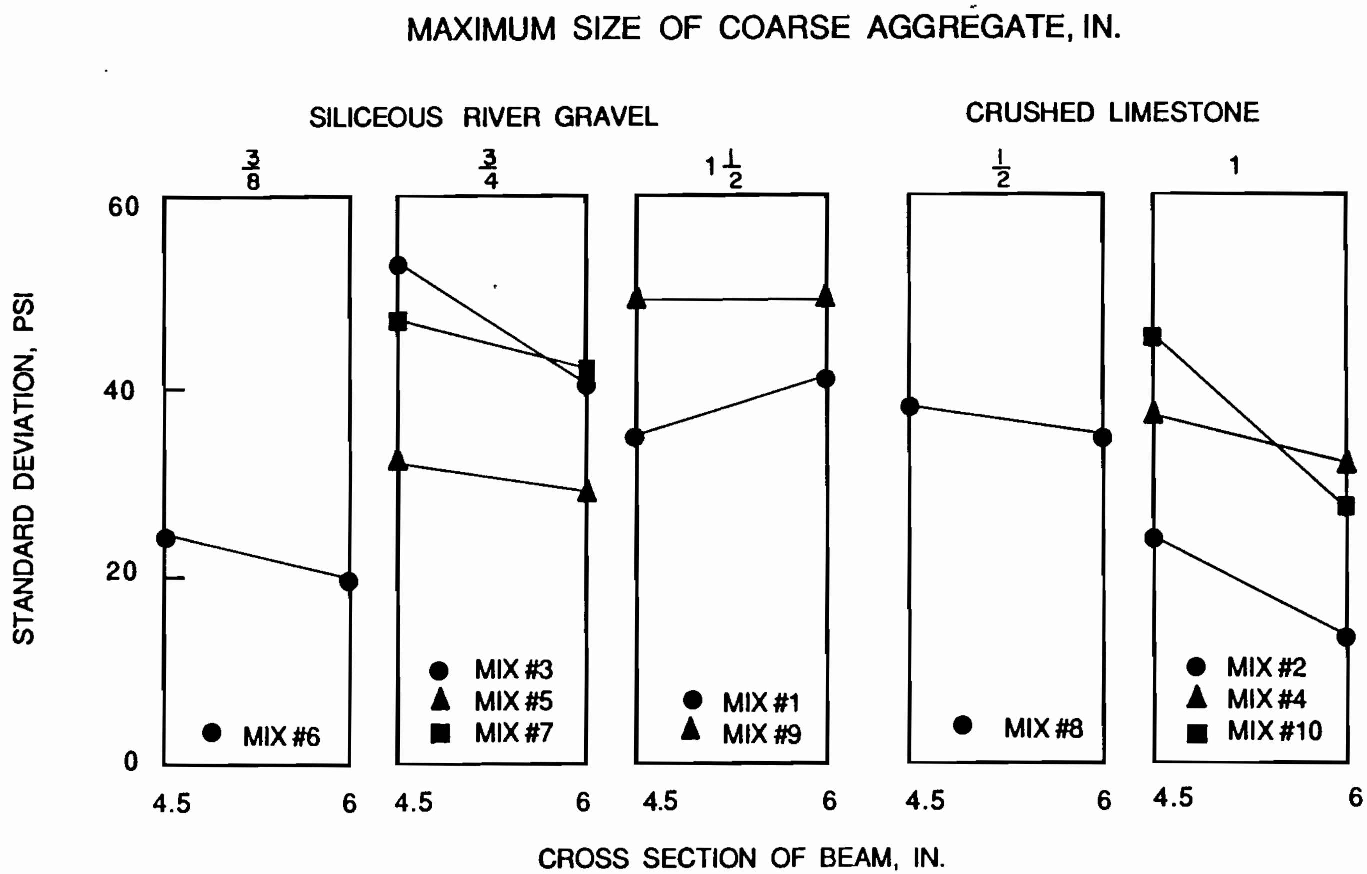


Fig. 4.2 Effect of specimen dimensions on the standard deviation of test results from beams loaded at their center point.

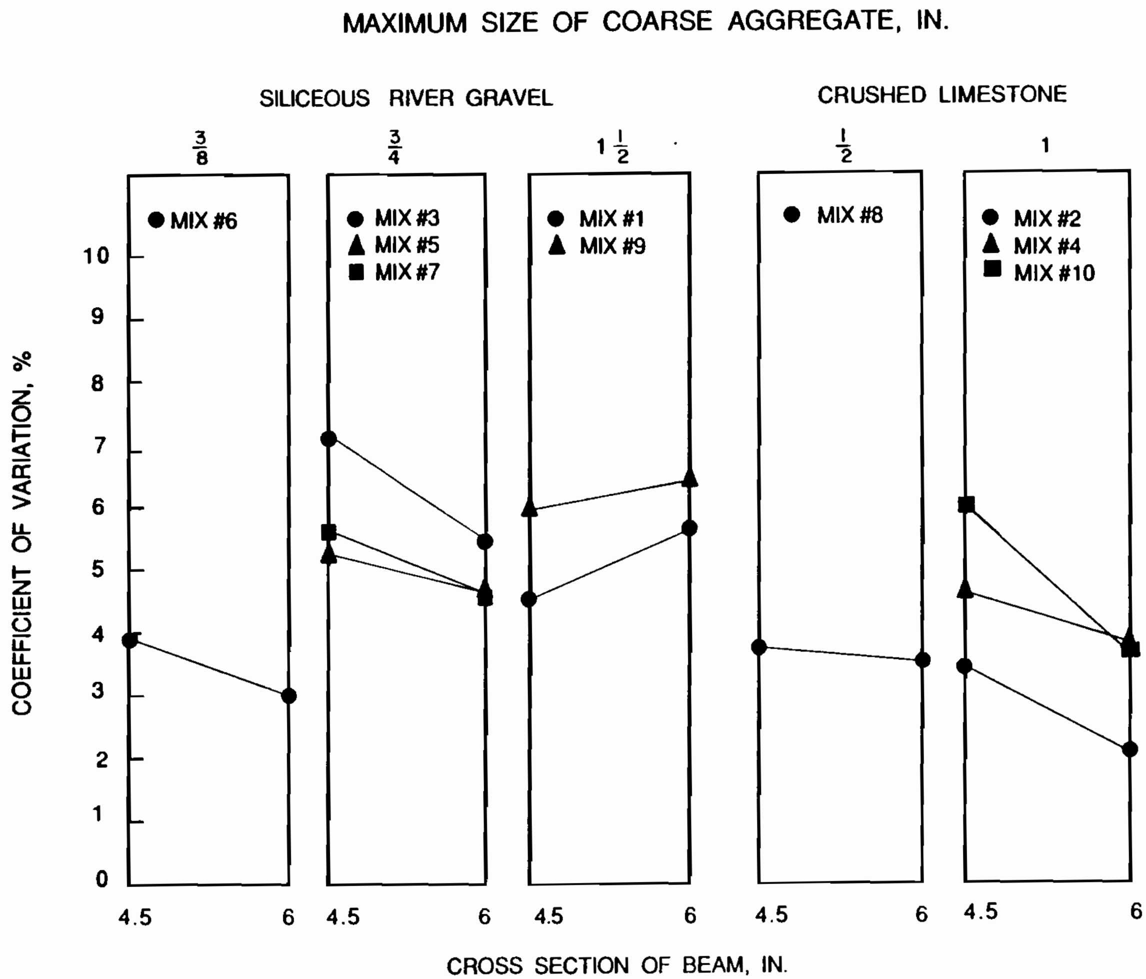


Fig. 4.3 Effect of specimen dimensions on the coefficient of variation of test results from beams loaded at their center point.

Table 4.1 Ratio of modulus of rupture of 4.5-in. x 4.5-in. x 15.5-in. beams to 6-in. x 6-in. x 20-in. beams, tested in center point loading with the moment calculated at midspan.

Mix No.	Coarse Agg. Size, in.	Modulus of Rupture, psi 4.5x4.5x15.5 Beams 1	6x6x20 Beams 2	Ratio, 1:2
1	1-1/2 SRG[1]	755	759	0.995
2	1 CS[2]	684	692	0.998
3	3/4 SRG	773	763	1.014
4	1 CS	822	853	0.964
5	3/4 SRG	630	627	1.006
6	3/8 SRG	604	624	0.968
7	3/4 SRG	865	914	0.946
8	1/2 CS	1018	983	1.036
9	1-1/2 SRG	835	785	1.064
10	1 CS	775	774	1.002
	Average	776	777	0.999

[1] Siliceous river gravel
[2] Crushed limestone

approximately 1.00, with its approximate range being from -5% to +6%. This is shown in Fig. 4.4. The individual ratios are plotted versus the modulus of rupture of the 6-in. x 6-in. x 20-in. beams in Fig. 4.5, and versus coarse aggregate size in Fig. 4.6. From these graphs, no trend is evident relating the effect of specimen dimensions to concrete strength level or coarse aggregate size.

4.2.2 Third Point Loading. The effect of beam dimensions on the average modulus of rupture of specimens tested in third point loading is shown graphically in Fig. 4.7. The average modulus of rupture obtained from 6-in. x 6-in. x 20-in. beams is lower than that obtained from 4.5-in. x 4.5-in. x 15.5- in. beams for all concrete mixtures except Mix No. 6, which contained 3/8-in. gravel, in which case the results are approximately equal. The standard deviation and coefficient of variation of the test results are plotted in Figs. 4.8 and 4.9 versus specimen dimensions for each mix and coarse aggregate size. Both the standard deviation and coefficient of variation decrease with increasing specimen size for all cases except Mix No. 10, which showed the opposite trend. However, specimens from both Mix Nos. 2 and 4, which, like Mix No. 10, contained 1-in. crushed limestone, showed higher variation of test results for the smaller specimen size.

The ratios of modulus of rupture of the smaller beams to the larger beams, both tested in third point loading, are given in Table 4.2 for each mix. On the average, the modulus of rupture of 4.5-in. x 4.5-in. x 15.5-in. beams was 7% higher than that of 6-in. x 6-in. x 20-in. beams, with the individual values ranging from 0.99 to 1.16. This is shown in Fig. 4.10. The ratios are plotted versus modulus of rupture of 6-in. x 6-in. x 20-in. beams in Fig. 4.11, and versus coarse aggregate size in Fig. 4.12. Similar to center point loading, there is no clear relationship between the ratio of modulus of rupture of specimens of different dimensions tested in third point loading and either concrete strength level or coarse aggregate size.

4.3 Coarse Aggregate

Siliceous river gravel and crushed limestone were used having a range of nominal maximum sizes. The effects of coarse aggregate type and maximum size on the variation of test results will be examined for each test method.

4.3.1 Center Point Loading. The coefficient of variation of test results obtained from 6-in. x 6-in. x 20-in. beams tested in center point loading is plotted versus coarse aggregate size in Fig. 4.13. As shown in this figure, the variation of test results was higher for specimens containing gravel than for specimens containing

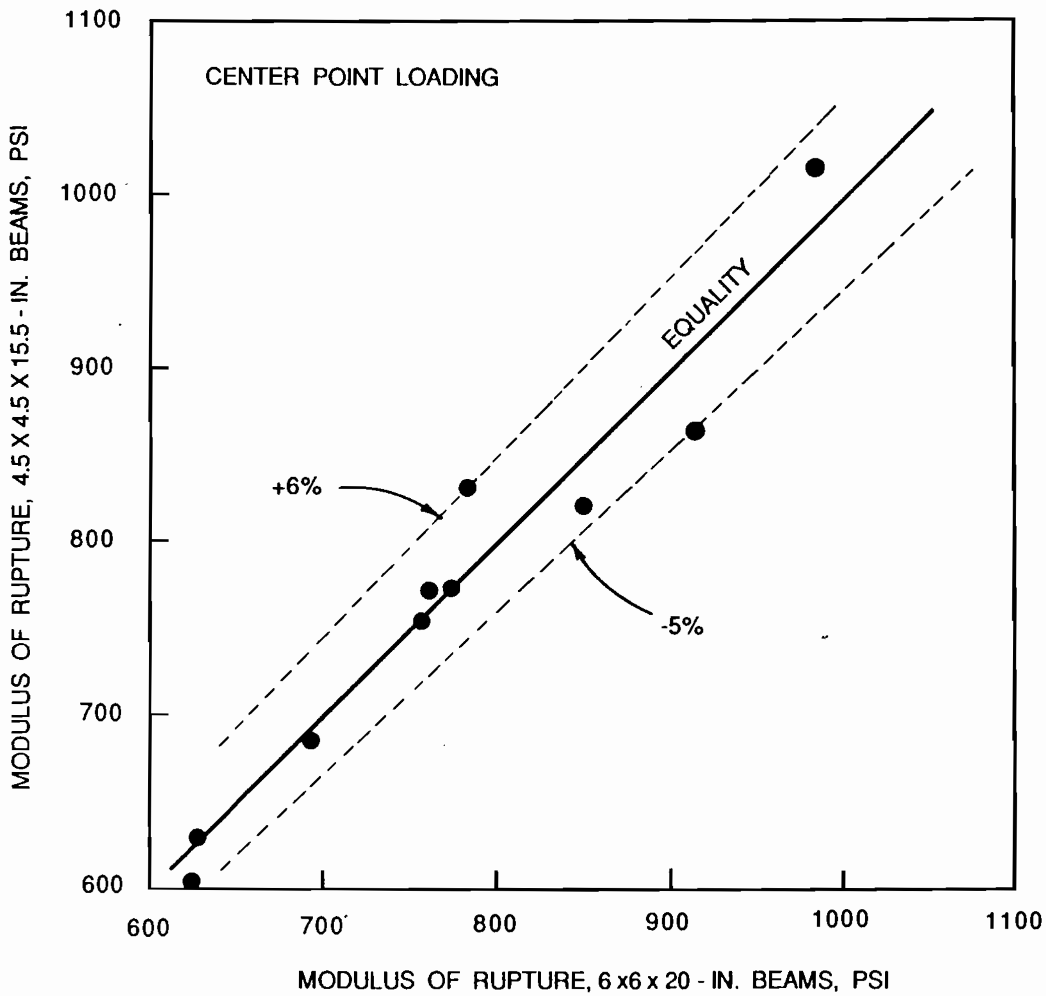


Fig. 4.4 Modulus of rupture of 4.5-in. x 4.5-in. x 15.5-in. beams versus that of 6-in. x 6-in.x 12-in. beams, both tested in center point loading.

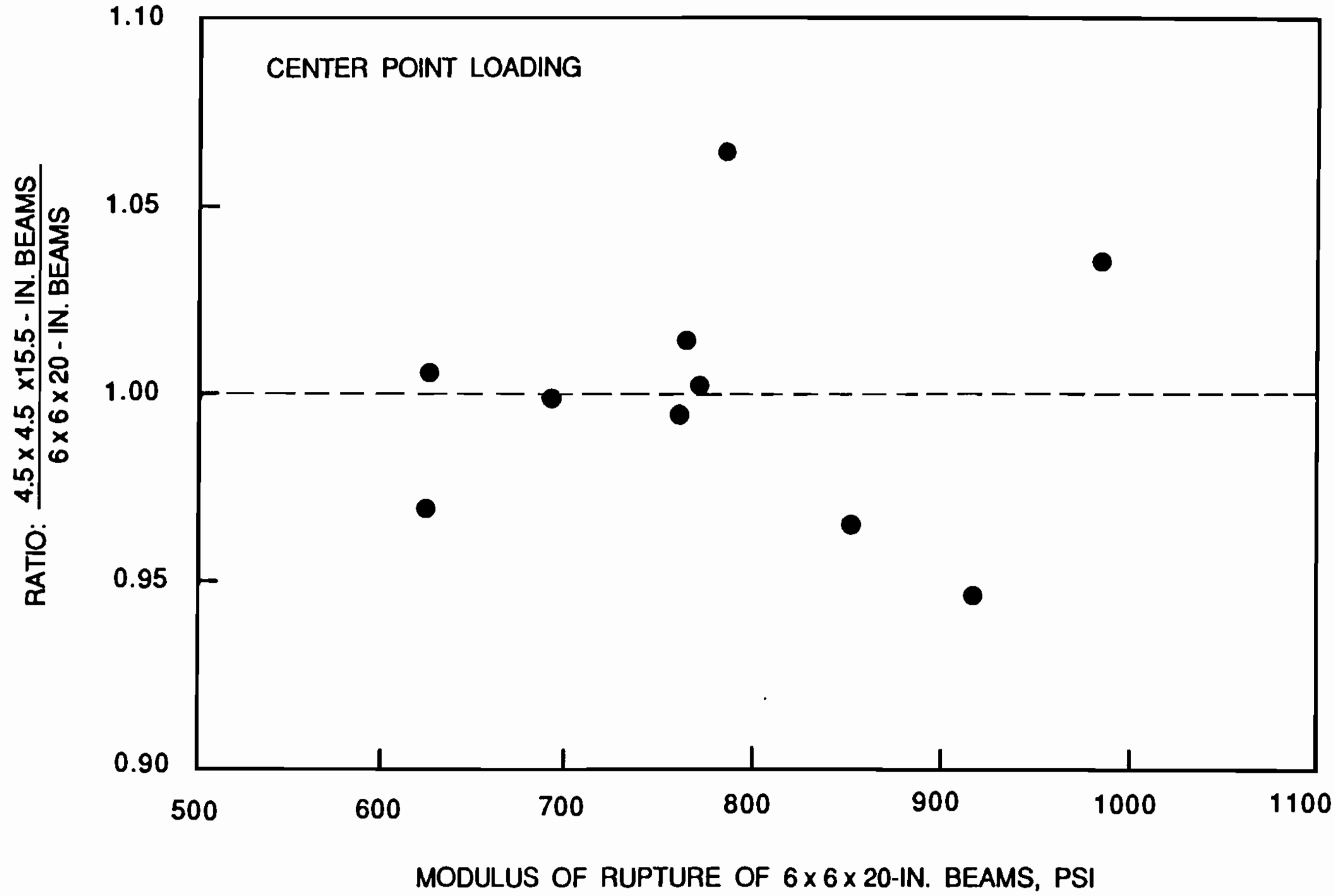


Fig. 4.5 Ratio of modulus of rupture of 4.5-in. x 4.5-in. x 15.5-in. beams to 6-in. x 6-in. x 20-in. beams, tested in center point loading, plotted versus the modulus of rupture of 6-in. x 6-in. x 20-in. beams.

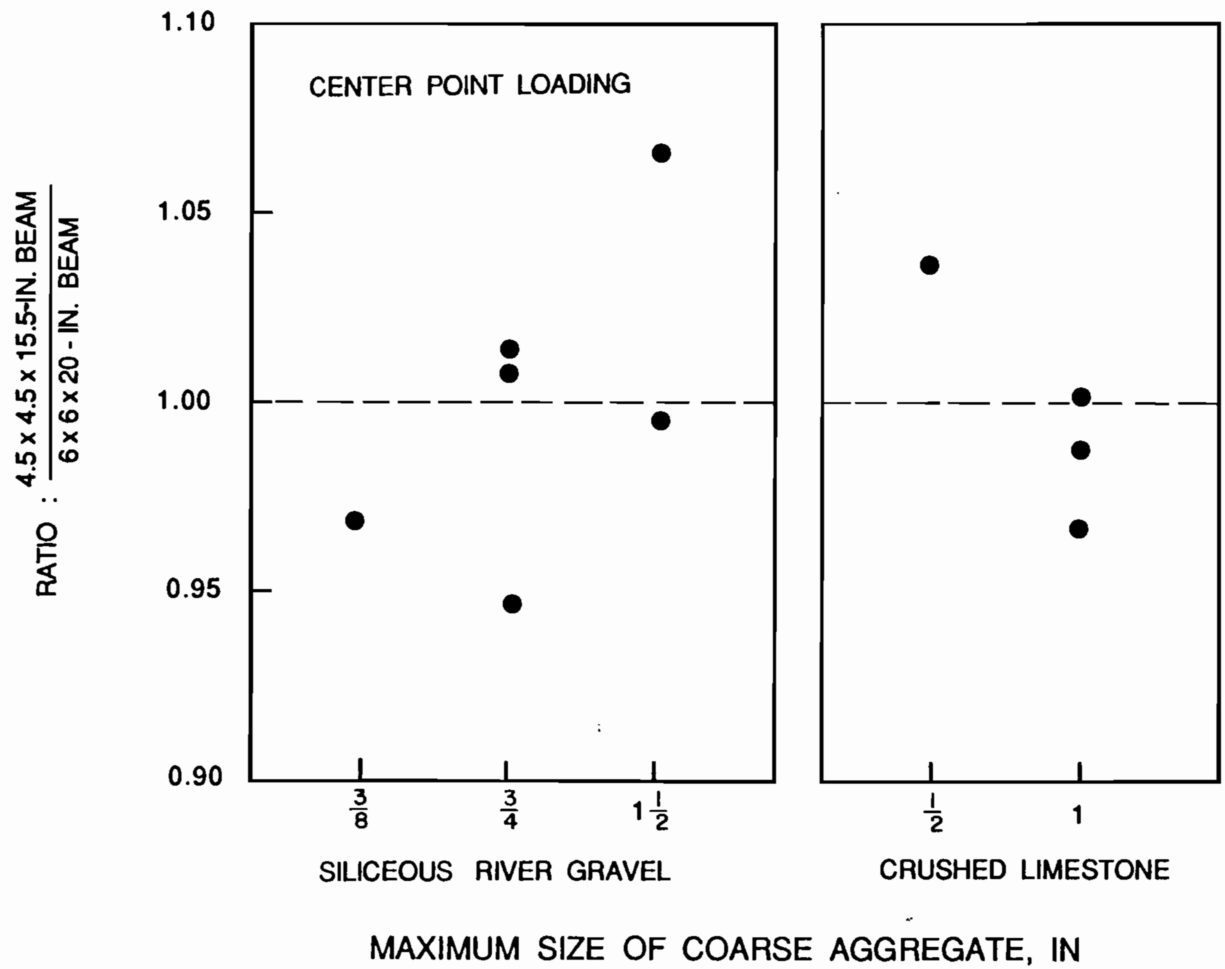


Fig. 4.6 Ratio of modulus of rupture of 4.5-in. x 4.5-in. x 15.5-in. beams to 6-in. x 6-in. x 20-in. beams, for center point loading, plotted versus coarse aggregate size.

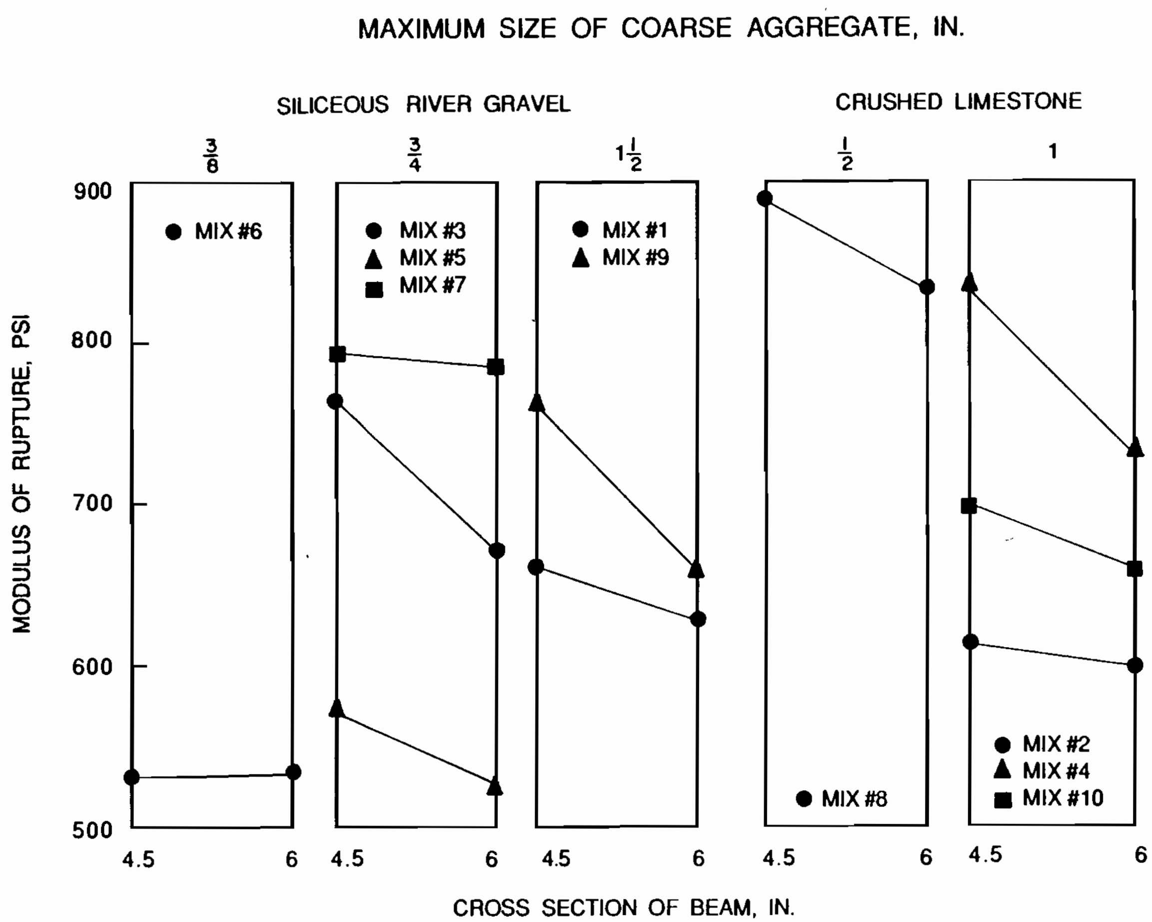


Fig. 4.7 Effect of specimen dimensions on the modulus of rupture of beams loaded at their third points for each coarse aggregate size.

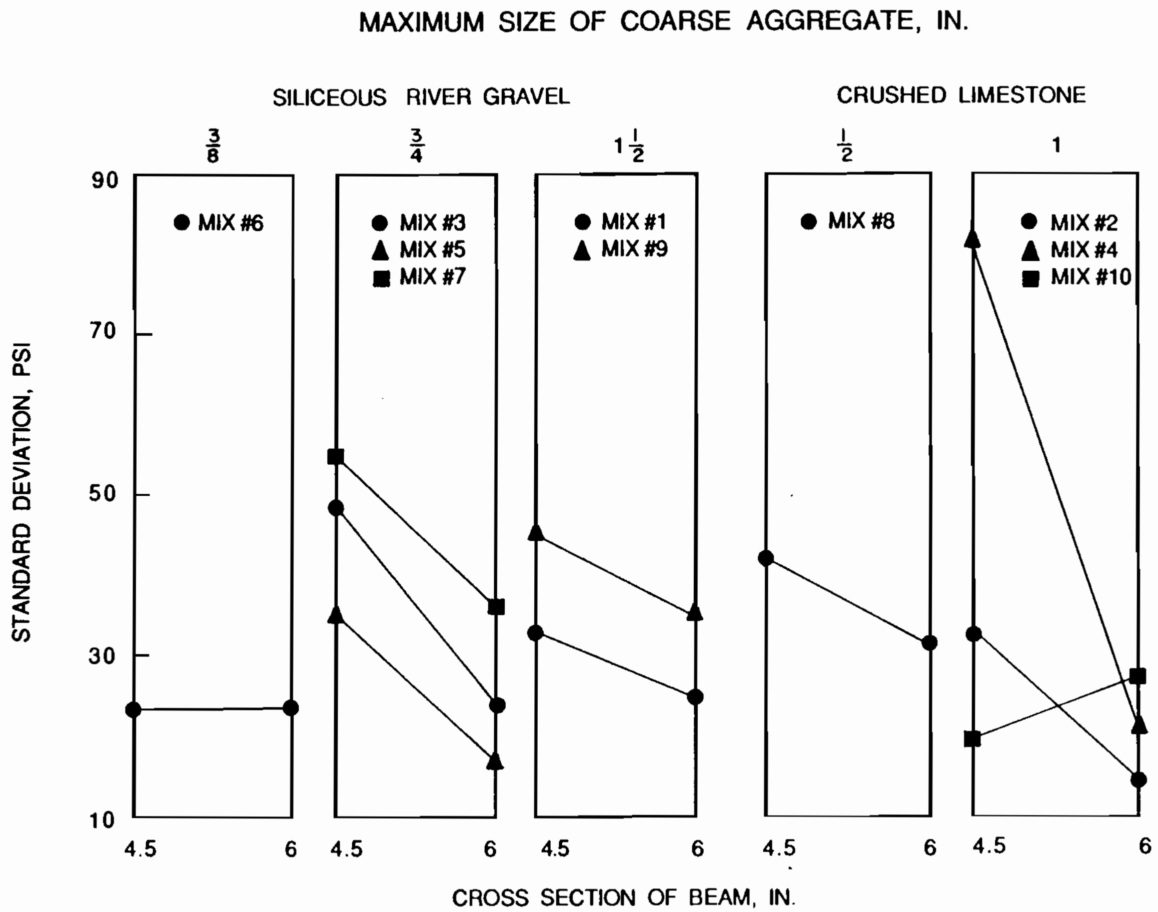


Fig. 4.8 Effect of specimen dimensions on the standard deviation of test results from beams loaded at their third poits for each coarse aggregate size

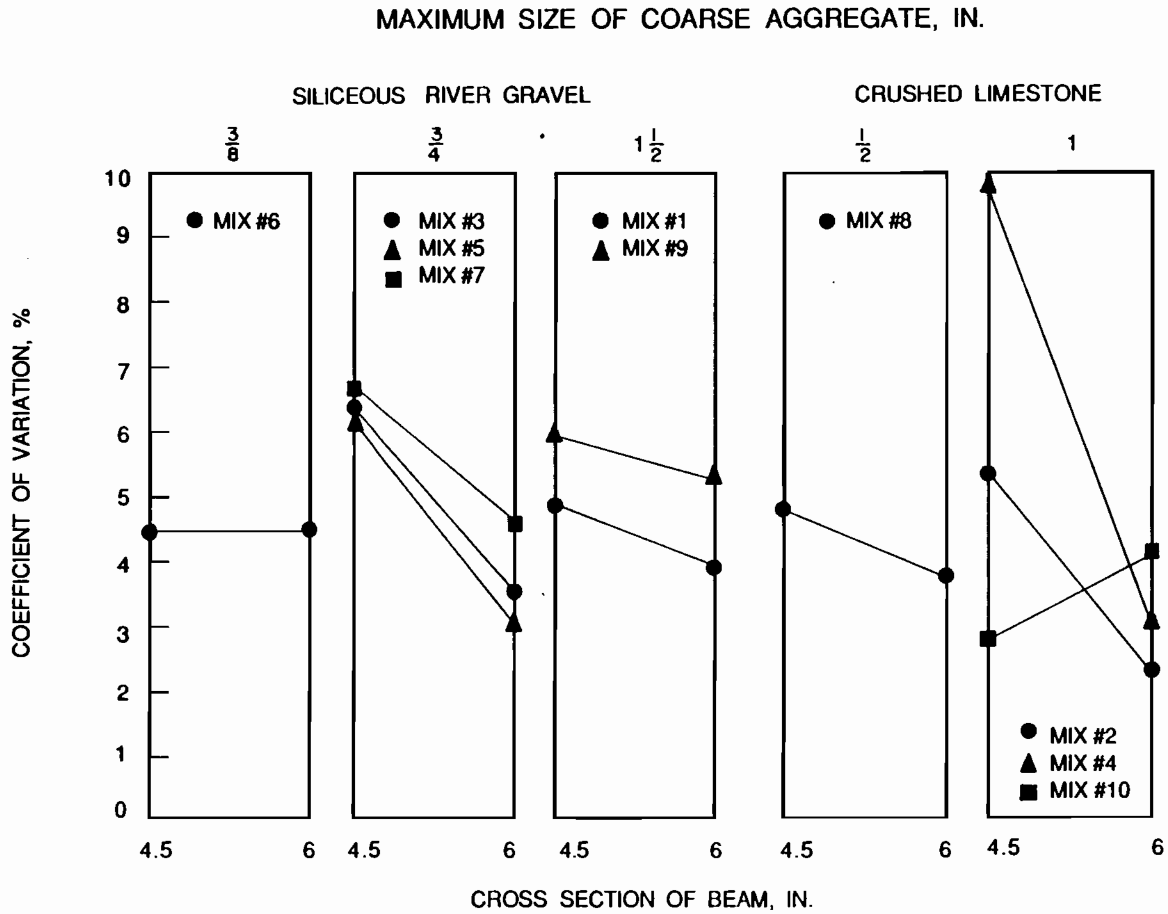


Fig. 4.9 Effect of specimen dimensions on the coefficient of variation of test results from beams loaded at their third points for each coarse aggregate size

Table 4.2 Ratio of modulus of rupture of 4.5-in. x 4.5-in. x 15.5-in. beams to 6-in. x 6-in. x 20-in. beams, tested in third point loading.

Mix No.	Coarse Agg. Size, in.	Modulus of Rupture, psi 4.5x4.5x15.5 Beams 1	Modulus of Rupture, psi 6x6x20 Beams 2	Ratio, 1:2
1	1-1/2 SRG[1]	668	637	1.049
2	1 CS[2]	618	604	1.023
3	3/4 SRG	768	675	1.138
4	1 CS	837	735	1.139
5	3/4 SRG	569	529	1.076
6	3/8 SRG	534	538	0.993
7	3/4 SRG	798	791	1.009
8	1/2 CS	891	835	1.067
9	1-1/2 SRG	768	662	1.160
10	1 CS	702	666	1.054
	Average	715	667	1.071

[1] Siliceous river gravel
[2] Crushed limestone

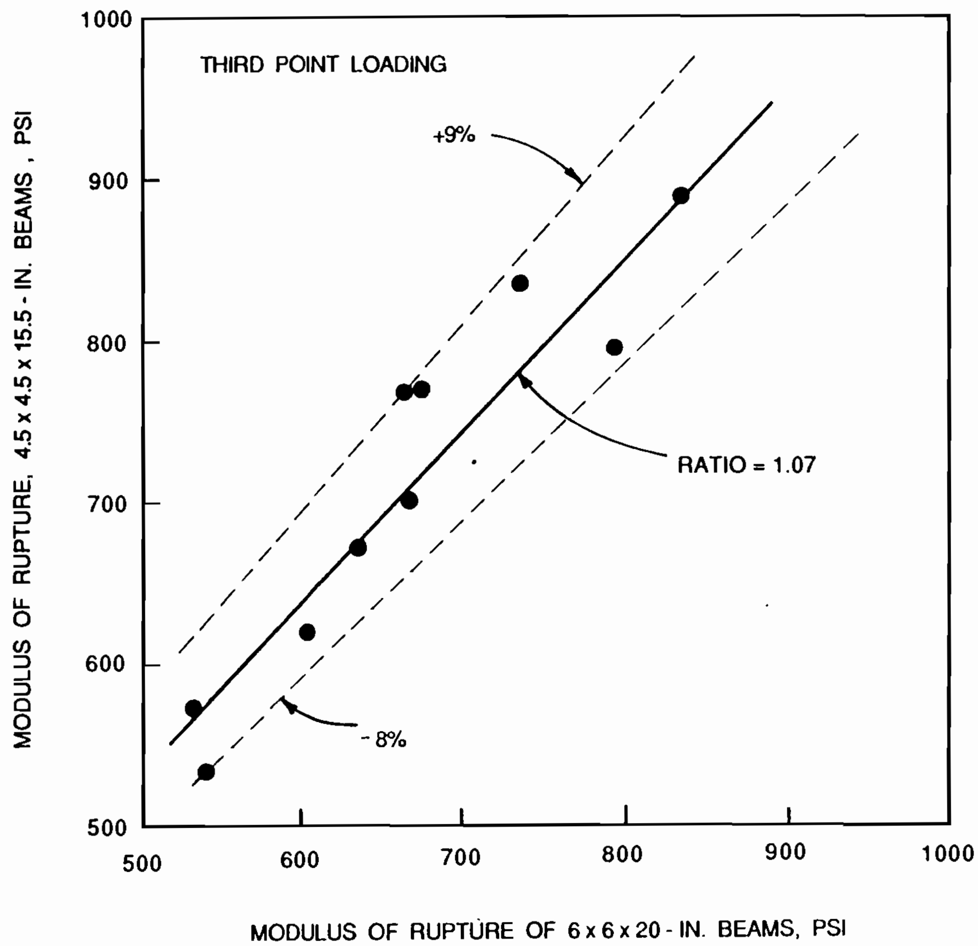


Fig. 4.10 Modulus of rupture in third point loading of 4.5-in. x 4.5-in. x 15.5-in. beams versus that of 6-in. x 6-in. x 20-in. beams.

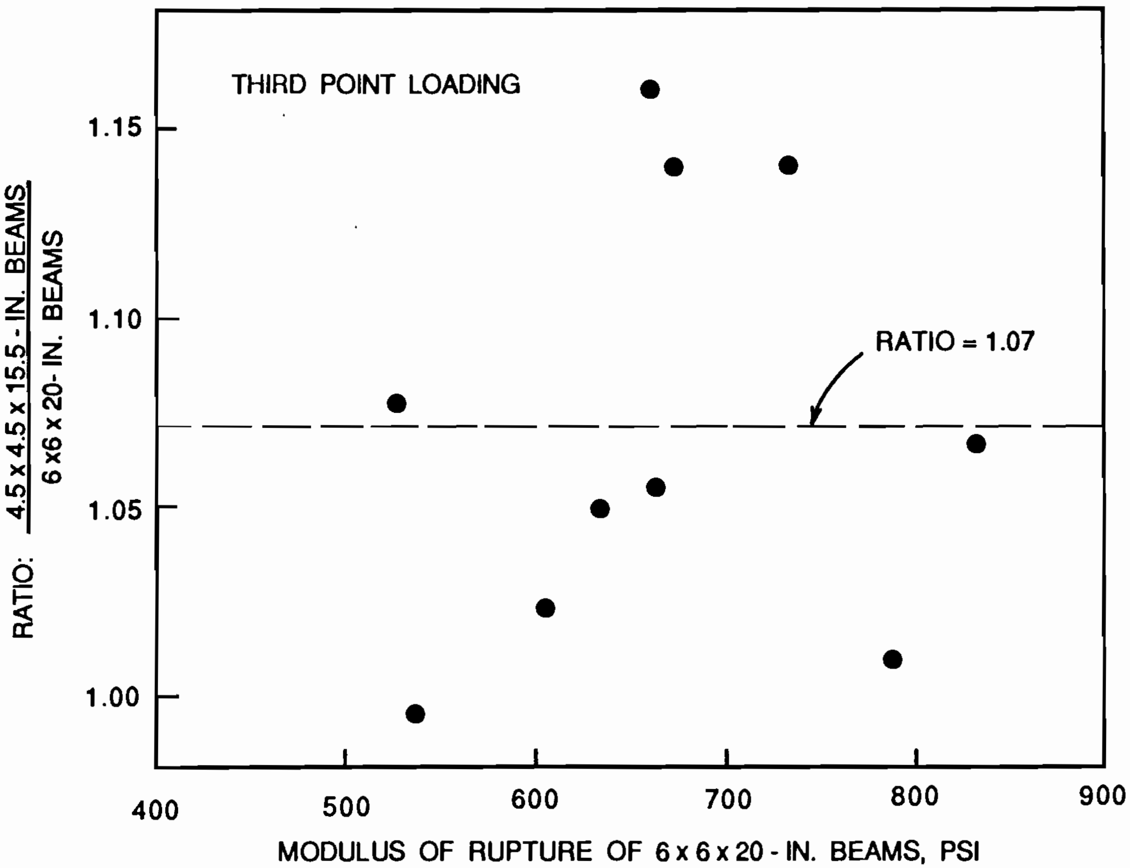


Fig. 4.11 Ratio of modulus of rupture in third point loading of 4.5-in. x 4.5-in. x 15.5-in. beams to 6-in. x 6-in. x 20-in. beams, plotted versus the modulus of rupture of 6-in. x 6-in. x 20-in. beams.

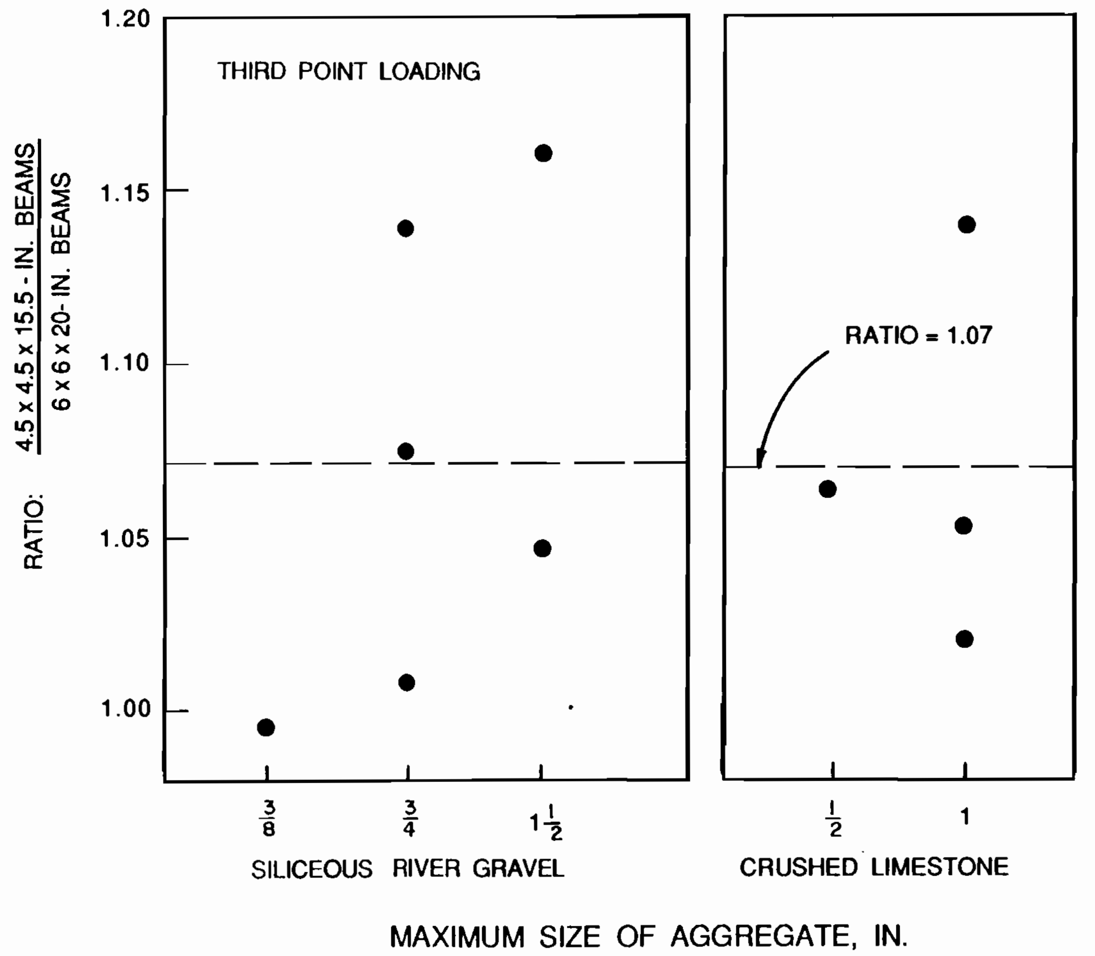


Fig. 4.12 Ratio of modulus of rupture in third point loading of 4.5-in. x 4.5-in. x 15.5-in. beams to 6-in. x 6-in. x 20-in. beams plotted versus coarse aggregate size.

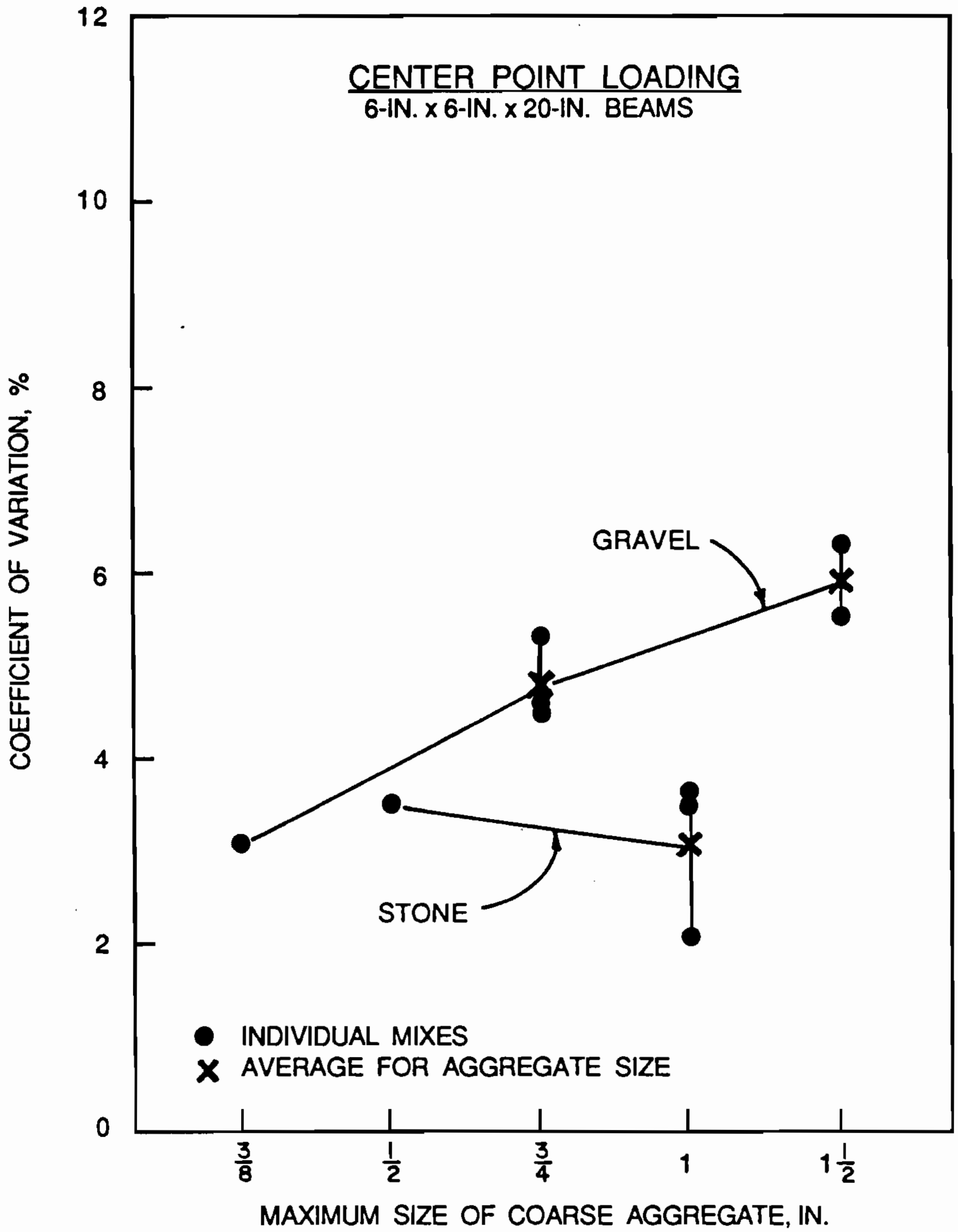


Fig. 4.13 Coefficient of variation of test results from 6-in. x 6-in. x 20-in. beams loaded at their center point, plotted versus coarse aggregate size.

crushed limestone. In addition, the variation of test results increased as larger size gravel was used. In general, the trends were similar for 4.5-in. x 4.5-in. x 15.5-in. specimens tested in center point loading, as shown in Fig. 4.14.

4.3.2 Third Point Loading. The coefficient of variation of test results obtained from specimens tested in third point loading is plotted versus coarse aggregate size for 6-in. x 6-in. x 20-in. beams in Fig. 4.15, and for 4.5-in. x 4.5-in. x 15.5-in. beams in Fig. 4.16. For both beam sizes, the variation of test results for specimens containing gravel was higher than for those containing stone. The only exception to this was for 4.5-in. x 4.5-in. x 15.5-in. specimens from one mix containing 1- in. crushed limestone, which appears to be an outlier with respect to the other data.

4.4 Third Point Loading Versus Center Point Loading

Two loading methods, center point and third point, were used in testing specimens of two sizes, 6-in. x 6-in. x 20-in. beams and 4.5-in. x 4.5-in. x 15.5-in. beams. Thus, four combinations were tested, these being large beams with center point loading, large beams with third point loading, small beams with center point loading, and small beams with third point loading. Since the current flexural strength test being used by the SDHPT is with large beams and center point loading, each of the other test methods will be evaluated with respect to the standard 6-in. x 6-in. x 20-in. beams subjected to center point loading. Comparison of results obtained from 4.5-in. x 4.5-in. x 15.5-in. beams tested in center point loading to 6-in. x 6-in. x 20-in. beams tested in center point loading was made in Section 4.2.

4.4.1 Large Beam Third Point Loading. Concrete specimens tested in third point loading yield lower results than if tested in center point loading. As shown in Fig. 4.17, 6-in. x 6-in. x 20-in. beams tested in third point loading gave modulus of rupture results which were, on the average, only 86% of those tested in center point loading. These values are tabulated in Table 4.3, where it is shown that the ratio of third point loading test results to center point loading test results ranges between approximately 84 to 89 percent. These ratios are plotted versus the standard beam test results in Fig. 4.18, and versus coarse aggregate size in Fig. 4.19. From these figures, no trend is evident with respect to concrete strength level or maximum size of coarse aggregate.

The standard deviation and coefficient of variation of 6-in. x 6-in. x 20-in. beams tested in third point loading versus center point loading are shown in Figs. 4.20 and 4.21. From these figures it

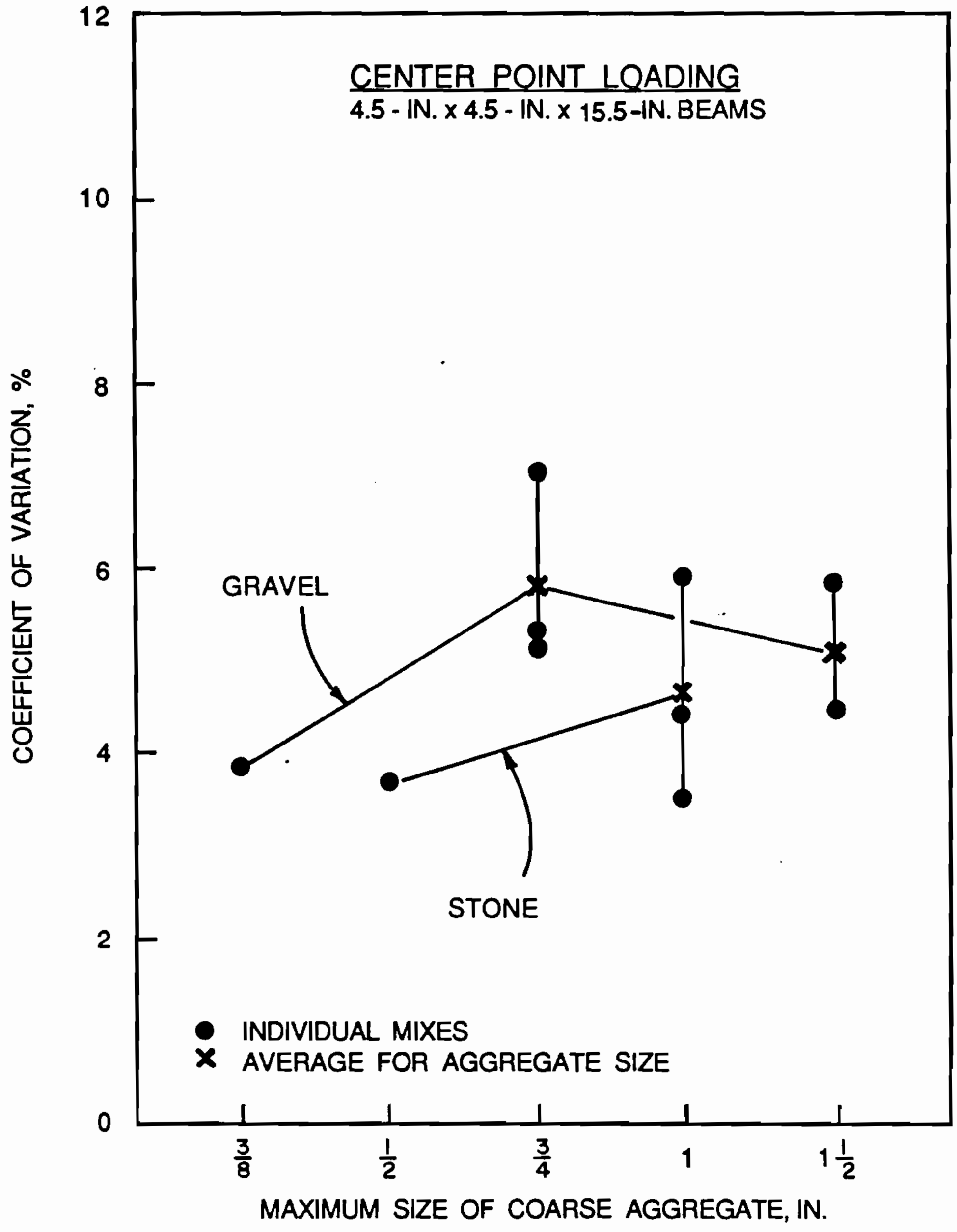


Fig. 4.14 Coefficient of variation of test results from 4.5-in. x 4.5-in. x 15.5-in. beams loaded at their center point, plotted versus coarse aggregate size.

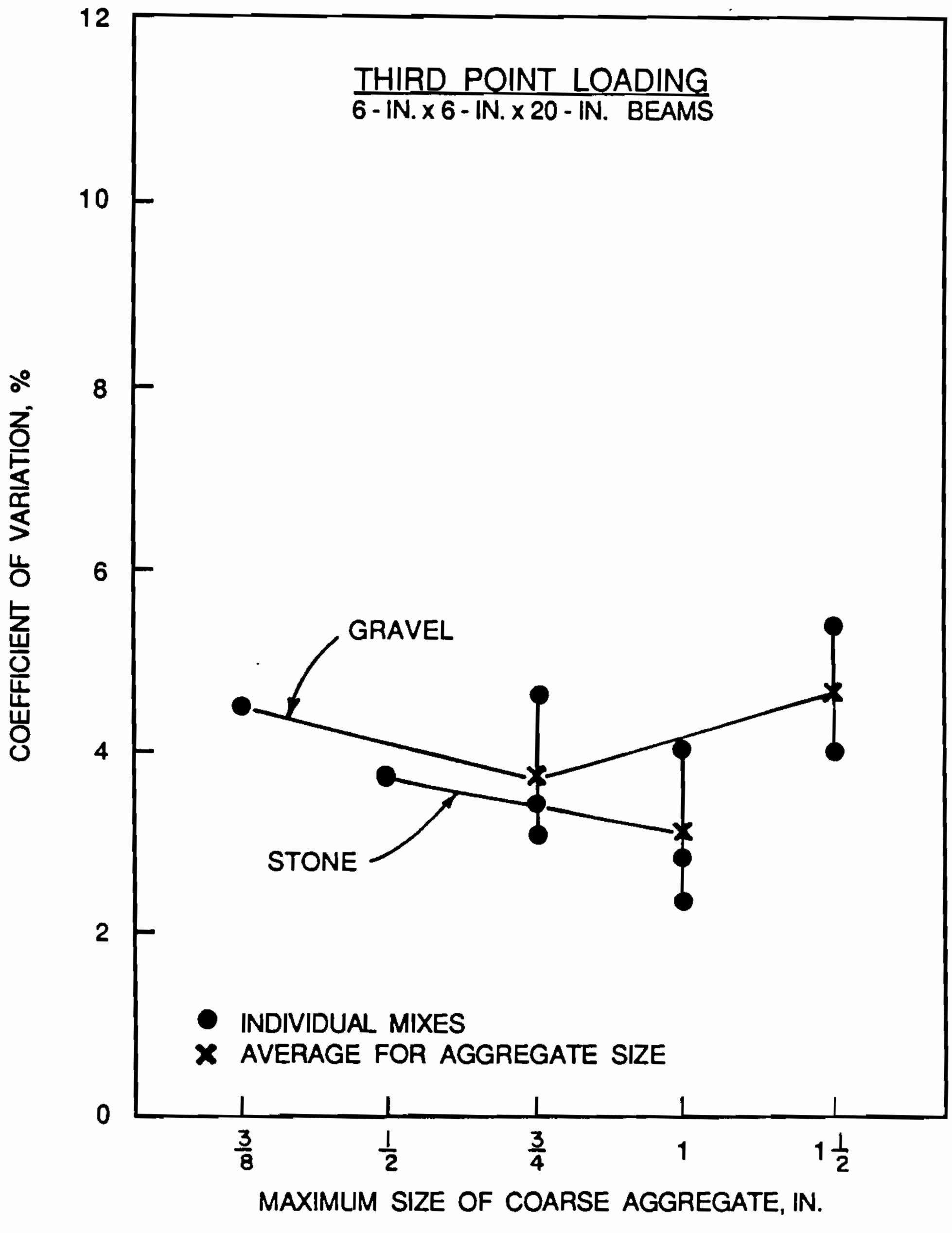


Fig. 4.15 Coefficient of variation of test results from 6-in. x 6-in. x 20-in. beams loaded at their third points, plotted versus coarse aggregate size.

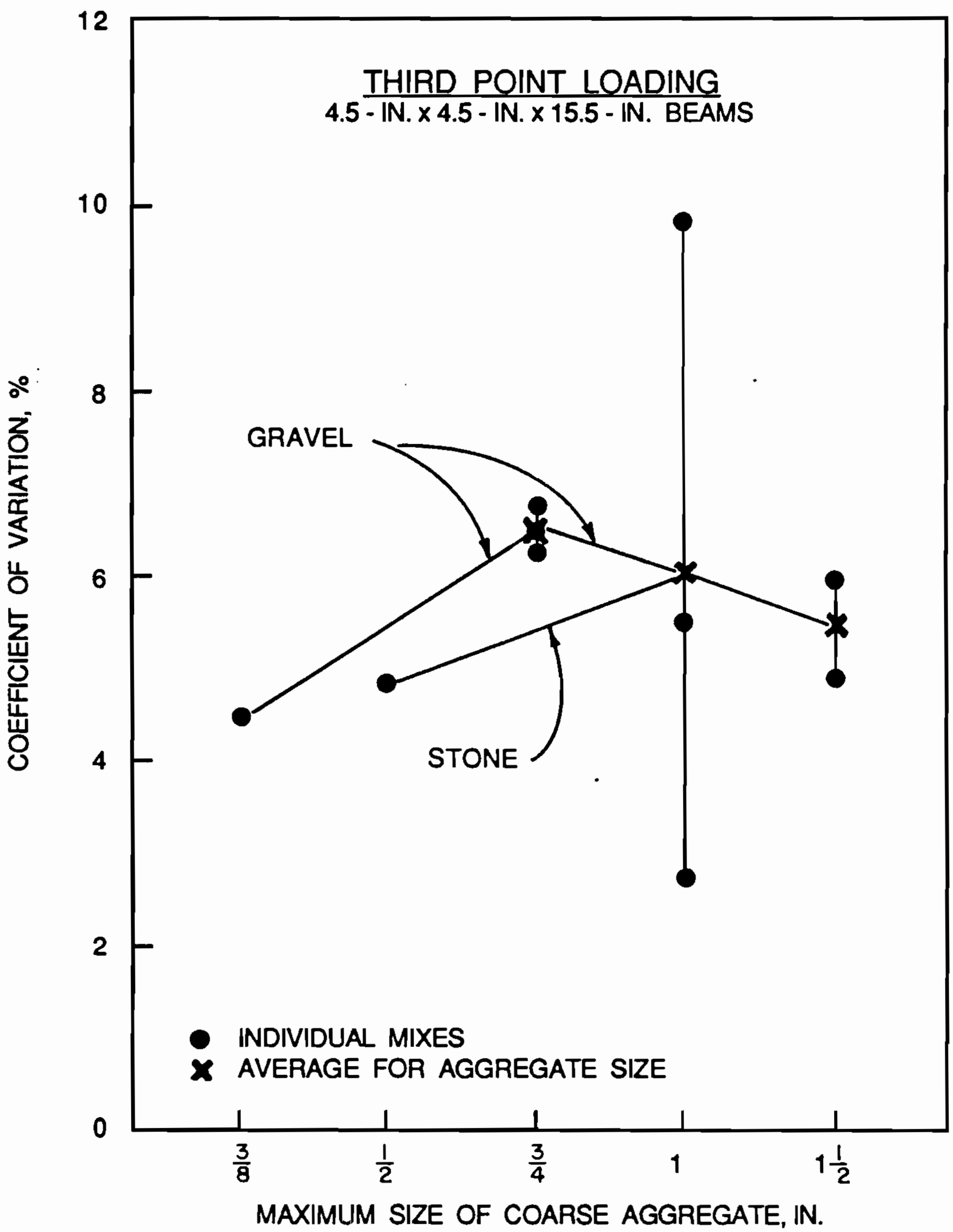


Fig. 4.16 Coefficient of variation of test results from 4.5-in. x 4.5-in. x 15.5-in. beams loaded at their third points, plotted versus coarse aggregate size.

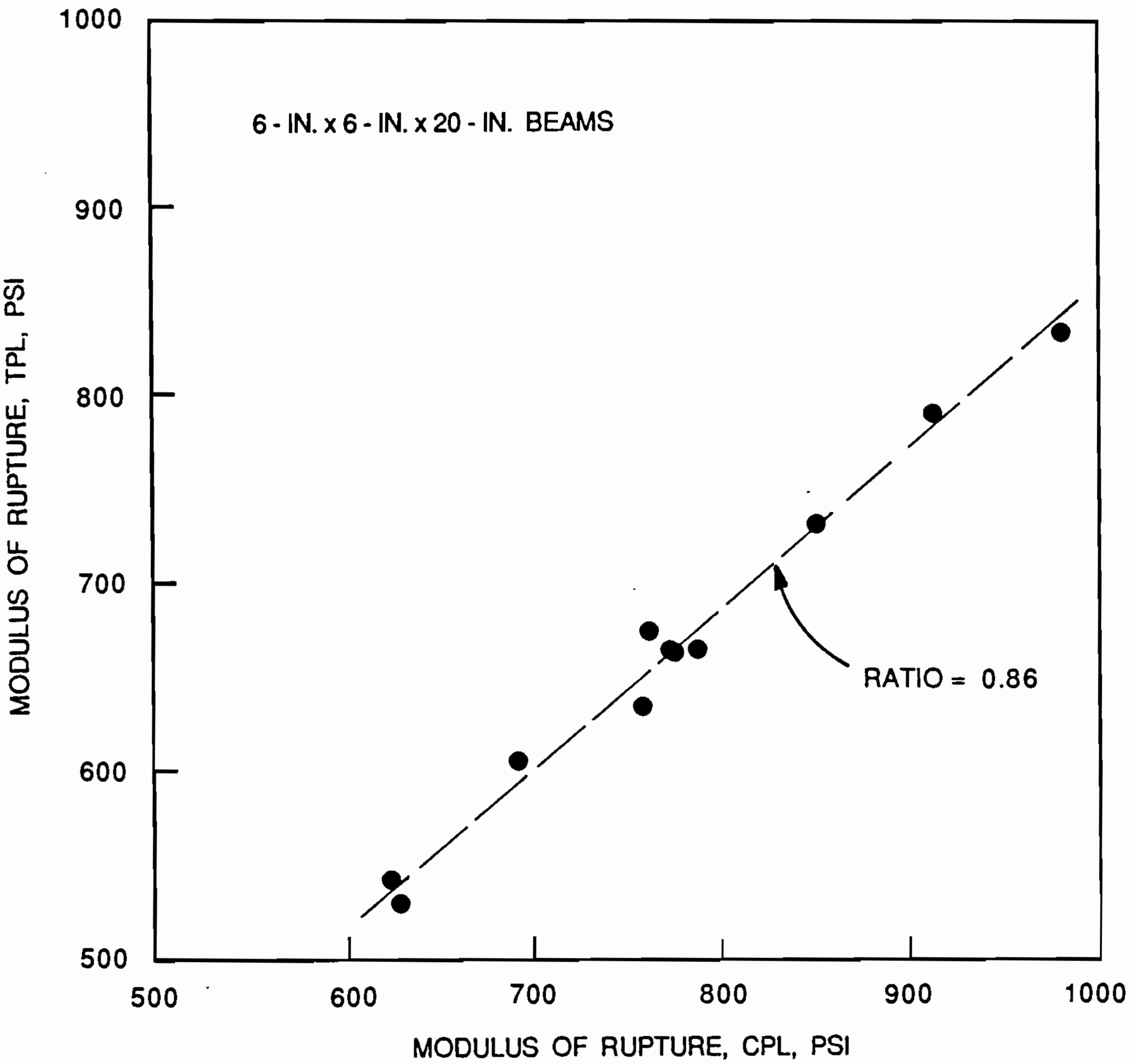


Fig. 4.17 Modulus of rupture of beams tested in center point loading versus third point loading, for 6-in. x 6-in. x 20-in. beams.

Table 4.3 Ratio of average modulus of rupture results obtained from specimens tested in third point loading to those tested in center point loading for 6-in. x 6-in. x 20-in. beams.

Mix No.	Coarse Agg. Size, in.	Modulus of Rupture, psi 6-in.x6-in.x20-in. beams TPL[3] 1	CPL[4] 2	Ratio, 1:2
1	1-1/2 SRG[1]	637	759	0.839
2	1 CS[2]	604	692	0.873
3	3/4 SRG	675	763	0.885
4	1 CS	735	853	0.862
5	3/4 SRG	529	627	0.844
6	3/8 SRG	538	624	0.862
7	3/4 SRG	791	914	0.865
8	1/2 CS	835	983	0.849
9	1-1/2 SRG	662	785	0.843
10	1 CS	666	774	0.860
	Average	667	777	0.858

[1] Siliceous river gravel
[2] Crushed limestone
[3] Third point loading
[4] Center point loading

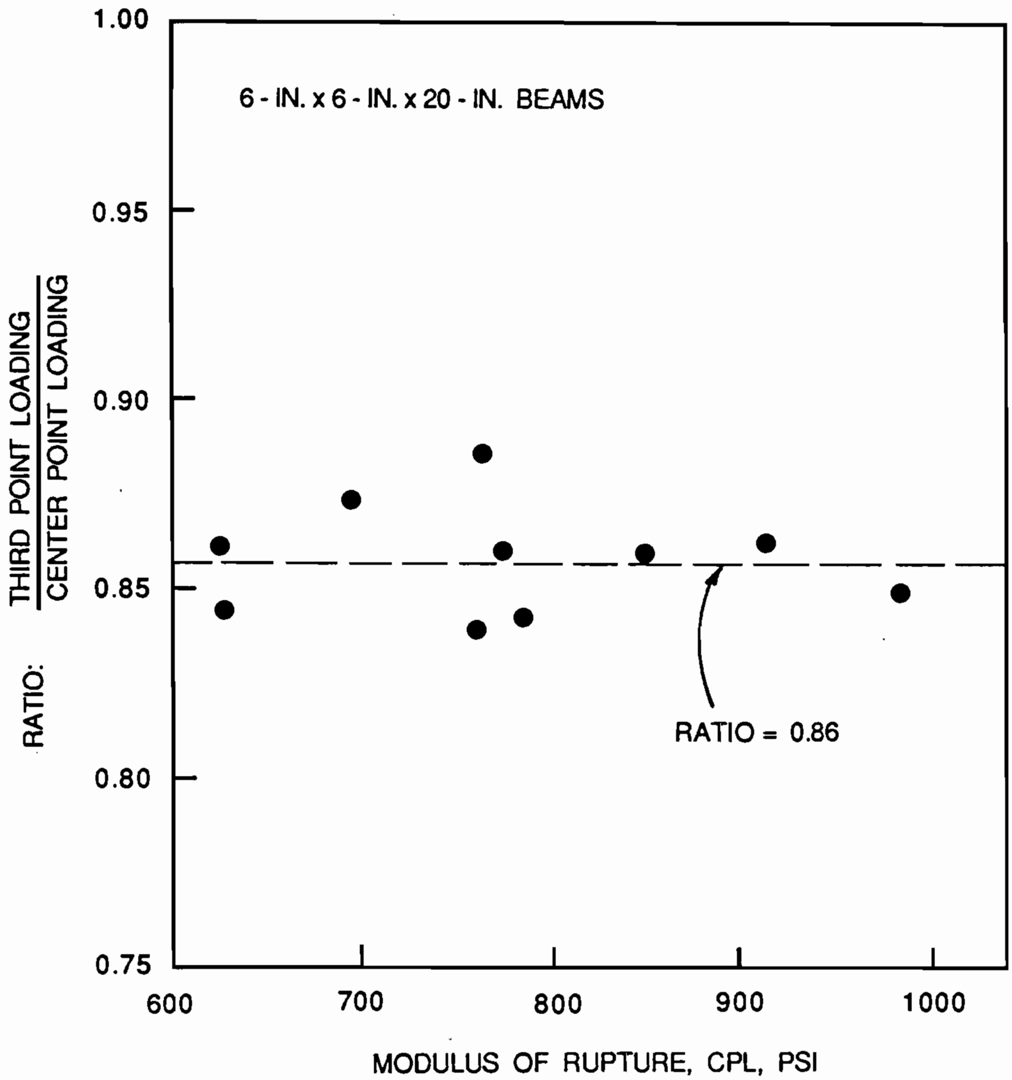


Fig. 4.18 Ratio of modulus of rupture test results obtained from third point loading to those obtained from center point loading, for 6-in. x 6-in. x 20-in. beams, potted versus results from the TSDHPT standard test method.

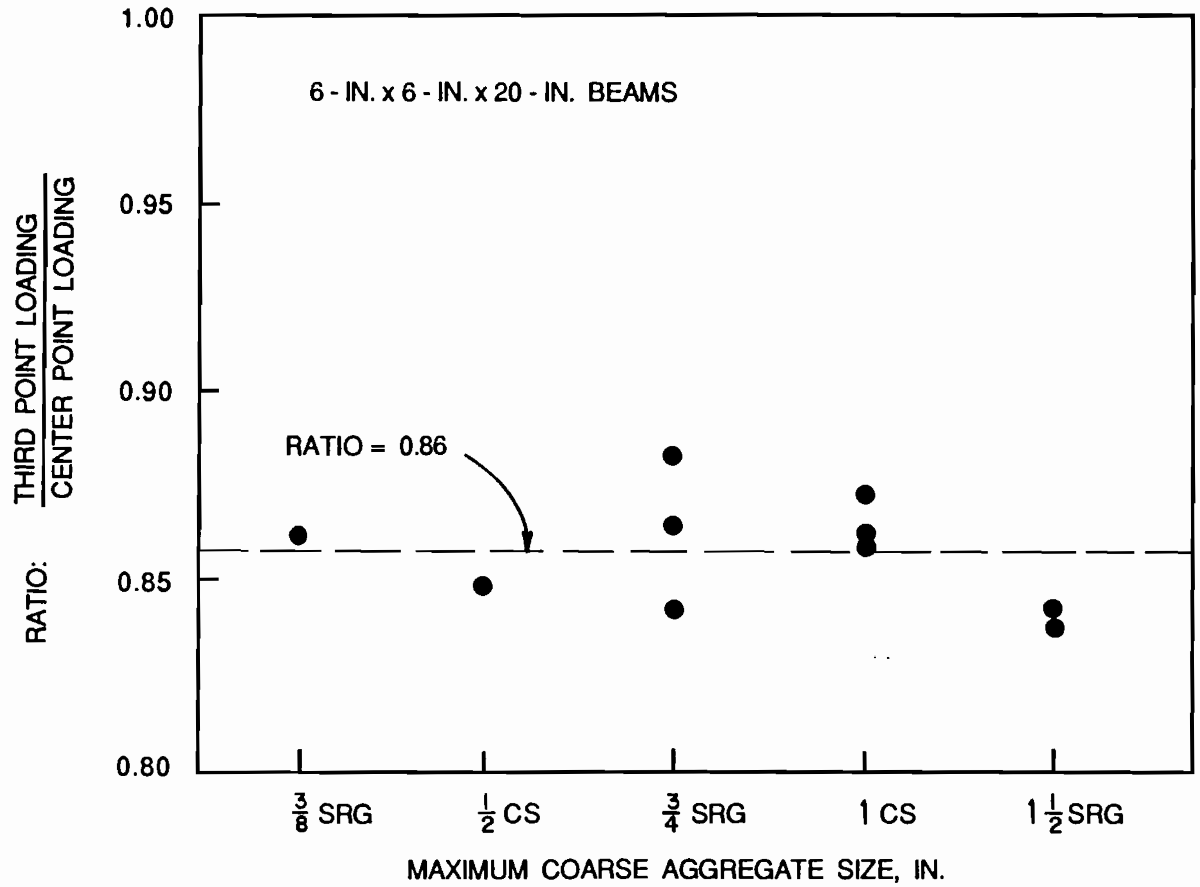


Fig. 4.19 Ratio of modulus of rupture test results obtained from third point loading to those obtained from center point loading, for 6-in. x 6-in. x 20-in. beams, plotted versus coarse aggregate size.

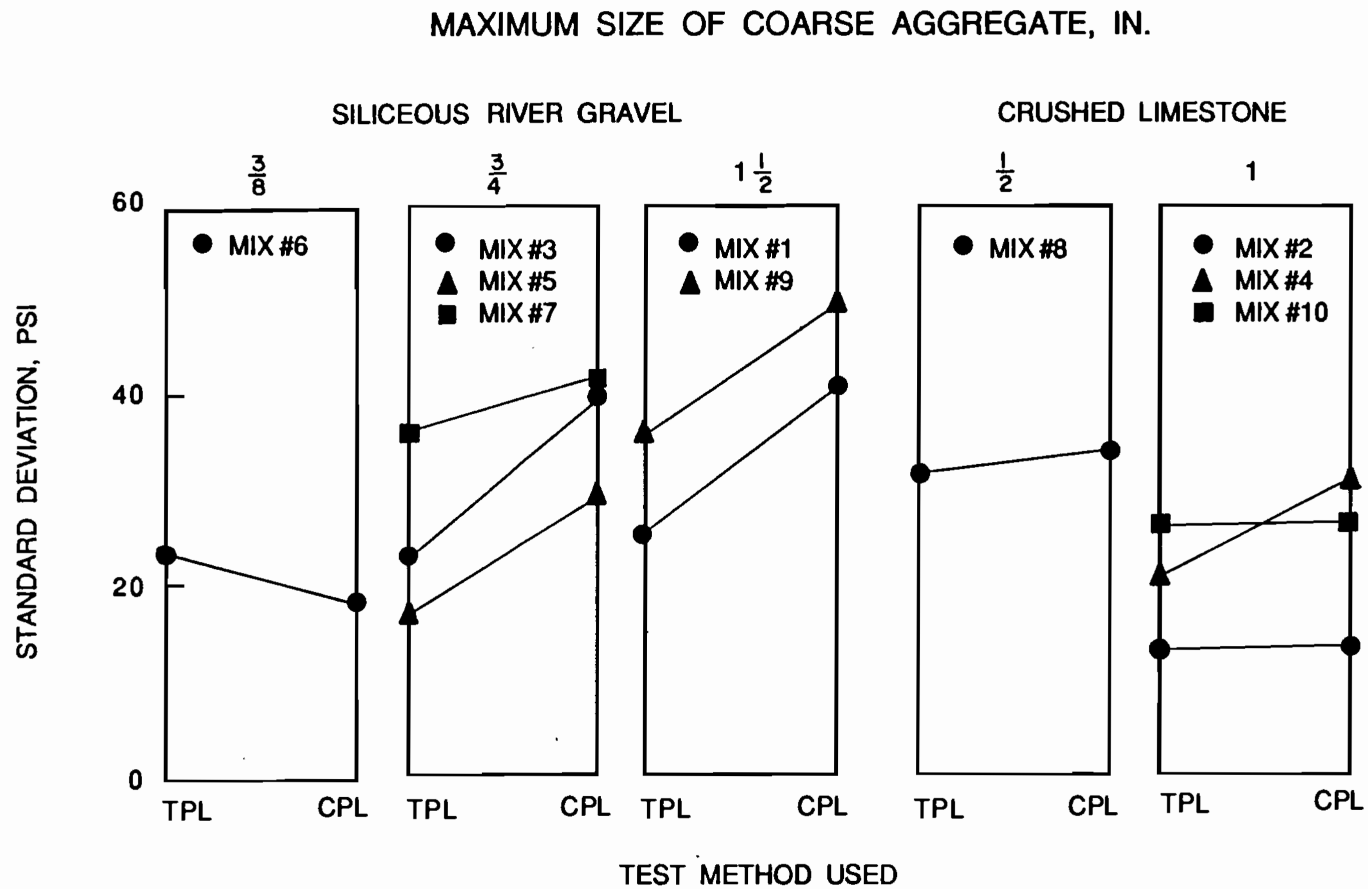


Fig. 4.20 Standard deviation of 6-in. x 6-in. x 20-in. beams tested in third point loading versus center point loading for each aggregate size.

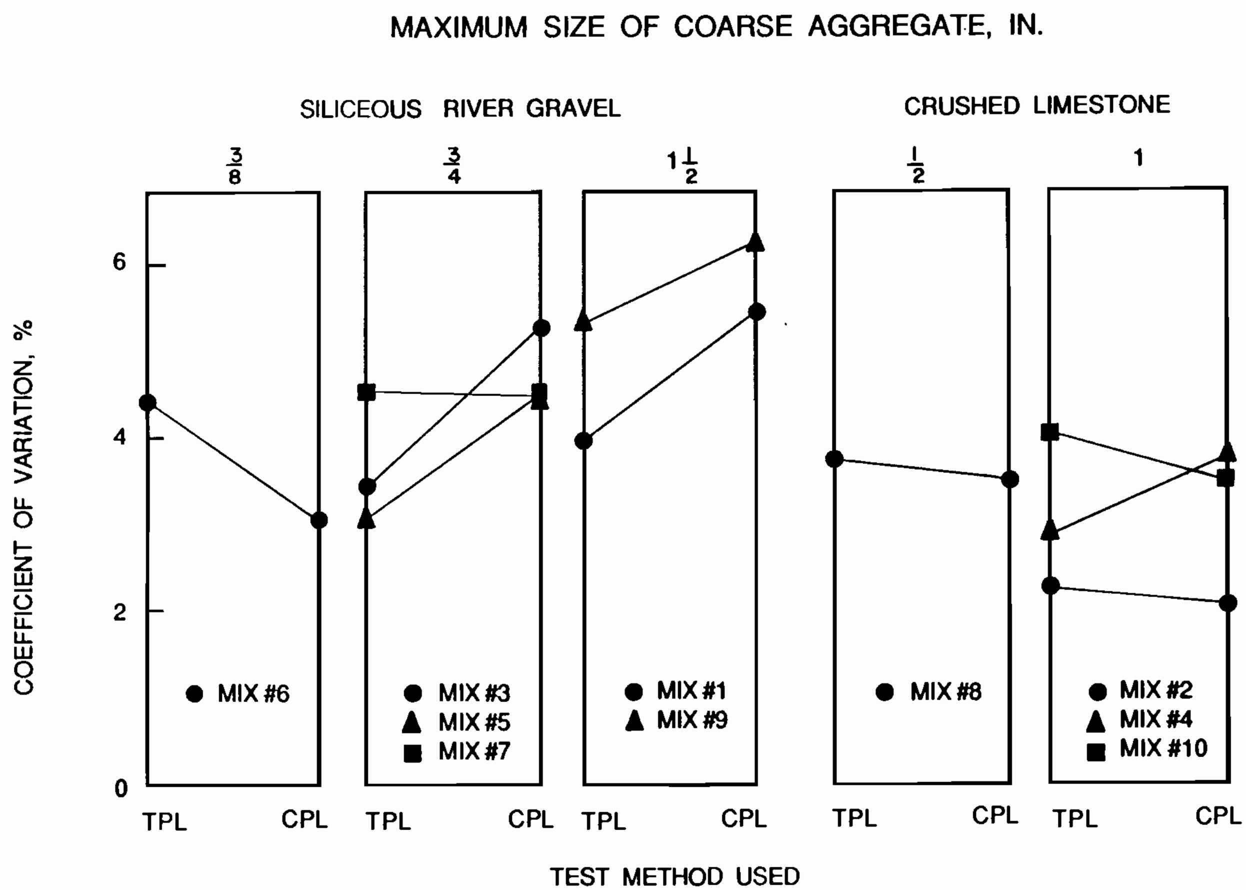


Fig. 4.21 Coefficient of variation of 6-in. x 6-in. x 20-in. beams tested in third point loading versus center point loading for each aggregate size.

can be seen that the standard deviation and coefficient of variation of results obtained from third point loading were lower than or similar to those from center point loading for all cases except Mix No. 6.

4.4.2 Small Beam Third Point Loading. Modulus of rupture test results from 4.5-in. x 4.5-in. x 15.5-in. specimens tested in third point loading are plotted versus those from 6-in. x 6- in. x 20-in. specimens tested in center point loading in Fig. 4.22. The average ratio of the two test methods, as shown in Table 4.4, is 0.92, with individual values ranging between 0.85 and 1.01. This ratio is plotted versus the modulus of rupture obtained from the standard beams in Fig. 4.23, and versus coarse aggregate size in Fig. 4.24. No trend is evident from either graph.

The standard deviations and coefficients of variation for both test methods are shown in Figs. 4.25 and 4.26. In seven cases out of ten, test results obtained from third point loading of 4.5-in. x 4.5-in. x 15.5-in. beams were less uniform than results from 6-in. x 6-in. x 20-in. beams tested in center point loading.

4.5 Location of Failure Plane for Center Point Loading

Often when concrete beams are tested in center point loading, failure does not occur at midspan, which is the point of maximum moment, as illustrated in Fig. 4.27. When this occurs, the concrete has failed at a section which has a strength lower than that at midspan. In the first stage of this study, the location of the failure plane was measured for all beams tested in center point loading, and the actual stress at the fracture was calculated, in addition to the stress occurring at midspan. Average values for each of the mixes are given in Table 4.5, and are plotted in Fig. 4.28. On the average, the actual stress causing failure of the concrete beams tested was only 94% of the reported value, which is based on the stress at midspan.

From these results, it is clear that beams tested in center point loading very often fracture at a location other than midspan. Therefore, results obtained from the test method indicate the stress existing in the concrete at midspan when failure occurs, rather than the actual stress which caused a section of the concrete to fail. These two values would coincide only when failure occurs at midspan. However, the difficulty encountered in measuring the location of the failure plane, due to the irregularity of the crack propagation, makes it inadvisable to include that measurement in the test procedure.

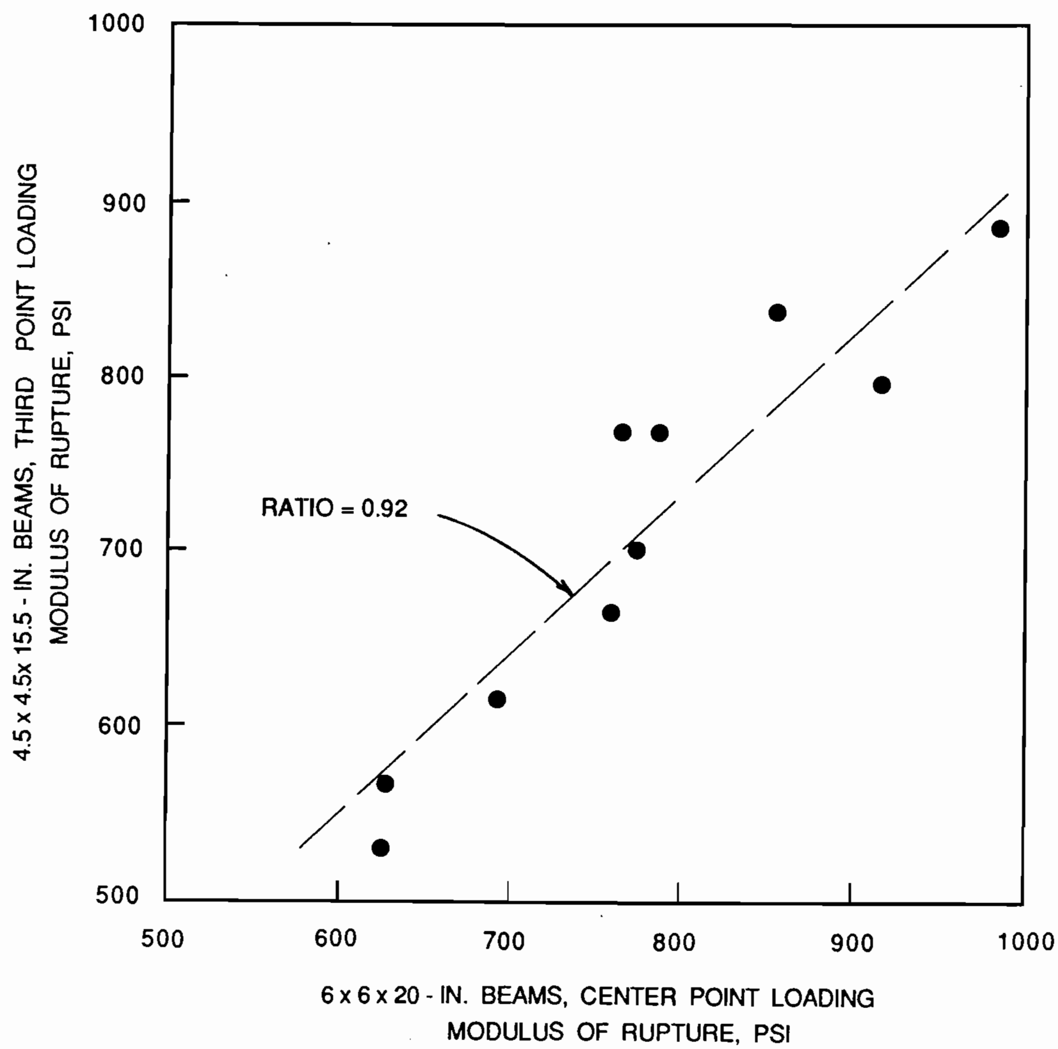


Fig. 4.22 Modulus of rupture of 4.5-in. x 4.5-in. x 15.5-in. beams tsted in third point loading plotted versus 6-in. x 6-in. x 20-in. beams tested in center point loading.

Table 4.4 Ratio of average modulus of rupture results obtained from 4.5-in. x 4.5-in. x 15.5-in. specimens tested in third point loading to 6-in. x 6-in. x 20-in. specimens tested in center point loading.

Mix No.	Coarse Agg. Size, in.	Modulus of Rupture, psi: 4.5x4.5x15.5 Beams, TPL[3] 1	Modulus of Rupture, psi: 6x6x20 Beams, CPL[4] 2	Ratio, 1:2
1	1-1/2 SRG[1]	668	759	0.880
2	1 CS[2]	618	692	0.893
3	3/4 SRG	768	763	1.007
4	1 CS	837	853	0.981
5	3/4 SRG	569	627	0.907
6	3/8 SRG	534	624	0.856
7	3/4 SRG	798	914	0.873
8	1/2 CS	891	983	0.906
9	1-1/2 SRG	768	785	0.978
10	1 CS	702	774	0.907
	Average	715	777	0.920

[1] Siliceous river gravel
[2] Crushed limestone
[3] Third point loading
[4] Center point loading

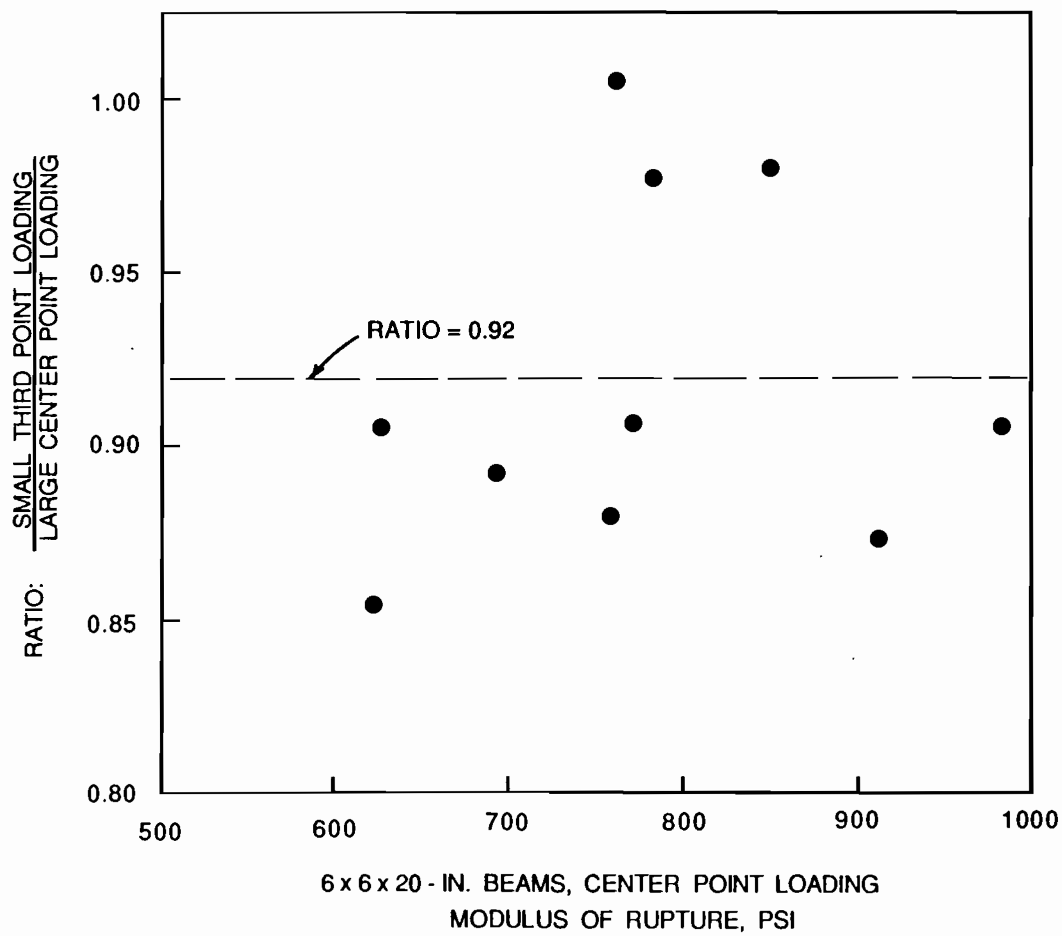


Fig. 4.23 Ratio of modulus of rupture from 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading to 6-in. x 6-in. x 20-in. beams tested in center point loading, plotted versus the modulus of rupture of 6-in. x 6-in. x 20-in. beams tested in center point loading.

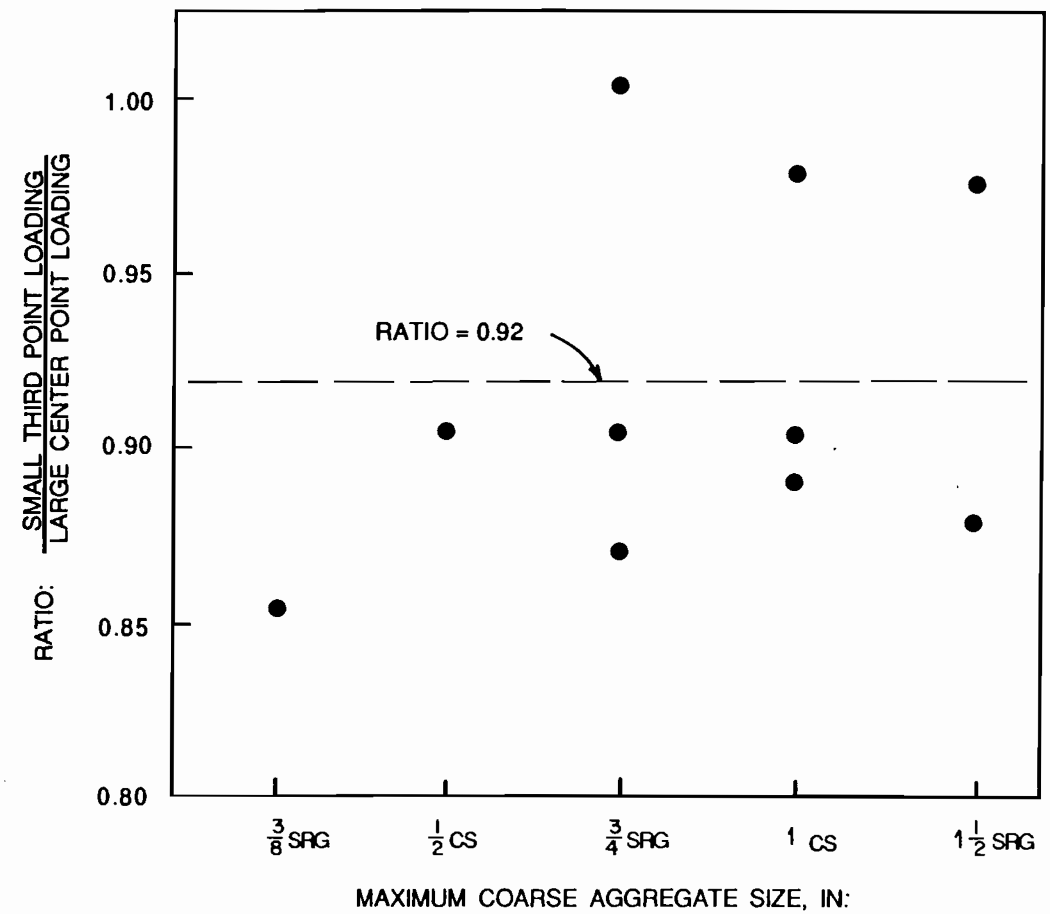


Fig. 4.24 Ratio of modulus of rupture from 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading to 6-in. x 6-in. x 20-in. beams tested in center point loading, plotted versus coarse aggregate size.

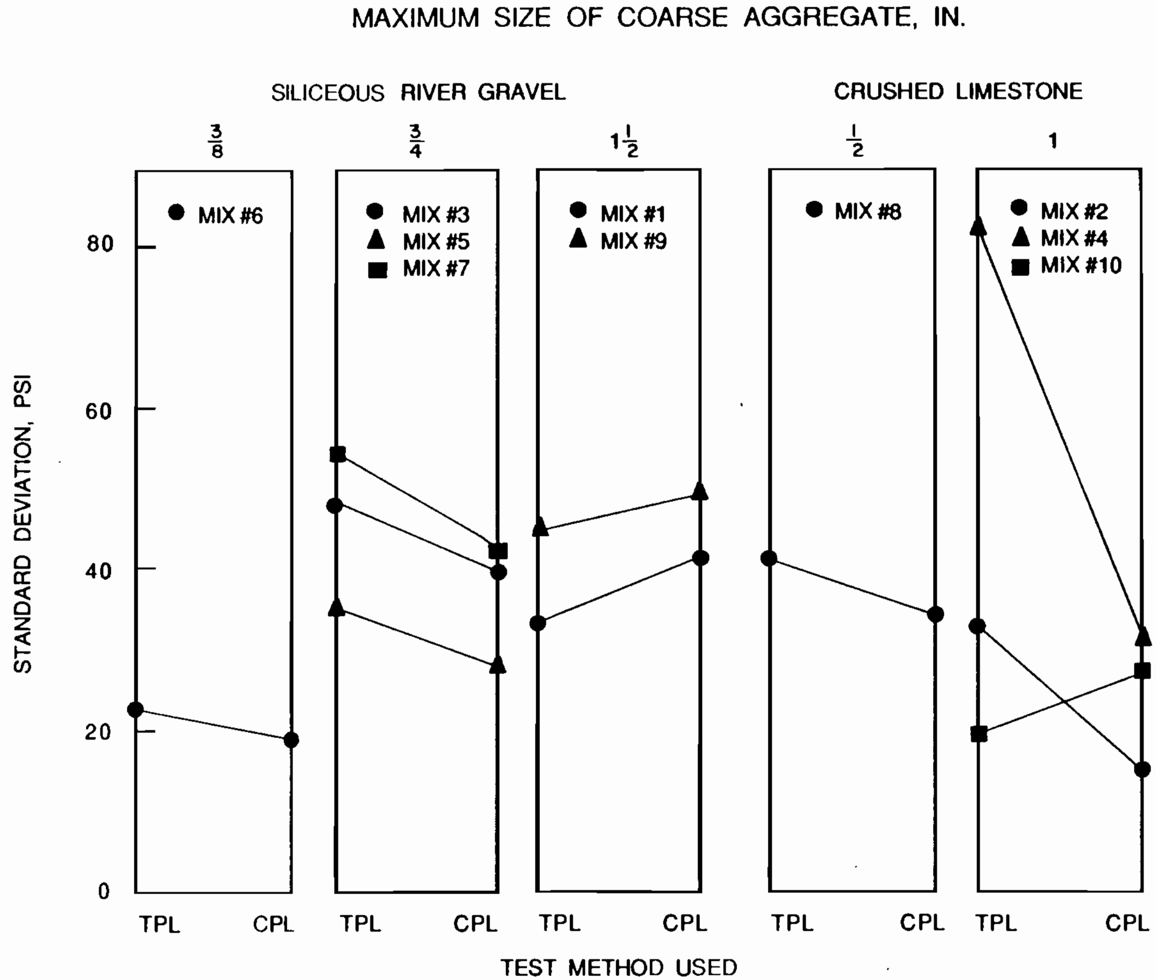


Fig. 4.25 Standard deviation of test results obtained from third point loading of 4.5-in. x 4.5-in. x 15.5-in. beams and center point loading of 6-in. x 6-in. x 20-in. beams for each coarse aggregate size.

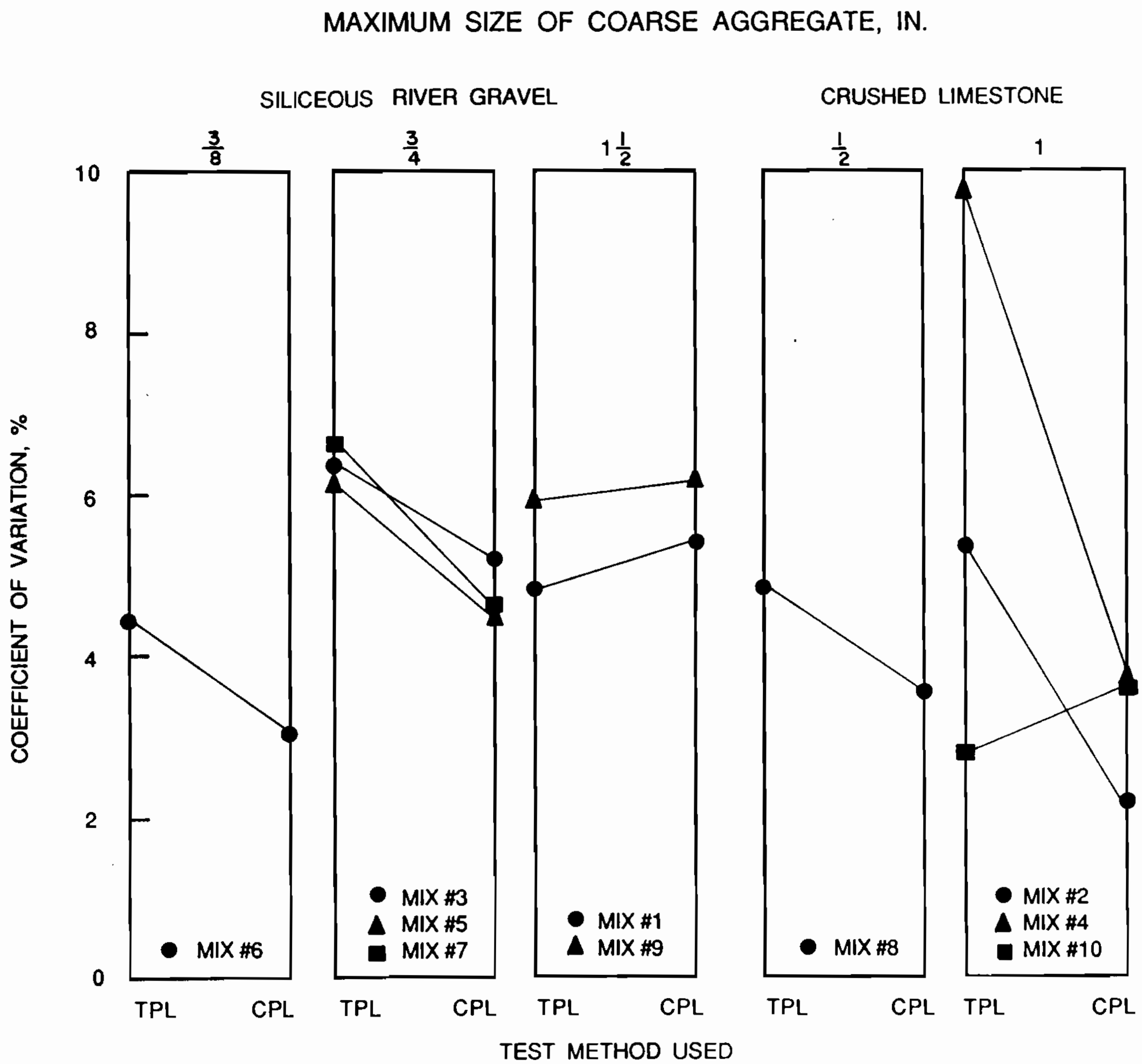
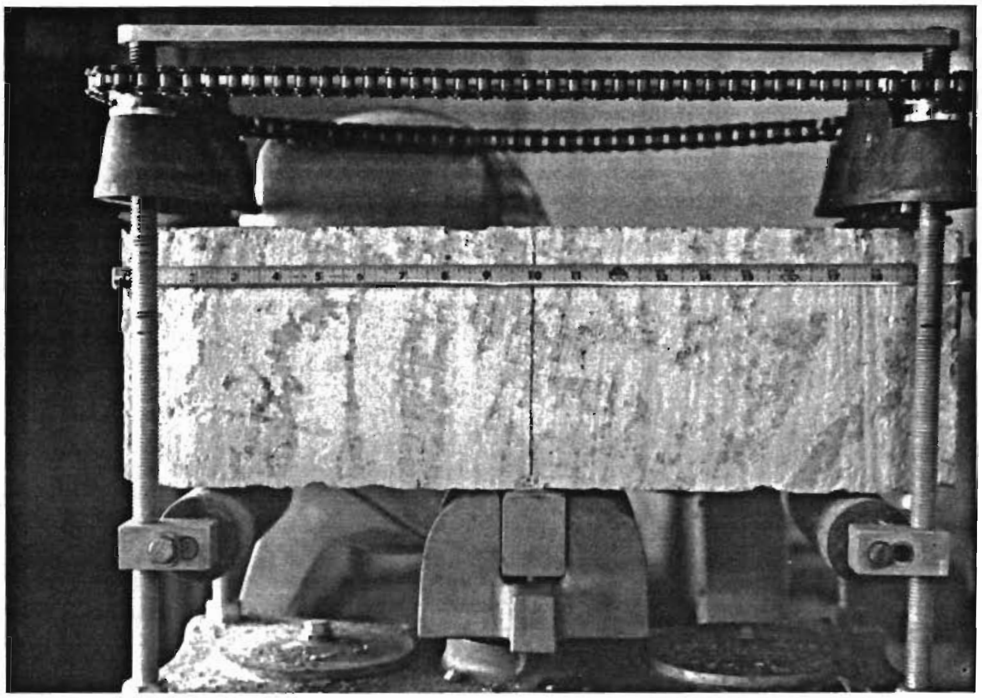
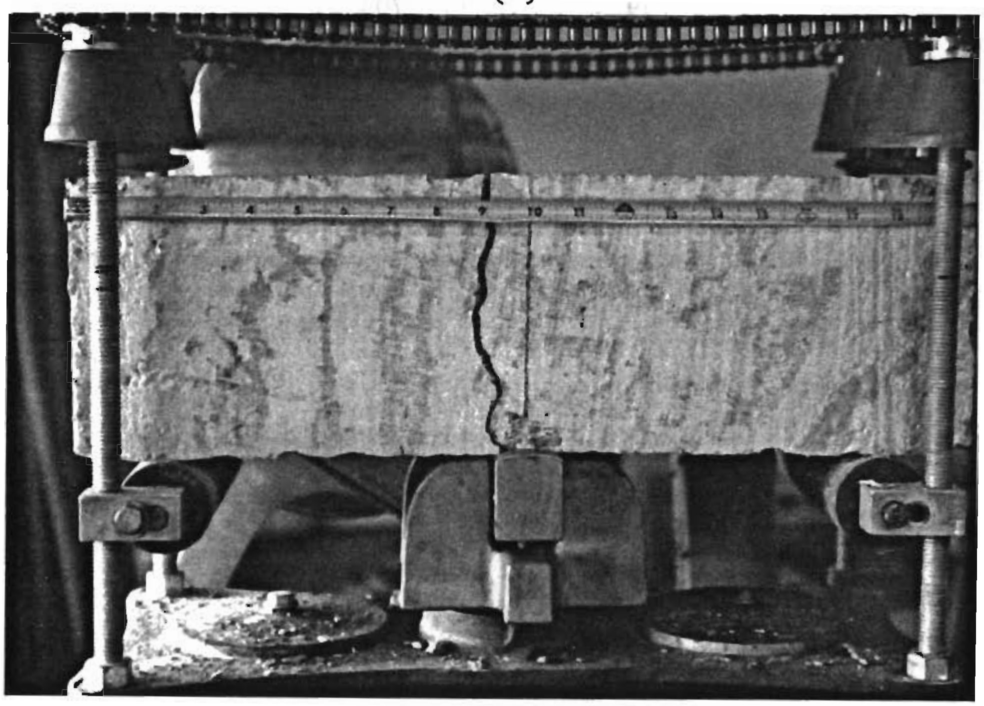


Fig. 4.26 Coefficient of variation of test results obtained from third point loading of 4.5-in. x 4.5-in. x 15.5-in. beams and center point loading of 6-in. x 6-in. x 20-in. beams for each coarse aggregate size.



(a)



(b)

Fig. 4.27 (a) Beam to be tested in center point loading with plane of maximum moment marked; (b) Actual failure plane after testing.

Table 4.5 Average test results obtained from 6-in. x 6-in. x 20-in. beams tested in center point loading with the moment calculated at midspan versus the moment calculated at the actual plane of fracture.

Mix No.	Stress at Failure, psi: Midspan 1	Stress at Failure, psi: Fracture 2	Ratio, 2 ÷ 1
1	759	709	0.93
2	692	660	0.95
3	763	715	0.94
4	853	810	0.95
5	627	596	0.95
6	624	584	0.94
7	915	839	0.92
8	983	938	0.95
9	785	732	0.93
10	774	733	0.95
		Average:	0.94

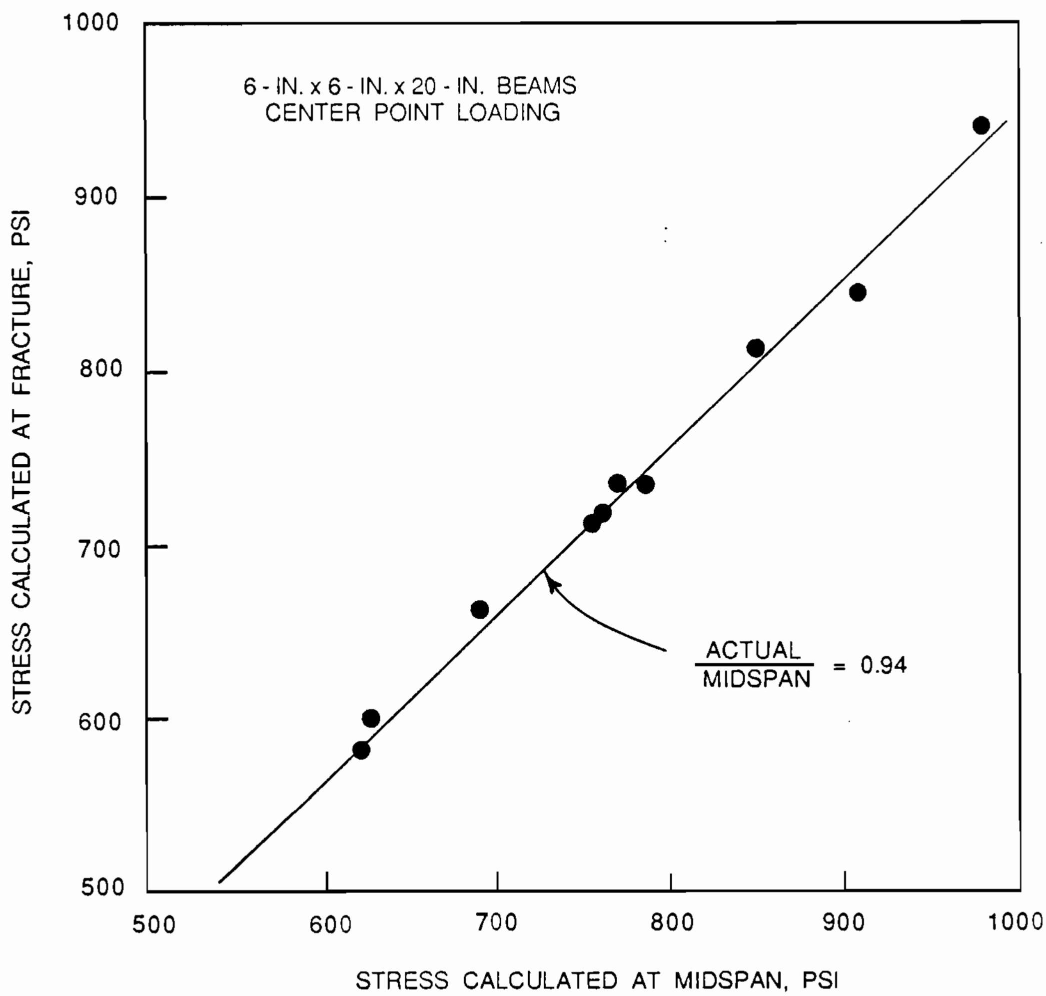


Fig. 4.28 Average modulus of rupture obtained from 6-in. x 6-in. x 20-in. beams tested in center point loading with the moment calculated at the plane of fracture versus the moment calculated at midspan.

4.6 Compression Tests Versus Standard Flexural Tests

Currently, SDHPT concrete specifications specify a minimum flexural strength at seven days and minimum compressive strength at twenty-eight days for each class of concrete, using a relationship of one-to-six; i.e., the specified compressive strength at 28 days is six times the specified flexural strength at seven days. For eight of the ten concrete mixtures used in the first stage tests, cylinders were cast and tested in compression at seven days with the beams. Average test results are given in Table 4.6, where it is shown that the average ratio of seven-day compressive strength to seven-day flexural strength is approximately six-to-one, with individual values ranging between 5.55 and 6.82. The results in Table 4.6 are plotted in Fig. 4.29.

From Fig. 4.29 it can be seen that at seven days the compressive strength of the concretes tested had already reached values which were approximately six times those for the flexural strength. Assuming that at seven days a standard concrete mixture has achieved 70% of its compressive strength at 28 days, and dividing the compressive strength values from Table 4.6 by a factor of 0.70, the values obtained for predicted 28-day strengths are given in Table 4.7. On the average, the ratio of 28-day compressive strength to 7-day flexural strength was 8.3:1, significantly above the value of 6:1 which is currently used in SDHPT Specifications, as shown in Fig. 4.30.

Based on these results, it can be seen that the relationship between the 28-day compressive strength and 7-day flexural strength of concrete is generally not 6:1, as used in SDHPT Specifications. Instead, the ratio is actually higher, being on the order of 8:1 or more. This does not necessarily indicate that the specifications are wrong. However, a problem could arise if a structural member is designed based on a required flexural strength, but the concrete is accepted based on its compressive strength. If this were to occur, the result could be the acceptance of an inferior concrete. For example, if the flexural strength required for a member is 600 psi, the acceptable 28-day compressive strength, based on a ratio of 6:1, would be 3600 psi. However, in reality, a normal concrete which would have a 28-day compressive strength of 3600 psi would have a 7-day flexural strength of only 435 psi. Thus, the concrete would have an inadequate flexural strength for the structural design requirements.

The ratio of test results obtained from 6-in. x 6-in. x 20-in. beams tested in third point loading to those tested in center point loading was found to be approximately 0.86, as was discussed in

Table 4.6 Compressive strength of 6-in. x 12-in. cylinders versus flexural strength of 6-in. x 6-in. x 20-in. beams tested in center point loading.

Mix No.	Cylinder Test Age, Days	Compressive Strength, psi 1	7-day Flexural Strength, psi 2	Ratio, 1:2
1	7	4620	760	6.08
2	7	4020	690	5.83
3*	11	4840	765	6.33
4	7	5830	855	6.82
5	7	3500	625	5.60
6	7	3470	625	5.55
7	7	5690	915	6.22
8*	12	8000	985	8.12
9	7	4430	785	5.64
10	7	4500	775	5.81
Average		4510	755	5.97

*Value not included in average since test age was other than seven days.

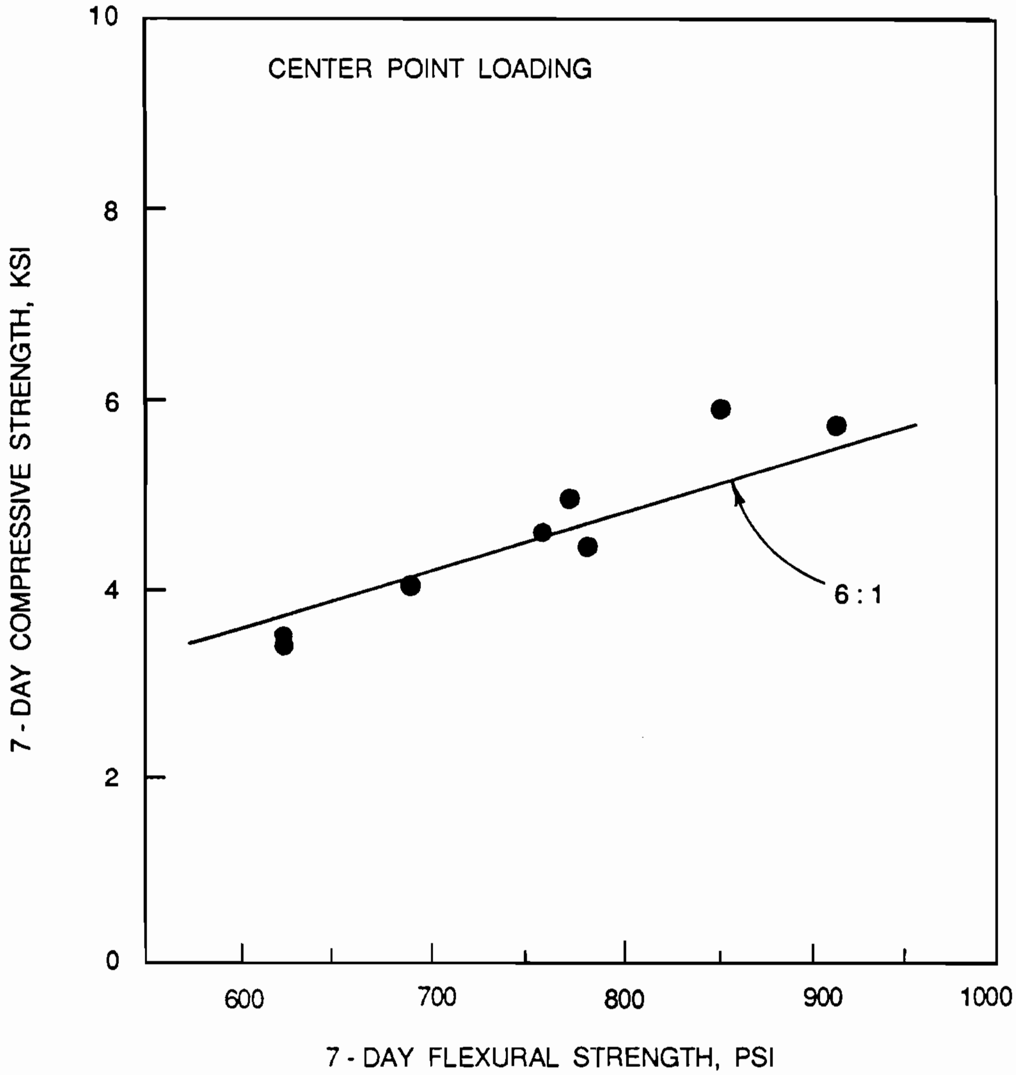


Fig. 4.29 Seven-day compressive strength versus 7-day flexural strength (center point loading).

Table 4.7 Predicted 28-day compressive strength of concretes based on the 7-day compressive strength of 6-in. x 12-in. cylinders, based on a ratio of compressive strength at 7 days to 28 days of 0.70.

Mix No.	Predicted 28-day Compressive Strength, psi* 1	7-day Flexural Strength, psi 2	Ratio, 1:2
1	6600	760	8.68
2	5740	690	8.32
4	8330	855	9.74
5	5000	625	8.00
6	4960	625	7.94
7	8130	915	8.89
9	6330	785	8.06
10	6430	775	8.30
Average:	6440	755	8.31

* Assumes that the ratio of the compressive strength of concrete cylinders at 7 days to that at 28 days is 0.70.

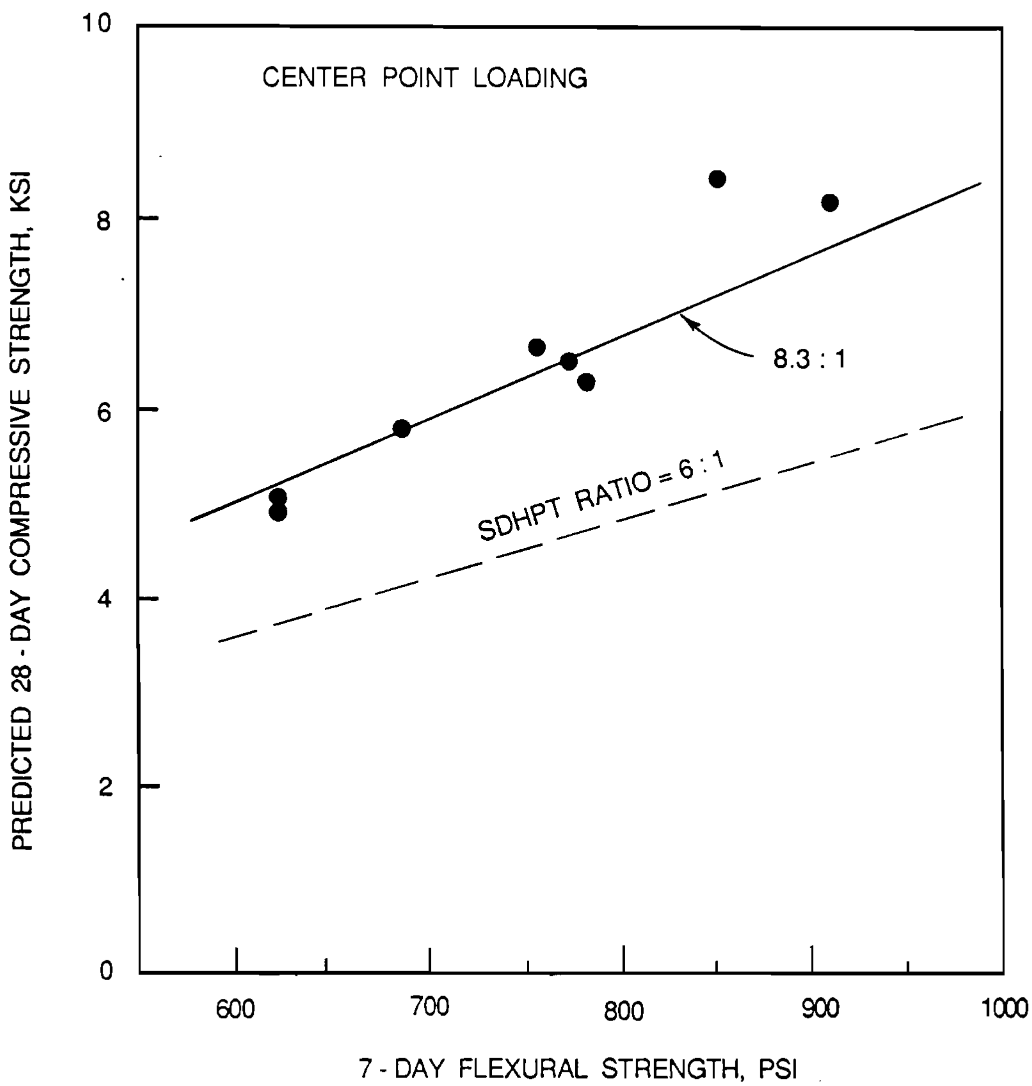


Fig. 4.30 Twenty-eight-day compressive strength versus 7-day flexural strength (center point loading).

Section 4.4. The 7-day flexural strength of 6-in. x 6-in. x 20-in. beams tested in third point loading and the corresponding predicted 28-day compressive strength are given in Table 4.8. These values are plotted in Fig. 4.31. On the average, the 28-day compressive strength of 6-in. x 12-in. cylinders from the concretes tested was ten times the 7-day flexural strength of 6-in. x 6-in. x 20-in. beams tested in third point loading.

4.7 Summary of First Stage Test Results

The results presented in the preceding section are summarized. This will include the effects of specimen dimensions, size and type of coarse aggregate, loading method, and also the relationship between flexural and compressive strength.

4.7.1 Specimen Dimensions. For beams tested in center point loading it was found that average modulus of rupture test results were largely independent of specimen dimensions. However, test results obtained from 4.5-in. x 4.5-in. x 15.5-in. beams were generally less uniform than those obtained from 6-in. x 6-in. x 20-in. beams.

The average modulus of rupture of beams tested in third point loading was higher for 4.5-in. x 4.5-in. x 15.5-in. beams than for 6-in. x 6-in. x 20-in. beams. In addition, the larger beams gave more uniform test results.

4.7.2 Coarse Aggregate. In general, for all test methods, test results from beams made of concrete containing siliceous river gravel were less uniform than those from beams made of concrete containing crushed limestone. Also, for beams tested in center point loading, the variation of test results increased with increasing coarse aggregate size.

4.7.3 Loading Method. The following is a summary of the performance of each of the other test methods when compared to 6-in. x 6-in. x 20-in. beams tested in center point loading.

4.7.3.1 Third Point Loading of 6-in. x 6-in. x 20-in. Beams. Test results obtained from 6-in. x 6-in. x 20-in. beams tested in third point loading were approximately 86% of those obtained from the standard test method. In addition, test results obtained from the former test method generally had a lower standard deviation than those from the standard test method.

4.7.3.2 Third Point Loading of 4.5-in. x 4.5-in. x 15.5-in. Beams. The modulus of rupture obtained from 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading was, on the average, approximately 92% of that obtained from the standard test method. In

Table 4.8 Predicted 28-day compressive strength of 6-in. x 12-in. cylinders versus the 7-day flexural strength of 6-in. x 6-in. x 20-in. beams tested in third point loading.

Mix No.	Predicted 28-day Compressive Strength, psi* 1	7-day Flexural Strength, psi 2	Ratio, 1:2
1	6600	635	10.39
2	5740	605	9.49
4	8330	735	11.33
5	5000	530	9.43
6	4960	540	9.19
7	8130	790	10.29
9	6330	660	9.59
10	6430	665	9.67
Average:	6440	645	9.98

*From Table 4.7

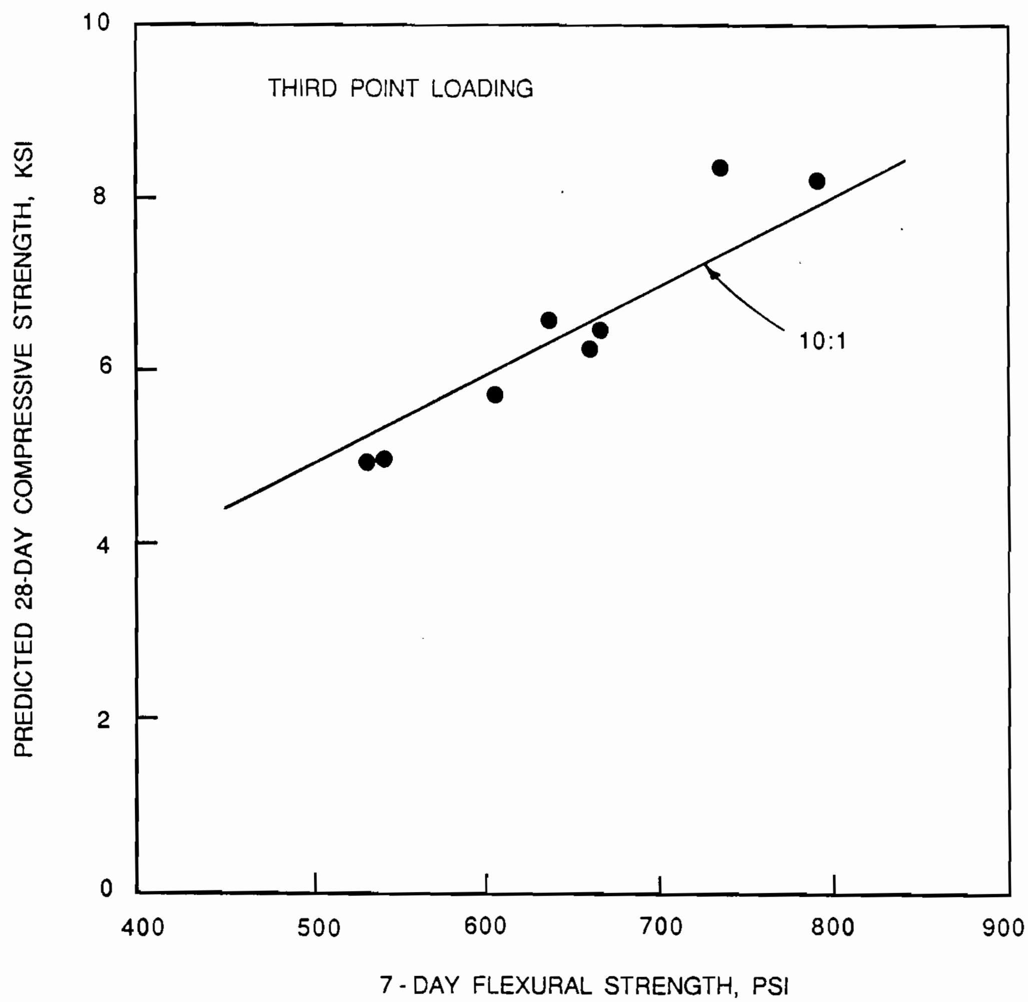


Fig. 4.31 Twenty-eight-day compressive strength versus 7-day flexural strength (third point loading).

most cases, test results obtained from 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading were less uniform than results obtained from the standard method.

4.7.4 Location of Failure Plane for Center Point Loading. For 6-in. x 6-in. x 20-in. beams tested in center point loading, the actual stress which caused failure of the concrete, based on the location of the failure plane, was only 94% of the reported stress. However, determining the location of the failure plane is difficult due to the irregularity of the crack propagation through the concrete.

4.7.5 Flexural Versus Compressive Strength. On the average, 6-in. x 12-in. cylinders tested in compression at seven days gave results that were approximately six times the flexural strength of 6-in. x 6-in. x 20-in. beams tested in center point loading at seven days. Based on a ratio of 7-day to 28-day compressive strength of 0.70, the predicted 28-day compressive strength would have been approximately 8.3 times the 7-day flexural strength from center point loading, and approximately 10 times the 7-day flexural strength from third point loading.

CHAPTER 5

SECOND STAGE TEST RESULTS

5.1 Introduction

The purpose of the second stage tests was to develop sufficient data for preparing a precision statement for each of the test methods. Based on the first stage test results, it was shown that specimens made with concrete containing 1-1/2-in. siliceous river gravel yielded test results with the highest variation. Thus, for the interlaboratory study one concrete mixture used contained 1-1/2-in. siliceous river gravel and four sacks of cement per cubic yard of concrete. For comparison, a second concrete mixture was chosen which contained 3/4-in. siliceous river gravel and 5-1/2 sacks of cement per cubic yard of concrete. For each of the four test methods, three specimens for each of ten laboratories plus five extra specimens were cast from each of the two concrete mixtures. Thus, thirty-five beams were cast for each test method from each of two concrete mixes, resulting in a total of 280 beams being cast for the interlaboratory study. Beams from the concrete mixture containing 1-1/2-in. siliceous river gravel and four sacks of cement were cast on two separate days. On the first day, thirty-five 6- in. x 6-in. x 20-in. beams and thirty-five 4.5-in. x 4.5-in. x 15.5-in. beams were cast for center point loading, and on the second day the same number of beams were cast for testing in third point loading. The same procedure was followed for the concrete containing 3/4-in. siliceous river gravel and 5-1/2 sacks of cement. The two batches of the concrete mix containing 1-1/2-in. gravel were labeled Mix Nos. 11 and 12, whereas those containing 3/4-in. gravel were labeled Mix Nos. 13 and 14. In this chapter, the data will be presented and analyzed according to ASTM C802-80, Standard Practice for Conducting an Interlaboratory Test Program to Determine the Precision of Test Methods for Construction Materials [8]. Individual test results and details of the analysis are presented in Appendix B.

5.2 Center Point Loading of 6-in x 6-in x 20-in. Beams

The test results for the interlaboratory study obtained from 6-in. x 6-in. x 20-in. beams tested in center point loading are presented and analyzed in this section. Stresses were calculated at midspan. The data will be investigated for homogeneity and interactions, statistically analyzed, and information on the precision of the test method will be prepared.

5.2.1 Investigation of Uniformity of Data. The within-laboratory variances for each laboratory are given in Appendix B. Examining these variances for agreement according to ASTM C802 yields Figs. 5.1 and 5.2 in which the variance of test results is plotted for each laboratory. Variance of results from 6-in. x 6-in. x 20-in. beams tested in center point loading are shown in Fig. 5.1 for the concrete mix containing 1-1/2-in. siliceous river gravel and 4 sacks of cement per cubic yard, and Fig. 5.2 shows results for beams cast from the mix containing 3/4-in. siliceous river gravel and 5.5 sacks of cement per cubic yard. According to the ASTM procedure for ten different laboratories and three replicates, the ratio of the highest individual variance to the average variance, and the lowest individual variance to the highest individual variance, should not exceed 5 and 550, respectively. These values and ratios are presented in Table 5.1 for the data shown in Figs. 5.1 and 5.2, and indicate that neither of the ratios are exceeded. In Fig. 5.3 the average strength obtained for each of the two mixes is plotted for each lab to indicate if any laboratory departs from the trend of increasing strength with higher cement content, which none does. Therefore, all data fulfills the requirements for use in the interlaboratory analysis.

5.2.2 Statistical Properties. The values for within- and between-lab standard deviation and coefficient of variation are given in Table 5.2 for 6-in. x 6-in. x 20-in. beams tested in center point loading. These values are shown graphically in Figs. 5.4 and 5.5. Both the within- and between-lab standard deviations increased with increasing modulus of rupture. The within-lab coefficient of variation, however, was unaffected by modulus of rupture, and the between-lab coefficient of variation increased only 8.0% of the average with increasing flexural strength.

5.2.3 Preparation of Information on Precision. Precision statements may be best expressed in one of the following forms:

1. constant standard deviation,
2. constant coefficient of variation, or
3. groups of data in which one of the above can be applied.

For 6-in. x 6-in. x 20-in. beams tested in center point loading it is clear that the coefficient of variation is nearly constant for the specimens tested. For example, the change in between- laboratory standard deviation with concrete strength is approximately 33% of their average, whereas the corresponding change in coefficient of variation is only 8% of the average. Thus, for 6-in. x 6-in. x 20-in. beams tested in center point loading, the precision statement should

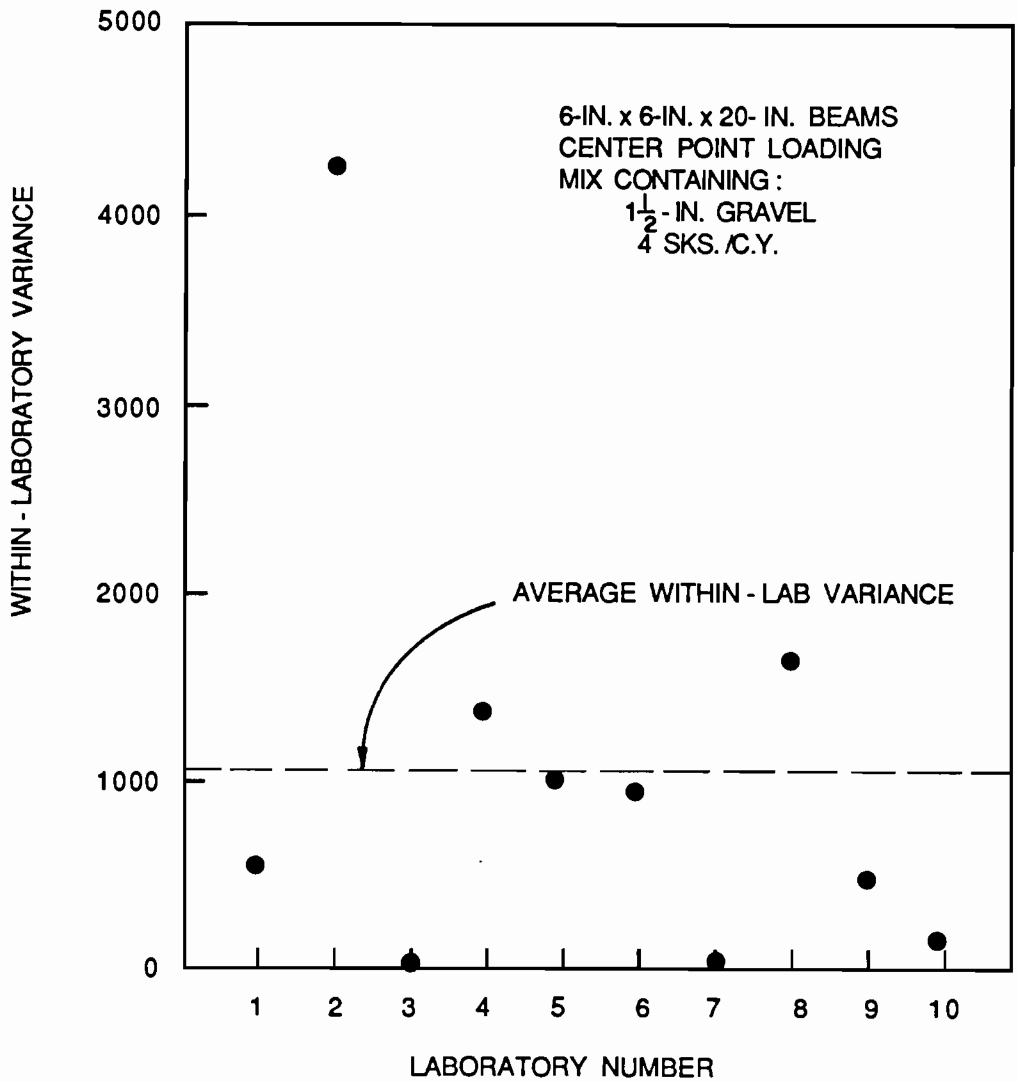


Fig. 5.1 Investigation for agreement of variances for each laboratory for test results obtained from 6-in. x 6-in. x 20-in. beams cast from the mix containing 1-1/2-in. gravel and four sacks of cement per cubic yard and tested in center point loading.

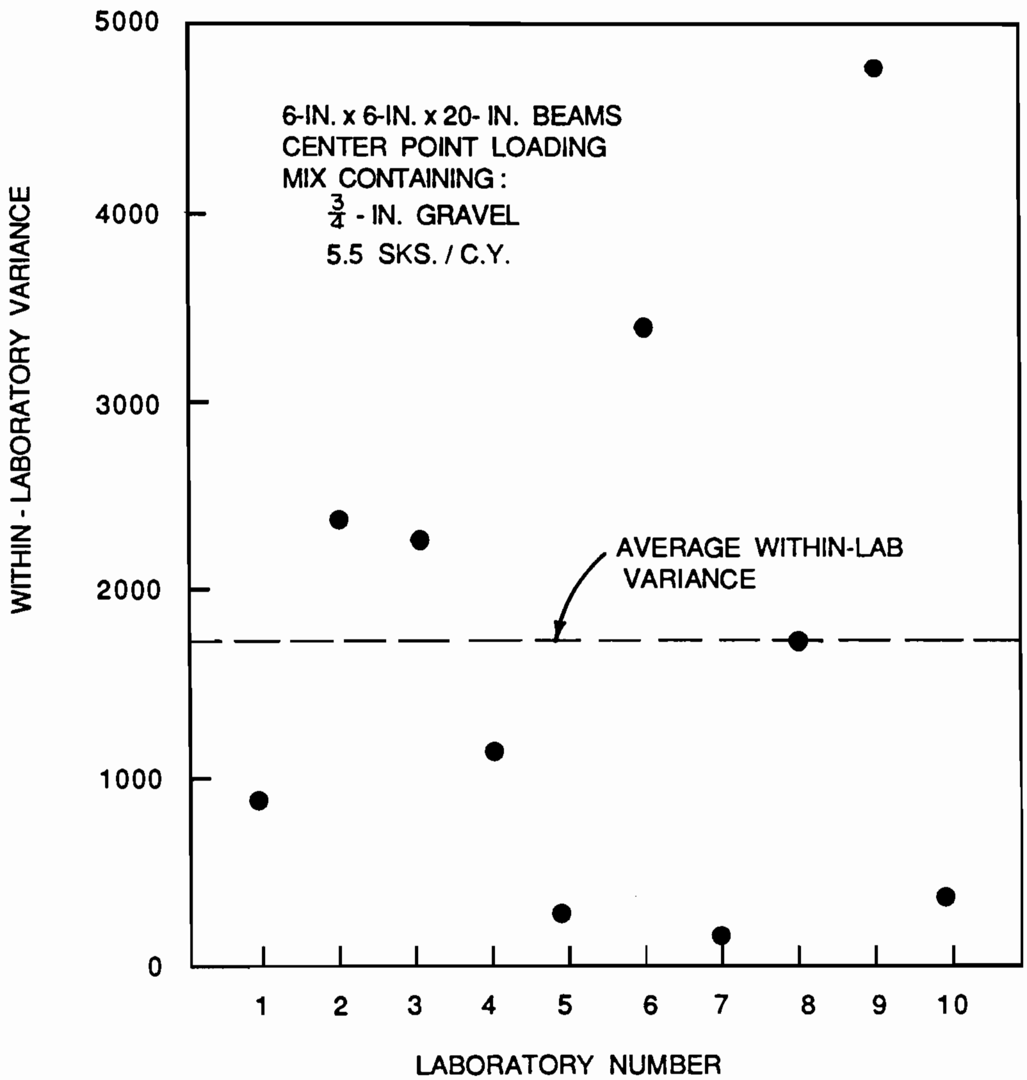


Fig. 5.2 Investigation for agreement of variances for each laboratory for test results obtained from 6-in. x 6-in. x 20-in. beams cast from the mix containing 3/4-in. gravel and 5.5 sacks of cement per cubic yard and tested in center point loading.

Table 5.1 Investigation of agreement of variances for 6-in. x 6-in. x 20-in. beams tested in center point loading.

Mix, sks/cy.	Highest Variance 1	Lowest Variance 2	Average Variance 3	Ratio, 1:3	Ratio, 1:2
4	4258	58	1067	3.99	73
5.5	4697	147	1720	2.73	32
		Ratio must not exceed:		5	550

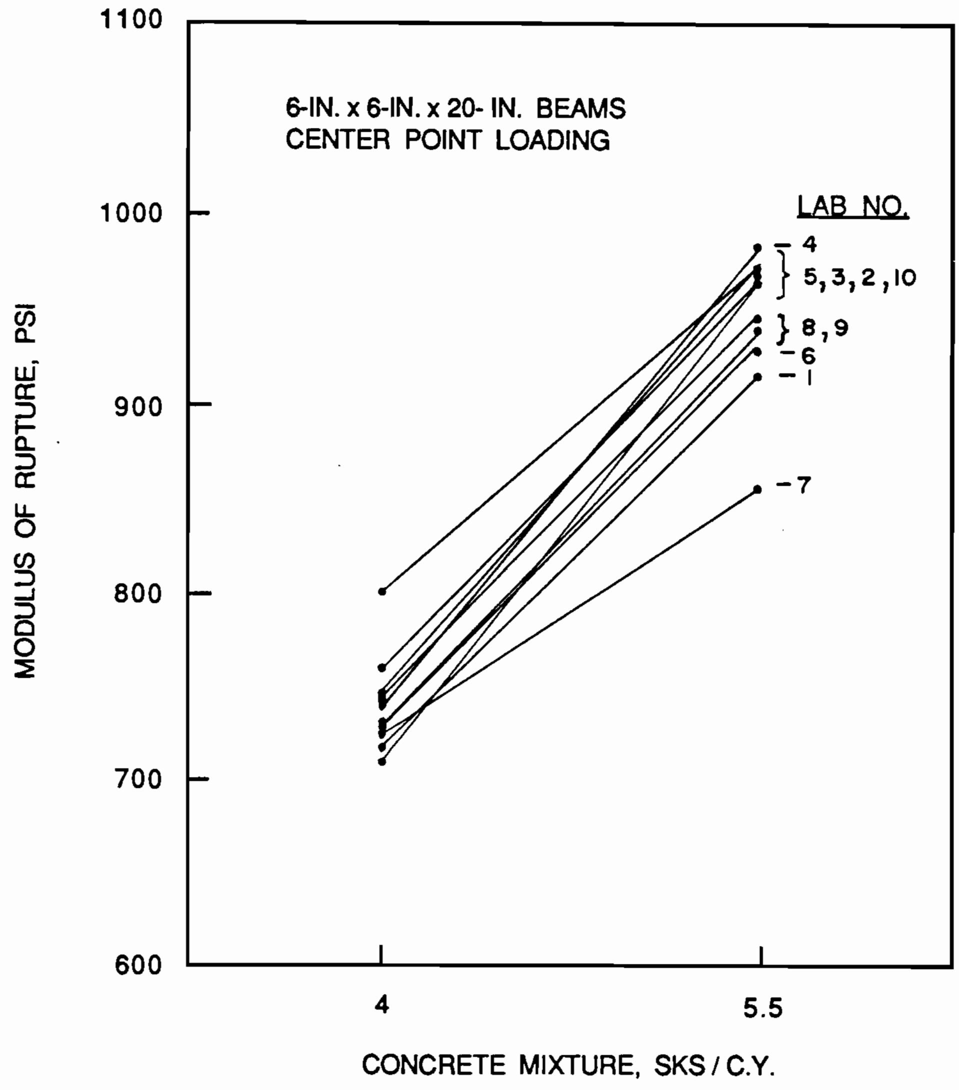


Fig. 5.3 Investigation for interactions in center point loading test results obtained from 6-in. x 6-in. x 20-in. beams.

Table 5.2 Standard deviations and coefficients of variation for 6-in. x 6-in. x 20-in. beams tested in center point loading.

Mix, sks/cy.	Overall Average, psi	Standard Deviation, psi		Coefficient of Variation, %	
		Within-Lab	Between-Lab	Within-Lab	Between-Lab
4	738	32.7	36.0	4.4	4.9
5.5	939	41.5	50.1	4.4	5.3

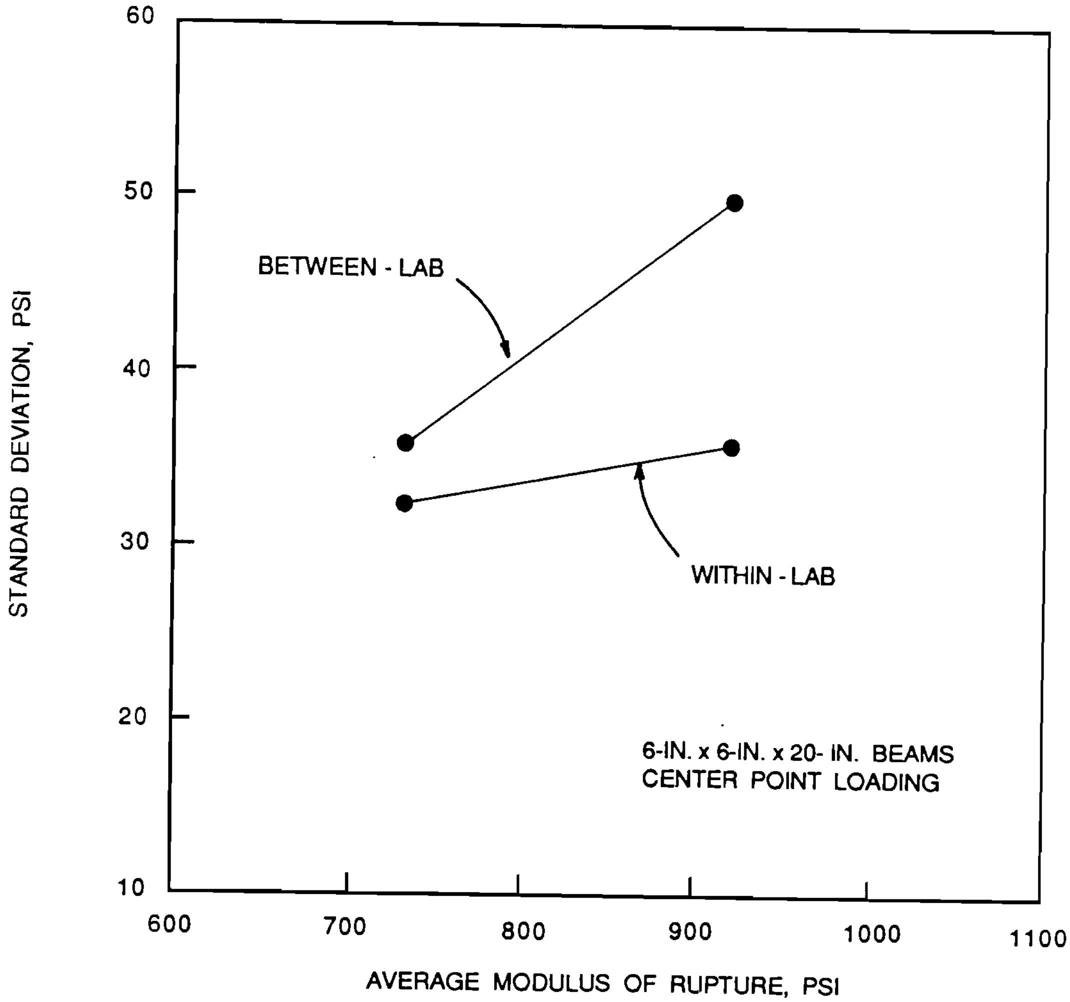


Fig. 5.4 Standard deviation versus average modulus of rupture for 6-in. x 6-in. x 20-in. beams tested in center point loading.

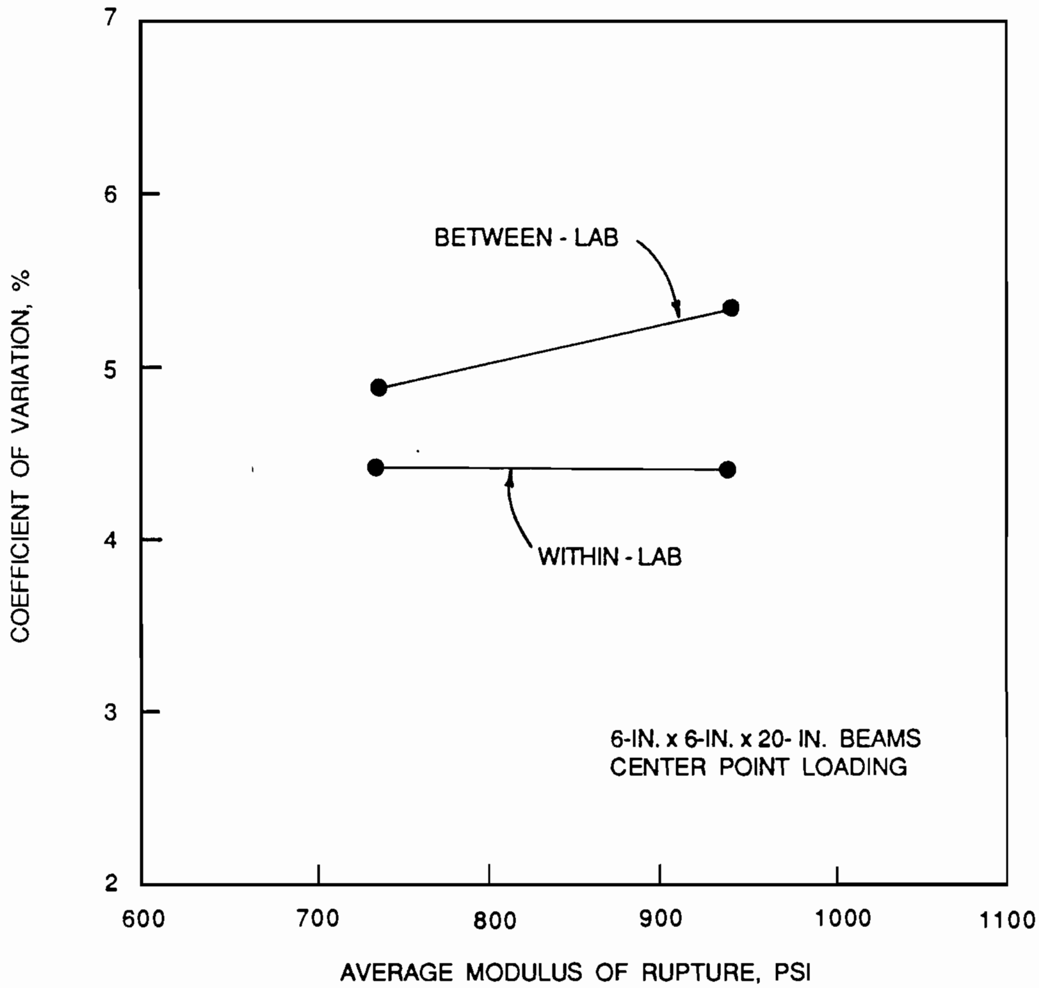


Fig. 5.5 Coefficient of variation versus average modulus of rupture for 6-in. x 6-in. x 20-in. beams tested in center point loading.

be based on the assumption of constant coefficients of variation of 4.4% and 5.1%, respectively, for within-laboratory and between-laboratory results.

5.3 Third Point Loading of 6-in. x 6-in. x 20-in. Beams

The test results for the interlaboratory study obtained from 6-in. x 6-in. x 20-in. beams tested in third point loading are presented and analyzed in this section, and information for statements of precision for the test method prepared.

5.3.1 Investigation of Uniformity of Data. For all 6- in. x 6-in. x 20-in. beams tested in third point loading, the within-laboratory variance for each lab is plotted in Figs. 5.6 and 5.7 for the two different concrete mixtures. The data is analyzed for low and high variances in Table 5.3, and the maximum ratios are not exceeded. Examinations of the relationship of modulus of rupture to cement content for each laboratory, shown in Fig. 5.8, indicates that all laboratories show similar results. Thus, data from all laboratories are valid for use in the interlaboratory analysis.

5.3.2 Calculation of Statistical Properties. The within-lab and between-lab standard deviations and coefficients of variation are given in Table 5.4 for 6-in. x 6-in. x 20-in. beams tested in third point loading. Both the standard deviation and coefficient of variation increased with concrete strength, as shown in Figs. 5.9 and 5.10.

5.3.3 Preparation of Information on Precision. For 6- in. x 6-in. x 20-in. beams tested in third point loading, both the values for standard deviation and coefficient of variation increased with concrete strength. The change in within-lab and between-lab standard deviations with concrete strength is 54% and 52% of their average, respectively. The corresponding change in coefficient of variation is 26% and 22%, respectively. Thus, unlike the center point test method, the variation of test results obtained from third point loading is dependent on the strength of the concrete being tested, based on the results of this study.

5.4 Center Point Loading of 4.5-in. x 4.5-in. x 15.5-in. Beams

Results obtained from 4.5-in. x 4.5-in. x 15.5-in. beams tested in center point loading are presented and analyzed in this section. Information for use in determining the precision of the test method is prepared.

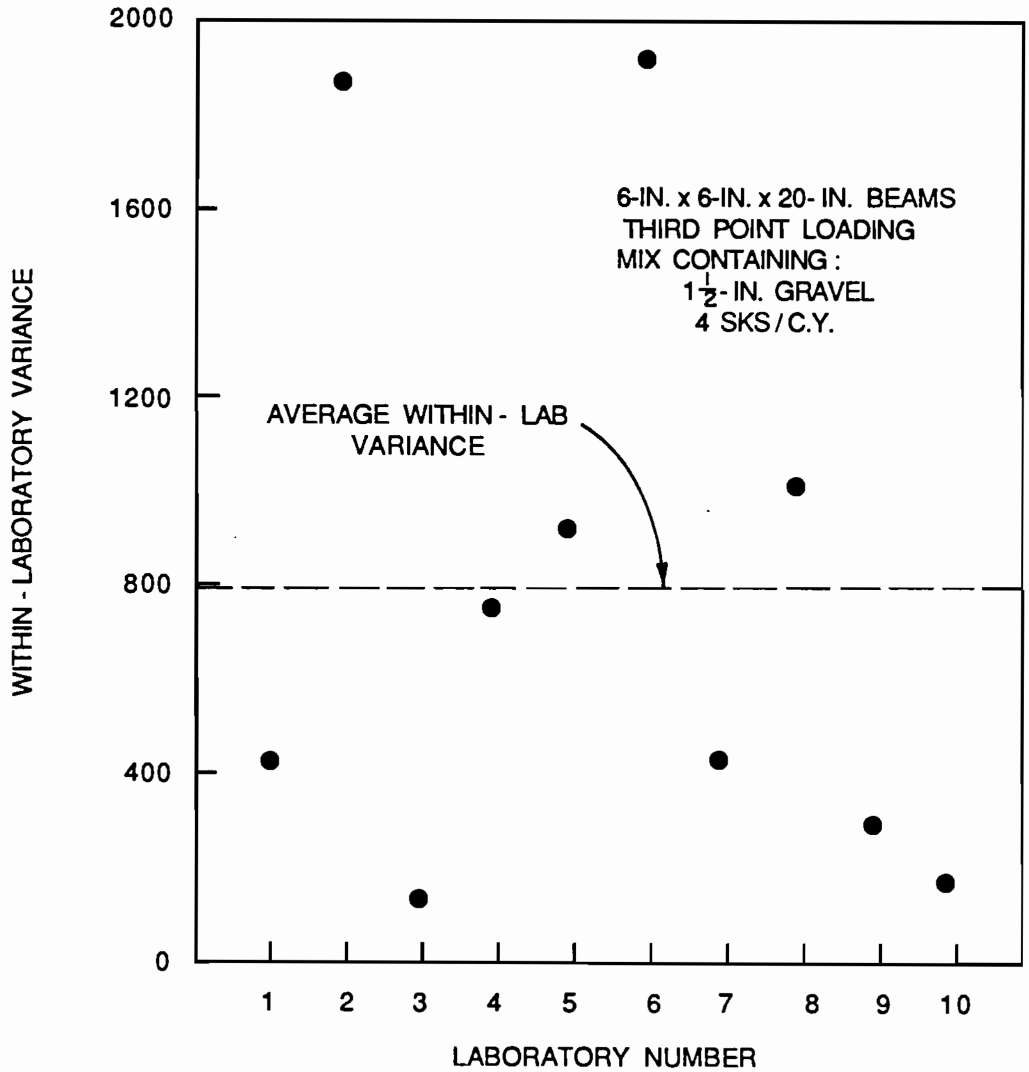


Fig. 5.6 Investigation for agreement of variances for each laboratory for test results obtained from 6-in. x 6-in. x 20-in. beams cast from the mix containing 1-1/2-in. gravel and four sacks of cement per cubic yard and tested in third point loading.

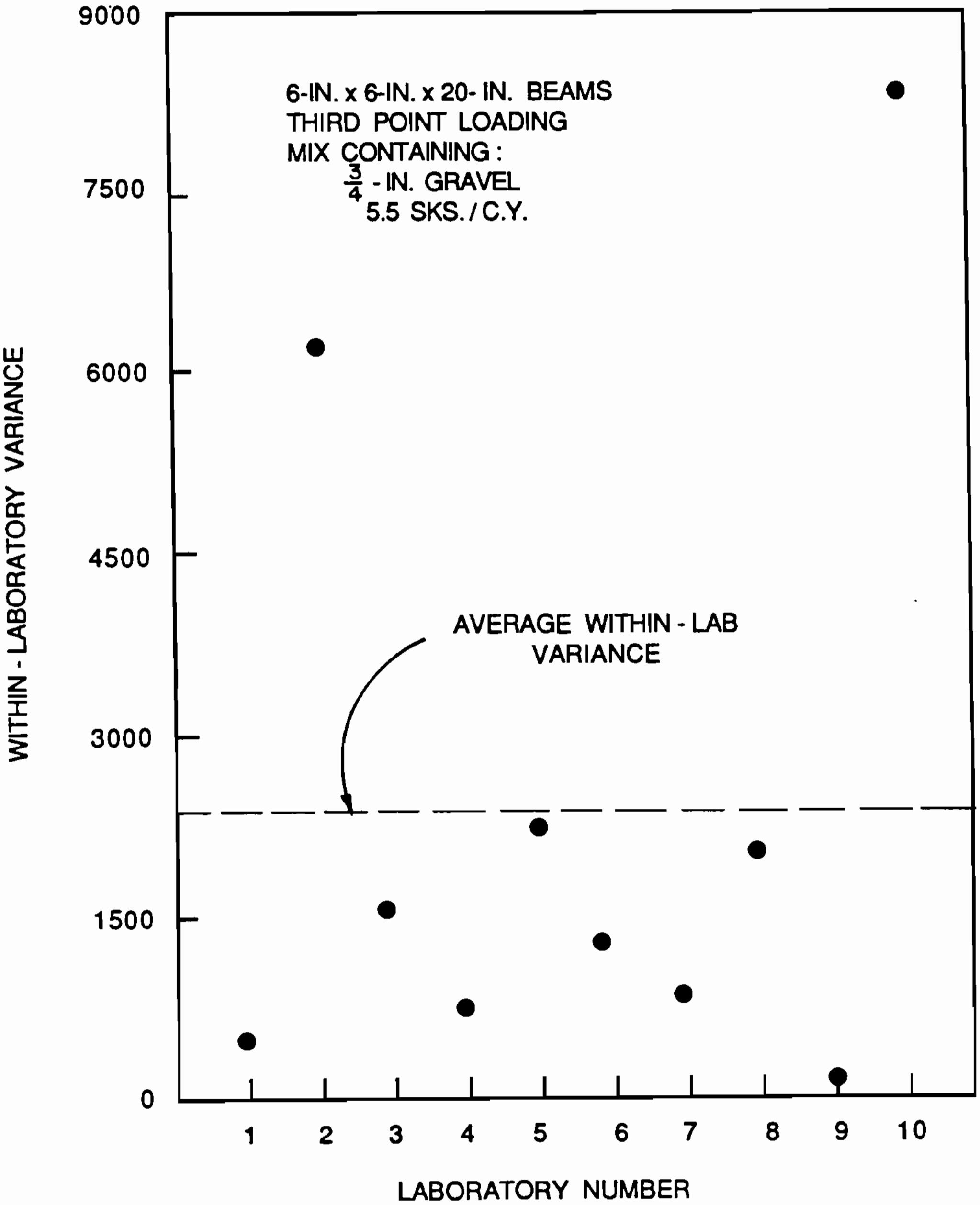


Fig. 5.7 Investigation for agreement of variances for each laboratory for test results obtained from 6-in. x 6-in. x 20-in. beams cast from the mix containing 3/4-in. gravel and 5.5 sacks of cement per cubic yard and tested in third point loading.

Table 5.3 Investigation of agreement of variances for 6-in. x 6-in. x 20-in. beams tested in third point loading.

Mix, sks/cy.	Highest Variance 1	Lowest Variance 2	Average Variance 3	Ratio, 1:3	Ratio, 1:2
4	1900	135	787	2.41	14.1
5.5	8296	200	2406	3.45	41.5
		Ratio must not exceed:		5	550

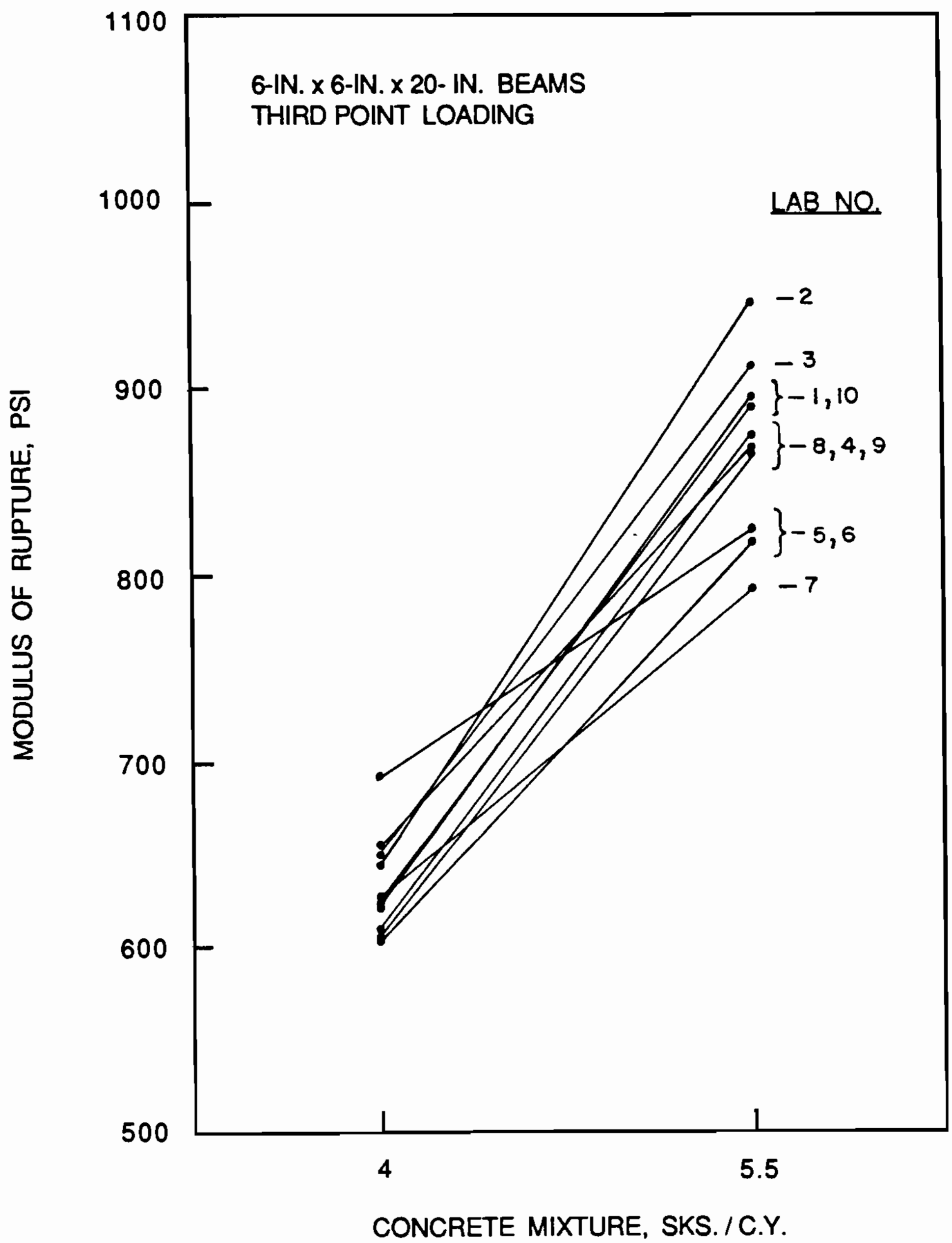


Fig. 5.8 Investigation for interactions in third point loading test results obtained from 6-in. x 6-in. x 20-in. beams.

Table 5.4 Standard deviations and coefficients of variation for 6-in. x 6-in. x 20-in. beams tested in third point loading.

Mix, sks/cy.	Overall Average, psi	Standard Deviation, psi		Coefficient of Variation, %	
		Within-Lab	Between-Lab	Within-Lab	Between-Lab
4	634	28.1	35.6	4.4	5.6
5.5	867	49.1	60.3	5.7	7.0

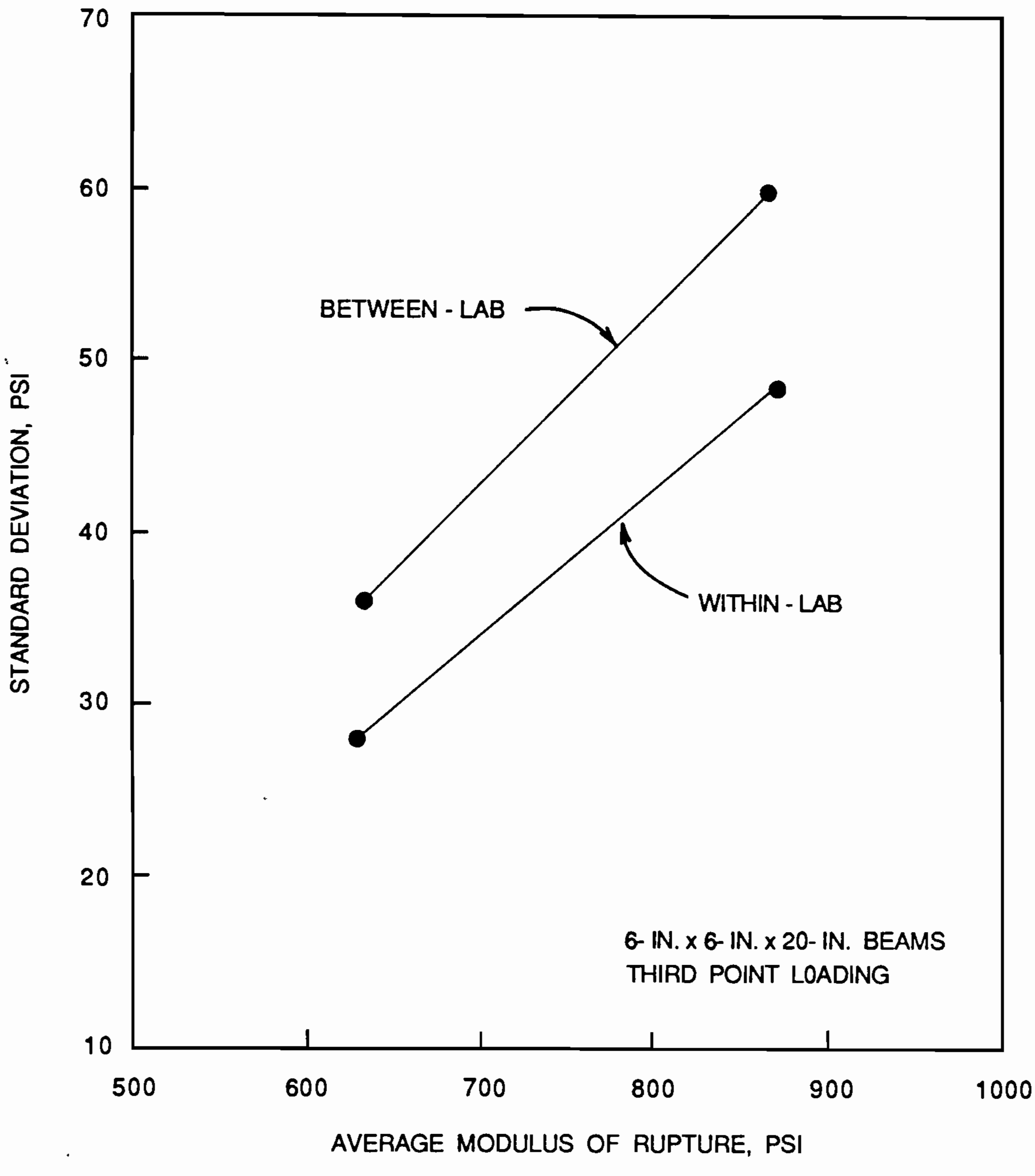


Fig. 5.9 Standard deviation versus average modulus of rupture for 6-in. x 6-in. x 20-in. beams tested in third point loading.

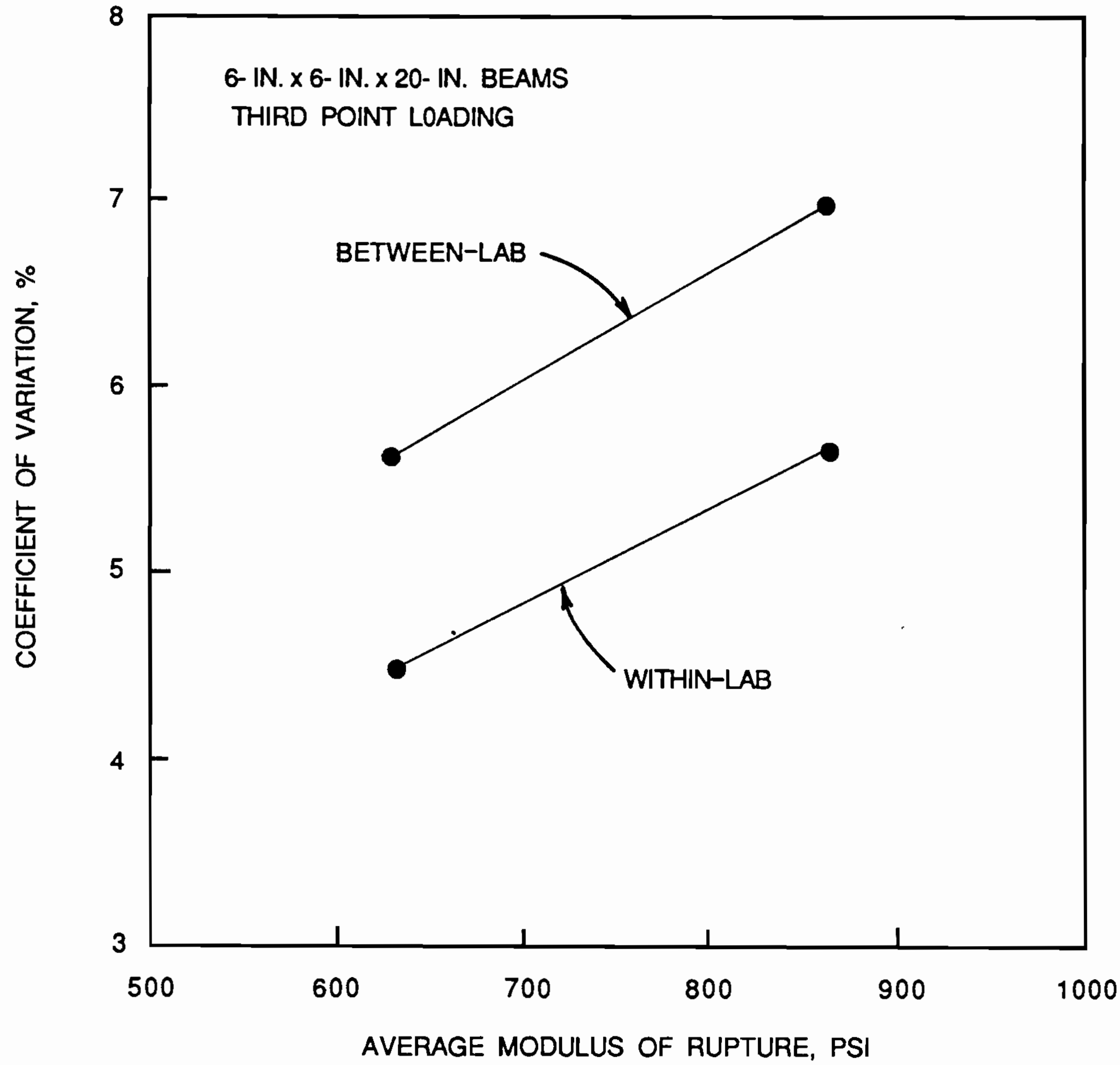


Fig. 5.10 Coefficient of variation versus average modulus of rupture for 6-in. x 6-in. x 20-in. beams tested in third point loading.

5.4.1 Investigation of Uniformity of Data. The within-laboratory variances of this test method are plotted for each laboratory in Figs. 5.11 and 5.12 for the mixes containing 4 sacks and 5.5 sacks of cement per cubic yard, respectively. When these values are checked for compliance with the limits set for low and high variances, shown in Table 5.5, all values are found to be within the allowable limits. Average modulus of rupture is plotted in Fig. 5.13 versus cement content, and results from all laboratories are in agreement, indicating no invalid data.

5.4.2 Calculation of Statistical Properties. The values for within- and between-laboratory standard deviation and coefficient of variation are given in Table 5.6. The standard deviation is plotted in Fig. 5.14 versus average modulus of rupture. As shown in this figure, the within-laboratory and between-laboratory standard deviations are seen to increase with flexural strength by amounts equal to 20% and 37% of their averages, respectively. The corresponding values for coefficient of variation, however, shown in Fig. 5.15, do not exhibit the same behavior. Instead, both values of coefficient of variation are roughly independent of flexural strength. The within- laboratory coefficient of variation decreased by 11% of the average, and the between-laboratory values increased by only 5% of the average with increasing flexural strength.

5.4.3 Preparation of Information on Precision. For 4.5-in. x 4.5-in. x 15.5-in. beams tested in center point loading, since the within- and between-lab coefficients of variation remained approximately constant for increasing modulus of rupture, any statements of precision should be based on those values. Thus, in preparing precision statements, the within- laboratory and between-laboratory coefficients of variation should be taken to be 5.3% and 6.7%, respectively.

5.5 Third Point Loading of 4.5-in. x 4.5-in. x 15.5-in. Beams

The data obtained from 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading are presented and analyzed in this section.

5.5.1 Investigation of Uniformity of Data. The within-laboratory variance for each laboratory is plotted in Figs. 5.16 and 5.17 for 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading. This data is checked for compliance with the limits set for high and low values in Table 5.7, and is seen to not exceed the applicable limits. From Fig. 5.18, in which average modulus of ruptures is plotted versus cement content, all laboratories follow the

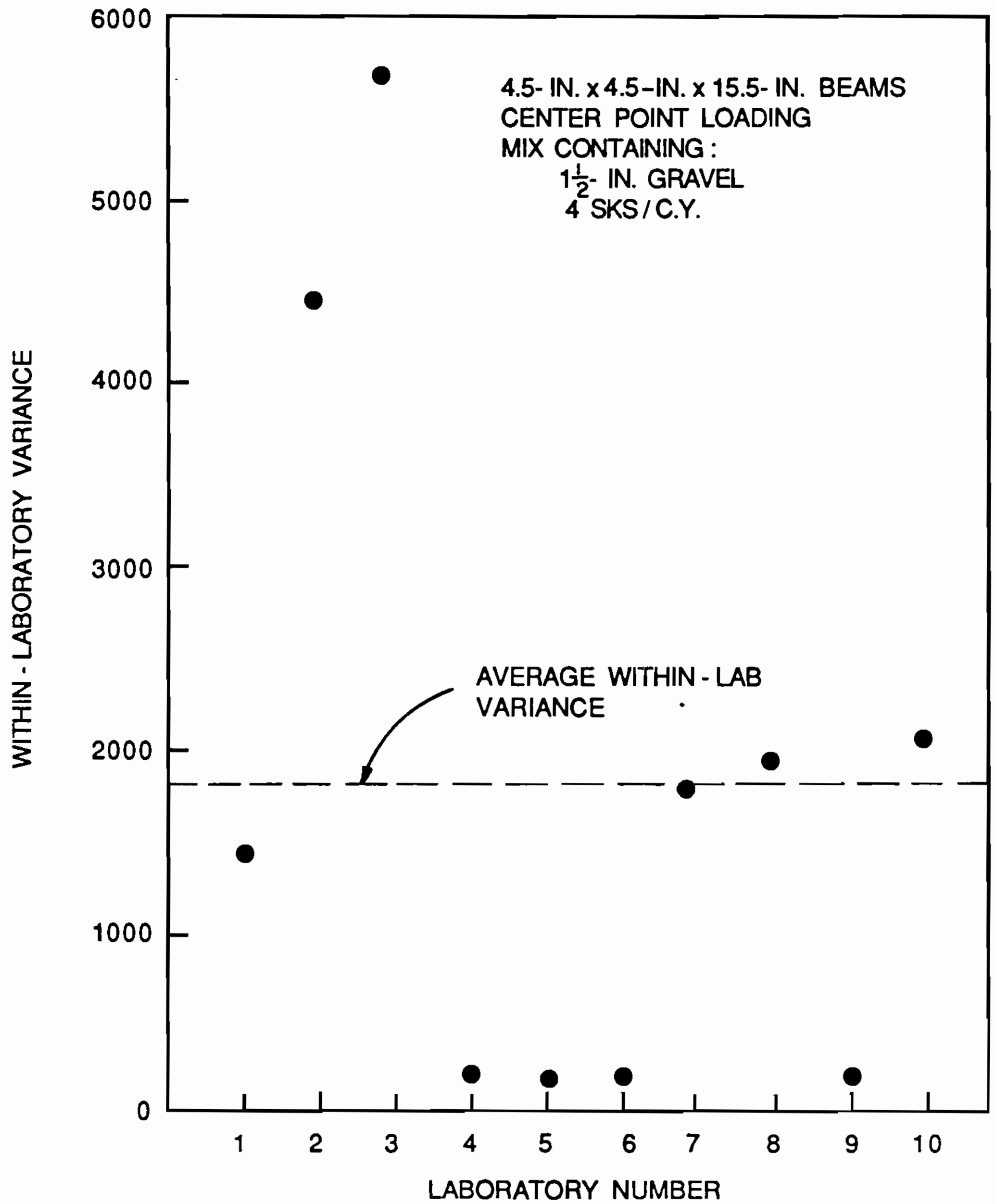


Fig. 5.11 Investigation for agreement of variances for each laboratory for test results obtained from 4.5-in. x 4.5-in. x 15.5-in. beams cast from the mix containing 1-1/2-in. gravel and 4 sacks of cement per cubic yard and tested in center point loading.

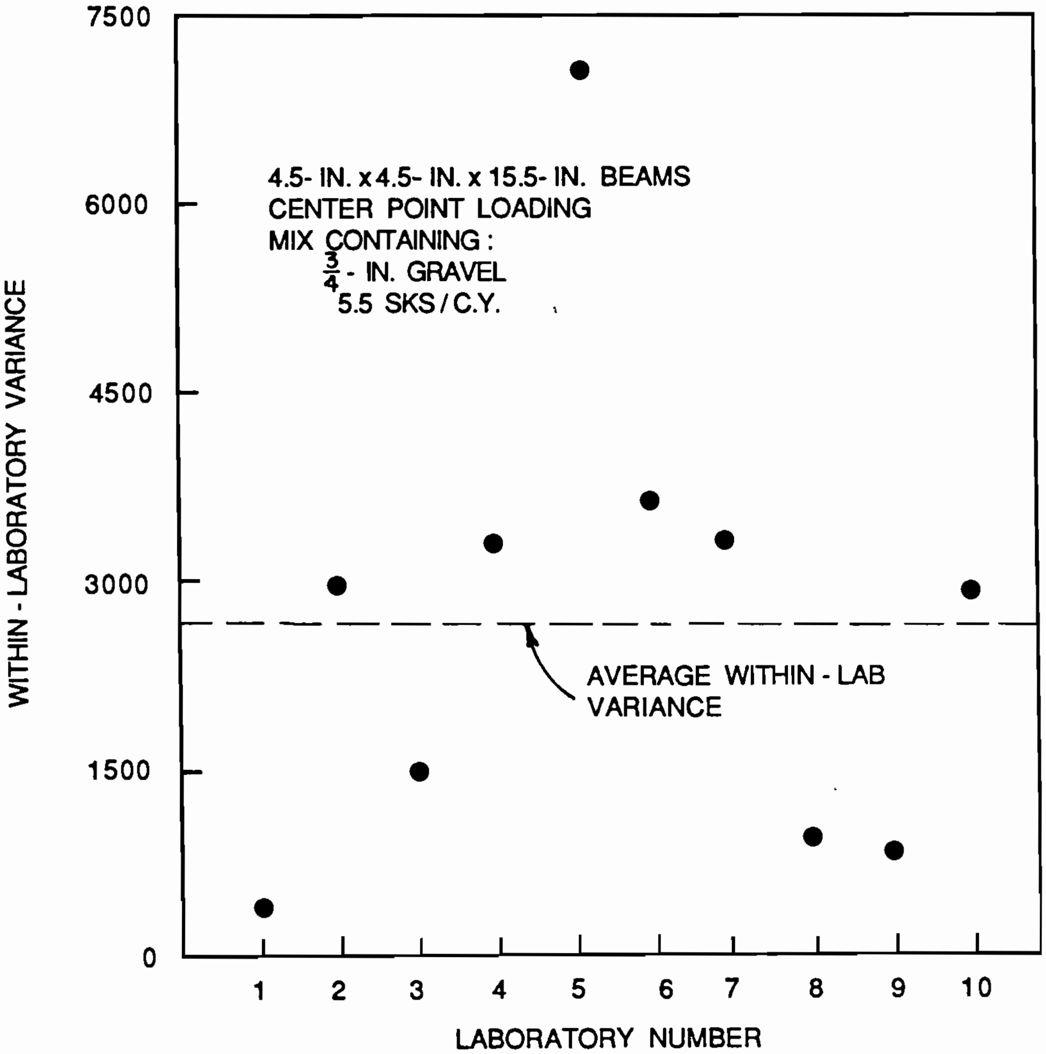


Fig. 5.12 Investigation for agreement of variances for each laboratory for test results obtained from 4.5-in. x 4.5-in. x 15.5-in. beams cast from the mix containing 3/4-in. gravel and 5.5 sacks of cement per cubic yard and tested in center point loading.

Table 5.5 Investigation of agreement of variances for 4.5-in. x 4.5-in. x 15.5-in. beams tested in center point loading.

Mix, sks/cy.	Highest Variance 1	Lowest Variance 2	Average Variance 3	Ratio, 1:3	Ratio, 1:2
4	5678	123	1780	3.2	46.2
5.5	7037	414	2649	2.7	17.0
		Ratio must not exceed:		5	550

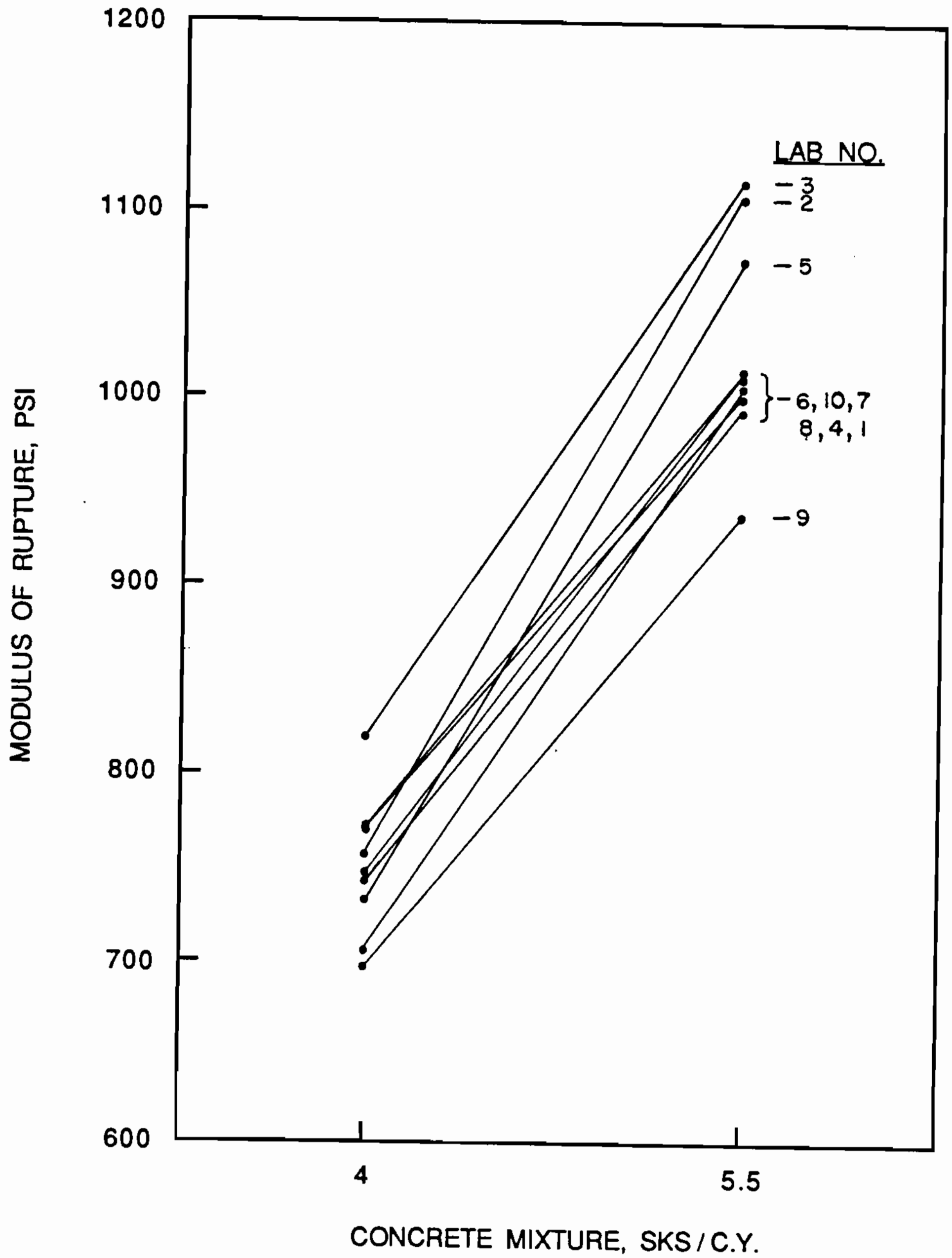


Fig. 5.13 Investigation for interactions in center point loading test results obtained from 4.5-in. x 4.5-in. x 15.5-in. beams.

Table 5.6 Standard deviations and coefficients of variation for 4.5-in. x 4.5-in. x 15.5-in. beams tested in center point loading.

Mix, sks/cy.	Overall Average,	Standard Deviation, psi		Coefficient of Variation, %	
		Within-Lab	Between-Lab	Within-Lab	Between-Lab
4	750	42.2	48.5	5.6	6.5
5.5	1028	51.5	70.2	5.0	6.8

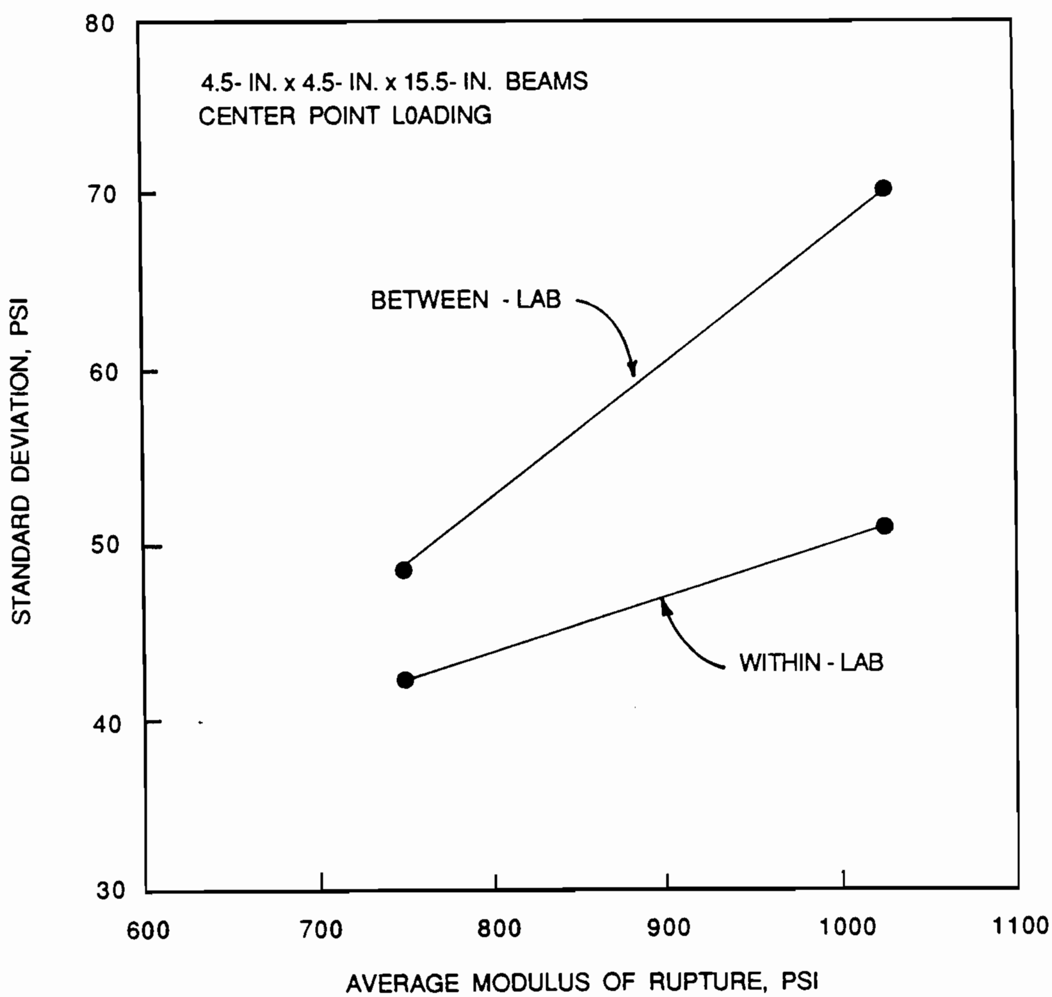


Fig. 5.14 Standard deviation versus average modulus of rupture for 4.5-in. x 4.5-in. x 15.5-in. beams tested in center point loading.

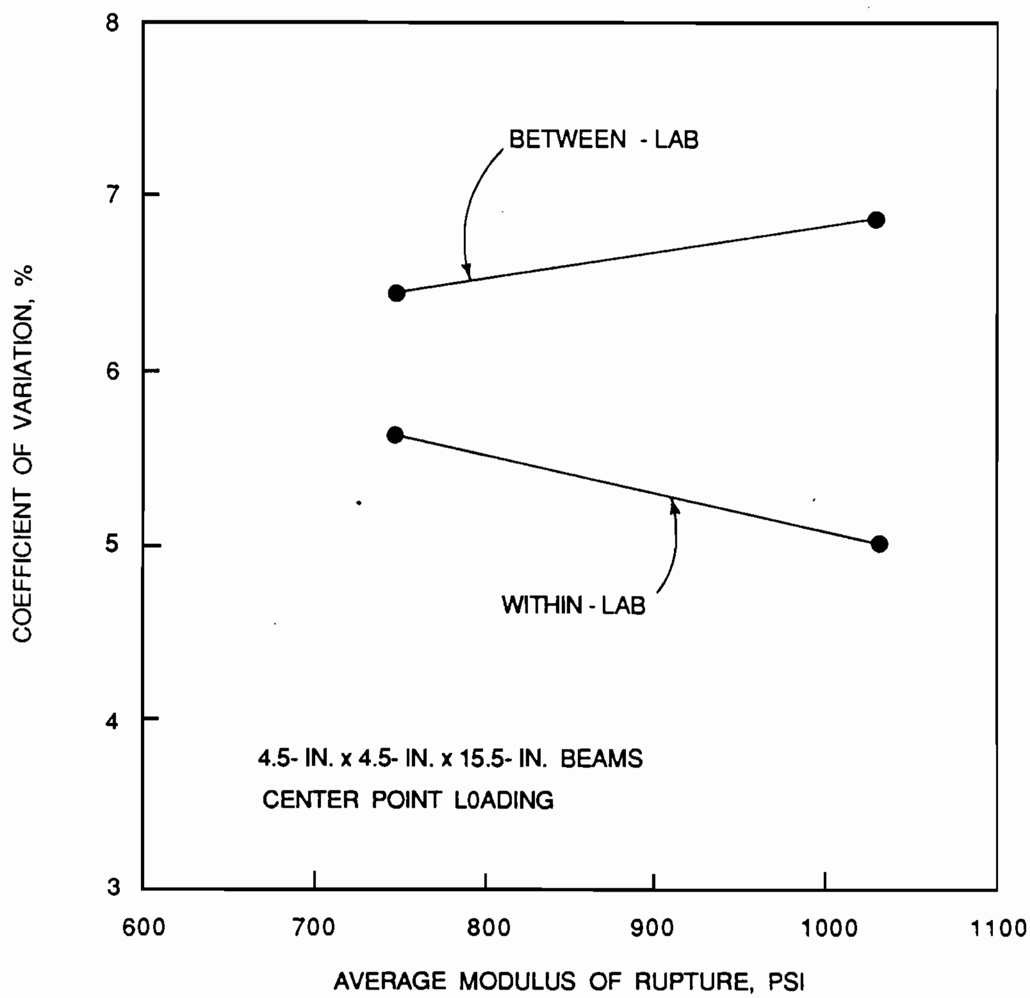


Fig. 5.15 Coefficient of variation versus average modulus of rupture for 4.5-in. x 4.5-in. x 15.5-in. beams tested in center point loading.

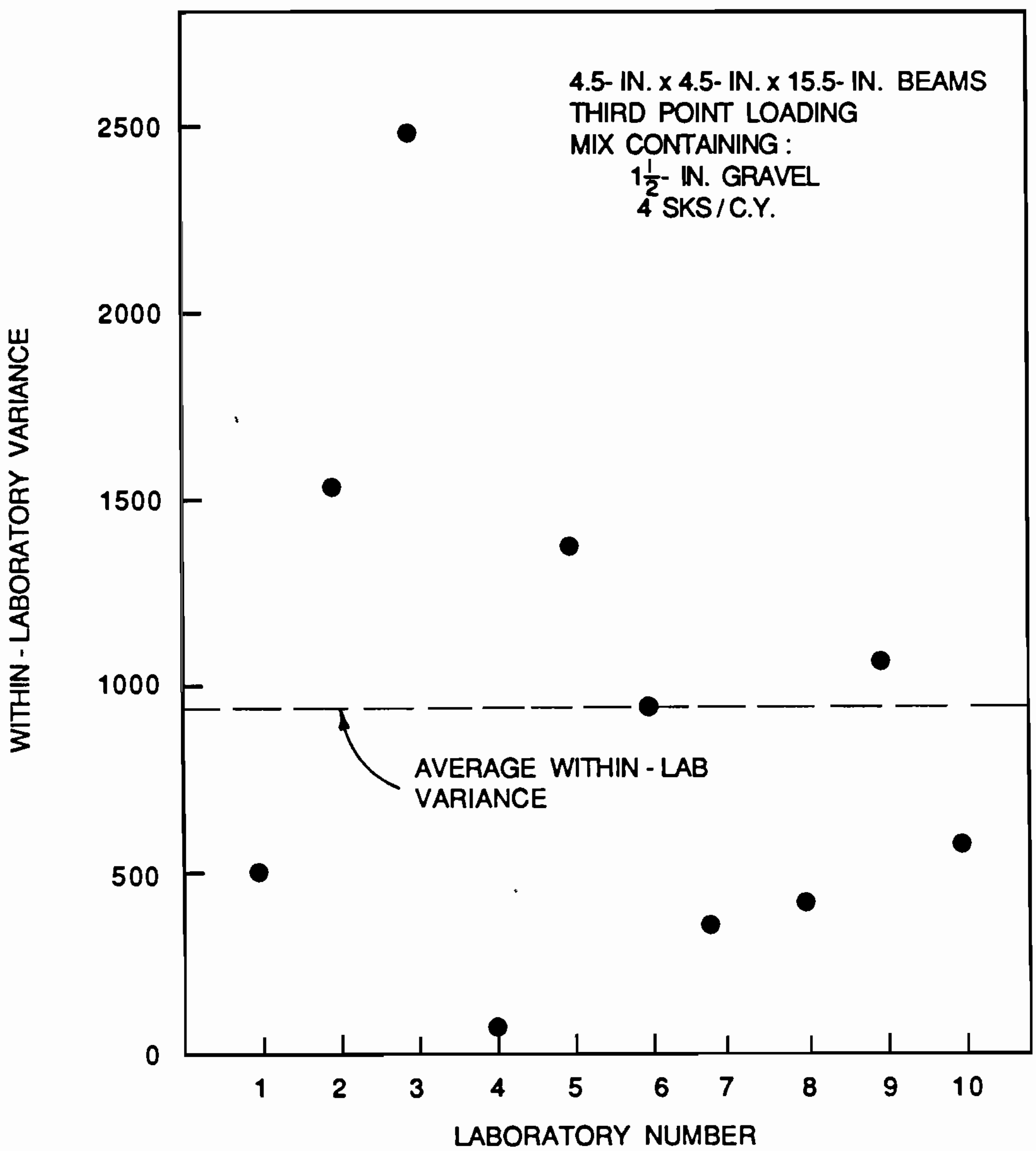


Fig. 5.16 Investigation for agreement of variances for each laboratory for test results obtained from 4.5-in. x 4.5-in. x 15.5-in. beams cast from the mix containing 1-1/2-in. gravel and four sacks of cement per cubic yard and tested in third point loading.

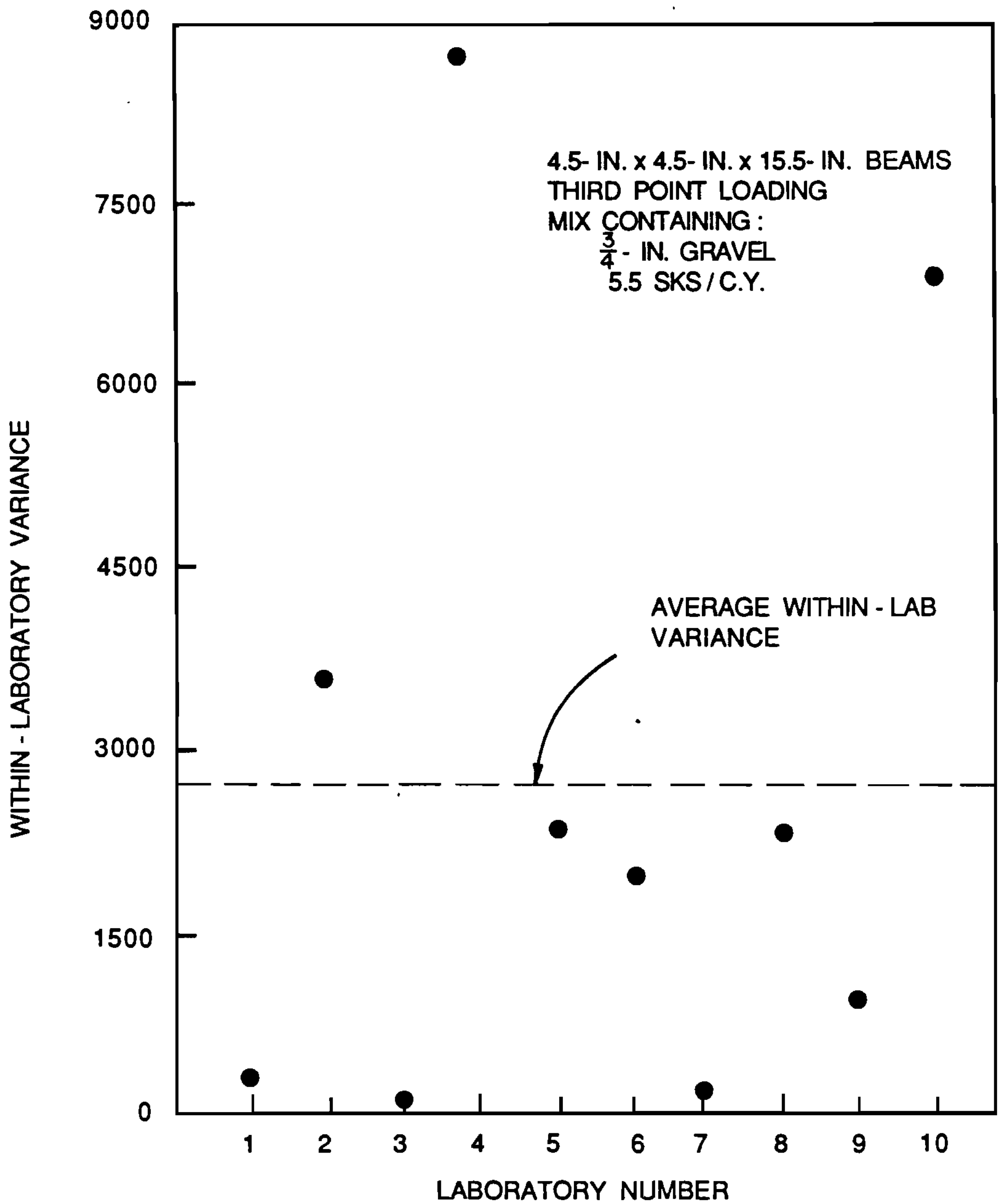


Fig. 5.17 Investigation for agreement of variances for each laboratory for test results obtained from 4.5-in. x 4.5-in. x 15.5-in. beams cast from the mix containing 3/4-in. gravel and 5.5 sacks of cement per cubic yard and tested in third point loading.

Table 5.7 Investigation of agreement of variances for 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading.

Mix, sks/cy.	Highest Variance 1	Lowest Variance 2	Average Variance 3	Ratio, 1:3	Ratio, 1:2
4	2482	55	925	2.7	45
5.5	8716	62	2709	3.2	141
		Ratio must not exceed:		5	550

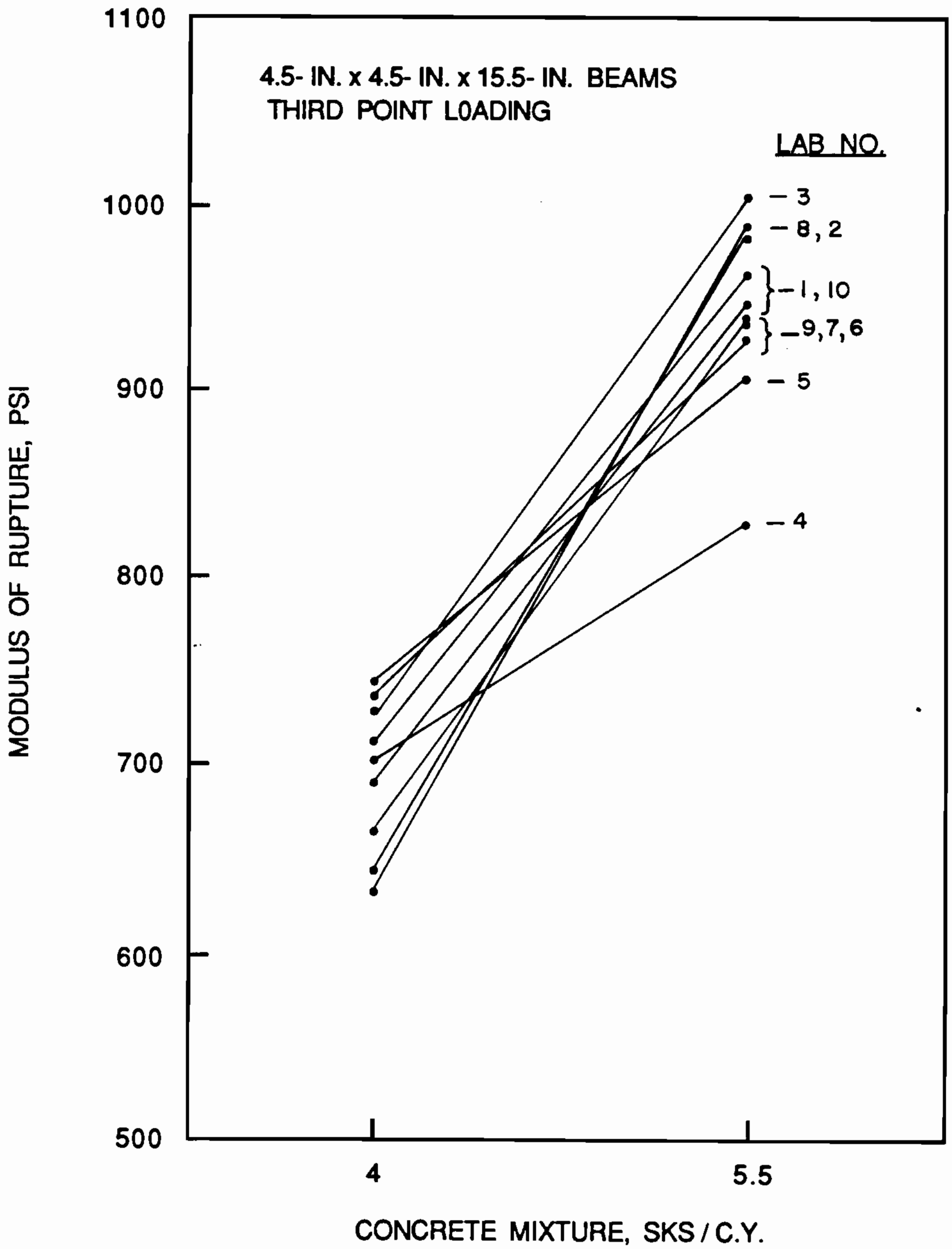


Fig. 5.18 Investigation for interactions in third point loading test results obtained from 4.5-in. x 4.5-in. x 15.5-in. beams.

general trend of higher flexural strength with higher cement content. Thus, for the 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading, all data obtained from the interlaboratory testing program meets the requirements for use in determining the precision of the test method.

5.5.2 Calculation of Statistical Properties. The within- and between-laboratory standard deviations and coefficients of variation for 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading are given in Table 5.8. These values are plotted versus average modulus of rupture in Figs. 5.19 and 5.20. Examination of these figures indicate that both the within- and between-laboratory standard deviation increase with increasing modulus of rupture, as does the within-laboratory coefficient of variation. The between-laboratory coefficient of variation, on the other hand, remains approximately constant with increasing flexural strength.

5.5.3 Preparation of Information on Precision. For 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading, both the within- and between-laboratory standard deviation increased with increasing strength, by amounts equal to 53% and 37% of the average, respectively. The within-laboratory coefficient of variation increased with increasing flexural strength by 22% of the average. An increase of only 8% of the average occurred in the between-laboratory coefficient of variation with increasing flexural strength. Thus, it is not clear that either standard deviation or coefficient of variation are constant for changing flexural strength, and, like third point loading of 6-in. x 6-in. x 20-in. beams, the precision of this test method must be dependent on concrete strength.

5.6 Summary of Second Stage Test Results

For center point loading of 6-in. x 6-in. x 20-in. beams, statements of precision should be based on within- laboratory and between-laboratory coefficients of variation of 4.4% and 5.1%, respectively. Statements of precision for 4.5-in. x 4.5-in. x 15.5-in. beams tested in center point loading should be based on within- and between-laboratory coefficients of variation of 5.3% and 6.7%, respectively.

For third point loading of either 6-in. x 6-in. x 20-in. beams or 4.5-in. x 4.5-in. x 15.5-in. beams, neither the standard deviation nor coefficient of variation is constant with respect to concrete strength. Since only two strength levels are available in defining each property, it is impossible to determine exactly the relationship of these properties to strength based on the results of this research study.

Table 5.8 Standard deviations and coefficients of variation for 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading.

Mix, sks/cy.	Overall Average, psi	Standard Deviation, psi		Coefficient of Variation, %	
		Within-Lab	Between-Lab	Within-Lab	Between-Lab
4	697	30.4	44.6	4.4	6.4
5.5	942	52.1	64.7	5.5	6.9

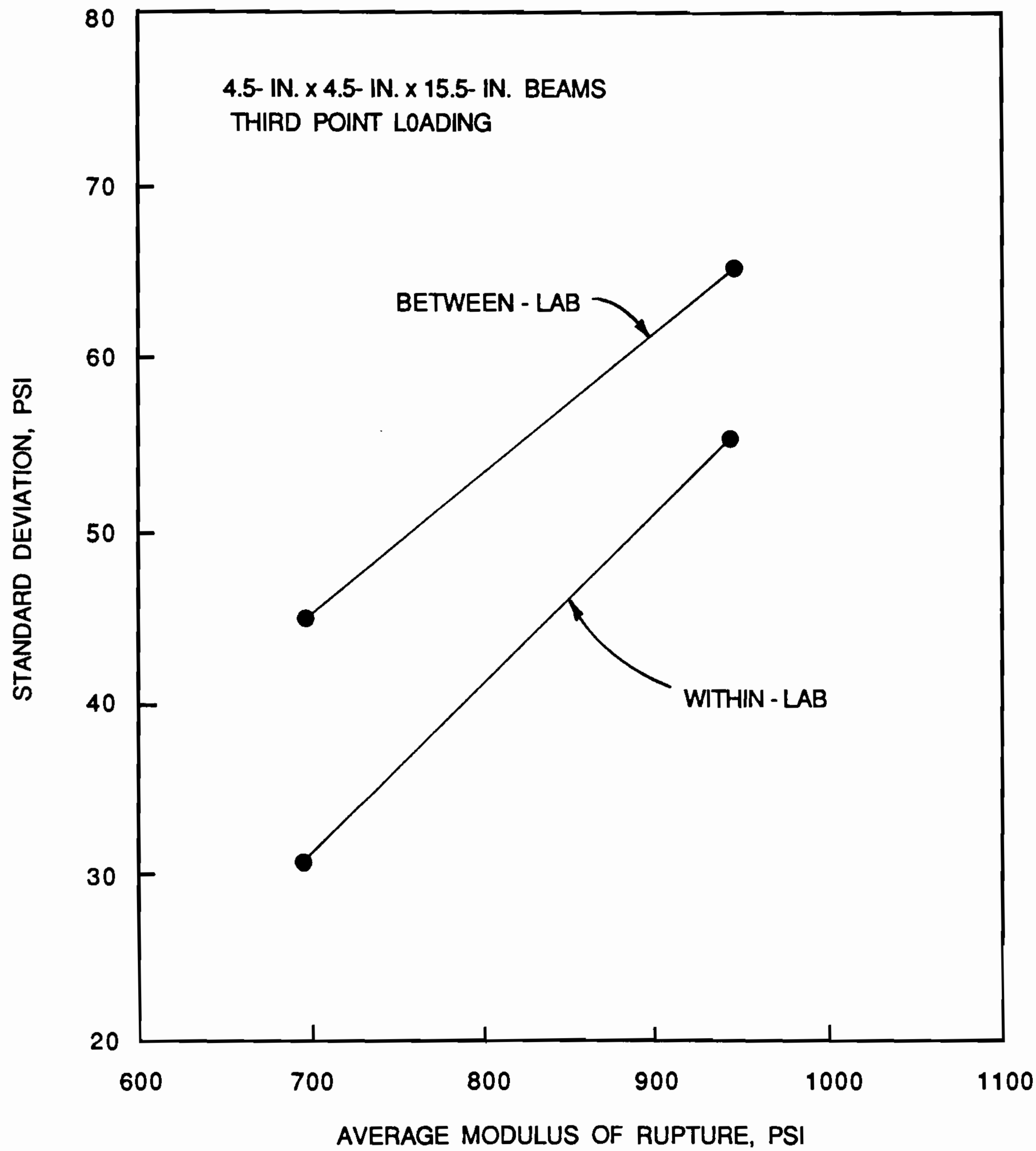


Fig. 5.19 Standard deviation versus average modulus of rupture for 4.5-in. x 4.5-in x 15.5-in. beams tested in third point loading.

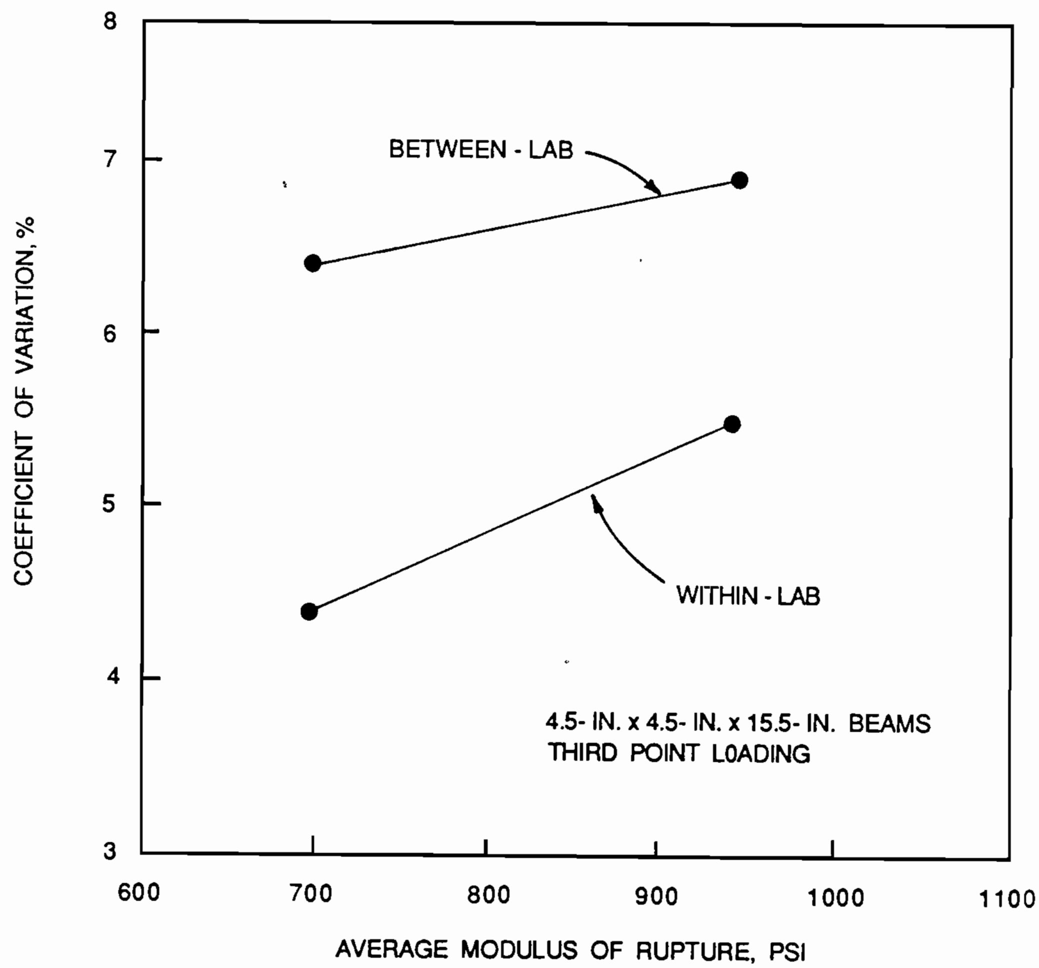


Fig. 5.20 Coefficient of variation versus average modulus of rupture for 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading.

CHAPTER 6

DISCUSSION OF TEST RESULTS

6.1 Introduction

Results from the research program, which were presented in Chapters 4 and 5, will be discussed in this chapter. Test results from the first stage tests and second stage tests will be compared.

6.2 Average Modulus of Rupture

The average modulus of rupture obtained in the first stage tests for each concrete mixture, loading method, and specimen size is given in Table 6.1, and Table 6.2 contains the average modulus of rupture results obtained during the second stage tests. The ratios of test results obtained from all test methods to 6-in. x 6-in. x 20-in. beams tested in center point loading are given in Table 6.3.

As seen in Table 6.3a, the ratio of average modulus of rupture test results obtained from 4.5-in. x 4.5-in. x 15.5-in. beams tested in center point loading to that of 6-in. x 6-in. x 20-in. beams tested in center point loading was, on the average, equality, based on first stage test results. That ratio, obtained using second stage results, however, was found to be 1.06. This latter value, which was based on results obtained from ten different laboratories, was as high as the highest individual value achieved during the first stage tests.

6.3 Standard Deviation of Test Results

The standard deviation of modulus of rupture test results for each concrete mixture, loading method, and specimen size tested in the first stage tests is given in Table 6.4. Similar data, obtained from the second stage tests, is given in Table 6.5.

Based on the results obtained from the first stage tests with 6-in. x 6-in. x 20-in. beams, the average standard deviation of third point loading test results was lower than that of center point loading test results by approximately seven psi. When converted to the allowable range of test results obtained from two companion beams (multiply by $2\sqrt{2}$, as per Ref. [9]), the range of test

Table 6.1 Average modulus of rupture, in psi, for each concrete mixture, loading method, and specimen size tested in the first stage tests.

Mix No.*	6-in. x 6-in. x 20-in.		4.5-in. x 4.5-in. x 15.5-in.	
	Center Point	Third Point	Center Point	Third Point
5	627	529	630	569
6	624	538	604	534
2	692	604	684	618
1	759	637	755	668
9	785	662	835	768
10	774	666	775	702
3	763	675	773	768
4	853	735	822	837
7	914	791	865	798
8	983	835	1018	891
Average	777	667	776	715

* Arranged in order of increasing strength based on 6-in. x 6-in. x 20-in. beams tested in third point loading.

Table 6.2 Average modulus of rupture, in psi, obtained from second stage tests, all laboratories combined.

Mix No.	6.-in. x 6-in. x 20-in.		4.5-in. x 4.5-in. x 15.5-in.	
	Center Point	Third Point	Center Point	Third Point
11	738	---	750	---
12	---	634	---	697
13	939	---	1028	---
14	---	867	---	942

Table 6.3 Ratio of test results obtained from all test methods to 6-in. x 6-in. x 20-in. beams tested in center point loading for a) first stage tests, and b) second stage tests

	6-in. x 6-in. x 20-in.	4.5-in. x 4.5-in. x 15.5-in.	
Mix No.	Third Point	Center Point	Third Point
5	0.84	1.00	0.91
6	0.86	0.97	0.86
2	0.87	0.99	0.89
1	0.84	0.99	0.88
9	0.84	1.06	0.98
10	0.86	1.00	0.91
3	0.88	1.01	1.01
4	0.86	0.96	0.98
7	0.87	0.95	0.87
8	0.85	1.04	0.91
Average	0.86	1.00	0.92

(a)

	6-in. x 6-in. x 20-in.	4.5-in. x 4.5-in. x 15.5-in.	
Mix No.	Third Point	Center Point	Third Point
11	---	1.02	---
12	---	----	---
13	---	1.09	---
14	---	----	---
Average	---	1.06	---

(b)

Table 6.4 Standard deviation, in psi, of modulus of rupture test results obtained from the first stage tests.

Mix No.*	6.-in. x 6-in. x 20-in.		4.5-in. x 4.5-in. x 15.5-in.	
	Center Point	Third Point	Center Point	Third Point
5	28.4	16.7	31.7	36.3
6	19.5	24.2	23.8	23.7
2	14.9	14.4	24.5	33.5
1	41.5	25.7	34.5	33.8
9	49.2	35.5	48.5	45.8
10	27.6	27.3	46.8	19.6
3	40.4	23.7	52.7	49.6
4	31.3	21.4	38.6	82.8
7	41.9	36.6	46.9	55.6
8	35.1	32.0	38.0	42.4
Average	33.0	25.8	38.6	42.3

Table 6.5 Within-laboratory standard deviation, in psi, of modulus of rupture test results obtained from the second stage tests.

Mix Designation	6-in. x 6-in. x 20-in.		4.5-in. x 4.5-in. x 15.5-in.	
	Center Point	Third Point	Center Point	Third Point
"Low"	32.7	28.1	42.2	30.4
"High"	41.5	49.1	51.5	52.1
Average	37.1	38.6	46.9	41.3

results obtained using third point loading would be approximately 20 psi less than that obtained using center point loading. Based on the first stage test results, the maximum range of test results obtained from two companion beams tested in one laboratory by one technician on the same day would be 93 psi if tested in center point loading, and only 73 psi if tested in third point loading. Results obtained from testing 4.5-in. x 4.5-in. x 15.5-in. beams have a higher standard deviation than tests conducted using 6-in. x 6-in. x 20-in. beams.

Results obtained from the interlaboratory study (second stage tests) indicate that the average standard deviations of test results from 6-in. x 6-in. x 20-in. beams tested in third point and center point loading are approximately equal. Based on these results, the maximum range of two test results from companion beams tested in the same laboratory by the same technician on the same day would be 105 psi for center point loading and 109 psi for third point loading. However, looking at the "low" mix results only, it is seen that the standard deviation of test results obtained from third point loading is less than that obtained from center point loading, resulting in a range of only 79 psi as opposed to 92 psi with center point loading. These results, obtained from the "low" mix, are in close agreement with those obtained from the first stage tests.

6.4 Coefficient of Variation of Test Results

The coefficient of variation of modulus of rupture test results for each concrete mixture, loading method, and specimen size tested in the first stage tests is given in Table 6.6. Similar data, obtained from the second stage tests, is presented in Table 6.7. The values from the first and second stage tests correspond closely for center point loading, but differ greatly for third point loading. Considering only the results from the "low" mix from the second stage tests, however, yields a much closer agreement with first stage results for 6-in. x 6-in. x 20-in. beams tested in third point loading.

6.5 Summary of Test Results

The results from the first stage tests showed that the smallest range of test results, in psi, would be obtained when 6- in. x 6-in. x 20-in. beams are tested in third point loading. Results from the second stage tests agree with this for the "low" mix design.

Table 6.6 Coefficient of variation, in percent, of modulus of rupture test results obtained from the first stage tests.

Mix No.	6.-in. x 6-in. x 20-in.		4.5-in. x 4.5-in. x 15.5-in.	
	Center Point	Third Point	Center Point	Third Point
5	4.5	3.2	5.2	6.3
6	3.1	4.5	3.9	4.5
2	2.2	2.4	3.6	5.5
1	5.5	4.0	4.5	4.9
9	6.3	5.4	5.9	6.0
10	3.6	4.1	5.9	2.8
3	5.3	3.5	7.0	6.5
4	3.7	2.9	4.5	9.8
7	4.6	4.6	5.4	6.8
8	3.6	3.8	3.8	4.9
Average	4.2	3.8	5.0	5.8

Table 6.7 Within-laboratory coefficient of variation, in percent, of modulus of rupture test results obtained from the second stage tests.

Mix Designation	6.-in. x 6-in. x 20-in.		4.5-in. x 4.5-in. x 15.5-in.	
	Center Point	Third Point	Center Point	Third Point
"Low"	4.4	4.4	5.6	4.4
"High"	4.4	5.7	5.0	5.5
Average	4.4	5.1	5.3	5.0

However, at the high strength level, corresponding to approximately 870 psi for third point loading or 1010 psi for center point loading (if the ratio of third point loading to center point loading is taken to be 0.86), the variation of test results, measured by standard deviation, obtained from testing 6-in. x 6-in. x 20-in. beams in third point loading is higher than if tested in center point loading. As was noted in the preceding chapter, both the standard deviation and coefficient of variation of test results obtained from third point loading increased with concrete strength.

Most of the concrete placed for the Texas SDHPT, however, has a minimum specified flexural strength of 650 psi in center point loading, or less depending on the class of concrete. Only Class C-C and Class F concretes would have a higher minimum flexural strength requirement. Thus, for a majority of the concrete used by the SDHPT, 6-in. x 6-in. x 20-in. beams tested in third point loading would yield more uniform test results, and thus would be an improved quality control procedure, than center point loading. Indeed, the uniformity of test results becomes critical when the average approaches the minimum specified strength. Therefore, for all classes of concrete, with the possible exception of Class C-C and Class F, the testing of 6-in. x 6-in. x 20-in. beams in third point loading would be a better quality control test. In addition, the ratio of results obtained from third point loading to those obtained from center point loading was found to be 0.86. The range in the ratio, from 0.84 to 0.88, indicates that a close relationship exists, and thus the modification of existing strength specifications from values for center point loading to those for third point loading could be achieved with a high level of confidence in the applicability of those values.

Although the use of the smaller, 4.5-in. x 4.5-in. x 15.5-in. beams was met with much enthusiasm by SDHPT field personnel due to their decreased weight and bulk, the fact that the test results obtained were much more variable than those obtained from 6-in. x 6-in. x 20-in. beams makes the use of the smaller beams as a quality control procedure less desirable.

CHAPTER 7

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

In this chapter, the objectives of this research study will be summarized, and conclusions given. Also, recommendations are given for the implementation of the test results, as well as for further research to be conducted on the subject of concrete quality control.

7.2 Summary of Test Program

The objective of this research program was to identify those variables affecting the magnitude and uniformity of flexural strength test results, and to gather sufficient data to form the basis of precision statements for the various test methods. A total of more than 700 flexure specimens and 100 compression specimens were cast from fourteen different batches of ready-mix concrete. The variables studied included:

a) specimen dimensions of 4.5-in. x 4.5-in. x 15.5-in. (tested on a 13.5-in. span) versus the standard 6-in. x 6-in. x 20-in. (tested on an 18-in. span),

b) third point loading versus center point loading,

c) crushed limestone versus siliceous river gravel,

d) coarse aggregate nominal maximum size, and

e) concrete strength level.

7.3 Conclusions

Based on the results of this research, the following conclusions can be drawn:

Average Modulus of Rupture

1. For beams tested in center point loading, the average modulus of rupture obtained from 4.5-in. x 4.5-in. x 15.5-in. specimens was approximately equal to that obtained from 6-in. x 6-in. x 20-in. beams.

2. For beams tested in third point loading, the average modulus of rupture obtained from 4.5-in. x 4.5-in. x 15.5-in. beams was, on the average, approximately seven percent higher than that obtained from 6-in. x 6-in. x 20-in. beams.

3. 6-in. x 6-in. x 20-in. beams tested in center point loading yielded an average modulus of rupture which was approximately 14 percent higher than that from 6-in. x 6-in. x 20-in. beams tested in third point loading.

4. 6-in. x 6-in. x 20-in. beams tested in center point loading yielded an average modulus of rupture which was approximately eight percent higher than that from 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading.

5. The relationship between 7-day compressive strength and 7-day flexural strength of standard beams tested in center point loading was found to be, on the average, in a ratio of 6:1. In general, a ratio of at least 8:1 would exist between 28-day compressive strength and 7-day flexural strength for center point loading. However, these ratios are dependent on individual mixture proportions.

6. For third point loading, the ratio between 28-day compressive strength and 7-day flexural strength would be approximately 10:1. The exact ratio would depend on individual mixture proportions.

7. On the average, the actual modulus of rupture of 6-in. x 6-in. x 20-in. beams tested in center point loading, based on the stress at the location of fracture, was only 94% of the reported stress, which is based on stress at midspan.

Uniformity of Test Results

1. For both center point loading and third point loading, slightly more uniform test results were obtained from testing 6-in. x 6-in. x 20-in. specimens than from 4.5-in. x 4.5-in. x 15.5-in. specimens.

2. For 6-in. x 6-in. x 20-in. beams, the standard deviation of test results was lower for third point loading than for center point loading. However, the coefficients of

variation obtained from the two test methods were similar.

3. The uniformity of test results was greater when crushed limestone coarse aggregate was used, as opposed to siliceous river gravel, for 6-in. x 6-in. x 20-in. beams tested in center point loading.

4. A statement of precision for 6-in. x 6-in. x 20-in. beams tested in center point loading should be based on within-laboratory and between-laboratory coefficients of variation of 4.4% and 5.1%, respectively.

5. A statement of precision for 4.5-in. x 4.5-in. x 15.5-in. beams tested in center point loading should be based on within-laboratory and between-laboratory coefficients of variation of 5.2% and 6.7%, respectively.

6. Both the standard deviation and coefficient of variation are dependent on strength level for beams tested in third point loading.

7.4 Implementation of Research Findings

Based on the results of this study, more uniform test results are obtained with the use of third point loading in place of center point loading for testing the flexural strength of 6-in. x 6-in. x 20-in. concrete beams. It is recommended that prior to incorporation of the research results into the TSDHPT Concrete Specifications, comparative tests be conducted in the field by SDHPT personnel using both test methods on companion beams, in order to familiarize field personnel to the new test method. Based on the test results from this study, changes to the concrete specifications are recommended to convert to the third point loading of concrete beams as the standard field quality control procedure to evaluate the flexural strength of concrete. Successful transition to the new test method would entail the addition of the new test procedure to TEX 420A, the education of field personnel on the correct procedure for the new test method, the modification of concrete flexural strength specifications, and the purchase and installation of a third point loading head on each existing test machine at an approximate cost of $200 per loading head.

7.5 Recommendations for Research

Based on the findings of the present investigation, the following recommendations for further research are made:

1. Study the effect of concrete strength on the uniformity of specimens tested in third point loading.

2. Study the use of compressive strength as a quality control procedure after correlating compressive strength test results with flexural strength test results.

3. Conduct flexural strength tests in both center point loading and third point loading for concrete strengths below 600 psi.

4. Conduct field tests to determine the effect of field handling and curing on the strength test results for both center point loading and third point loading

APPENDIX A
DATA AND CALCULATIONS FOR FIRST STAGE TESTS

A.1 Introduction

Individual test results from the first stage test specimens are given in this Appendix. Also included are equations used in the reduction and analysis of the data.

The designation A or B following the mix number indicates the personnel who prepared the specimens, as was discussed in Chapter 3. However, in analysis of the data in Chapter 4 through 6, all 12 tests from a single mix were combined to produce one average test result.

A.2 Individual Flexural Strength Test Results

Individual test results for each of the ten different concrete mixtures are presented in this section.

A.2.1 Center Point Loading of 6-in. x 6-in. x 20-in. Beams. Table A.1 gives individual test results for 6-in. x 6-in. x 20-in. beams tested in center point loading. The load given in Column 2 represents the maximum stress recorded on the test chart multiplied by a factor of eight. This is based on the following equations:

$$\sigma = \frac{M \cdot Y}{I} \tag{A.1}$$

$$M = \frac{PL}{4} \text{ (at midspan)} \tag{A.2}$$

$$Y = \frac{d}{2} \text{ , and} \tag{A.3}$$

$$I = \frac{1}{12} wd^3, \tag{A.4}$$

where
- σ = stress, psi
- M = moment, lb-in.
- Y = distance from the neutral axis to the extreme fiber, in.
- I = moment of inertia, in.^{4}
- P = applied load, lbs.
- L = unsupported length of beam, in.
- d = depth of beam, in.
- w = width of beam, in.

For a beam having a cross section of 6-in. x 6-in., which is what the recording charts are based upon, and an 18-in. span:

$$M = \frac{(18) \cdot P}{4} = (4.5)\ P \tag{A.2a}$$

$$Y = \frac{6}{2} = 3 \tag{A.3a}$$

$$I = \frac{1}{12}\ (6)^4 = 108 \tag{A.4a}$$

Plugging these values into Eq. (A.1) and rearranging gives:

$$\sigma = \frac{P}{8}, \text{ or} \tag{A.1a}$$

$$P = (8) \cdot \sigma \tag{A.5}$$

Columns 3 and 4 give the actual measured beam dimensions as tested at the plane of fracture. Column 5 lists values which represent the actual measured distance, from the end support, of the plane of fracture. A value of 9.00-in. would indicate fracture occurring at midspan.

In Column 6 the actual stress occurring at the plane of fracture is calculated. This is done using Eqs. (A.1), (A.3) and (A.4). The actual moment occurring at the plane of fracture is calculated as follows:

$$M = \frac{P}{2} \cdot D \tag{A.6}$$

where D is the value given in Column 5. Thus, Eq. (A.1) for calculation of the actual stress at the plane of fracture becomes:

$$\sigma_{actual} = \frac{(\frac{P}{2}) \cdot D \cdot \frac{d}{2}}{(\frac{1}{12})\ w \cdot d^3}, \tag{A.7a}$$

or

$$\sigma_{actual} = \frac{3PD}{wd^2} \tag{A.7b}$$

In order to calculate the stress at midspan at the time of failure for Column 7, Eq. (A.7b) is used, with D = L/2 = 9 in., as follows:

$$\sigma_{midspan} = \frac{3P \cdot 9}{wd^2}$$

$$= \frac{27P}{wd^2} \tag{A.8}$$

The average stress at the plane of fracture and at midspan are calculated and entered into Columns 8 and 9, respectively.

In the representation and discussion of test results in Chapters 4 and 6, only the results from following the standard test procedure are used; that is, calculation of stress at midspan. However, the data obtained based on the actual location of the failure plane have been included in this section to give the reader full benefit of the test program.

A.2.2 Third Point Loading of 6-in. x 6-in. x 20-in. Beams. Individual test results for 6-in. x 6-in. x 20-in. beams tested in third point loading are given in Table A.2. The load given in Column 2 represents the maximum stress recorded on the test chart multiplied by a factor of twelve. This is based on Eq. (A.1), (A.3) and (A.4). The equation for calculating the moment, however, is as follows:

$$M = \frac{PL}{6} \text{ (middle third of span)} \qquad \text{(A.9)}$$

Thus, for a beam having a cross-section of 6-in. x 6-in. and an unsupported span of 18 inches, substituting values for Eq. (A.3a), (A.4a) and (A.9) into Eq. (A.1) yields:

$$\sigma = \frac{(3P)(3)}{108} = \frac{P}{12}$$

and rearranging gives:

$$P = (12) \cdot \sigma$$

The actual stress at failure is calculated in Column 5 using the actual beam dimensions given in Columns 3 and 4. The following equation is used:

$$\sigma = \frac{(3P)(\frac{d}{2})}{(\frac{1}{12})wd^3}$$

or

$$\sigma_{TPL} = \frac{18P}{wd^2} \qquad \text{(A.10)}$$

The average stress is calculated and given in Column 6.

A.2.3 Center Point Loading of 4.5-in. x 4.5-in. x 15.5-in. Beams. Individual test results of 4.5-in. x 4.5-in. x 15.5- in. beams tested in center point loading are given in Table A.3. The load entered in Column 2 is read directly from the recording chart, and the measured beam dimensions at the plane of fracture are entered in Columns 3 and 4. The measured distance of the plane of fracture from the end support is entered in Column 5. The calculation of actual stress, Column 6, and midspan stress, Column 7, is performed similar to that described in section A.2.1, with the exception of the ideal beam dimensions which are, for Table A.3, 4.5-in. x 4.5-in. cross section and 13.5-in. unsupported span length.

A.2.4 Third Point Loading of 4.5-in. x 4.5-in. x 15.5-in. Beams. Table A.4 lists individual test values for 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading. The load entered into Column 2 for each beam is read directly from the recording chart. Columns 3 and 4 contain the measured beam dimensions at the plane of fracture. The stress for Column 5 is calculated similarly to that described in Section A.2.2, except that the span length is 13.5-in., and the ideal beam cross section is 4.5-in. x 4.5-in. Column 6 contains the average stress.

A.3 Uniformity of Test Results

The standard deviation and coefficient of variation for specimens cast from each mix are given in this section for each test method in Tables A.5 through A.8. The calculation of standard deviation and coefficient of variation was done according to the following equations:

$$SD = \left[(n \cdot (\sum_{i=1}^{n} X_i^2) - (\sum_{i=1}^{n} X_i)^2/(n \cdot (n-1)) \right]^{1/2} \qquad (A.11)$$

$$CV = \frac{SD}{\bar{X}} \cdot 100\% \qquad (A.12)$$

where SD = standard deviation, psi

n = number of individual tests

X_i = individual test result, psi

CV = coefficient of variation, %

$\bar{X}$ = average value of test results, psi

A.4 Compressive Strength Test Results

Individual compressive strength test results for each of the ten concrete mixtures are given in Table A.9. Also given is data on the uniformity of the test results.

Table A.1 Individual test results from 6-in. x 6-in. x 20-in. beams tested in center point loading.

Mix No.	Load, lbs.	Beam Width, in.	Beam Depth, in.	Fracture, in.	Actual Stress, psi	Midspan Stress, psi	Actual Average, psi	Midspan Average, psi
1A	5880	6.03	6.00	9.00	731	731		
	6520	6.06	6.06	7.00	614	790		
	6120	6.03	6.00	9.00	761	761		
	6040	6.06	6.03	9.00	739	739		
	5880	6.03	6.06	9.00	716	716		
	6240	6.06	6.00	8.00	686	772	708	752
1B	6760	6.09	6.00	9.00	832	832		
	6440	6.06	6.00	8.00	708	797		
	6560	6.09	6.03	8.00	710	799		
	5600	6.09	6.00	9.00	689	689		
	6320	6.09	6.06	8.00	677	762		
	5840	6.09	6.00	8.00	639	719	709	766
2A	5600	6.13	6.00	8.00	610	686		
	5280	6.00	6.00	8.00	587	660		
	5720	6.09	6.00	9.00	704	704		
	5560	6.00	6.00	9.00	695	695		
	5600	6.13	6.00	9.00	686	686		
	5680	6.13	6.06	9.00	681	681	660	685
2B	5640	6.09	6.03	9.00	687	687		
	5840	6.09	6.00	8.00	639	719		
	5680	6.13	6.03	8.00	612	688		
	5640	6.09	6.00	8.00	617	694		
	5600	6.03	6.00	9.00	696	696		
	5760	6.09	6.00	9.00	709	709	660	699
3A	7000	6.06	6.06	9.00	848	848		
	6440	6.13	6.03	8.00	694	780		
	6400	6.13	6.03	8.00	689	776		
	6120	6.06	6.00	8.00	673	757		
	6000	6.13	6.00	9.00	735	735		
	5600	6.06	6.00	9.00	718	718	726	769
3B	6040	6.13	6.00	8.00	657	740		
	5960	6.03	6.00	8.50	700	741		
	6160	6.19	6.00	9.00	747	747		
	5880	6.09	6.06	8.50	669	709		
	6480	6.09	6.03	9.00	789	789		
	6600	6.09	6.00	7.25	654	812	703	756
4A	6840	6.13	6.06	8.50	775	820		
	7160	6.06	6.00	8.75	861	886		
	7000	6.13	6.00	8.50	810	857		
	6560	6.13	6.00	8.50	759	803		
	7360	6.13	6.00	8.25	826	901		
	6960	6.06	6.00	9.00	861	861	815	855
4B	7200	6.09	6.00	8.50	837	886		
	6920	6.13	6.03	9.00	839	839		
	7120	6.06	6.00	8.50	832	881		
	6920	6.09	6.00	8.50	804	852		
	6680	6.13	6.00	8.50	773	818		
	6800	6.06	6.03	8.00	740	833	804	851

Table A.1 Individual test results from 6-in. x 6-in. x 20-in. beams tested in center point loading (continued).

Mix No.	Load, lbs.	Beam Width, in.	Beam Depth, in.	Fracture, in.	Actual Stress, psi	Midspan Stress, psi	Actual Average, psi	Midspan Average, psi
5A	5360	6.00	6.00	8.50	633	670		
	4720	6.00	6.00	7.75	508	590		
	4800	6.13	6.00	8.00	522	588		
	5040	6.06	6.00	8.00	554	624		
	5200	6.00	6.00	8.75	632	650		
	5080	6.13	6.00	9.00	622	622	579	624
5B	4760	6.00	6.03	8.00	523	589		
	5200	6.03	6.03	9.00	640	640		
	5240	6.06	6.00	9.00	648	648		
	5160	6.00	6.00	9.00	645	645		
	5240	6.03	6.00	9.00	652	652		
	4880	6.00	6.03	8.50	570	604	613	630
6A	5240	6.06	6.00	8.50	612	648		
	5080	6.13	6.00	7.75	536	622		
	4920	6.00	6.00	8.50	581	615		
	5160	6.00	6.00	8.50	609	645		
	5000	6.06	6.00	8.50	584	619		
	4720	6.00	6.00	8.25	541	590	577	623
6B	5320	6.06	6.03	8.00	579	651		
	5080	6.03	6.00	8.25	579	632		
	5160	6.03	6.03	8.75	617	635		
	4800	6.00	6.03	8.50	561	594		
	5040	6.03	6.03	8.50	586	620		
	5000	6.06	6.00	9.00	619	619	590	625
7A	7400	6.00	6.00	8.25	848	925		
	7160	6.06	6.00	8.75	861	886		
	7240	6.13	6.00	8.25	813	887		
	7040	6.00	6.00	8.25	807	880		
	7720	6.06	6.06	8.75	909	935		
	7320	6.00	6.06	7.50	747	896	831	902
7B	7840	6.09	6.03	8.25	875	955		
	7400	6.06	6.00	8.50	865	915		
	6920	6.09	6.03	8.00	749	843		
	7480	6.06	6.00	8.50	874	925		
	7600	6.09	6.06	8.00	814	916		
	8320	6.06	6.06	8.00	896	1008	846	927
8A	7400	6.06	6.06	8.75	872	897		
	7880	6.00	6.00	8.50	930	985		
	8320	6.06	6.00	9.00	1029	1029		
	8280	6.06	6.00	8.75	996	1024		
	8320	6.00	6.06	8.25	934	1019		
	7920	6.00	6.00	8.75	963	990	954	991
8B	7880	6.03	6.03	9.00	970	970		
	7760	6.00	6.00	8.50	916	970		
	7960	6.06	6.03	8.25	893	975		
	7840	6.06	6.00	8.50	916	970		
	8000	6.13	6.03	8.00	862	969		
	8000	6.03	6.00	8.75	967	995	921	975

Table A.1 Individual test results from 6-in. x 6-in. x 20-in. beams tested in center point loading (continued).

Mix No.	Load, lbs.	Beam Width, in.	Beam Depth, in.	Fracture in.	Actual Stress, psi	Midspan Stress, psi	Actual Average, psi	Midspan Average, psi
9A	6200	6.06	6.00	8.75	746	767		
	6000	6.13	6.00	8.00	653	735		
	6440	6.06	6.06	8.50	737	780		
	6440	6.06	6.00	8.50	752	797		
	7160	6.06	6.06	8.50	819	868		
	6360	6.13	6.00	8.00	692	779	733	788
9B	6600	6.13	6.00	8.50	763	808		
	7080	6.13	6.00	8.00	771	867		
	6480	6.06	6.06	8.00	698	785		
	5720	6.06	6.00	8.00	708	708		
	6520	6.13	6.00	8.75	776	798		
	5880	6.00	6.03	8.25	667	727	730	782
10A	5880	6.06	6.06	8.75	693	713		
	6560	6.06	6.00	9.00	812	812		
	6480	6.19	6.06	8.50	727	769		
	6320	6.06	6.00	8.75	760	782		
	6400	6.06	6.00	8.75	770	792		
	6080	6.06	6.06	8.50	696	737	743	767
10B	6280	6.13	6.00	8.25	705	769		
	6320	6.00	6.03	8.25	717	782		
	6440	6.06	6.06	8.50	737	780		
	6640	6.06	6.06	8.75	782	805		
	6200	6.13	6.00	8.25	696	759		
	6400	6.13	6.00	8.00	697	784	722	780

Table A.2 Individual test results from 6-in. x 6-in. x 20-in. beams tested in third point loading.

Mix No.	Load, psi	Beam Width, in.	Beam Depth, in.	Stress, psi	Average, psi
1A	7440	6.06	6.00	614	
	7860	6.06	6.00	648	
	7620	6.09	6.00	625	
	8280	6.09	6.00	679	
	8100	6.13	6.03	654	
	8040	6.06	6.06	649	645
1B	7560	6.09	6.00	620	
	7080	6.06	6.03	578	
	7800	6.09	6.00	640	
	7860	6.06	6.00	648	
	8040	6.09	6.03	653	
	7800	6.09	6.03	633	629
2A	7620	6.06	6.00	628	
	7080	6.06	6.00	584	
	7680	6.13	6.00	627	
	7320	6.13	6.00	598	
	7440	6.13	6.06	595	
	7380	6.13	6.06	590	604
2B	7500	6.09	6.03	609	
	7560	6.13	6.03	611	
	7440	6.09	6.03	604	
	7560	6.13	6.00	617	
	7260	6.13	6.00	593	
	7260	6.09	6.00	596	605
3A	7740	6.06	6.03	632	
	8340	6.00	6.00	695	
	8520	6.06	6.06	688	
	8580	6.00	6.00	715	
	8340	6.13	6.03	674	
	8280	6.06	6.00	683	681
3B	7920	6.09	6.00	650	
	8520	6.13	6.03	688	
	8040	6.09	6.03	653	
	8100	6.03	6.00	672	
	8580	6.13	6.03	693	
	8100	6.13	6.03	654	668
4A	9360	6.13	6.00	764	
	9240	6.13	6.00	754	
	9000	6.19	6.00	727	
	8940	6.13	6.00	730	
	9240	6.13	6.06	738	
	9300	6.13	6.06	744	743
4B	9420	6.19	6.03	753	
	8580	6.09	6.00	704	
	8400	6.09	6.00	689	
	9300	6.13	6.03	751	
	9120	6.16	6.03	733	
	9060	6.09	6.03	736	728

Table A.2 Individual test results from 6-in. x 6-in. x 20-in. beams tested in third point loading (continued).

Mix No.	Load, psi	Beam Width, in.	Beam Depth, in.	Stress, psi	Average, psi
5A	6720	6.06	6.00	554	
	6360	6.00	6.00	530	
	6600	6.00	5.94	562	
	6300	6.00	6.00	525	
	6360	6.06	6.00	525	
	----	----	----	---	539
5B	6120	6.06	6.03	500	
	6300	6.00	6.00	525	
	6300	6.06	6.00	520	
	6240	5.97	6.00	523	
	6360	6.03	6.00	527	
	6360	6.06	6.00	525	520
6A	6120	6.00	6.00	510	
	6060	6.00	6.00	505	
	6300	6.00	6.00	525	
	6780	6.00	6.00	565	
	6360	6.13	6.00	519	
	6780	6.06	6.00	559	531
6B	6300	6.06	6.00	520	
	6660	6.06	6.03	544	
	6780	6.00	6.00	565	
	6540	6.00	6.00	545	
	6300	6.06	6.00	520	
	6900	6.00	6.00	575	545
7A	8580	6.06	6.00	708	
	9660	6.06	6.00	797	
	9900	6.06	6.06	800	
	10440	6.00	6.06	852	
	8880	6.00	6.00	740	
	9720	6.06	6.06	785	780
7B	9900	6.13	6.03	800	
	9660	6.03	6.00	801	
	9660	6.03	6.00	801	
	9540	6.06	6.00	787	
	9900	6.03	6.00	821	
	9720	6.06	6.00	802	802
8A	9900	6.06	6.06	800	
	10200	6.00	6.06	833	
	10500	6.00	6.06	857	
	10020	6.06	6.00	826	
	9840	6.06	6.06	795	
	9660	6.06	6.00	797	818
8B	11040	6.06	6.06	892	
	10620	6.03	6.03	871	
	10500	6.03	6.03	861	
	9960	6.06	6.00	821	
	9900	6.03	6.03	812	
	10380	6.00	6.03	856	852

Table A.2 Individual test results from 6-in. x 6-in. x 20-in. beams tested in third point loading (continued).

Mix No.	Load, psi	Beam Width, in.	Beam Depth, in.	Stress, psi	Average, psi
9A	7440	6.00	6.00	620	
	7500	6.13	6.00	612	
	7740	6.00	6.00	645	
	8340	6.13	6.00	681	
	8340	6.06	6.00	688	
	7740	6.06	6.00	638	647
9B	8160	6.06	6.00	673	
	7920	6.03	6.00	657	
	8700	6.09	6.03	706	
	7560	6.00	6.03	623	
	8880	6.13	6.00	725	
	8100	6.00	6.00	675	677
10A	7920	6.13	6.00	647	
	8340	6.06	6.00	688	
	8100	6.06	6.06	654	
	8220	6.13	6.06	657	
	7620	6.13	6.06	609	
	7800	6.13	6.00	637	649
10B	8280	6.13	6.00	676	
	8520	6.03	6.03	699	
	8160	6.06	6.00	673	
	8220	6.09	6.06	661	
	8220	6.03	6.00	681	
	8640	6.06	6.03	705	683

Table A.3 Individual test results from 4.5-in. x 4.5-in. x 15.5-in. beams tested in center point loading.

Mix No.	Load, lbs.	Beam Width, in.	Beam Depth, in.	Fracture, in.	Actual Stress, psi	Midspan Stress, psi	Actual Average, psi	Midspan Average, psi
1A	3350	4.56	4.56	6.75	714	714		
	3300	4.63	4.50	6.75	714	714		
	3500	4.69	4.50	6.75	747	747		
	3450	4.56	4.50	6.75	756	756		
	3600	4.63	4.50	6.25	721	778		
	3300	4.50	4.50	6.75	733	733	731	741
1B	3750	4.63	4.50	6.75	811	811		
	3300	4.63	4.50	6.25	661	714		
	3550	4.56	4.44	6.75	800	800		
	3550	4.63	4.50	6.75	768	768		
	3650	4.63	4.50	6.75	789	789		
	3400	4.63	4.50	6.00	653	735	747	769
2A	3250	4.63	4.50	6.25	651	703		
	3150	4.63	4.50	6.75	681	681		
	3250	4.63	4.50	6.75	703	703		
	3300	4.69	4.50	6.75	704	704		
	3200	4.63	4.50	6.75	692	692		
	3050	4.63	4.56	6.75	642	642	679	687
2B	3100	4.63	4.50	6.50	645	670		
	3050	4.63	4.53	6.75	650	650		
	3350	4.63	4.50	6.75	724	724		
	3200	4.63	4.50	6.75	692	692		
	3050	4.63	4.50	6.75	659	659		
	3100	4.53	4.50	6.00	608	684	663	680
3A	3500	4.56	4.50	6.50	739	767		
	3650	4.63	4.50	6.50	760	789		
	3450	4.63	4.50	6.00	663	746		
	3850	4.56	4.50	6.50	813	844		
	3800	4.56	4.56	6.50	780	810		
	3800	4.56	4.50	6.50	802	833	759	798
3B	3400	4.63	4.53	6.50	698	725		
	3800	4.59	4.53	6.50	786	816		
	3550	4.63	4.50	6.50	739	768		
	3100	4.63	4.53	6.00	588	661		
	3650	4.53	4.53	6.50	765	794		
	3350	4.63	4.50	6.50	698	724	712	748
4A	3550	4.63	4.50	6.50	739	768		
	3700	4.63	4.56	6.00	692	778		
	3650	4.63	4.50	6.50	760	789		
	3900	4.63	4.63	6.50	769	798		
	3600	4.63	4.50	6.25	721	778		
	3750	4.63	4.50	5.50	661	811	723	787
4B	4050	4.66	4.50	6.00	773	870		
	3900	4.56	4.50	6.50	823	855		
	3900	4.63	4.50	6.50	812	843		
	3900	4.56	4.50	5.75	728	855		
	3950	4.59	4.50	6.00	764	860		
	3900	4.53	4.50	6.50	829	861	788	857

Table A.3 Individual test results from 4.5-in. x 4.5-in. x 15.5-in. beams tested in center point loading (continued).

Mix No.	Load, lbs.	Beam Width, in.	Beam Depth, in.	Fracture, in.	Actual Stress, psi	Midspan Stress, psi	Actual Average, psi	Midspan Average, psi
5A	2850	4.56	4.50	6.75	625	625		
	2900	4.56	4.50	6.00	565	636		
	2950	4.50	4.50	6.50	631	656		
	3100	4.50	4.50	6.50	663	689		
	2900	4.50	4.50	6.50	621	644		
	2950	4.63	4.50	6.00	567	638	612	648
5B	2650	4.56	4.50	6.50	559	581		
	2950	4.53	4.50	6.25	603	651		
	2800	4.56	4.44	6.00	561	631		
	2600	4.53	4.50	6.00	510	574		
	2750	4.53	4.50	6.50	584	607		
	2850	4.50	4.50	6.75	633	633	575	613
6A	2650	4.56	4.50	6.00	516	581		
	2700	4.50	4.50	6.75	600	600		
	2700	4.50	4.50	6.50	578	600		
	2600	4.50	4.50	6.50	556	578		
	2650	4.50	4.50	5.75	502	589		
	2750	4.44	4.50	6.25	573	620	554	595
6B	2700	4.56	4.50	6.50	570	592		
	2900	4.53	4.50	6.50	616	640		
	2900	4.50	4.50	6.25	597	644		
	2850	4.56	4.50	6.50	602	625		
	2800	4.63	4.50	5.75	516	605		
	2650	4.63	4.50	6.00	509	573	568	613
7A	3750	4.56	4.50	6.50	791	822		
	3750	4.63	4.50	6.50	781	811		
	4150	4.56	4.50	5.25	707	910		
	3700	4.63	4.50	6.25	741	800		
	3850	4.63	4.50	6.50	802	832		
	4300	4.50	4.50	6.00	849	956	779	855
7B	4100	4.50	4.50	6.50	877	911		
	4050	4.53	4.53	6.00	784	882		
	3850	4.53	4.50	5.75	724	850		
	4150	4.56	4.53	5.50	731	897		
	3950	4.63	4.50	6.50	822	854		
	4000	4.56	4.56	6.75	853	853	799	874
8A	4800	4.50	4.50	6.75	1067	1067		
	4650	4.56	4.50	5.75	868	1019		
	4700	4.63	4.50	6.00	903	1016		
	4650	4.50	4.50	6.75	1033	1033		
	4350	4.50	4.50	5.50	788	967		
	4750	4.56	4.50	6.00	925	1041	931	1024
8B	4700	4.63	4.50	6.50	979	1016		
	4400	4.56	4.50	6.25	893	964		
	4700	4.56	4.50	6.50	992	1030		
	4450	4.56	4.50	6.50	939	975		
	4450	4.44	4.50	6.50	966	1003		
	4900	4.50	4.50	6.25	1008	1089	963	1013

Table A.3 Individual test results from 4.5-in. x 4.5-in. x 15.5-in. beams tested in center point loading (continued).

Mix No.	Load, lbs.	Beam Width, in.	Beam Depth, in.	Fracture, in.	Actual Stress, psi	Midspan Stress, psi	Actual Average, psi	Midspan Average, psi
9A	4050	4.50	4.50	5.25	700	900		
	3950	4.50	4.50	6.25	813	878		
	3950	4.63	4.50	6.25	791	854		
	3850	4.50	4.50	5.50	697	856		
	3750	4.56	4.50	6.50	792	822		
	3450	4.56	4.50	6.75	756	756	758	844
9B	3900	4.50	4.56	6.00	749	843		
	4050	4.56	4.56	6.25	800	864		
	3850	4.56	4.56	6.50	791	821		
	3600	4.56	4.63	6.50	719	747		
	4150	4.56	4.56	6.00	787	885		
	3900	4.63	4.63	6.25	739	798	764	826
10A	3550	4.56	4.50	6.25	720	778		
	3350	4.56	4.50	6.00	653	734		
	3550	4.63	4.50	6.50	739	768		
	3650	4.63	4.50	6.75	789	789		
	3600	4.56	4.50	6.25	731	789		
	3250	4.63	4.56	5.50	557	684	698	757
10B	3700	4.56	4.50	6.50	781	811		
	3650	4.53	4.50	6.00	716	806		
	3900	4.63	4.50	6.00	750	843		
	3600	4.63	4.50	6.50	750	778		
	3750	4.59	4.50	6.25	756	816		
	3300	4.69	4.50	6.50	678	704	738	793

Table A.4 Individual test results from 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading.

Mix No.	Load, psi	Beam Width, in.	Beam Depth, in.	Stress, psi	Average, psi
1A	4250	4.59	4.50	617	
	4600	4.56	4.50	672	
	4650	4.63	4.50	670	
	4450	4.63	4.50	641	
	4400	4.56	4.50	643	
	4350	4.56	4.50	636	647
1B	4850	4.63	4.50	699	
	4450	4.59	4.47	655	
	4700	4.63	4.50	678	
	5100	4.63	4.50	635	
	4550	4.63	4.50	656	
	5050	4.75	4.50	709	689
2A	4450	4.63	4.44	660	
	4400	4.69	4.50	626	
	4350	4.69	4.50	619	
	4350	4.69	4.50	619	
	4250	4.56	4.50	621	
	4200	4.69	4.56	581	621
2B	4450	4.59	4.53	637	
	3950	4.56	4.56	561	
	4700	4.59	4.50	682	
	4300	4.63	4.50	620	
	4000	4.53	4.53	580	
	4250	4.59	4.53	608	615
3A	4850	4.53	4.50	714	
	5750	4.56	4.50	840	
	5450	4.56	4.50	796	
	5050	4.56	4.50	738	
	5000	4.56	4.50	731	
	5350	4.50	4.50	793	769
3B	4900	4.50	4.56	706	
	4950	4.59	4.50	718	
	5150	4.56	4.50	753	
	5550	4.63	4.50	800	
	5350	4.53	4.53	776	
	5850	4.56	4.50	855	768
4A	5400	4.50	4.50	800	
	5900	4.56	4.50	862	
	5450	4.63	4.47	797	
	5600	4.63	4.50	807	
	5800	4.56	4.50	847	
	5850	4.56	4.50	855	828
4B	4600	4.59	4.50	668	
	6700	4.56	4.53	966	
	5450	4.59	4.50	791	
	5450	4.56	4.50	796	
	6250	4.66	4.53	883	
	6400	4.63	4.38	976	846

Table A.4 Individual test results from 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading (continued).

Mix No.	Load, psi	Beam Width, in.	Beam Depth, in.	Stress, psi	Average, psi
5A	3750	4.50	4.50	556	
	3950	4.50	4.50	585	
	3900	4.50	4.50	578	
	3900	4.50	4.50	578	
	3200	4.50	4.50	474	
	4000	4.50	4.50	593	560
5B	3900	4.53	4.50	574	
	3900	4.63	4.50	561	
	3600	4.53	4.50	530	
	4050	4.50	4.50	600	
	4100	4.59	4.53	587	
	4150	4.56	4.50	606	576
6A	3500	4.56	4.50	511	
	3650	4.50	4.50	541	
	4000	4.63	4.50	577	
	3900	4.63	4.50	562	
	3650	4.50	4.50	541	
	3600	4.56	4.44	541	545
6B	3650	4.50	4.53	533	
	3800	4.56	4.50	555	
	3400	4.56	4.50	497	
	3600	4.56	4.50	526	
	3550	4.53	4.50	522	
	3500	4.56	4.53	504	523
7A	5250	4.50	4.50	778	
	4900	4.56	4.50	716	
	5000	4.63	4.50	721	
	5400	4.50	4.50	800	
	5650	4.56	4.50	826	
	5500	4.56	4.50	804	774
7B	5150	4.56	4.53	742	
	5550	4.53	4.53	805	
	5650	4.50	4.53	826	
	5400	4.56	4.50	789	
	6200	4.59	4.50	900	
	5900	4.50	4.50	874	823
8A	5900	4.50	4.50	874	
	6050	4.50	4.50	896	
	6750	4.56	4.50	986	
	6050	4.50	4.50	896	
	6250	4.50	4.50	926	
	6050	4.56	4.50	884	910
8B	6000	4.56	4.50	877	
	5650	4.50	4.50	837	
	6400	4.56	4.50	935	
	5650	4.56	4.47	837	
	5950	4.53	4.50	875	
	5900	4.56	4.50	862	871

Table A.4 Individual test results from 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading (continued).

Mix No.	Load, psi	Beam Width, in.	Beam Depth, in.	Stress, psi	Average, psi
9A	5200	4.50	4.50	770	
	5200	4.50	4.50	770	
	4900	4.50	4.50	726	
	5550	4.56	4.50	811	
	4850	4.50	4.44	739	
	5300	4.50	4.50	785	767
9B	5600	4.50	4.50	830	
	4950	4.53	4.50	728	
	5100	4.56	4.50	745	
	5800	4.50	4.50	859	
	5100	4.63	4.50	735	
	4850	4.53	4.50	714	769
10A	4650	4.50	4.50	689	
	4850	4.63	4.50	699	
	4950	4.63	4.50	714	
	5000	4.63	4.56	701	
	4600	4.69	4.50	654	
	4900	4.63	4.50	706	694
10B	4800	4.56	4.50	701	
	5050	4.63	4.50	728	
	4900	4.63	4.53	697	
	4950	4.63	4.50	714	
	5050	4.63	4.50	728	
	4800	4.63	4.50	692	710

Table A.5 Uniformity of test results from 6-in. x 6-in. x 20-in. beams tested in center point loading.

Mix No.	At Fracture		At Fracture		At Midspan		At Midspan	
	SD[1], psi	CV[2], %	SD, psi	CV, %	SD, psi	CV, %	SD, psi	CV, %
1A	52.2	7.4			27.6	3.7		
1B	65.5	9.2			53.9	7.0		
1A & 1B			56.5	8.0			41.5	5.5
2A	49.4	7.5			14.8	2.2		
2B	42.6	6.5			12.5	1.8		
2A & 2B			44.0	6.7			14.9	2.2
3A	63.7	8.8			45.6	5.9		
3B	54.7	7.8			37.6	5.0		
3A & 3B			57.9	8.1			40.4	5.3
4A	42.9	5.3			37.4	4.4		
4B	40.4	5.0			27.3	3.2		
4A & 4B			40.1	5.0			31.3	3.7
5A	57.3	9.9			32.5	5.2		
5B	53.6	8.7			26.5	4.2		
5A & 5B			55.8	9.4			28.4	4.5
6A	32.7	5.7			21.4	3.4		
6B	23.1	3.9			19.4	3.1		
6A & 6B			27.9	4.8			19.5	3.1
7A	55.4	6.7			23.1	2.6		
7B	54.5	6.5			54.2	5.9		
7A & 7B			53.0	6.3			41.9	4.6
8A	55.2	5.8			49.5	5.0		
8B	42.0	4.6			10.0	1.0		
8A & 8B			49.9	5.3			35.1	3.6
9A	56.7	7.7			44.4	5.6		
9B	45.6	6.3			57.8	7.4		
9A & 9B			49.1	6.7			49.2	6.3
10A	46.3	6.2			36.6	4.8		
10B	33.2	4.6			15.3	2.0		
10A & 10B			39.9	5.5			27.6	3.6

1 Standard deviation
2 Coefficient of variation

Table A.6 Uniformity of test results from 6-in. x 6-in. x 20-in. beams tested in third point loading.

Mix No.	SD[1], psi	CV[2], %	SD, psi	CV, %
1A	23.1	3.6		
1B	27.5	4.4		
1A & 1B			25.7	4.0
2A	19.2	3.2		
2B	9.3	1.5		
2A & 2B			14.4	2.4
3A	27.9	4.1		
3B	19.0	2.8		
3A & 3B			23.7	3.5
4A	14.2	1.9		
4B	25.9	3.6		
4A & 4B			21.4	2.9
5A	17.5	3.3		
5B	10.2	2.0		
5A & 5B			16.7	3.2
6A	25.5	4.8		
6B	22.8	4.2		
6A & 6B			24.2	4.5
7A	50.5	6.5		
7B	10.9	1.4		
7A & 7B			36.6	4.6
8A	25.0	3.1		
8B	30.3	3.6		
8A & 8B			32.0	3.8
9A	31.1	4.8		
9B	36.0	5.3		
9A & 9B			35.5	5.4
10A	25.8	4.0		
10B	16.8	2.5		
10A & 10B			27.3	4.1

1 Standard deviation
2 Coefficient of variation

Table A.7 Uniformity of test results from 4.5-in. x 4.5-in. x 15.5-in. beams tested in center point loading.

Mix No.	At Fracture		At Fracture		At Midspan		At Midspan	
	SD[1], psi	CV[2], %	SD, psi	CV, %	SD, psi	CV, %	SD, psi	CV, %
1A	17.8	2.4			25.2	3.4		
1B	71.1	9.5			38.4	5.0		
1A & 1B			50.2	6.7			34.5	4.5
2A	26.7	3.9			24.1	3.5		
2B	40.2	6.1			26.5	3.9		
2A & 2B			33.5	5.1			24.5	3.6
3A	54.4	7.2			38.0	4.8		
3B	70.5	9.9			56.2	7.5		
3A & 3B			64.9	9.1			52.7	7.0
4A	41.4	5.7			15.7	2.0		
4B	39.6	5.0			8.8	1.0		
4A & 4B			51.4	6.5			38.6	4.5
5A	38.7	6.3			22.6	3.5		
5B	42.3	7.4			31.0	5.1		
5A & 5B			43.2	7.5			31.7	5.2
6A	38.1	6.9			15.5	2.6		
6B	45.7	8.1			28.2	4.6		
6A & 6B			40.8	7.2			23.8	3.9
7A	49.4	6.4			62.7	7.3		
7B	63.4	7.9			26.1	3.0		
7A & 7B			55.2	6.9			46.9	5.4
8A	104.1	11.2			33.4	3.3		
8B	41.5	4.3			44.6	4.4		
8A & 8B			77.4	8.0			38.0	3.8
9A	49.5	6.5			50.4	6.0		
9B	32.6	4.3			49.4	6.0		
9A & 9B			40.1	5.3			48.5	5.9
10A	81.9	11.7			41.3	5.5		
10B	36.1	4.9			48.3	6.1		
10A & 10B			63.9	8.7			46.8	5.9

1 Standard deviation
2 Coefficient of variation

Table A.8 Uniformity of test results from 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading.

Mix No.	SD[1], psi	CV[2], %	SD, psi	CV, %
1A	21.3	3.3		
1B	31.7	4.6		
1A & 1B			33.8	4.9
2A	25.0	4.0		
2B	42.7	6.9		
2A & 2B			33.5	5.5
3A	48.8	6.3		
3B	55.1	7.2		
3A & 3b			49.6	6.5
4A	29.9	3.6		
4B	118.2	14.0		
4A & 4B			82.8	9.8
5A	44.1	7.9		
5B	28.1	4.9		
5A & 5B			36.3	6.3
6A	22.2	4.1		
6B	20.9	4.0		
6A & 6B			23.7	4.5
7A	45.7	5.9		
7B	57.5	7.0		
7A & 7B			55.6	6.8
8A	41.0	4.5		
8B	36.2	4.2		
8A & 8B			42.4	4.9
9A	30.9	4.0		
9B	60.4	7.9		
9A & 9B			45.8	6.0
10A	21.1	3.0		
10B	15.7	2.2		
10A & 10B			19.6	2.8

1 Standard deviation
2 Coefficient of variation

Table A.9 Compressive strength test results from first stage tests.

Mix No.	Individual Test, psi	Average, psi	Standard Deviation, psi	Coefficient of Variation, %
1A	4635			
	4573			
	4682			
	4631			
	4731	4650	68	1.5
1B	4627			
	4517			
	4648			
	4432			
	4704	4586	117	2.6
2A	4120			
	4001			
	4074			
	4131			
	4092	4084	56	1.4
2B	3970			
	3803			
	4021			
	3995			
	3969	3952	94	2.4
3A	4895			
	4752			
	4618			
	5010			
	4722	4799	169	3.5
3B	4906			
	4833			
	4937			
	4927			
	4780	4877	67	1.4
4A	5958			
	5958			
	5999			
	5911			
	6125	5990	92	1.5
4B	5820			
	5749			
	5661			
	5309			
	5759	5660	220	3.9

Table A.9 Compressive strength test results from first stage tests (continued).

Mix No.	Individual Test, psi	Average, psi	Standard Deviation, psi	Coefficient of Variation, %
5A	3443 3573 3466 3458 3383	3465	82	2.4
5B	3565 3552 3415 3556 3619	3541	88	2.5
6A	3410 3578 3151 3522 3531	3438	184	5.3
6B	3510 3473 3535 3500 3448	3493	37	1.1
7	5717 5573 5572 5754 5671 5645 5816 5624 5603 5931	5691	117	2.0
8A	7886 7822 8046 8067 7979	7960	105	1.3
8B	8001 7939 8124 8268 7885	8043	165	2.0

Table A.9 Compressive strength test results from first stage tests (continued).

Mix No.	Individual Test, psi	Average, psi	Standard Deviation, psi	Coefficient of Variation, %
9A	4238			
	4378			
	4592			
	4551			
	4445	4441	152	3.4
9B	4043			
	4401			
	4624			
	4435			
	4571	4415	250	5.7
10A	4460			
	4502			
	4461			
	4444			
	4282	4430	95	2.1
10B	4687			
	4554			
	4481			
	4654			
	4512	4578	89	1.9

APPENDIX B
DATA AND CALCULATIONS FOR SECOND STAGE TESTS

B.1 Introduction

Individual test results from the interlaboratory study are presented in this Appendix. In addition, the calculations used in the data reduction and analyses are outlined.

Tables B.1 through B.8 list individual test results and averages obtained for each laboratory for each concrete mixture and test method. Referring to Table B.1 as an example, it is seen that the first five laboratories each received four beams to test, whereas the remaining five laboratories tested only three beams each. In order for the statistical analysis to be valid, each laboratory must test the same number of beams, and therefore the fourth beam tested in each laboratory was not included in any of the statistical analyses. However, the value was reported herein to provide additional information to the reader.

The within-laboratory variance was calculated for each laboratory using Eq. (B.1):

$$S_i^2 = \left(\sum X_i^2 - n\,\bar{X}_i^2\right) \Big/ (n - 1) \qquad \text{(B.1)}$$

where S_i^2 = within-laboratory variance, $(\text{psi})^2$, for laboratory "i"

X_i = individual test result, psi

$\bar{X}_i$ = average modulus of rupture, psi

n = number of replicates.

Below each of these tables are four additional calculated values. The first of these is the overall average, which is the sum of all of the individual laboratory averages divided by the number of laboratories. The pooled within-laboratory variance is similar to the overall average, except that the individual within laboratory variances are summed and divided by the number of laboratories. The variance of laboratory averages and the between-laboratory component of variance are calculated using the following two equations:

$$S_x^2 = \left[(\sum \bar{X}_i^2 - p(\bar{\bar{X}})^2 \right] /(p-1) \qquad \text{(B.2)}$$

$$S_L^2 = S_x^2 - \left[S^2(\text{pooled})/n\right] \qquad \text{(B.3)}$$

where $S_{\bar{x}}^2$ = variance of laboratory averages, $(psi)^2$

p = number of laboratories

$\bar{\bar{X}}$ = overall average, psi (defined above)

S_L^2 = between-laboratory component of variance, $(psi)^2$

S^2(pooled) = pooled within-laboratory variance, $(psi)^2$ (defined above)

The components of variance and variance are listed for each test method in Tables B.9 through B.12. In the third column of these tables, the within-laboratory component of variance refers to the pooled within-laboratory variance, which was calculated previously, and from column four the between-laboratory component of variance refers to the value calculated previously using Eq. (B.3). The value in the fifth column, the within-laboratory variance, is simply the same as the within-laboratory component of variance, which is in the third column. The between-laboratory variance, in column six, is calculated by adding the within- and between- laboratory components of variance, which are in columns three and four.

The standard deviations and coefficients of variation are given in Tables B.13 through B.16 for each test method. The within- and between-laboratory standard deviations are calculated by taking the square root of the within- and between-laboratory variances, respectively. The coefficient of variation is found by dividing the standard deviation by the overall average modulus of rupture.

It is not within the scope of this report to describe the limitations and criteria involved with conducting an interlaboratory study. For a more detailed explanation of the process, refer to ASTM C802-80 [8].

Table B.1 Individual test results for each lab for 6-in. x 6- in. x 20-in. beams tested in center point loading from the concrete mixture containing 4 sacks of cement per cubic yard and 1-1/2-in. siliceous river gravel.

Lab No.	Test 1, psi	Test 2, psi	Test 3, psi	Test 4, psi*	Average, psi	With-Laboratory Variance
1	688	727	732	656	716	585
2	640	735	765	745	713	4258
3	745	750	735	758	743	58
4	713	780	720	725	738	1367
5	834	780	776	725	797	1034
6	751	745	695	---	730	943
7	715	730	725	---	723	58
8	739	695	777	---	737	1683
9	735	742	700	---	726	511
10	750	745	770	---	755	175

*Values not included in calculations in order to keep number of replicates equal for all laboratories

p = 10 laboratories

n = 3 replicates

Overall average, $\bar{\bar{X}}$ = 738

Pooled within-lab variance, S^2(pooled) = 1067

Variances of lab averages, $S_{\bar{x}}^2$ = 585

Between-lab component of variance, S_L^2 = 230

Table B.2 Individual test results for each lab for 6-in. x 6- in. x 20-in. beams tested in third point loading from the concrete mixture containing 4 sacks of cement per cubic yard and 1-1/2-in. siliceous river gravel.

Lab No.	Test 1, psi	Test 2, psi	Test 3, psi	Test 4, psi*	Average, psi	With-Laboratory Variance
1	600	628	640	624	623	420
2	690	635	605	660	643	1858
3	656	654	635	673	648	135
4	622	673	665	651	653	751
5	720	661	703	681	695	915
6	635	555	625	---	605	1900
7	605	625	647	---	626	427
8	617	638	576	---	611	1017
9	602	627	595	---	608	279
10	633	615	Bad Test	---	624	169

*Values not included in calculations in order to keep number of replicates equal for all laboratories

p = 10 laboratories

n = 3 replicates

Overall average, $\bar{\bar{X}}$ = 634

Pooled within-lab variance, S^2(pooled) = 787

Variances of lab averages, S_x^2 = 744

Between-lab component of variance, S_L^2 = 481

Table B.3 Individual test results for each lab for 4.5-in. x 4.5-in. x 15.5-in. beams tested in center point loading from the concrete mixture containing 4 sacks of cement per cubic yard and 1-1/2-in. siliceous river gravel.

Lab No.	Test 1, psi	Test 2, psi	Test 3, psi	Test 4, psi*	Average, psi	With-Laboratory Variance
1	789	714	744	811	749	1407
2	689	756	822	789	756	4444
3	846	877	733	856	819	5687
4	777	756	777	800	770	146
5	744	722	733	733	733	123
6	756	756	733	---	748	165
7	710	744	661	---	705	1759
8	789	757	703	---	749	1908
9	699	687	711	---	699	142
10	811	778	722	---	770	2017

*Values not included in calculations in order to keep number of replicates equal for all laboratories

p = 10 laboratories

n = 3 replicates

Overall average, $\bar{\bar{X}}$ = 750

Pooled within-lab variance, S^2(pooled) = 1780

Variances of lab averages, S_x^2 = 1161

Between-lab component of variance, S_L^2 = 568

Table B.4 Individual test results for each lab for 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading from the concrete mixture containing 4 sacks of cement per cubic yard and 1-1/2-in. siliceous river gravel.

Lab No.	Test 1, psi	Test 2, psi	Test 3, psi	Test 4, psi*	Average, psi	With-Laboratory Variance
1	716	736	691	656	714	507
2	615	630	689	704	644	1537
3	696	789	711	699	732	2482
4	711	704	696	696	704	55
5	777	704	748	778	743	1368
6	711	731	770	---	737	912
7	665	689	652	---	669	353
8	660	636	620	---	639	403
9	704	719	656	---	693	1072
10	714	667	697	---	692	565

*Values not included in calculations in order to keep number of replicates equal for all laboratories

p = 10 laboratories

n = 3 replicates

Overall average, $\bar{\bar{X}}$ = 697

Pooled within-lab variance, S^2(pooled) = 925

Variances of lab averages, S_x^2 = 1373

Between-lab component of variance, S_L^2 = 1065

Table B.5 Individual test results for each lab for 6-in. x 6-in. x 20-in. beams tested in center point loading from the concrete mixture containing 5.5 sacks of cement per cubic yard and 3/4-in. siliceous river gravel.

Lab No.	Test 1, psi	Test 2, psi	Test 3, psi	Test 4, psi*	Average, psi	With-Laboratory Variance
1	886	945	907	906	913	907
2	920	950	1015	895	962	2371
3	1003	911	975	975	963	2232
4	970	1019	955	995	981	1133
5	965	980	945	886	963	300
6	915	870	985	---	923	3342
7	849	866	842	---	853	147
8	925	905	985	---	938	1717
9	960	859	989	---	936	4697
10	950	980	945	---	958	355

*Values not included in calculations in order to keep number of replicates equal for all laboratories

p = 10 laboratories

n = 3 replicates

Overall average, $\bar{\bar{X}}$ = 939

Pooled within-lab variance, S^2(pooled) = 1720

Variances of lab averages, S_x^2 = 1364

Between-lab component of variance, S_L^2 = 790

Table B.6 Individual test results for each lab for 6-in. x 6-in. x 20-in. beams tested in third point loading from the concrete mixture containing 5.5 sacks of cement per cubic yard and 3/4-in. siliceous river gravel.

Lab No.	Test 1, psi	Test 2, psi	Test 3, psi	Test 4, psi*	Average, psi	With-Laboratory Variance
1	895	867	911	887	891	498
2	895	902	1035	840	944	6245
3	940	930	867	896	912	1569
4	891	938	870	871	866	718
5	785	877	806	871	823	2304
6	860	795	802	---	819	1280
7	763	821	803	---	796	888
8	880	915	825	---	873	2058
9	881	858	855	---	865	200
10	877	798	980	---	885	8296

*Values not included in calculations in order to keep number of replicates equal for all laboratories

p = 10 laboratories

n = 3 replicates

Overall average, $\bar{\bar{X}}$ = 868

Pooled within-lab variance, S^2(pooled) = 2406

Variances of lab averages, S_x^2 = 2033

Between-lab component of variance, S_L^2 = 1231

Table B.7 Individual test results for each lab for 4.5-in. x 4.5-in. x 15.5-in. beams tested in center point loading from the concrete mixture containing 5.5 sacks of cement per cubic yard and 3/4-in. siliceous river gravel.

Lab No.	Test 1, psi	Test 2, psi	Test 3, psi	Test 4, psi*	Average, psi	With-Laboratory Variance
1	1019	989	980	980	996	414
2	1089	1172	1070	1020	1110	2917
3	1092	1162	1100	1063	1118	1455
4	986	951	1063	942	1000	3262
5	1167	1000	1067	1078	1078	7037
6	1011	956	1074	---	1014	3510
7	1071	984	962	---	1006	3296
8	1008	1027	967	---	1001	935
9	930	919	973	---	941	818
10	1049	1038	951	---	1013	2844

*Values not included in calculations in order to keep number of replicates equal for all laboratories

p = 10 laboratories

n = 3 replicates

Overall average, $\bar{\bar{X}}$ = 1028

Pooled within-lab variance, S^2(pooled) = 2649

Variances of lab averages, $S_{\bar{x}}^2$ = 3162

Between-lab component of variance, S_L^2 = 2279

Table B.8 Individual test results for each lab for 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading from the concrete mixture containing 5.5 sacks of cement per cubic yard and 3/4-in. siliceous river gravel.

Lab No.	Test 1, psi	Test 2, psi	Test 3, psi	Test 4, psi*	Average, psi	With-Laboratory Variance
1	970	942	972	815	962	272
2	943	1052	956	1030	983	3546
3	1008	1008	995	980	1004	62
4	728	909	858	847	832	8716
5	881	877	963	894	907	2350
6	979	896	906	---	927	2033
7	951	923	930	---	935	225
8	1016	929	1009	---	985	2303
9	974	919	923	---	938	965
10	978	1008	855	---	947	6616

*Values not included in calculations in order to keep number of replicates equal for all laboratories

p = 10 laboratories

n = 3 replicates

Overall average, $\bar{\bar{X}}$ = 942

Pooled within-lab variance, S^2(pooled) = 2709

Variances of lab averages, $S_{\bar{x}}^2$ = 2382

Between-lab component of variance, S_L^2 = 1479

Table B.9 Statistical analyses of test results from 6-in. x 6- in. x 20-in. beams tested in center point loading.

Mix, sks/cy	Overall Average, psi	Components of Variance		Variance	
		Within-Lab	Between-Lab	Within-Lab	Between-Lab
4	738	1067	230	1067	1297
5.5	939	1720	790	1720	2510

Table B.10 Statistical analyses of test results from 6-in. x 6- in. x 20-in. beams tested in third point loading.

Mix, sks/cy	Overall Average, psi	Components of Variance		Variance	
		Within-Lab	Between-Lab	Within-Lab	Between-Lab
4	634	787	481	787	1269
5.5	867	2406	1231	2406	3636

Table B.11 Statistical analyses of test results from 4.5-in. x 4.5-in. x 15.5-in. beams tested in center point loading.

Mix, sks/cy	Overall Average, psi	Components of Variance		Variance	
		Within-Lab	Between-Lab	Within-Lab	Between-Lab
4	750	1780	568	1780	2348
5.5	1028	2649	2279	2649	4928

Table B.12 Statistical analyses of test results from 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading.

Mix, sks/cy	Overall Average, psi	Components of Variance		Variance	
		Within-Lab	Between-Lab	Within-Lab	Between-Lab
4	697	925	1065	925	1990
5.5	942	2709	1479	2709	4188

Table B.13 Standard deviations and coefficients of variation for 6-in. x 6-in. x 20-in. beams tested in center point loading.

Mix, sks/cy	Overall Average, psi	Standard Deviation, psi		Coefficient of Variation, %	
		Within-Lab	Between-Lab	Within-Lab	Between-Lab
4	738	32.7	36.0	4.4	4.9
5.5	939	41.5	50.1	4.4	5.3

Table B.14 Standard deviations and coefficients of variation for 6-in. x 6-in. x 20-in. beams tested in third point loading.

Mix, sks/cy	Overall Average, psi	Standard Deviation, psi		Coefficient of Variation, %	
		Within-Lab	Between-Lab	Within-Lab	Between-Lab
4	634	28.1	35.6	4.4	5.6
5.5	867	49.1	60.3	5.7	7.0

Table B.15 Standard deviations and coefficients of variation for 4.5-in. x 4.5-in. x 15.5-in. beams tested in center point loading.

Mix, sks/cy	Overall Average, psi	Standard Deviation, psi		Coefficient of Variation, %	
		Within-Lab	Between-Lab	Within-Lab	Between-Lab
4	750	42.2	48.5	5.6	6.5
5.5	1028	51.5	70.2	5.0	6.8

Table B.16 Standard deviations and coefficients of variation for 4.5-in. x 4.5-in. x 15.5-in. beams tested in third point loading.

Mix, sks/cy	Overall Average, psi	Standard Deviation, psi		Coefficient of Variation, %	
		Within-Lab	Between-Lab	Within-Lab	Between-Lab
4	697	30.4	44.6	4.4	6.4
5.5	942	52.1	64.7	5.5	6.9

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