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MISCELLANEOUS PAPER C-69-5

# EVALUATION OF A RING TEST FOR DETERMINING THE TENSILE STRENGTH OF MORTARS AND CONCRETE

by

G. C. Hoff



May 1969

Sponsored by

Assistant Secretary of the Army (R&D)  
Department of the Army

Conducted by

U. S. Army Engineer Waterways Experiment Station  
CORPS OF ENGINEERS  
Vicksburg, Mississippi

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## FOREWORD

The study entitled "Evaluation of a Ring Test for Determining the Tensile Strength of Concrete," was funded by Department of the Army Project 4A013001A91D, "In-House Laboratory Independent Research Program," Item AS, sponsored by the Assistant Secretary of the Army (R&D). It was conducted during the period January 1968 through January 1969 at the U. S. Army Engineer Waterways Experiment Station (WES) Concrete Division by Messrs. G. C. Hoff and F. S. Stewart, under the direction of Messrs. B. Mather, J. M. Polatty, and W. O. Tynes. This report was prepared by Mr. Hoff.

Special appreciation is extended to Mr. V. Mohan Malhotra of the Construction Materials Section, Mines Branch, Department of Energy, Mines, and Resources, Ottawa, Ontario, Canada, who furnished some of the testing equipment and the basic designs for the ring casting and testing jigs and whose comments and observations were most helpful during the initiation of the test program.

Directors of the WES during the investigation and the preparation and publication of this report were COL John R. Oswalt, Jr., CE, and COL Levi A. Brown, CE. Technical Director was Mr. J. B. Tiffany; Assistant Technical Director was Mr. F. R. Brown.

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## NOTATION

$a, b$  = regression coefficients

$B$  = width of flexural beam specimen, in.

$d$  = diameter of tensile splitting specimen, in.

$D$  = depth of flexural beam specimen, in.

$L$  = length (between supports) of flexural beam specimen, in.

$n$  = number of test observations

$p$  = applied load, lb

$p_i$  = internal hydrostatic pressure, psi

$r$  = radius, in.

$r_i$  = internal radius, in.

$r_m$  = mean radius, in.

$r_o$  = external radius, in.

$R$  = modulus of rupture, psi

$S$  = arc length, in.

$S_{\text{est}, y}$  = standard error of estimate

$t$  = length of tensile splitting specimen, in.

$T$  = tensile splitting strength, psi

$T_t$  = tangential ring tensile stress, psi

$T_r$  = radial ring tensile stress, psi

$X, Y$  = rectilinear coordinate values

$y_i$  = observed dependent variable

$\hat{y}$  = predicted dependent variable

$\theta$  = internal angle, deg

## CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
inches	2.54	centimeters
square inches	6.4516	square centimeters
feet	0.3048	meters
cubic feet	0.02832	cubic meters
cubic yards	0.764555	cubic meters
pounds	453.5924	grams
pounds per square inch	0.070307	kilograms per square centimeter
pounds per cubic foot	16.02	kilograms per cubic meter
Fahrenheit degrees	5/9	Celsius or Kelvin degrees*

---

\* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula:  $C = (5/9) (F-32)$ . To obtain Kelvin (K) readings, use:  $K = (5/9) (F-32) + 273.16$ .

## SUMMARY

The investigation consisted of the evaluation of a ring tensile test method for determining a measure of the tensile strength of mortars and concretes. The evaluation was based on the reproducibility and degree of simplicity of the test method. Correlations were made between the ring tensile strength and the cylinder compressive strength and tensile strength values obtained from beam flexural and cylinder splitting tests of sanded mortar, 3/8-in. maximum size aggregate concrete, and 1-in. maximum size aggregate concrete, all made at water-cement ratios (by weight) varying from 0.4 to 0.9. Two sizes of test rings were evaluated: 1.5 in. high by 1.5 in. thick by 6 in. inside diameter and 3 in. high by 3 in. thick by 12 in. inside diameter. The mortar tests used 6-in. rings, the 3/8-in. concrete used both 6- and 12-in. rings, and the 1-in. concrete used only 12-in. rings. A total of ninety-two 6-in. rings and eighty-three 12-in. rings were tested.

EVALUATION OF A RING TEST FOR DETERMINING  
THE TENSILE STRENGTH OF MORTARS AND CONCRETE

PART I: INTRODUCTION

Background and Purpose

1. The purpose of this paper is to report the results of an evaluation of a specific type of test procedure, the ring tensile test, which results in a measure of the tensile strength of concrete. No attempt is made to document the many references to and discussions of specific values of "tensile strength" and the techniques used to obtain them by other investigators over the years with the exception of the work involving the ring tensile test. Some general comments about tensile strength testing are made to provide the reader with the background which ultimately prompted the development of the ring test for concrete.

2. Although considerable attention has been paid to the investigation of the "tensile" strength of concrete in recent years, there is general disagreement among investigators as to which test of concrete provides a "true" measure of the tensile strength. The type of tests used can be categorically described as either "direct" or "indirect" methods for obtaining a numerical representation of tensile strength. The direct tensile strength tests usually involve long, axially loaded specimens which are pulled in a testing machine until fracture occurs. The direct tensile stress is simply the load divided by the cross-sectional area of the specimen at the point of failure. If the loading on the specimen is perfectly uniaxial (a possible but highly unlikely

situation for most testing), the actual tensile stress is determined. The reproducibility of this test depends to a large extent upon the type of method used and to what degree the extraneous stresses are eliminated.

3. A number of indirect methods for obtaining a measure of the tensile strength of the concrete have also been developed in hopes of providing a simpler and/or more reproducible test procedure than the direct tension test. These methods are:

- a. Flexure test.
- b. Splitting tension test.
- c. Torsion tension test.
- d. Ring tension test.

4. The flexure test uses a plain concrete or mortar beam of a given span length, width, and depth, which is supported at its ends and loaded at either its third points or at its center. The flexural strength of the beam is represented by a "modulus of rupture" which is defined as the tensile stress in the outer fiber of the beam at failure of the beam. This tensile stress is developed by the beam action and determination of the modulus of rupture assumes that the stress and deformation in the beam are directly proportional to the distance from the neutral axis of the beam.

5. The splitting tension test as it is commonly used in the United States involves the placing of a cylindrical specimen horizontally between the loading surfaces of a testing machine so

that the load is applied to the specimen along its entire length on two diametrically opposed lines. The application of a compressive force along these two opposite lines produces a biaxial stress distribution within the specimen. Immediately adjacent to the lines of load application, regions of high compressive stresses are developed. These stresses vary to a minimum at the center of the cylinder and are accompanied by an almost constant tensile stress over approximately three-quarters of the vertical plane between the two lines of load application. The concrete, being considerably weaker in tension than in compression, fails along this vertical plane because of the tensile forces developed there. The magnitude of the average tensile stresses along this plane at the time of failure is considered to be the tensile strength of the concrete.

6. In countries where cylinders are generally not used, cubes or prisms are often used in splitting tests. In the cube splitting test, the cube is placed between the loading surfaces of the testing machine with its top and bottom surfaces parallel to the loading surfaces of the machine. A load generator strip is then placed between the bottom of the cube and the testing machine along a line perpendicular to two opposite sides of the cube and passing through the center of the bottom surface area of the cube. A second generator strip is placed between the top surface of the cube and the testing machine and is directly over and parallel to the bottom strip. A compressive load is then applied to the generator strips. A stress distribution, similar to

that just described for the cylinder splitting test, develops and the cube fails along the vertical plane between the two generator strips when the average tensile stress developed there exceeds the tensile strength of the concrete. Cubes and prisms are also tested by applying the load to the specimens across the diagonal plane from corner to corner with a type of stress distribution and tensile failure occurring that is similar to the cylinder splitting test.

7. The torsion tension test uses long cylindrical specimens which are subjected to pure torsion by means of a specially designed loading frame. The state of pure shear being developed at a point in a specimen being subjected to torsional loading is also accompanied by normal stresses (tensile and compressive) at the point on planes that bisect the angles between the planes on which the shearing stresses act. The magnitudes of these normal stresses are equal to those of the shearing stresses, and if the specimen is made of a brittle material (such as concrete) which is weak in tension, the diagonal tensile stresses will reach a value that will cause the specimen to fracture. This value is then considered the tensile strength of the material.

8. The determination of the ring tensile strength of **rock-like** materials and concrete has been approached using two different methods. The first method uses discs with concentric holes (e.g., rings) in a diametral compression test identical to the cylinder splitting test described earlier.<sup>1,2</sup> The basic idea in this test is to change, by addition of the hole in the disc, the rather uniform tensile stress

field which occurs across approximately the center three-fourths of the failure plane such that the tensile stress component at the edge of the hole is increased. In doing this, it insures that the origin of the fracture is known. The only component of stress acting at the edge of the hole is the unidirectional tensile stress which then would be the stress which causes fracture and, hence, represents the tensile strength of the concrete.

9. The second method used for the ring tension test utilizes a uniform hydrostatic pressure which is applied radially against the inside periphery of the ring. The application of this pressure produces tangential tensile stresses and radial compressive stresses throughout the entire volume of the ring with a uniformly distributed maximum tensile stress occurring along the entire internal periphery of the ring. The magnitude of the radial compressive stress is quite small when compared with the tangential tensile stress so that when failure occurs, it is the result of the tensile stresses. If the ratio of the radius of the ring to its wall thickness is less than 10 (as is generally the case for tests of concrete), the classic equations for determining stresses in thick-walled cylinders due to internal hydrostatic pressure can be used to determine the tangential tensile stress at failure. This second method was originally suggested by Desov,<sup>3</sup> but most, if not all, of the published data to date have been provided by Malhotra et al.<sup>4,5,6,7</sup>

10. All of the stress analysis techniques used to provide a measure of tensile strength from the output generated by using one of the above indirect test methods make the assumption that the concrete obeys Hooke's law of linear stress-strain proportionality whereas in fact the stress-strain relation for concrete is curvilinear almost from the onset of loading. This assumption then introduces an error into the tensile strength determination and the actual numerical representations of tensile strength obtained for any of the indirect test methods does not represent the "true" tensile strength of the concrete. On the other hand, the ultimate tensile strength obtained from direct tension testing is independent of the stress-strain relationship in the concrete and is simply the load at failure divided by the cross-sectional area at failure. Why, then, use an indirect method?

11. The classic direct tension tests initiated at the start of this century were and still are burdened with misalignment and/or clamping stresses, both of which introduce errors into the strength determination. Test procedures developed to eliminate these problems are slow and expensive, requiring relatively high skilled operators and sophisticated equipment and techniques. The indirect tests (principally the flexural and splitting tests) are generally easy to perform and are fairly reproducible when reasonable care is exercised. Not enough is known at present about the torsion test and the diametral compression test of rings to comment on their reproducibility at this time. The internal pressure ring test is discussed in the following paragraphs.

12. The results of the flexure test are dependent on where the beam is loaded (third-point or center loading), on the size and configuration of the beam, and on the residual stresses in the beam fibers caused by moisture changes in the beam. The splitting test produces a biaxial stress condition with high compressive stresses in the region of load contact which may, in some cases, precipitate premature failure. Because strains play a significant role in a biaxial stress condition, the analysis used in determining the tensile strength should include the Poisson's effect, but it does not. In both the flexure and splitting test, the plane or region of failure is predetermined by the selection of the points of loading and this plane or region may or may not contain the weakest zone of the concrete. Higher values of tensile strength may then be determined for a concrete which is inherently weaker. Despite these limitations, the flexural and splitting tests appear to be fairly reproducible and have generally met with wide acceptance. A number of investigators have suggested various conversion factors for the tensile strength values obtained from these indirect test methods so that the test values could be adjusted to represent the "true" tensile strength of the concrete.

13. The ring tension test data and analysis provided by Malhotra<sup>4,5,6,7</sup> conclude that:

a. The ring test appears to be a satisfactory means for determining the tensile strength of mortars and concrete.

b. The nature of the load application in the ring test is such that no clamping and/or misalignment stresses, such as occur in direct tension tests, occur in the ring specimens.

c. The entire volume of the ring specimen is subjected to tensile stresses, with a uniformly distributed maximum stress occurring along the entire internal periphery of the ring. The failure will occur then at the weakest zone in the ring, thus providing a measure of strength that closely approximates the actual tensile strength of the concrete. This is never achieved in flexural tests and, even in the cylinder splitting tension tests, a compressive load acting on a diametral plane creates a uniform tensile stress over a portion of that plane only.

d. The magnitude of the radial compressive stress is quite small when compared with the tangential stress, thus tending to minimize the effect of a biaxial stress condition on the failure mode. This is an advantage over the splitting tension test in which the minimum compressive stress occurring at the center line of the splitting plane is about 3.1 times (theoretically) the corresponding tensile stress.

e. The specimen and the testing apparatus are so simple that ring fabrication and testing can be carried out rapidly even at a construction site.

f. The within-batch and between-batches reproducibility of the ring test is comparable to that achieved in the flexure and splitting tension tests.

g. There is a high degree of correlation between ring tensile strength and compression, flexural, and splitting tension tests.

14. Items a, b, c, and d of paragraph 13 and the limitations of the ring tension test have been discussed by other investigators<sup>4,5</sup> and will not be discussed further here. The objective of this study is to evaluate, on the basis of simplicity and reproducibility, a tension ring test as a method of obtaining a measure of the tensile strength of mortar and concrete and to correlate the ring tensile strength values to the tensile strength values obtained from flexural and cylinder splitting tension tests.

#### Scope

15. The following rounds of mortar and concrete were cast and evaluated during the study:

- a. Series M. Eighteen rounds of sanded mortar at water-cement ratios (by weight) varying from 0.4 to 0.9.
- b. Series C1. Seventeen rounds of 3/8-in. aggregate concrete at water-cement ratios (by weight) varying from 0.4 to 0.8.
- c. Series C2. Fifteen rounds of 1-in. aggregate concrete at water-cement ratios (by weight) varying from 0.4 to 0.8.

16. Each round of each series was evaluated for compressive, flexural, cylinder splitting, and ring tensile strength. The M and C1 series utilized 6-in.-inside-diameter rings for the ring test with the C1 series also using 12-in.-inside-diameter rings. The C2 series used only 12-in.-inside-diameter rings.

## PART II: MATERIALS AND TEST SPECIMENS

### Materials

#### Cement

17. The portland cement (RC-579)\* used for all three phases of the study met the requirements for type II and had the following chemical and physical characteristics:

Chemical Analysis		Physical Properties	
Constituents	Percent		
		Normal consistency, percent	23.8
SiO <sub>2</sub>	21.3	Setting time, Gillmore,	
Al <sub>2</sub> O <sub>3</sub>	4.2	hr:min	
		Initial	3:10
Fe <sub>2</sub> O <sub>3</sub>	4.2	Final	6.35
CaO	63.0	Autoclave expansion, percent	0.02
MgO	2.1	Air content of mortar,	
SO <sub>3</sub>	2.3	percent	6.9
Ignition loss	1.6	Compressive strength of	
		mortar, psi	
Total	98.7	3 days	2720
		7 days	3685
Insoluble residue	0.14	Surface area, air permeability	
Na <sub>2</sub> O	0.12	fineness (Blaine), cm <sup>2</sup> /g	3515
K <sub>2</sub> O	0.43	False set of paste (initial	
Total alkalis as		penetration), percent	83.9
Na <sub>2</sub> O	0.40	Specific gravity	3.15
C <sub>3</sub> A	4.0		
C <sub>3</sub> S	54.0		
C <sub>2</sub> S	20.0		
C <sub>4</sub> AF	13.0		

\*WES designation.

## Aggregates

18. The coarse and fine aggregates were crushed limestone from Tennessee with the following gradations, specific gravities, and absorptions:

Sieve Size	Cumulative Percent Passing				
	Fine Aggregate	Coarse Aggregate			
	CRD-MS 17(4)*	CRD-G 31(4)*	CRD-G 31(7)*	CRD-G 31(10)*	CRD-G 31(12)*
1 in.	-	100	-	100	-
3/4 in.	-	98	100	83	-
1/2 in.	-	65	89	7	-
3/8 in.	-	40	58	--	100
No. 4	99	4	2	-	4
No. 8	94	-	-	-	-
No. 16	67	-	-	-	-
No. 30	39	-	-	-	-
No. 50	23	-	-	-	-
No. 100	14	-	-	-	-
No. 200	10	-	-	-	-
Specific Gravity	2.67	2.69	2.70	2.71	2.71
Absorption, %	1.6	0.6	0.8	0.4	0.6

\*WES designation.

The M series batches used only the fine aggregate CRD-MS-17(4). The C1 series batches used CRD-MS-17(4) as fine aggregate and CRD-G-31(12) as coarse aggregate with the exception of mixture C1-4, round 1,

and mixture C1-8, rounds 1, 2, and 3, which used the minus 3/8-in. portion of CRD-G-31(4) as coarse aggregate. The C2 series batches used CRD-MS-17(4) as fine aggregate and 60% of CRD-G-31 (10) and 40% of CRD-G-31(7) as the coarse aggregate.

#### Admixtures

19. No admixtures were used in any of the batches. All air contents were the result of entrapped air.

#### Mixture Designs

20. A summary of the mixture designs and batch data for all three mixture design series is given in table 1. The M-series of batches were designed to have water-cement ratios (by weight) varying from 0.4 to 0.9 at 0.1 intervals with a slump of  $4\frac{1}{2} \pm \frac{1}{2}$  in. at each water-cement ratio. The C1 and C2 series of batches were designed for 3/8-in. and 1-in. maximum aggregate size respectively and were to have water-cement ratios (by weight) varying from 0.4 to 0.8 at 0.1 intervals and slumps of  $3 \pm \frac{1}{2}$  in. at each water-cement ratio. The slump, air content, and actual unit weight were determined in accordance with the procedures outlined in the Handbook for Concrete and Cement.<sup>8</sup>

#### Batching Equipment

21. All batches for the M series were made in a 1.2-cu-ft bread dough mixer. The batches for the C1 and C2 series were made in a 7-1/2-cu-ft rocking-tilting mixer.

## Test Specimens

### M series

22. Normally 18 test specimens were cast and tested from each M series round. These consisted of three 2-in. cubes, six 3- by 6-in. cylinders, three 1-in. tensile briquettes, three 3-1/2- by 4-1/2- by 16-in. beams, and three 1-1/2-in.-high by 1-1/2-in.-thick by 6-in.-inside-diameter rings. One ring each from M5, round 2, M6, round 1, and M9, round 2 were damaged during the removal of the casting molds and were not evaluated. The rings from M5, round 3, inadvertently were not tested.

### C1 series

23. Normally 18 test specimens were cast and tested from each C1 series round. These consisted of six 6- by 12-in. cylinders, three 3-1/2- by 4-1/2- by 16-in. beams, three 6- by 6- by 30-in. beams, three 6-in.-inside-diameter rings, and three 3-in.-high by 3-in.-thick by 12-in.-inside-diameter rings. The following rings were damaged upon removal from the casting molds and were not evaluated:

<u>Mixture</u>	<u>Round</u>	<u>Ring Size</u>	<u>No. of Damaged Rings</u>
C1-4	2	6 in.	3
C1-6	2	12 in.	1
C1-6	3	6 in.	1
C1-6	3	12 in.	1
C1-6	4	12 in.	1
C1-8	1	6 in.	1
C1-8	1	12 in.	1
C1-8	3	12 in.	2

In a few instances, some rings were observed to have casting flaws and were not evaluated.

### C2 series

24. Twelve test specimens were cast and tested from each C2 series round. These consisted of six 6- by 12-in. cylinders, three 6- by 6- by 30-in. beams, and three 12-in.-inside-diameter rings. One 12-in. ring from C2-8, round 1, had a flaw in it and was not evaluated.

### Test Specimen Preparation

#### Ring molds

25. The basic design of the 6-in.-diameter ring mold was provided by the Construction Materials Section, Department of Energy, Mines and Resources, Mines Branch, Ottawa, Canada. This design was used by Malhotra<sup>4, 5, 6</sup> to construct the molds used to provide the 6-in. rings he evaluated. A plan and sectional view of the mold assembly are detailed in plates A1 and A2 respectively. An assembled 6-in. ring mold is shown in photograph 1. Three 6-in. molds were fabricated at WES and used for the entire study. These molds differed slightly from those used by Malhotra by having a greater taper on the central aluminum plug: 0.001 in./in. for Malhotra's molds versus 0.0015 in./in. for WES molds. The central plugs originally were made with a taper of 0.001 in./in. but based on the high stripping ring loss rate of a number of trial batches (not reported in this study), the taper was increased, and this evidently reduced the number of rings being damaged during stripping.

26. The 12-in.-diameter ring mold used by Malhotra<sup>7</sup> is a scale-up of the 6-in. ring mold with the exception that the central aluminum plug is replaced by a mild steel ring with a taper on its outer surface of 0.0005 in./in. The WES 12-in.-diameter ring mold also has a mild steel inner ring but with a taper of 0.0015 in./in. The base plate and outer ring of the WES mold were constructed of wood, which was treated to prevent moisture absorption. An assembled 12-in. WES ring mold is shown in photograph 1. A plan and section view of the 12-in. inner ring are shown in plate A3. After completion of all casting involving the 12-in. ring molds (approximately 35 use times), the wood parts of the molds were no longer serviceable.

#### Other molds

27. All molds used to cast the cylinders and beams were in accordance with the applicable portions of CRD-C 10<sup>8</sup>, "Method of Making and Curing Concrete Test Specimens in the Laboratory." The 2-in. cube molds were constructed of steel, and each mold produced three cubes. The tensile briquette molds were made of brass and in accordance with ASTM C 190-63, "Tensile Strength of Hydraulic Cement Mortars."

#### Molding

28. The cubes, cylinders, briquettes, and rings for the M series were cast by filling each of the molds and then vibrating them on a vibrating table for 25 to 40 seconds, depending on the specimen size and consistency of the mixture. The 6-in. rings from the C1 series were also cast in this manner. The 3-1/2- by 4-1/2- by 16-in. beams from

both the M and C1 series were cast in accordance with Section D, "Beams for Laboratory Freezing and Thawing," of CRD-C 10.<sup>8</sup>

29. The 6- by 12-in. cylinders, 6- by 6- by 30-in. beams, and the 12-in.-diameter rings from the C1 and C2 series were cast and consolidated by internal vibration in accordance with the procedures outlined in CRD-C 10.<sup>8</sup>

30. After casting, all molds were covered with wet burlap and the specimens kept moist in this condition until removed from the molds. This removal generally occurred 24 hours after casting. In a few instances the specimens were allowed to remain in the molds over the weekend.

#### Ring demolding

31. Prior to casting each ring, the outer surface of inner plug or ring (depending on which size ring was being cast) was coated with a heavy industrial lubricant which was to act as a bond breaker. The use of ordinary form oil as a bond breaker did not produce satisfactory results at the initiation of the study and was subsequently replaced by the heavier industrial lubricant. After each ring had cured 24 hours, the outer ring form was removed, and any bond existing between the ring and the inner form was broken by turning the ring on the stationary inner form. The ring was then lifted off the inner form by alternating the direction of turning and gradually working the ring to the top of the form.

### Curing

32. After removal from the casting molds, all of the M-series specimens were transferred to the moist curing room where they remained at a temperature of  $73.4 \pm 2$  F and 100 percent humidity until they were tested at 28 days age.

33. Because of a storage space problem, the specimens from the C1 and C2 series could not be cured in the moist curing room and instead were cured by immersion in specially constructed tanks containing water saturated with calcium hydroxide until they were tested at 28 days age.

### Capping

34. All 3- by 6-in. and 6- by 12-in. cylinders were capped with commercially available capping compound two to three hours before they were tested.

35. Any small voids that may have occurred on the inner periphery of a ring were filled with a cement paste five to 10 minutes before the ring was tested. The paste was worked into the voids by the fingers and served the purpose of eliminating jagged edges which could damage the loading bladder used in the ring test.

## PART III: TEST PROCEDURES AND RESULTS

### Test Procedures

#### Compression tests

36. All 2-in. cubes and 3- by 6-in. cylinders were tested in a 90,000-lb compression testing machine, and all 6- by 12-in. cylinders were tested in a 440,000-lb universal testing machine. The cubes were tested in accordance with CRD-C 227,<sup>8</sup> "Compressive Strength, Two-Inch Cubes," and the cylinders were tested in accordance with CRD-C 14,<sup>8</sup> "Compressive Strength of Molded Concrete Cylinders." In all cases the compressive strength was determined by dividing the maximum load carried by the specimen during the test by the average cross-sectional area of the specimen before the test.

#### Tensile briquette test

37. The M series tensile briquette tests of the mortar were conducted in accordance with ASTM C 190-63, "Tensile Strength of Hydraulic Cement Mortars," using a 30,000-lb universal testing machine. The tensile strength of the briquette was determined by dividing the maximum load carried by the briquette during the test by the cross-sectional area normal to the direction of loading at the point of fracture.

### Flexure tests

38. The 3-1/2- by 4-1/2- by 16-in. beams and the 6- by 6- by 30-in. beams were tested at third-point loading in accordance with the procedures outlined in CRD-C 16,<sup>8</sup> "Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)." The 3-1/2- by 4-1/2- by 16-in. beams used a 30,000-lb universal testing machine to apply the load while the 6- by 6- by 30-in. beams used a standard flexure beam tester. The flexural strength in both cases was expressed as the modulus of rupture, R in lb/sq in., where:

$$R = \frac{PL}{BD^2}$$

where:

P = maximum applied load, lb

L = span length, in.

= 13-1/2 in. for 3-1/2- x 4-1/2- x 16-in. beams

= 18 in. for 6- x 6- x 30-in. beams

B = average width of specimen, in.

= approximately 3-1/2 in. for the 3-1/2-x 4-1/2- x 16-in. beam

= approximately 6 in. for the 6- x 6- x 30-in. beams

D = average depth of specimen, in.

= approximately 4-1/2 in. for 3-1/2- x 4-1/2- x 16-in. beam

= approximately 6 in. for 6- x 6- x 30-in. beam

In testing the 6-by 6- by 30-in. beams, the first 20 in. from one end of the beam was tested first. In most instances after failure, a piece of unbroken beam approximately 20 in. long remained, and this piece was then tested. The reported flexural strength of the beam was then the average of the two breaks.

#### Tensile splitting test

39. The 3- by 6-in. and 6- by 12-in. cylinders evaluated for splitting strength were tested in a 440,000-lb universal testing machine in accordance with the procedures outlined in CRD-C 77,<sup>8</sup> "Method of Test for Tensile Splitting Strength of Cylindrical Concrete Specimens." The tensile splitting strength of a specimen was calculated as

$$T = \frac{2P}{\pi td}$$

where: T = tensile splitting strength, psi

P = maximum applied load, lb.

t = length of specimen, in.

d = diameter of specimen, in.

## Ring tension test

40. The 6-in.- and 12-in.-diameter rings were evaluated in specially designed testing jigs. The basic design for the 6-in.-diameter ring testing jig was provided by the Construction Materials Section, Department of Energy, Mines and Resources, Mines Branch, Canada. The plan and section views of the 6-in. testing jig as it was fabricated in the WES machine shop are shown in plates A4 and A5. The 12-in. testing jig was designed at WES and is essentially a scale-up of the 6-in. jig with some modifications. The plan and section views of the 12-in. jig are shown in plates A6 and A7. Photographs 2, 3, and 4 show the testing jigs in various stages of assembly.

41. The mechanisms used to apply the load to the rings were either a nominal 6-in. or nominal 12-in. rubber bladder, depending on the ring size being evaluated. These bladders can be seen in photograph 2. The bladders used in this study were borrowed from the Canadian Department of Energy, Mines and Resources, as they could not be produced locally. The bladders were filled with castor oil, which acted as the medium for pressure transfer to the walls of the bladder. Each bladder has a flat, cylindrical face which is slightly greater in height than the height of the ring being evaluated. Initially the ring is centered on the testing jig and fits loosely over the bladder (photograph 3). Upon some slight application of pressure on the fluid in the bladder, the bladder expands, and the flat, cylindrical face comes in contact with the inner surface of the ring. Before applying any pressure, however, the top plate of the testing jig is set in place and the fastening nuts screwed down to finger tightness (photograph 4). Some small pressure is then applied which seats the ring on the bladder

and also causes the top plate to become "free-floating." Thus no constraint is provided by the top plate during testing.

42. The pressure was applied to the bladders by two different methods during the program. The 6-in.-diameter M series rings were evaluated first during the program. A hand-operated hydraulic jack similar to that used by Malhotra<sup>4, 5, 6</sup> was used for these tests with the first 150-psi gage pressure being applied very rapidly, the remaining gage psi to failure of the ring being applied at an approximate rate of 3 psi gage per second. The same system was used in the same manner to evaluate the 6-in. and 12-in. rings from the first batch of the C1 series. It was found that the hand-operated jack was satisfactory for the smaller rings but that, because of the large volume of oil in the 12-in. bladders used to test the larger rings, pressure surges were developing upon completion of the downstroke of the hydraulic jack and pressure gage fluctuations of 5 to 7 psi gage were resulting, thus making it extremely difficult to obtain an accurate gage reading when the ring fractured. The loading system was then converted to an automatic, high-pressure, low-volume pump arrangement which enabled the pressure to be applied at a uniform, controlled rate. This arrangement worked satisfactorily and was used for both sizes of the rings in the remainder of the C1 and for all the C2 series ring tests. The rate of gage pressure application to ring failure after 150 psi gage had been reached was approximately 5, 6, and 4 psi gage per second for the 6-in. C1 series rings, 12-in. C1 series rings, and 12-in. C2 series rings, respectively.

43. The tensile strength of the rings was determined using the classical relations derived from the stress analysis of open-ended thick

wall cylinders subjected to an internal hydrostatic pressure up to the moment of failure.

$$T_i = \frac{P_i r_i^2}{(r_o^2 - r_i^2)} \left( 1 + \frac{r_o^2}{r^2} \right)$$

where:  $T_i$  = tangential tensile stress, psi,

$P_i$  = internal hydrostatic pressure, psi,

$r_i$  = internal radius, in.,

$r_o$  = external radius, in.,

$r$  = radius at point of failure, in.

44. Using the above equation and the internal and external radii of the rings evaluated in this study (3 and 4.5 in., respectively, for the 6-in. rings and 6 and 9 in., respectively, for the 12-in. rings), the tensile stresses for both sizes of rings can be found to vary from a maximum of  $2.6 P_i$  at the inside periphery to a minimum of  $1.6 P_i$  at the outside surface (see plate 1). The corresponding compressive stresses are  $P_i$  at the inside periphery, diminishing to zero at the outside surface. Malhotra<sup>6</sup> has shown experimentally that fracture of the ring initiates at the inside periphery; hence the value of  $r$  to be used in the above equation is equal to  $r_i$ . The maximum tensile stress at failure in either size ring can be determined as

$$T_{t \max} = 2.6 P_{i \max}$$

where  $P_i$  = the maximum applied hydrostatic pressure, psi.

Photographs 5, 6, 7, and 8 show typical rings from the M, C1 (6-in. and 12-in. rings), and C2 series, respectively, after failure. For each

ring tested, the number of distinct failure planes was noted and the internal angle,  $\theta$ , for each ring portion determined as shown in plate 2, where

$$\theta = (57.296) \frac{S}{r_m}$$

$r_m$  = radius to the center line of the ring, in.

$S$  = arc length of the center line of the ring portion, in.

### Test Results

45. A summary of the test results from all three mixture series is shown in table 2. Each test result observation is shown along with the average values for each round. Table 3 is a summary of the ring portion data and shows the number of distinct fracture planes observed in each ring after failure and the angle between the adjacent fracture planes. The manner in which the angles are listed is the actual order in which the fracture planes occurred. This order was determined by viewing the top of the ring as it was cast and tested and proceeding clockwise around the ring from the smallest angle measured.

46. The relations for compressive strength and water-cement ratio (by weight) for all three mixture series are shown in plate 3. Only the cylinder strength relation for the M series is shown, however, as cylinder strength is what will be used to relate to other variables in the remainder of this report. The relation between the cubes and cylinders from the M series is shown in plate 4. Curves showing the relationship between compressive and tensile strengths for the M, C1, and C2 series tests are shown in plates 5, 6, and 7 respectively. In order to nondimensionalize

the data for comparative purposes, curves showing the ratio of tensile strength to the corresponding 28-day compressive strength versus the compressive strength were developed and are shown in plates 8, 9, and 10 for M, C1, and C2 series tests, respectively. The average strength values of each round were used in developing the curves in plates 5 to 10.

#### Analyses of Test Results

47. The test results were analyzed using standard statistical methods.<sup>9</sup> Regression analyses were used to establish correlations between the data obtained from the various types of tests.<sup>10</sup> The within-batch and between-batch coefficients of variation are given in table 4. The solutions for the regression equation coefficients and the other pertinent statistical parameters were handled by GE 265 and GE 420 computers.

48. The graphical presentations of the regression analyses include, in most cases, statistical tolerance limits for the data. These limits were established from the standard error of the estimate,  $S_{\text{est}, y}$ , where

$$S_{\text{est}, y} = \sqrt{\frac{n}{\sum_{i=1}^n \frac{(y_i - \hat{y})^2}{n-2}}}$$

and  $y_i$  = observed dependent variable

$\hat{y}$  = predicted dependent variable

$n$  = number of observations

An expression of  $\pm 2 S_{\text{est}, y}$  established statistical tolerance limits that enclosed the range within which approximately 95 percent of all future observations may be expected to fall.

49. Plates 11 through 14 show the relation between the 6-in. ring tensile strength and the briquette, splitting, flexural, and compressive strengths, respectively, of the M series tests. Plates 15 and 16 show the relation between the two sizes of rings, and the two sizes of flexural specimens evaluated during the C1 series tests. Plates 17 through 20 show the relation between the 6-in. ring tensile strength and the splitting, small flexure beam, large flexure beam, and compressive strengths, respectively, while plates 21 through 24 show similar relations for the 12 ring tensile strengths, respectively, for the C1 series tests. Plates 25 through 27 show relations between the 12 ring tensile strengths and the splitting, flexural, and compressive strengths of the C2 series tests. Plates 28 and 29 show the relation between the average 12-in. ring tensile strengths and the average number of distinct ring fracture planes observed in each round of the C1 and C2 series tests, respectively. No discernible trend could be detected in similar data for the 6-in. rings in this study and those data are not shown for that reason.

#### PART IV: DISCUSSION OF TEST RESULTS

50. When evaluating new equipment, procedures, and techniques in the laboratory, there is a tendency to routinely exercise a greater degree of care in collecting the data for evaluation than will normally be realized in the field performance. The resulting laboratory evaluation may then be somewhat misleading by indicating a better performance than will probably be obtained in the field. To avoid this problem in the evaluation of the ring test equipment and procedures, the personnel who ultimately collected the data were initially trained in the proper use of the equipment and in the test procedures and techniques to be used by evaluating numerous trial batches of rings. Once the proper techniques were established, the actual test program began. From the start of the testing, six different individuals assisted in the testing of the samples and thus introduced an operator variable into the test results. This was by design. The actual testing was incorporated into the everyday routine testing and was given no preferential treatment. It was hoped that by using this approach a more realistic evaluation could be made.

##### Reproducibility of Test Results

51. The coefficients of variation shown in table 4 for the various types of tests are for very small samples (three observations in most cases) and therefore tend to appear as slightly larger numbers with respect to the coefficients of variation of larger populations of mortar and concrete specimens made and evaluated in the laboratory.<sup>11</sup> It is the relativity

of these values to each other that is of primary interest in this study, however, and with that thought in mind, the following observations can be made.

a. M series tests.

(1) The average within-batch and between-batches variations for the flexural and tensile tests are greater than those of the cylinder compression tests.

(2) There is some variation between the average within-batch results for the various flexural and tensile tests. These vary from 5.4 percent for the splitting test (excluding the 0.9 w/c batches) to 7.6 percent for the briquette test, the values of the ring test and flexural test being 5.5 and 7.3 percent, respectively. There is also some variation between the average between-batch results. These vary from 5.8 percent for the briquette test to 10.3 percent for the splitting test (excluding the 0.9 w/c batches), the values of the ring test and flexural test being 6.4 and 8.2 percent, respectively.

b. C1 series tests.

(1) The average within- and between-batch variations for the flexural and tension tests are greater than those of the cylinder compression tests.

(2) With the exception of small flexural beams and 12-in. rings, there is little difference among the average between-batches variations for the other flexural and tensile tests. These vary from 5.7 to 6.2 percent, with the small flexural beams and the 12-in. rings having average variations of 4.3 and 9.5, respectively.

(3) With the exception of the 12-in. rings whose average within-batch variation is 7.9 percent, there are some small differences between the average within-batch variations for the flexural and tensile tests. These vary from 3.9 percent for the large flexural beams to 6.2 percent for the splitting tests, with the small flexural beams and the 6-in. rings having values of 4.9 and 5.2 percent, respectively.

(4) Based on the coefficients of variation shown in table 4, a decision as to which size flexural beam gives more reproducible results is not clearly indicated. While the small flexure beams resulted in generally smaller and more consistent between-batches variations, the larger flexure beams produced generally smaller and more consistent within-batch variations. The decision as to which ring size gives more reproducible results with 3/8-in. aggregate concrete is more obvious with the 6-in. rings producing smaller and more consistent variations both within and between batches than the 12 rings.

c. C2 series tests.

(1) The average within- and between-batches variations for the flexural and tensile tests are greater than those variations for the cylinder compression tests.

(2) The average within- and between-batches variations (9.0 and 9.3) for the 12-in. rings made with 1-in. aggregate concrete are quite different from those obtained from the flexural (3.0 and 4.1) and splitting (5.8 and 3.9) tests of the same concrete. They are not very much different, however, from the values obtained from the 12-in. rings made with 3/8-in. aggregate concrete (7.9 and 9.5).

52. As can be deduced from the information contained in table 4 and the observations made above, the 6-in. rings, when used to evaluate the tensile strength of mortars and 3/8-in. aggregate concrete, produce within- and between-batches variations that are comparable to those obtained from the other tests which produce some measure of tensile strength. The 12-in. rings, however, resulted in variations which were greater than those produced by the other test methods. It is suspected that the casting mold configuration and construction was the primary factor in causing the 12-in. ring variations to be high. First, the one-piece central core of the mold did not allow the mold to be removed with a minimum of handling of the "green" concrete. Instead, the concrete ring had to be twisted and jostled off of the core when the concrete was only 24 hr old. In some instances, quite a lot of force was necessary to free the ring from the core. This rough handling may have produced some zones of weakness in the concrete that ordinarily would not have existed and, thus, introduced more variation into the test results than normally expected. Secondly, the outer wooden form and the wooden raised base form did not allow the concrete to be vibrated (and hence consolidated) properly. Some of the energy for consolidation that was being put into the system by the vibrator was probably being absorbed by the wooden form and, hence, improper consolidation was resulting. Improper consolidation also introduces additional variations into the test results.

53. An examination was also made of the relation between ring strength and the within-batch variations. No discernible effect of ring strength on

the coefficient of variation for the 6-in. rings in either the M or C1 series could be seen. In the case of the 12-in. rings from both the C1 and C2 series, a trend was developing that indicated that the lower the ring strengths were, the larger the coefficients of variation were. There are a number of factors which can affect the variation such as variations in cement and water content, the gradation and water content of the aggregate, inadequate mixing, irregular curing, variations in testing procedures, insufficient compaction and rough handling. It is felt that sufficient care was exercised in design, batching, mixing, and curing to minimize these effects in both the 6- and 12-in. rings. The 6-in. rings were adequately compacted and received no rough handling, whereas, although compaction was attempted on the 12-in. rings, it may not have been very effective and in some instances the rough handling of the larger rings at 24 hr age was unavoidable. Of the two of these factors, rough handling would probably be the predominant factor causing greater variations at lower strengths of the concrete because the rings with less strength would be more susceptible to damage than higher strength rings and if damaged would result in higher variations when tested. The trend towards greater variations at lower strengths was not evident for specimens cast from the same concrete but tested in compression, flexure, and splitting.

#### Regression analyses

54. The regression analyses of the various correlations between ring-tensile strength and compression, flexural, and splitting strengths, with the exception of the mortar tests (M series), do not indicate as high a degree of correlation between the ring test and the other tests as was found by Malhotra.<sup>6,7</sup>

55. The work by Malhotra<sup>6,7</sup> involved concrete whose cylinder compressive strengths were less than 7000 psi, and his correlations are linear in rectilinear coordinates. He observes that the linear model assumed in his analyses may not hold good for compressive strengths in excess of 7000 psi at 28 days. The compressive strengths in this study exceed 7000 psi with individual cylinder tests going as high as 9815 psi, 8950 psi, 9050 psi for the M, C1, and C2 series tests, respectively. The lines of best fit correlating compressive strength to ring strength for all three series cannot be satisfactorily represented by the linear model but instead are best represented in simple form as a power function of the form  $y = ax^b$  where the exponent  $b$  is less than 0.5 (see plates 14, 20, 24, and 27). In the form of a simple power function, the compressive strength versus ring strength correlation coefficients for the M series, both the 6- and 12-in. ring strengths of the C1 series and the C2 series are 0.951, 0.868, 0.774, and 0.901, respectively.

56. All of the correlations between the 6-in. ring tensile strengths and the briquette flexural, and splitting strengths of the mortar tests (M series) can be represented by the linear model (see plates 11, 12, and 13), having correlation coefficients of 0.958, 0.945, and 0.965, respectively. These coefficients indicate a high degree of correlation between the ring test and the other standard tests for mortars having cube and cylinder compressive strengths up to approximately 13,000 psi and 10,000 psi, respectively.

57. The correlations between the ring tensile strengths and the flexural and splitting strengths for the concrete tests (C1 and C2 series) do not satisfactorily fit the linear model, however. The regression analyses indicate that the relation between ring strength and splitting strength is best fitted by the simple power function  $Y = ax^b$ . The correlations between ring strength and splitting strength in this form have correlation coefficients of 0.838, 0.739, and 0.873 for the 6- and 12-in.-diameter ring strengths of the C1 series and the 12-in.-diameter ring strengths of the C2 series, respectively (see plates 17, 21, and 25). These coefficients indicate that some correlation exists between the ring and splitting strengths but that the correlation is not as good as that obtained for the mortar series or by Malhotra.<sup>6,7</sup>

58. The regression analyses also indicate that the correlation between ring tensile strengths and the flexural strengths of the concrete tests (C1 and C2 series) is best fitted by a semilog relation of the form  $Y = a(10)^{bX}$ . The correlations, in this form, between the small flexural beam strength and the 6-in.- and 12-in.-diameter ring strengths of the C1 series (see plates 18 and 22) have correlations coefficients of 0.764 and 0.656, respectively. These correlations are not very good. The correlations in the semilog form between the large flexural beam strengths and the 6-in.- and 12-in.-diameter ring strengths of the C1 series, and the 12-in.-diameter ring strengths of the C2 series (see plates 19, 23, and 26) are somewhat better having correlations coefficients of 0.852, 0.743, and 0.852, respectively.

59. No attempt was made to obtain other possibly better fitting, higher ordered functions for any of the correlations discussed above.

### Strength ratios

60. M series. The ratio of the 6-in. ring tensile strength to the cylinder compressive strength expressed as a percentage varied from 20.4 to 10.9 at corresponding compressive strengths of 3000 and 9000 psi (plate 8). The corresponding ratios for the small flexural beam, splitting, and briquette strengths are 16.8 to 10.0, 11.0 to 8.6, 15.3 to 7.7, respectively.

61. C1 series. The ratio of the 6- and 12-in. ring tensile strength to the cylinder compressive strength expressed as a percentage varied from 20.6 to 9.8 and 17.1 to 8.6, respectively, at corresponding compressive strengths of 3000 and 9000 psi (plate 9). The relation for the 6-in. rings made with the 3/8-in. aggregate concrete gives somewhat higher ratios than those observed by Malhotra<sup>6</sup> for similar size aggregate concrete rings. The relation for the 12-in. rings made with the 3/8-in. aggregate concrete results in similar ratios to those Malhotra<sup>7</sup> observed for similar rings. The corresponding ratios for the C1 series large flexural beam, small flexural beam, and splitting strengths are 20.9 to 12.1, 19.5 to 11.5, and 12.8 to 8.2, respectively.

62. C2 series. The ratio of the 12-in. ring tensile strength to the cylinder compressive strength expressed as a percentage varied from 16.2 to 9.1 at corresponding compressive strengths of 3000 and 9000 psi (plate 10). This relation, which is for 1-in. aggregate concrete, results in slightly higher ratios at lower compressive strengths than Malhotra observed<sup>7</sup> for similar size rings made with 3/4-in. aggregate. The corresponding ratios for the large flexural beam and splitting strengths are 19.7 to 11.0 and 12.9 to 8.3, respectively.

63. It is interesting to note that the ratios of 12-in. ring strength, flexural strength (regardless of beam size), and splitting strength to the cylinder compressive strengths for the C1 series made with 3/8-in. aggregate are not significantly different from the corresponding ratios for the C2 series made with 1-in. aggregate over the range of compressive strengths from 3000 to 9000 psi. The flexural and splitting ratios for the mortar series are somewhat smaller for lower compressive strengths, however, than the corresponding ratios from the two concrete series. The ratios of 6-in. ring tensile strengths to compressive strength for the M and C1 series are approximately the same at 3000 and 9000 psi compressive strength, but vary from each other over the central portion of the compressive strength range.

#### Size effects

64. In most instances, two sizes of rings were cast and tested from each batch of 3/8-in. limestone aggregate concrete (C1 series). The tensile strength test results indicated that the average strength over the range of water-cement ratios studied of the 6-in.-inside-diameter rings was 19.4 percent higher than the 12-in.-inside-diameter rings. Individual batch increases ranged from 4.5 to 39.6 percent. Because the concrete in the rings used in the comparisons in each case came from the same batch, variations in strength due to design, material differences, and curing can be neglected. The strength differences are then principally affected by the variations introduced by casting, handling, testing, and size and configuration. The casting and handling aspects have been discussed previously. The testing procedures and equipment (except for size) were the same for both size rings. The

general configuration of the rings varied only in the degree of vertical planeness (total taper) of the inside loaded surface. This aspect of ring testing needs further study. The remaining factor is the actual size of the ring with all dimensions of the 12-in. ring being twice those of the 6-in. ring. Over a similar range of water-cement ratios, Malhotra<sup>7</sup> has found an average strength increase for 6-in. rings compared to 12-in. rings of 15 percent. The concrete in that study also used 3/8-in. crushed limestone aggregate. His individual batch variations ranged from 6.4 to 31.6 percent. In view of these findings, it is felt that the 19.4 percent increase obtained in this study is not unreasonable. The strengths of the two sizes of rings are related by a power function as shown in plate 15 with a correlation coefficient of 0.893.

65. A size effect also existed for the flexural beams evaluated during the C1 series tests. In all but three of the 17 batches where a comparison could be made, the larger 6- by 6- by 30-in. beams resulted in higher moduli of rupture than those obtained from the 3-1/2- by 4-1/2- by 16-in. beams. Individual batch increases varied from 0.7 to 26.3 percent, while the three decreases varied from -3.3 to -9.9 percent. The average increase in modulus of rupture over the entire range of water-cement ratios studied was 5.5 percent. The only predominant factors affecting these results were the method of testing (primarily the testing machine) and the size of the specimens being tested. A fairly good correlation exists between the strengths of the two sizes of beams, being linear with a correlation coefficient of 0.921.

### Fracture surfaces

66. No detailed analysis was made to determine the reasons or mechanisms why the rings fracture on as many distinct planes as they do. The information contained in table 3 and in plates 28 and 29 is there solely for the record. A few observations can be made, however, which may be of assistance in future testing and analyses.

67. Malkotra<sup>4,12</sup> observed that for concrete with an average cylinder compressive strength of 4050 psi, the number of distinct fracture planes per cast 6-in.-inside-diameter ring was four with a few exceptions, while identically sized rings sawed from long, hollow, concrete cylinders experienced two to five distinct fracture planes but generally had either three or four. Based on this observation, together with variations measured in the weight and strength of the sawed rings, Malkotra concluded that the individually cast rings were preferred. In the study reported herein, individually cast 6-in.- and 12-in.-inside-diameter rings were used, and while the weight of the rings was fairly uniform, the strengths and number of fracture planes tended to vary considerably in some instances.

68. For the forty-seven 6-in. mortar rings tested with ring-tensile strengths varying from 507 to 1118 psi, the average number of distinct fracture planes per ring was 4.85, with individual rings having from four to six breaks. Approximately two-thirds of the rings had five breaks. For the forty-five 6-in. concrete rings (C1 series) having ring tensile strengths from 598 to 1105 psi, the average number of distinct fracture planes per ring was 4.48, with individual rings having three to six breaks.

More than half of the rings had only four breaks. An analysis of the relation of ring tensile strength to the number of distinct ring fracture planes for the 6-in. rings of both the M and C1 series tests indicated that the tensile strength had little effect on the number of planes occurring.

69. For the thirty-nine 12-in. concrete rings of the C1 series, having ring tensile strengths from 429 to 897 psi, the average number of distinct fracture planes per ring was 5.79, with individual rings varying from three to eight breaks. For the forty-four 12-in. concrete rings of the C2 series, having ring tensile strengths from 338 to 975 psi, the average number of distinct fracture planes per ring was 5.27, with individual rings varying from four to nine breaks. More than half of the rings had only five breaks. An analysis of the relation of ring tensile strengths to the number of distinct fracture planes for the 12-in. rings of both the C1 and C2 series tests indicated that a trend was developing as shown in plates 28 and 29 and that higher ring tensile strengths are accompanied by an increased number of fracture planes.

70. Upon fracturing, the ring literally explodes away from the rubber testing bladder, and for higher strength concretes, some pieces of the fractured ring may even fly out of the testing equipment. It was first suspected that the additional fracture planes over those observed by Malhotra were the result of the ring fragments hitting the fastening posts of the testing rig and thus fracturing again. Inspection of all of the

rings immediately after fracture showed that, while in many instances the additional fracture planes could have conceivably been the planes aligned with the fastening posts, often as not none of the planes were aligned with a post. As can be seen from table 3, the spacing between fracture planes was not very uniform. Photographs were made of each ring after failure and are on record at WES.

#### Equipment and Procedures

71. In general, the casting molds and testing jigs are relatively simple in design (Appendix A) and were easy to fabricate and transport.

72. The 12-in. ring casting molds as used in this program can be greatly improved. The entire mold should be constructed of steel. The outer wooden form and base that were used did not present, as mentioned previously, an ideal situation for the consolidation of the concrete and were rather short lived. At the time of the construction of these molds, steel rings of sufficient inside diameter (slightly less than 18 in.) could not be obtained locally or from other sources within a reasonable length of time; hence, the wooden forms were used. The inner steel core of the 12-in. rings should be made as a split ring instead of a solid core in order to facilitate form removal with a minimum of handling of the "green" concrete rings. The large within-batch coefficients of variation for most of the 12-in. rings are believed to have been the result, in large part, of the force, and subsequent internal damage, that was necessary to remove the large rings from the central core of the molds. The solid

aluminum core of the 6-in. casting molds should also be replaced but by a solid steel core in order to alleviate a bonding problem that frequently occurred throughout the program as the cement paste bonded to the aluminum oxide that formed on the core walls. The casting molds as used in this program with the modifications suggested above should be durable, perform satisfactorily with a minimum of form-removal problems, and, hopefully, should improve on the reproducibility of the test data.

73. The very simple and portable testing jigs performed satisfactorily and appeared to be very durable pieces of equipment. The only vulnerable part of the jigs is the threaded fastening posts and these, if damaged, can be easily removed and replaced. When testing high-strength concrete and mortars, a protective screen should be placed around the jig as fragments of the ring do fly out of the jig because of the explosive nature of the failure. Circular pieces cut from 20- and 55-gal drums were used for this purpose for the 6- and 12-in. jigs, respectively.

74. The testing bladders performed very well and showed no indication of wear. The bladders were borrowed because local rubber product fabricators could not produce limited numbers of test bladders except at prohibitive costs. This was due to the fact that they did not possess the techniques necessary to begin producing satisfactory bladders on the first attempts. The cost undoubtedly would be reduced if the demand for and number of bladders were great enough.

75. The hand-operated hydraulic-loading system for the 6-in. ring test was adequate. Because of a surging pressure problem (discussed earlier),

the hand-operated equipment had to be replaced by an automatic-loading system for the 12-in. ring tests, and this system performed satisfactorily. If such a system is available, it should also be used on the small ring tests in order to provide a uniform rate of load application. Because there generally is no advanced warning of failure of the ring during test, a "rider" dial indicator is desirable on all pressure gages so that the internal pressure at failure is discernible.

76. The test procedures, as described in this report, are very simple and are easily learned. Some future work should be done, however, in evaluating and standardizing the rate of loading in these tests.

## PART V: CONCLUSIONS AND RECOMMENDATIONS

### Conclusions.

77. The 6-in. ring tensile test appears to be a satisfactory means for determining a measure of the tensile strength of mortars and 3/8-in. concrete. The 12-in. ring tensile test of 3/8- and 1-in. aggregate concrete was burdened with specimen fabrication problems and, although the within-batch and between-batches coefficients of variation for the 12-in. rings were somewhat greater than for the flexural and tensile splitting tests, it appears that, with additional development work, the 12-in. rings could be satisfactorily used for concretes with aggregate sizes up to 1 in.

78. For mortar, the within-batch and between-batches coefficients of variation for the 6-in. ring test appear to be slightly better, in general, than the variations obtained for the other flexural and tensile strength tests.

79. For 3/8-in. concrete, the within-batch and between-batches coefficients of variation for the 6-in. ring test appear to be comparable to those variations obtained from the flexural and tensile splitting tests.

80. The 12-in. ring tensile test used with either 3/8- or 1-in. concrete rings resulted in higher within-batch and between-batches coefficients of variation than did the flexural and tensile splitting tests. It is believed that with additional development work the 12-in. ring strength variations can be made comparable to those obtained from the flexural and splitting tests.

81. The correlation between ring tensile strength and flexural and tensile splitting strengths for mortars having a cylinder compressive strength range of 2500 to 10,000 psi follows a linear model and has a high degree of correlation with correlation coefficients of 0.965 and 0.945, respectively. The correlation between ring tensile strength and cylinder compressive strength fits a power function and has a correlation coefficient of 0.951.

82. The correlation between cylinder compressive strength and 6- and 12-in. ring tensile strengths for both 3/8- and 1-in. concrete is best fitted by a power function in the strength range of 3000 to 9000 psi. The degrees of correlation in these cases were not as good as for the mortar tests, being 0.868, 0.774, 0.901 for the 3/8-in. concrete 6- and 12-in. rings and the 1-in. concrete 12-in. ring, respectively. The correlations between tensile splitting strength and the 6- and 12-in. ring tensile strengths for both the 3/8- and 1-in. concretes are also best fitted by a power function with correlation coefficients of 0.838, 0.739, 0.873 for the 6- and 12-in. rings of 3/8-in. concrete and the 12-in. rings of 1-in. concrete, respectively.

83. The correlations between flexural beam strength and the 6- and 12-in. ring tensile strengths for both the 3/8- and 1-in. concretes having a cylinder compressive strength range of 3000 to 9000 psi are best fitted by semilog relations with correlation coefficients of 0.764, 0.852, 0.656, 0.743, and 0.852 for the two sizes of flexural beams compared to the 6- and 12-in. rings of 3/8-in. concrete and the large flexural beam strengths compared to the 12-in. rings of 1-in. concrete, respectively.

84. The 12-in. rings of 3/8-in. concrete generally have lower ring tensile strengths than 6-in. rings of the same concrete. The correlation between the two strengths for a range of compressive strengths of 3000 to 9000 psi was best fitted by a power function and had a correlation coefficient of 0.893.

85. With some exceptions, most of the 6-in. mortar and concrete rings had four or five distinct fracture planes. The number of fracture planes in this case did not appear to be affected by the strength of the concrete. The 12-in. rings, however, experienced, on the average, an increase in two fracture planes per ring as the ring tensile strength of the concrete increased from 400 to 900 psi.

86. The testing equipment is very simple, portable, and easy to use. The test procedures are not complex and are easily learned. The ring casting molds as used in the study should be modified as discussed in order to alleviate form removal problems and improve the reproducibility of the test results.

#### Recommendations for Future Work

87. Further considerations should be given to the effect of ring casting equipment and procedures on the reproducibility of ring tensile test results. These considerations should include the effects of casting mold assembly configurations, inner core tapers, consolidation of the concrete, and demolding procedures.

88. The exact stress and strain distribution across the radial surfaces of the ring under load should be determined and compared to the assumed distributions used in the ring strength determinations. When the actual distributions are known, the ring test should be given consideration as a possible method for conducting tensile creep tests of concrete.

89. The effects of aggregate type, shape, and gradations, plus the effects of various types of cement and mixture consistency, on the tensile strength of concrete and mortar rings should also be studied.

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**TABLE 1 - SUMMARY OF MIXTURE DESIGNS AND BATCH DATA**

Mixture	Round No.	Water-Cement Ratio	SSD Batch Weights, lb				Fine Aggregate Moisture Content, %	Coarse Aggregate Moisture Content, %	Mixture Data					Actual Unit Weight pcf
			Cement <sup>1</sup>	Fine <sup>2</sup> Aggregate	Coarse <sup>3</sup> Aggregate	Water			Batch Volume, cu ft	Cement Factor Bag/cu yd	Sand/Aggregate Ratio % vol	Slump Inches	Air Content, %	
M4	1	0.4	41.4	70.4	--	16.5	2.2	--	0.9	13.2	--	4-1/2	3.1	139.8
	2	0.4	41.4	70.4	--	16.5	2.0	--	0.9	13.2	--	4-1/2	2.3	139.8
	3	0.4	41.4	70.4	--	16.5	2.5	--	0.9	13.2	--	4-1/4	2.4	139.6
M5	1	0.5	30.2	83.5	--	15.2	2.4	--	0.9	9.63	--	4-1/4	2.0	141.6
	2	0.5	30.2	83.5	--	15.2	2.2	--	0.9	9.63	--	4-1/2	2.0	142.4
	3	0.5	30.2	83.5	--	15.2	2.2	--	0.9	9.63	--	4-1/2	2.2	141.2
M6	1	0.6	24.6	89.1	--	14.8	2.1	--	0.9	7.88	--	4-3/4	3.4	139.2
	2	0.6	24.6	89.1	--	14.8	2.4	--	0.9	7.88	--	4	2.7	140.6
	3	0.6	24.6	89.1	--	14.8	2.5	--	0.9	7.88	--	4	2.9	140.6
M7	1	0.7	20.9	93.2	--	14.6	2.5	--	0.9	6.65	--	4	2.2	141.0
	2	0.7	20.9	93.2	--	14.6	2.5	--	0.9	6.65	--	4	2.3	140.8
	3	0.7	20.9	93.2	--	14.6	2.5	--	0.9	6.65	--	4	2.5	141.6
M8	1	0.8	18.0	96.0	--	14.4	2.0	--	0.9	5.75	--	4-1/2	3.4	139.0
	2	0.8	18.0	96.0	--	14.4	2.1	--	0.9	5.75	--	4-3/4	2.8	138.6
	3	0.8	18.0	96.0	--	14.4	2.5	--	0.9	5.75	--	4-1/4	2.9	138.6
M9	1	0.9	16.2	97.2	--	14.6	2.2	--	0.9	5.16	--	4	3.1	140.6
	2	0.9	16.2	97.2	--	14.6	2.2	--	0.9	5.16	--	4	3.2	140.4
	3	0.9	16.2	97.2	--	14.6	2.2	--	0.9	5.16	--	4	3.6	139.4

(CONTINUED)

TABLE 1 (CONTINUED)

Mixture	Round No.	Water-Cement Ratio	SSD Batch Weights, lb				Fine Aggregate Moisture Content %	Coarse Aggregate Moisture Content %	Mixture Data					
			Cement <sup>1</sup>	Fine <sup>2</sup> Aggregate	Coarse <sup>3</sup> Aggregate	Water			Batch Volume, cu ft	Cement Factor Bag/cu yd	Sand/Aggregate Ratio % vol	Slump Inches	Air Content, %	Actual Unit Weight pcf
C1-4	1	0.4	210.6	204.2	306.6	84.2	2.6	0.4	5.5	11.0	40.0	3-1/4	1.9	146.4
	2	0.4	210.6	204.2	306.6	84.2	2.6	0.4	5.5	11.0	40.0	3-1/2	2.0	146.0
	3	0.4	210.6	204.2	306.6	84.2	2.3	0.4	5.5	11.0	40.0	3-1/2	2.1	145.6
	4	0.4	210.6	204.2	306.6	84.2	2.3	0.4	5.5	11.0	40.0	3-1/2	2.1	145.8
C1-5	1	0.5	145.7	281.0	321.9	72.8	2.1	0.4	5.5	7.6	47.0	3-1/4	1.7	149.0
	2	0.5	145.7	281.0	321.9	72.8	2.0	0.4	5.5	7.6	47.0	3	2.2	147.6
	3	0.5	145.7	281.0	321.9	72.8	1.9	0.4	5.5	7.6	47.0	2-3/4	2.1	148.0
C1-6	1	0.6	124.1	298.0	314.9	74.4	2.1	0.4	5.5	6.5	49.0	3	1.9	146.8
	2	0.6	124.1	298.0	314.9	74.4	2.4	0.4	5.5	6.5	49.0	3	1.9	146.8
	3	0.6	124.1	298.0	314.9	74.4	2.2	0.4	5.5	6.5	49.0	3-1/4	1.9	147.2
	4	0.6	124.1	298.0	314.9	74.4	2.3	0.4	5.5	6.5	49.0	3-1/4	1.8	147.0
C1-7	1	0.7	107.2	317.8	309.9	75.0	1.7	0.4	5.5	5.6	51.0	3	1.8	147.4
	2	0.7	107.2	317.8	309.9	75.0	1.8	0.4	5.5	5.6	51.0	3	1.7	147.2
	3	0.7	107.2	317.8	309.9	75.0	1.9	0.4	5.5	5.6	51.0	3	1.6	146.8
C1-8	1	0.8	95.9	327.6	307.0	76.7	2.3	0.4	5.5	5.0	52.0	2-3/4	2.1	145.8
	2	0.8	95.9	327.6	307.0	76.7	2.3	0.4	5.5	5.0	52.0	2-3/4	2.2	145.8
	3	0.8	95.9	327.6	307.0	76.7	2.3	0.4	5.5	5.0	52.0	2-1/2	2.2	145.6

(CONTINUED)

TABLE 1 (CONTINUED)

Mixture	Round No.	Water-Cement Ratio	SSD Batch Weights, lb				Fine Aggregate Moisture Content %	Coarse Aggregate Moisture Content %	Mixture Data					Actual Unit Weight pcf
			Cement <sup>1</sup>	Fine <sup>2</sup> Aggregate	Coarse <sup>3</sup> Aggregate	Water			Batch Volume, cu ft	Cement Factor Bag/cu yd	Sand/Aggregate Ratio % vol	Slump Inches	Air Content, %	
C2-4	1	0.4	172.0	210.0	379.1	68.8	2.2	0.4	5.5	9.0	36.0	3	1.7	149.6
	2	0.4	172.0	210.0	379.1	68.8	2.0	0.4	5.5	9.0	36.0	2-3/4	1.8	150.4
	3	0.4	172.0	210.0	379.1	68.8	2.2	0.4	5.5	9.0	36.0	2-1/2	1.7	150.8
C2-5	1	0.5	131.6	249.6	380.1	65.8	2.3	0.4	5.5	6.9	40.0	2-1/2	1.6	149.6
	2	0.5	131.6	249.6	380.1	65.8	2.1	0.4	5.5	6.9	40.0	2-1/2	1.7	149.6
	3	0.5	131.6	249.6	380.1	65.8	2.0	0.4	5.5	6.9	40.0	2-3/4	1.7	150.0
C2-6	1	0.6	107.2	280.3	377.0	64.3	1.9	0.4	5.5	5.6	43.0	2-3/4	1.4	150.4
	2	0.6	107.2	280.3	377.0	64.3	2.4	0.4	5.5	5.6	43.0	2-3/4	1.5	150.2
	3	0.6	107.2	280.3	377.0	64.3	2.4	0.4	5.5	5.6	43.0	2-1/2	1.5	150.0
C2-7	1	0.7	94.0	290.3	375.8	65.8	2.3	0.4	5.5	4.9	44.0	2-3/4	1.3	150.2
	2	0.7	94.0	290.3	375.8	65.8	2.3	0.4	5.5	4.9	44.0	2-3/4	1.3	150.4
	3	0.7	94.0	290.3	375.8	65.8	2.6	0.4	5.5	4.9	44.0	2-1/2	1.2	150.4
C2-8	1	0.8	82.7	302.6	375.3	66.2	2.0	0.4	5.5	4.3	45.0	3-1/4	1.3	149.2
	2	0.8	82.7	302.6	375.3	66.2	2.0	0.4	5.5	4.3	45.0	3	1.1	150.2
	3	0.8	82.7	302.6	375.3	66.2	1.8	0.4	5.5	4.3	45.0	3	1.2	149.8

Note: 1 Type II, RC-579

2 CRD-MS-17(4)

3 For the C1 series, CRD-G-31(12) was used for all batches except C1-4, Round 1 and C1-8, Rounds 1, 2, and 3 which used CRD-G-31(4). The C2 series used 60% CRD-G-31(10) and 40% CRD-G-31(7) for each batch.

TABLE 2-SUMMARY OF TEST RESULTS

Mixture	Water-Cement Ratio	Round No.	Specimen No.	Compressive Strength, psi			Briquette Strength psi	Flexural Strength, psi		Splitting Strength, psi		Ring Strength, psi	
				2-in. Cubes	3 x 6-in. Cylinders	6 x 12-in. Cylinders		3½ x 4½ x 16-inch Beams	6 x 6 x 30-inch Beams	3 x 6-in. Cylinders	6 x 12-in. Cylinders	6-in. Rings	12-in. Rings
M4	0.4	1	1	11,700	9590	--	640	1050	--	798	--	1001	--
			2	11,350	9510	--	732	990	--	853	--	1019	--
			3	12,750	9815	--	717	985	--	790	--	1079	--
			Avg	11,930	9640	--	696	1008	--	814	--	1033	--
M4	0.4	2	1	9,900	8715	--	812	835	--	709	--	910	--
			2	11,450	8685	--	707	890	--	644	--	910	--
			3	11,100	9135	--	638	910	--	772	--	1019	--
			Avg	10,820	8845	--	719	878	--	708	--	946	--
M4	0.4	3	1	11,500	9280	--	685	955	--	872	--	832	--
			2	11,025	9135	--	722	930	--	842	--	1118	--
			3	11,600	9700	--	750	870	--	859	--	1014	--
			Avg	11,375	9372	--	719	918	--	858	--	988	--
M5	0.5	1	1	8,350	7820	--	495	755	--	644	--	871	--
			2	8,600	7780	--	600	740	--	617	--	806	--
			3	7,750	7265	--	650	780	--	650	--	897	--
			Avg	8,235	7620	--	582	758	--	637	--	856	--
M5	0.5	2	1	9,400	7865	--	772	875	--	710	--	876	--
			2	9,750	7695	--	770	855	--	742	--	962	--
			3	8,550	7665	--	638	670	--	734	--	--	--
			Avg	9,235	7740	--	727	800	--	729	--	919	--

(Continued)

TABLE 2 (CONTINUED)

Mixture	Water-Cement Ratio	Round No.	Specimen No.	Compressive Strength, psi			Briquette Strength psi	Flexural Strength, psi		Splitting Strength, psi		Ring Strength, psi	
				2-in. Cubes	3 x 6-in. Cylinders	6 x 12-in. Cylinders		3½ x 4½ x 16-inch Beams	6 x 6 x 30-inch Beams	3 x 6-in. Cylinders	6 x 12-in. Cylinders	6-in. Rings	12-in. Rings
M5	0.5	3	1	9,950	8035	--	670	910	--	673	--	--	--
			2	9,675	8145	--	612	780	--	686	--	--	--
			3	10,625	8430	--	670	810	--	--	--	--	--
			Avg	10,085	8205	--	651	833	--	680	--	--	--
M6	0.6	1	1	7,400	6310	--	708	889	--	609	--	949	--
			2	7,250	6250	--	708	859	--	609	--	962	--
			3	6,950	6225	--	620	918	--	693	--	--	--
			Avg	7,200	6260	--	679	889	--	637	--	956	--
M6	0.6	2	1	6,650	5600	--	725	795	--	435	--	819	--
			2	6,550	5630	--	610	745	--	560	--	806	--
			3	6,550	5910	--	650	655	--	471	--	858	--
			Avg	6,585	5715	--	660	730	--	489	--	828	--
M6	0.6	3	1	6,650	5460	--	722	946	--	593	--	819	--
			2	6,450	5740	--	715	784	--	575	--	858	--
			3	--	5370	--	633	751	--	594	--	845	--
			Avg	6,550	5525	--	690	827	--	587	--	841	--
M7	0.7	1	1	5,100	4740	--	578	780	--	564	--	767	--
			2	5,200	4625	--	670	735	--	546	--	806	--
			3	5,025	4595	--	535	810	--	545	--	728	--
			Avg	5,180	4633	--	594	775	--	552	--	767	--

(Continued)

TABLE 2 (CONTINUED)

Mixture	Water-Cement Ratio	Round No.	Specimen No.	Compressive Strength, psi			Briquette Strength psi	Flexural Strength, psi		Splitting Strength, psi		Ring Strength, psi	
				2-in. Cubes	3 x 6-in. Cylinders	6 x 12-in. Cylinders		3½ x 4½ x 16-inch Beams	6 x 6 x 30-inch Beams	3 x 6-in. Cylinders	6 x 12-in. Cylinders	6-in. Rings	12-in. Rings
M7	0.7	2	1	5,500	4750	--	588	719	--	422	--	767	--
			2	5,650	4670	--	585	628	--	472	--	689	--
			3	5,600	4610	--	542	684	--	427	--	754	--
			Avg	5,600	4675	--	572	677	--	440	--	737	--
M7	0.7	3	1	5,675	4570	--	508	616	--	526	--	715	--
			2	5,650	4525	--	510	557	--	530	--	676	--
			3	5,575	4640	--	575	530	--	497	--	650	--
			Avg	5,635	4580	--	531	568	--	518	--	680	--
M8	0.8	1	1	3,750	3310	--	495	545	--	350	--	637	--
			2	3,700	3340	--	513	545	--	372	--	663	--
			3	3,800	3395	--	485	640	--	385	--	--	--
			Avg	3,750	3350	--	498	575	--	369	--	650	--
M8	0.8	2	1	3,500	3170	--	500	580	--	294	--	533	--
			2	3,600	3480	--	455	560	--	333	--	663	--
			3	3,450	3280	--	430	550	--	403	--	507	--
			Avg	3,515	3310	--	462	563	--	343	--	568	--
M8	0.8	3	1	3,810	3340	--	475	570	--	443	--	611	--
			2	3,850	3170	--	508	490	--	419	--	624	--
			3	3,950	3140	--	450	495	--	400	--	629	--
			Avg	3,870	3215	--	478	518	--	421	--	621	--

(Continued)

TABLE 2 (CONTINUED)

Mixture	Water-Cement Ratio	Round No.	Specimen No.	Compressive Strength, psi			Briquette Strength psi	Flexural Strength, psi		Splitting Strength, psi		Ring Strength, psi	
				2-in. Cubes	3 x 6-in. Cylinders	6 x 12-in. Cylinders		3 1/2 x 4 1/2 x 16-inch Beams	6 x 6 x 30-inch Beams	3 x 6-in. Cylinders	6 x 12-in. Cylinders	6-in. Rings	12-in. Rings
M9	0.9	1	1	3,000	2660	--	418	498	--	172	--	585	--
			2	2,850	2630	--	390	453	--	327	--	624	--
			3	3,150	2885	--	415	396	--	157	--	494	--
			Avg	3,000	2725	--	408	449	--	219	--	568	--
M9	0.9	2	1	3,345	2770	--	508	466	--	336	--	676	--
			2	3,575	2915	--	475	525	--	393	--	663	--
			3	3,420	2870	--	518	544	--	328	--	--	--
			Avg	3,445	2850	--	500	512	--	352	--	670	--
M9	0.9	3	1	3,650	2970	--	428	432	--	367	--	598	--
			2	3,300	2855	--	520	477	--	263	--	611	--
			3	3,350	2855	--	427	512	--	266	--	611	--
			Avg	3,435	2905	--	458	474	--	299	--	607	--
C1-4	0.4	1	1	--	--	8820	--	1003	1110	--	700	988	728
			2	--	--	8590	--	1037	1100	--	750	962	715
			3	--	--	8390	--	1045	1110	--	770	975	650
			Avg	--	--	8600	--	1028	1107	--	740	975	698
C1-4	0.4	2	1	--	--	8670	--	1013	980	--	800	--	897
			2	--	--	8840	--	1033	1070	--	850	--	806
			3	--	--	8510	--	968	1000	--	520	--	845
			Avg	--	--	8675	--	1005	1017	--	723	--	849

(Continued)

TABLE 2 (CONTINUED)

Mixture	Water-Cement Ratio	Round No.	Specimen No.	Compressive Strength, psi			Briquette Strength psi	Flexural Strength, psi		Splitting Strength, psi		Ring Strength, psi	
				2-in. Cubes	3 x 6-in. Cylinders	6 x 12-in. Cylinders		3½ x 4½ x 16-inch Beams	6 x 6 x 30-inch Beams	3 x 6-in. Cylinders	6 x 12-in. Cylinders	6-in. Rings	12-in. Rings
C1-4	0.4	3	1	--	--	8680	--	1107	1050	--	680	910	806
			2	--	--	8950	--	1045	1120	--	630	923	858
			3	--	--	8860	--	1092	1150	--	720	936	923
			Avg	--	--	8830	--	1081	1107	--	677	923	862
C1-4	0.4	4	1	--	--	8210	--	952	1140	--	790	897	767
			2	--	--	8480	--	1043	1130	--	760	936	923
			3	--	--	8680	--	1047	1180	--	690	845	689
			Avg	--	--	8460	--	1014	1150	--	747	893	793
C1-5	0.5	1	1	--	--	7140	--	1003	870	--	610	819	819
			2	--	--	7120	--	926	900	--	750	936	715
			3	--	--	7380	--	968	840	--	570	832	780
			Avg	--	--	7215	--	966	870	--	643	862	771
C1-5	0.5	2	1	--	--	7670	--	1001	1030	--	730	793	728
			2	--	--	7710	--	930	990	--	710	832	520
			3	--	--	7660	--	997	930	--	780	845	--
			Avg	--	--	7680	--	976	983	--	740	823	624
C1-5	0.5	3	1	--	--	7710	--	841	960	--	700	884	871
			2	--	--	7730	--	926	1010	--	700	1066	871
			3	--	--	7570	--	903	970	--	670	1105	819
			Avg	--	--	7670	--	890	980	--	690	1018	854

(Continued)

TABLE 2 (CONTINUED)

Mixture	Water-Cement Ratio	Round No.	Specimen No.	Compressive Strength, psi			Briquette Strength psi	Flexural Strength, psi		Splitting Strength, psi		Ring Strength, psi	
				2-in. Cubes	3 x 6-in. Cylinders	6 x 12-in. Cylinders		3½ x 4½ x 16-inch Beams	6 x 6 x 30-inch Beams	3 x 6-in. Cylinders	6 x 12-in. Cylinders	6-in. Rings	12-in. Rings
C1-6	0.6	1	1	--	--	5380	--	867	890	--	580	923	715
			2	--	--	5250	--	794	900	--	580	936	767
			3	--	--	5250	--	832	860	--	580	806	741
			Avg	--	--	5295	--	831	883	--	580	888	741
C1-6	0.6	2	1	--	--	5360	--	725	820	--	640	845	819
			2	--	--	5450	--	859	850	--	650	806	780
			3	--	--	5590	--	796	780	--	790	858	--
			Avg	--	--	5455	--	793	817	--	693	836	800
C1-6	0.6	3	1	--	--	5670	--	841	920	--	580	910	--
			2	--	--	5890	--	774	980	--	610	897	--
			3	--	--	5730	--	867	930	--	610	--	--
			Avg	--	--	5765	--	827	943	--	600	903	--
C1-6	0.6	4	1	--	--	5840	--	895	860	--	560	910	--
			2	--	--	5750	--	866	760	--	630	845	--
			3	--	--	5770	--	812	790	--	570	910	--
			Avg	--	--	5785	--	857	803	--	587	888	--
C1-7	0.7	1	1	--	--	4410	--	764	780	--	470	728	637
			2	--	--	4380	--	715	740	--	430	793	715
			3	--	--	4460	--	650	795	--	460	793	--
			Avg	--	--	4415	--	710	772	--	453	771	676

(Continued)

TABLE 2 (CONTINUED)

Mixture	Water-Cement Ratio	Round No.	Specimen No.	Compressive Strength, psi			Briquette Strength psi	Flexural Strength, psi		Splitting Strength, psi		Ring Strength, psi	
				2-in. Cubes	3 x 6-in. Cylinders	6 x 12-in. Cylinders		3 1/4 x 4 1/4 x 16-inch Beams	6 x 6 x 30-inch Beams	3 x 6-in. Cylinders	6 x 12-in. Cylinders	6-in. Rings	12-in. Rings
Cl-7	0.7	2	1	--	--	4370	--	715	830	--	490	962	858
			2	--	--	4590	--	579	800	--	480	715	780
			3	--	--	4460	--	630	800	--	500	845	689
			Avg	--	--	4473	--	641	810	--	490	841	776
Cl-7	0.7	3	1	--	--	4300	--	606	730	--	450	806	624
			2	--	--	4680	--	670	660	--	460	754	676
			3	--	--	4250	--	616	660	--	510	--	728
			Avg	--	--	4410	--	631	683	--	473	780	676
Cl-8	0.8	1	1	--	--	3240	--	614	680	--	430	728	546
			2	--	--	3240	--	638	650	--	430	676	572
			3	--	--	3240	--	632	660	--	420	--	--
			Avg	--	--	3240	--	628	663	--	427	702	559
Cl-8	0.8	2	1	--	--	3240	--	616	620	--	420	650	429
			2	--	--	3210	--	620	640	--	420	676	538
			3	--	--	3110	--	579	670	--	420	624	468
			Avg	--	--	3190	--	605	643	--	420	650	478
Cl-8	0.8	3	1	--	--	3120	--	668	590	--	410	611	481
			2	--	--	3170	--	646	690	--	400	624	--
			3	--	--	3110	--	642	610	--	360	598	--
			Avg	--	--	3130	--	652	630	--	390	611	481

(Continued)

TABLE 2 (CONTINUED)

Mixture	Water-Cement Ratio	Round No.	Specimen No.	Compressive Strength, psi			Briquette Strength psi	Flexural Strength, psi		Splitting Strength, psi		Ring Strength, psi	
				2-in. Cubes	3 x 6-in. Cylinders	6 x 12-in. Cylinders		3½ x 4½ x 16-inch Beams	6 x 6 x 30-inch Beams	3 x 6-in. Cylinders	6 x 12-in. Cylinders	6-in. Rings	12-in. Rings
C2-4	0.4	1	1	--	--	9050	--	--	990	--	720	--	936
			2	--	--	8800	--	--	1030	--	750	--	975
			3	--	--	8910	--	--	1040	--	740	--	845
			Avg	--	--	8920	--	--	1020	--	737	--	919
C2-4	0.4	2	1	--	--	7790	--	--	960	--	760	--	650
			2	--	--	8210	--	--	950	--	700	--	650
			3	--	--	8430	--	--	900	--	760	--	806
			Avg	--	--	8145	--	--	937	--	740	--	702
C2-4	0.4	3	1	--	--	8660	--	--	990	--	800	--	819
			2	--	--	8210	--	--	1030	--	640	--	728
			3	--	--	8270	--	--	940	--	800	--	832
			Avg	--	--	8380	--	--	987	--	747	--	793
C2-5	0.5	1	1	--	--	6980	--	--	940	--	620	--	702
			2	--	--	7140	--	--	890	--	590	--	728
			3	--	--	7170	--	--	950	--	580	--	728
			Avg	--	--	7095	--	--	927	--	597	--	719
C2-5	0.5	2	1	--	--	7300	--	--	820	--	650	--	754
			2	--	--	7140	--	--	800	--	630	--	728
			3	--	--	7180	--	--	840	--	630	--	676
			Avg	--	--	7205	--	--	820	--	637	--	719

(Continued)

TABLE 2 (CONTINUED)

Mixture	Water-Cement Ratio	Round No.	Specimen No.	Compressive Strength, psi			Briquette Strength psi	Flexural Strength, psi		Splitting Strength, psi		Ring Strength, psi	
				2-in. Cubes	3 x 6-in. Cylinders	6 x 12-in. Cylinders		3½ x 4½ x 16-inch Beams	6 x 6 x 30-inch Beams	3 x 6-in. Cylinders	6 x 12-in. Cylinders	6-in. Rings	12-in. Rings
C2-5	0.5	3	1	--	--	7080	--	--	880	--	660	--	845
			2	--	--	7130	--	--	840	--	730	--	832
			3	--	--	7320	--	--	920	--	600	--	858
			Avg	--	--	7175	--	--	880	--	663	--	845
C2-6	0.6	1	1	--	--	5440	--	--	750	--	600	--	676
			2	--	--	5250	--	--	770	--	600	--	650
			3	--	--	5430	--	--	780	--	480	--	702
			Avg	--	--	5375	--	--	767	--	560	--	676
C2-6	0.6	2	1	--	--	5370	--	--	820	--	520	--	572
			2	--	--	5770	--	--	770	--	520	--	715
			3	--	--	5520	--	--	790	--	500	--	728
			Avg	--	--	5555	--	--	793	--	513	--	672
C2-6	0.6	3	1	--	--	5910	--	--	800	--	590	--	780
			2	--	--	5910	--	--	780	--	600	--	715
			3	--	--	5550	--	--	780	--	620	--	754
			Avg	--	--	5790	--	--	787	--	603	--	750
C2-7	0.7	1	1	--	--	4590	--	--	690	--	500	--	728
			2	--	--	4610	--	--	720	--	480	--	624
			3	--	--	4640	--	--	660	--	510	--	676
			Avg	--	--	4613	--	--	690	--	497	--	676

TABLE 3. SUMMARY OF RING PORTION DATA

6-in. Rings											
Mixture Number	Round No.	Ring No.	Ring Weight, lb	Tensile Strength, psi	Number of Breaks	Angle between Breaks, Degrees					
M4	1	1	4.56	1001	5	12,	100,	83,	98,	67	
		2	4.57	1019	5	34,	74,	86,	86,	80	
		3	4.54	1079	5	39,	52,	86,	87,	96	
	2	1	4.52	910	6	47,	88,	59,	49,	64,	52
		2	4.49	910	5	27,	81,	90,	88,	74	
		3	4.46	1019	5	44,	107,	87,	71,	51	
	3	1	4.58	832	5	49,	62,	88,	87,	74	
		2	4.56	1118	5	37,	75,	86,	79,	83	
		3	4.58	1014	6	44,	59,	68,	43,	69,	77
M5	1	1	4.46	871	5	30,	79,	103,	88,	60	
		2	4.50	806	4	77,	96,	110,	77		
		3	4.50	897	5	45,	88,	78,	82,	57	
	2	1	4.47	876	5	43,	81,	84,	81,	71	
		2	4.52	962	4	79,	88,	100,	93		
M6	1	1	-	949	5	43,	72,	82,	94,	69	
		2	-	962	5	52,	57,	89,	57,	105	
	2	1	4.43	819	6	30,	37,	38,	96,	84,	75
		2	4.56	806	5	40,	72,	108,	76,	64	
		3	4.54	858	5	31,	76,	102,	87,	64	
	3	1	4.54	819	6	42,	79,	56,	48,	78,	57
		2	4.53	858	5	30,	90,	84,	77,	79	
		3	4.54	845	5	41,	94,	91,	75,	59	
	M7	1	1	4.50	767	4	85,	90,	91,	94	
			2	4.54	806	5	49,	102,	72,	81,	56
			3	4.53	728	4	40,	142,	100,	78	
2		1	4.51	767	5	32,	72,	88,	89,	79	
		2	4.48	689	4	81,	100,	84,	95		
		3	4.50	754	4	89,	83,	92,	96		
3		1	4.48	715	6	35,	42,	45,	111,	69,	58
		2	4.51	676	4	78,	92,	78,	112		
		3	4.44	650	5	49,	45,	76,	91,	99	

(Continued)

TABLE 3 (CONTINUED)

6-in. Rings										
Mixture Number	Round No.	Ring No.	Ring Weight, lb	Tensile Strength, psi	Number of Breaks	Angle between Breaks, Degrees				
M8	1	1	4.45	637	5	50,	54,	92,	80,	84
		2	4.49	663	5	38,	81,	87,	88,	66
	2	1	4.47	533	5	59,	88,	57,	59,	97
		2	4.45	663	5	32,	71,	103,	91,	63
		3	4.46	507	4	71,	104,	80,	105	
	3	1	4.44	611	5	50,	104,	84,	66,	56
		2	4.44	624	5	37,	79,	74,	91,	79
		3	4.45	629	5	41,	52,	99,	87,	81
	M9	1	1	4.39	585	4	76,	92,	100,	92
2			4.46	624	4	74,	105,	86,	95	
3			4.42	494	4	75,	86,	100,	99	
2		1	4.46	676	5	58,	55,	89,	82,	76
		2	4.58	663	4	73,	88,	115,	84	
3		1	4.46	598	5	44,	96,	89,	82,	49
		2	4.45	611	5	46,	57,	89,	103,	68
		3	4.47	611	5	43,	49,	83,	89,	96
C1-4		1	1	4.88	988	4	76,	95,	78,	111
	2		4.81	962	5	40,	78,	117,	75,	50
	3		4.80	975	6	34,	82,	41,	74,	79, 50
	3	1	4.80	910	5	46,	105,	84,	60,	65
		2	4.78	923	4	83,	112,	86,	79	
		3	4.90	936	5	31,	73	78,	95,	83
	4	1	4.89	897	4	66,	95,	93,	106	
		2	4.83	936	6	42,	43,	82,	84,	51, 58
		3	4.80	845	4	68,	104,	106,	82	
C1-5	1	1	4.80	819	4	81,	92,	85,	102	
		2	4.75	936	4	51,	146,	100,	63	
		3	4.80	832	4	83,	87,	91,	99	
	2	1	4.92	793	5	55,	58,	100,	64,	83
		2	4.89	832	4	71,	101,	112,	76	
		3	4.85	845	4	69,	101,	92,	98	

(Continued)

TABLE 3 (CONTINUED)

6-in. Rings							
Mixture Number	Round No.	Ring No.	Ring Weight, lb	Tensile Strength, psi	Number of Breaks	Angle between Breaks, Degrees	
C1-5	3	1	4.91	884	4	58, 87, 101, 114	
		2	4.92	1066	4	87, 96, 88, 89	
		3	4.95	1105	4	68, 109, 108, 75	
C1-6	1	1	4.79	923	5	40, 83, 86, 44, 107	
		2	4.80	936	4	80, 95, 103, 82	
		3	4.85	806	4	79, 94, 104, 83	
	2	1	4.80	845	4	81, 104, 85, 90	
		2	4.82	806	5	18, 87, 105, 88, 62	
		3	4.79	858	4	81, 93, 95, 91	
	3	1	4.81	910	5	44, 48, 89, 98, 81	
		2	4.78	897	3	113, 114, 133	
	4	1	4.80	910	4	50, 74, 113, 123	
		2	4.79	845	4	73, 104, 102, 81	
		3	4.84	910	4	70, 74, 97, 119	
	C1-7	1	1	4.75	728	4	76, 113, 94, 77
			2	4.77	793	5	30, 77, 67, 97, 89
			3	4.80	793	4	80, 89, 98, 93
		2	1	4.80	962	5	31, 91, 73, 58, 107
			2	4.81	715	5	42, 69, 108, 84, 57
			3	4.79	845	4	63, 94, 110, 93
		3	1	--	806	5	48, 95, 62, 102, 53
			2	--	754	5	30, 69, 75, 104, 82
C1-8		1	1	4.71	728	5	40, 64, 89, 90, 77
			2	4.71	676	4	77, 109, 87, 87
	2	1	4.71	650	6	34, 70, 90, 44, 51, 71	
		2	4.67	676	5	41, 67, 83, 101, 68	
		3	4.71	624	5	48, 83, 81, 85, 63	
	3	1	4.75	611	4	69, 86, 119, 86	
		2	4.82	624	5	38, 97, 67, 109, 49	
		3	4.77	598	5	37, 61, 92, 79, 91	

(Continued).

TABLE 3 (CONTINUED)

Mix- ture No.	Round No.	Ring No.	12-in. Rings		Number of Breaks	Angle between Breaks, Degrees						
			Ring Weight, lb	Tensile Strength, psi								
C1-4	1	1	38.10	728	6	44	70	71	47	77	51	
		2	37.61	715	7	34	40	50	41	84	73	38
		3	37.95	650	6	47	76	67	49	53	68	
	2	1	37.62	897	7	30	30	44	60	36	78	82
		2	37.55	806	7	28	57	57	42	29	58	66
		3	37.95	845	6	40	46	64	60	48	102	
	3	1	38.20	806	7	15	51	41	79	73	45	56
		2	37.61	858	8	21	42	46	49	37	54	79
		3	37.92	923	6	45	45	79	63	55	73	32
	4	1	37.68	767	6	22	90	45	44	97	62	
		2	38.20	923	6	40	49	72	80	55	64	
		3	37.55	689	7	36	80	69	37	60	36	42
C1-5	1	1	37.90	819	6	29	84	38	54	84	71	
		2	38.45	715	6	28	66	60	53	50	103	
		3	38.50	780	7	20	44	81	41	71	66	37
	2	1	38.40	728	6	29	117	42	76	41	55	
		2	38.61	520	4	57	108	89	106			
	3	1	38.85	871	7	18	73	43	52	81	35	58
		2	38.40	871	8	32	40	34	49	37	45	43
		3	38.20	819	7	24	67	58	28	75	36	72
	80											
C1-6	1	1	38.29	715	5	44	95	80	92	47		
		2	38.09	767	6	35	48	35	54	90	98	
		3	38.20	741	6	35	64	78	37	61	85	
	2	1	37.55	819	7	32	35	78	39	48	76	52
		2	38.28	780	4	75	93	89	103			
C1-7	1	1	37.90	637	3	114	115	131				
		2	37.80	715	4	83	95	88	94			
	2	1	38.48	858	6	36	90	67	40	73	54	
		2	37.80	780	6	33	38	40	100	75	74	
		3	38.09	689	5	28	83	94	69	86		

(Continued)

TABLE 3 (CONTINUED)

Mixture Number	Round No.	Ring No.	12-in. Rings			Angle between Breaks, Degrees						
			Ring Weight, lb	Tensile Strength, psi	Number of Breaks							
C1-7	3	1	36.90	624	5	53	95	69	55	88		
		2	36.75	676	6	33	74	65	87	64	37	
		3	37.00	728	6	30	42	46	92	83	67	
C1-8	1	1	36.81	546	4	81	81	95	103			
		2	37.00	572	6	24	75	44	57	81	79	
	2	1	37.52	429	4	71	106	81	102			
		2	37.60	538	4	75	86	105	94			
		3	37.05	468	4	74	90	93	103			
	3	1	37.18	481	5	41	79	95	92	53		
	1	1	38.25	936	8	29	50	41	58	35	42	45 60
		2	37.70	975	5	40	58	96	89	77		
		3	37.95	845	5	41	57	75	82	105		
C2-4	2	1	37.80	650	5	33	72	104	95	56		
		2	38.10	650	5	37	46	90	104	83		
		3	38.25	806	6	45	83	50	47	78	57	
	3	1	39.00	819	5	45	72	71	88	84		
		2	38.70	728	9	32	40	38	48	34	56	34 41
		3	39.00	832	5	27	76	76	94	87		
	1	1	38.60	702	6	41	50	61	80	44	84	
		2	39.00	728	5	47	87	90	82	54		
		3	39.00	728	5	56	77	64	95	68		
C2-5	2	1	38.80	724	6	28	76	80	64	30	82	
		2	39.30	728	6	38	86	70	47	39	80	
		3	39.60	676	5	41	91	72	93	63		
	3	1	39.60	845	7	36	51	41	48	61	46	77
		2	39.50	832	7	31	53	48	48	45	39	96
		3	39.80	858	5	53	79	71	69	88		
	1	1	37.40	676	5	41	73	86	83	77		
		2	37.00	650	4	77	99	96	88			
		3	37.10	702	5	56	61	105	77	61		
C2-6												

(Continued)

TABLE 3 (CONTINUED)

12-in. Rings												
Mixture Number	Round No.	Ring No.	Ring Weight, lb	Tensile Strength, psi	Number of Breaks	Angle between Breaks, Degrees						
C2-6	2	1	36.18	572	4	73	101	91	95			
		2	36.40	715	4	54	94	112	100			
		3	36.90	728	5	37	84	83	82	74		
	3	1	36.30	780	6	20	66	26	80	81	87	
		2	36.87	715	5	42	73	92	105	48		
		3	36.55	754	6	30	64	74	61	45	86	
	C2-7	1	1	39.00	728	5	43	97	87	75	58	
			2	39.20	624	6	38	82	80	40	77	43
			3	38.55	676	5	30	66	74	95	95	
2		1	39.00	676	6	41	62	51	84	78	44	
		2	37.80	611	4	59	71	104	126			
		3	38.50	520	5	35	88	92	87	58		
3		1	37.95	624	5	49	106	50	71	84		
		2	38.75	611	4	64	89	96	111			
		3	39.00	598	5	30	63	108	62	97		
C2-8	1	1	38.30	624	5	44	79	92	85	60		
		2	38.50	546	4	84	85	99	92			
	2	1	39.05	572	6	25	71	83	77	32	72	
		2	39.00	546	4	67	87	100	106			
		3	38.70	390	5	51	71	79	76	83		
	3	1	38.50	338	5	56	62	94	64	84		
		2	38.70	546	4	67	117	98	78			
		3	39.00	546	5	52	73	84	54	97		

TABLE 4--WITHIN-BATCH AND BETWEEN-BATCHES  
COEFFICIENTS OF VARIATION FOR THE M SERIES TESTS

Mix Series	Water- Cement Ratio	No. of Test Batches	Pooled Average Compressive Strength at 28 Days age, psi		Coefficient of Variation, Percent											
			2-in. Cubes	3-x 6-in. Cylinders	Compression Test, 2-in. cubes		Compression Test 3 x 6-in. Cyl.		Direct Briquette Test		Flexure Test 3½ x 4½ x 16-in. Beams		Tensile Split- ting Test 3 x 6-in. Cyl.		Ring Tension Test 6-in. Diameter Rings	
					Within Batch, Avg.	Between Batches	Within Batch, Avg.	Between Batches	Within Batch, Avg.	Between Batches	Within Batch, Avg.	Between Batches	Within Batch, Avg.	Between Batches	Within Batch, Avg.	Between Batches
M	0.4	3	11375	9285	6.3	4.9	2.5	4.4	7.9	1.9	4.3	7.1	5.0	9.7	8.4	4.4
	0.5	3	9185	7855	5.6	10.1	2.6	3.9	9.8	11.1	8.3	4.7	2.1	6.7	6.0*	5.0*
	0.6	3	6780	5835	2.1	5.4	2.4	6.5	7.8	2.2	8.5	9.8	7.5	13.2	2.2	8.0
	0.7	3	5450	4635	1.3	5.4	1.5	1.1	7.8	5.6	6.5	15.4	3.9	11.4	5.2	6.1
	0.8	3	3660	3290	1.8	3.4	3.1	2.1	5.5	3.8	7.0	5.4	8.7	10.5	6.4	6.8
	0.9	3	3295	2825	4.6	7.7	3.2	3.2	6.6	10.1	9.3	6.6	24.3	23.1	4.8	8.4
Avg Values of Coefficient of Variation					3.6	6.2	2.6	3.5	7.6	5.8	7.3	8.2	8.6	12.4	5.5	6.4

(Continued)

\* Calculated using two batches.

(Continued)

TABLE 4 - WITHIN-BATCH AND BETWEEN-BATCHES  
COEFFICIENTS OF VARIATION FOR THE C1 SERIES TESTS

Mix Series	Water- Cement Ratio	No. of Test Batches	Pooled Average Compressive Strength at 28 Days Age, psi 6 x 12-in. Cyls.	Coefficient of Variation, Percent											
				Compression Test		Flexural Test				Tensile		Ring Tension Test			
				6 x 12-in. Cyl.		3½ x 4½ x 16 in. Beams		6 x 6 x 30 in. Beams		Splitting Test 6 x 12-in. Cyl.		6 in.-Dia. Ring		12-in. Dia Ring	
				Within Batch, Avg.	Between Batches	Within Batch, Avg.	Between Batches	Within Batch, Avg.	Between Batches	Within Batch, Avg.	Between Batches	Within Batch, Avg.	Between Batches	Within Batch, Avg.	Between Batches
C1	0.4	4	8640	2.2	1.8	3.4	3.3	3.0	5.1	10.8	4.4	2.6*	4.4*	8.3	9.3
	0.5	3	7520	1.2	3.5	4.3	5.0	3.8	6.8	7.4	7.0	7.4	11.4	11.3	15.5
	0.6	4	5575	1.6	4.3	5.9	3.2	4.1	7.5	5.4	8.6	4.1	3.3	3.5**	5.4**
	0.7	3	4435	2.9	0.8	8.1	6.5	3.9	8.6	4.5	3.9	8.1	4.8	8.9	8.1
	0.8	3	3185	1.0	1.7	2.6	3.7	4.9	2.6	2.7	4.8	3.8	7.0	7.4	9.1
Avg Values of Coefficient of Variation				1.8	2.4	4.9	4.3	3.9	6.1	6.2	5.7	5.2	6.2	7.9	9.5

(Continued)

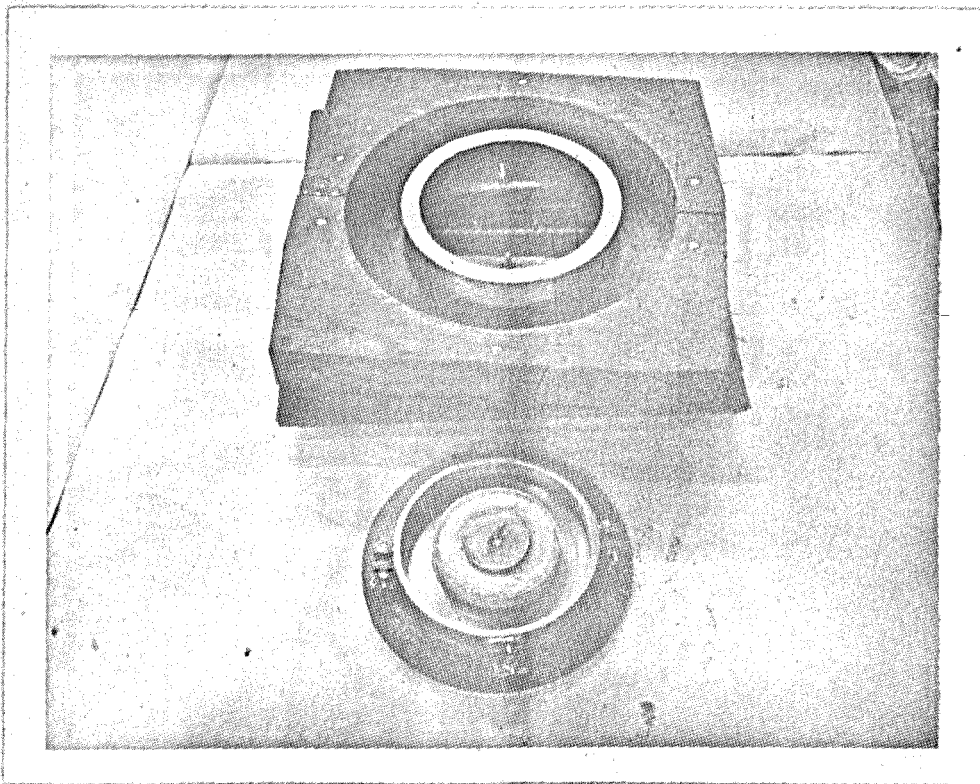
\* Calculated using three batches

\*\* Calculated using two batches

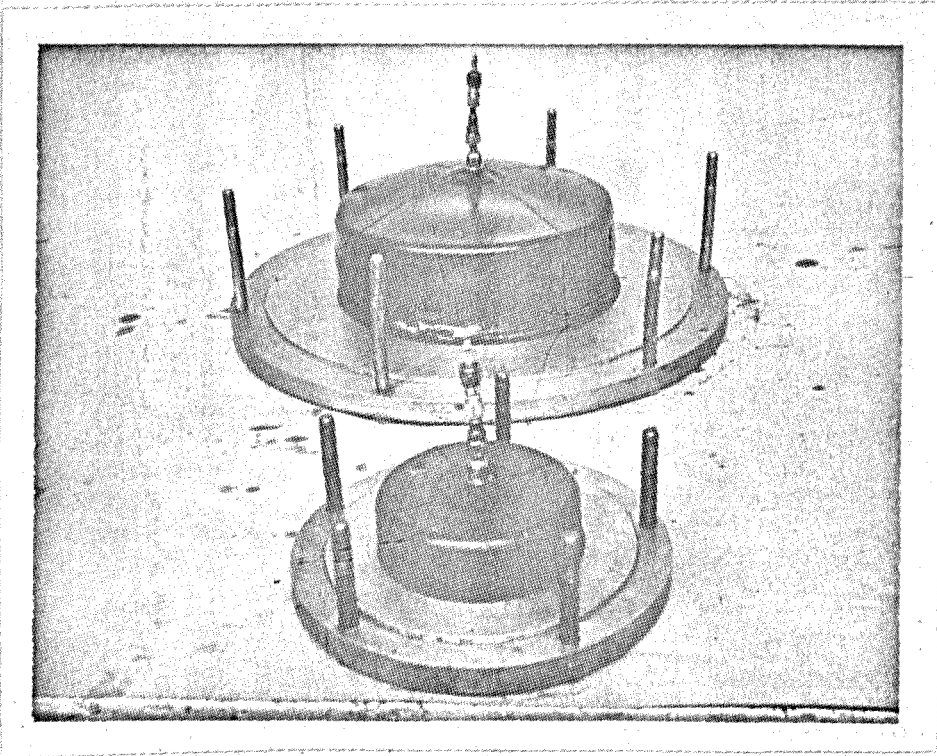
(Continued)

TABLE 4--WITHIN-BATCH AND BETWEEN-BATCHES  
COEFFICIENTS OF VARIATION FOR THE C2 SERIES TESTS

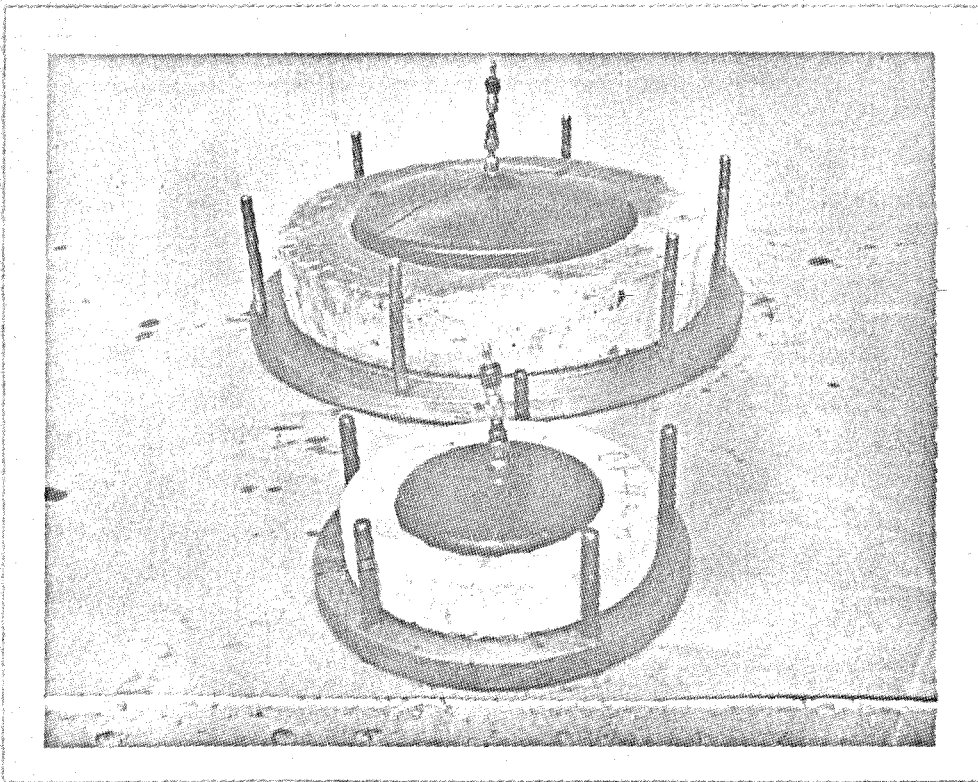
Mix Series	Cement Ratio	Test Batches	Pooled Average Compressive Strength at 28 Days Age, psi 6 x 12-in. Cyl	Coefficient of Variation, Percent							
				Compression Test 6 x 12-in. Cyl.		Flexure Test 6 x 6 x 30-in. Beams		Tensile Splitting Test 6 x 12-in. Cyl		Ring Tension Test 12-in. Dia. Rings	
				Within Batch,	Between Batches	Within Batch,	Between Batches	Within Batch,	Between Batches	Within Batch,	Between Batches
				Avg		Avg		Avg		Avg	
C2	0.4	3	8480	2.8	4.7	3.5	4.2	6.4	0.7	9.1	13.5
	0.5	3	7160	1.4	0.8	3.5	6.1	5.0	5.2	3.0	9.6
	0.6	3	5575	3.1	3.7	2.2	1.7	5.7	8.1	7.0	6.3
	0.7	3	4420	1.2	3.8	4.5	5.2	6.8	2.1	7.6	6.4
	0.8	3	3365	<u>2.6</u>	<u>2.7</u>	<u>1.5</u>	<u>3.2</u>	<u>5.1</u>	<u>3.3</u>	<u>18.1</u>	<u>10.8</u>
Avg Values of Coefficient of Variation				2.2	3.1	3.0	4.1	5.8	3.9	9.0	9.3



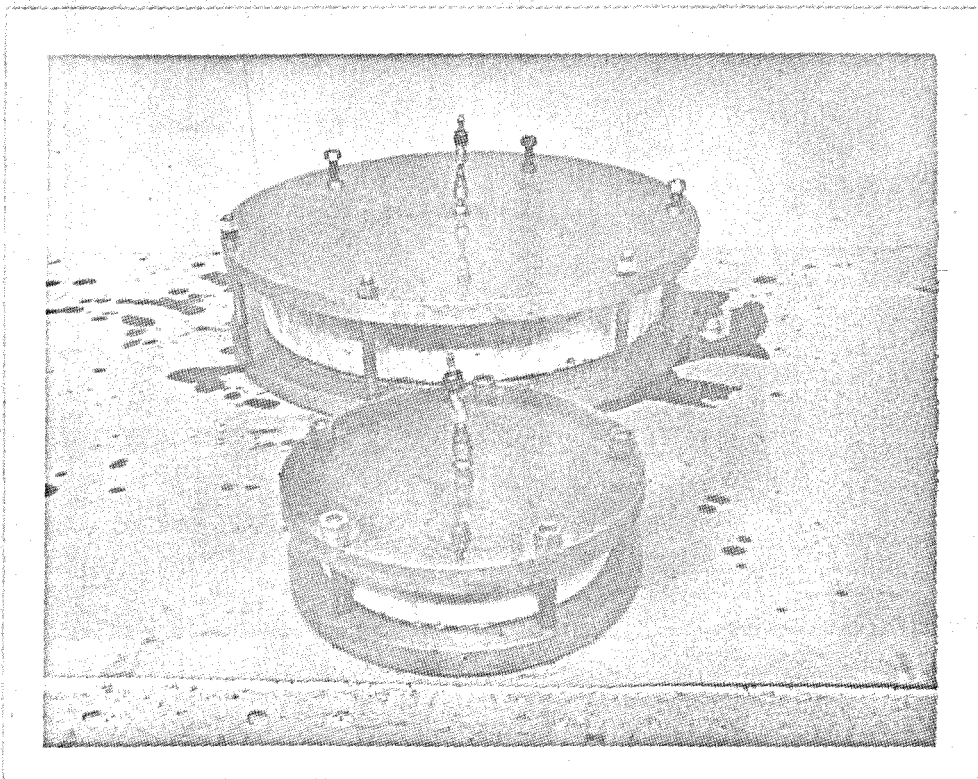
Photograph 1. 6- and 12-in. ring casting molds.



**Photograph 2. Testing jig base plates and loading bladders.**



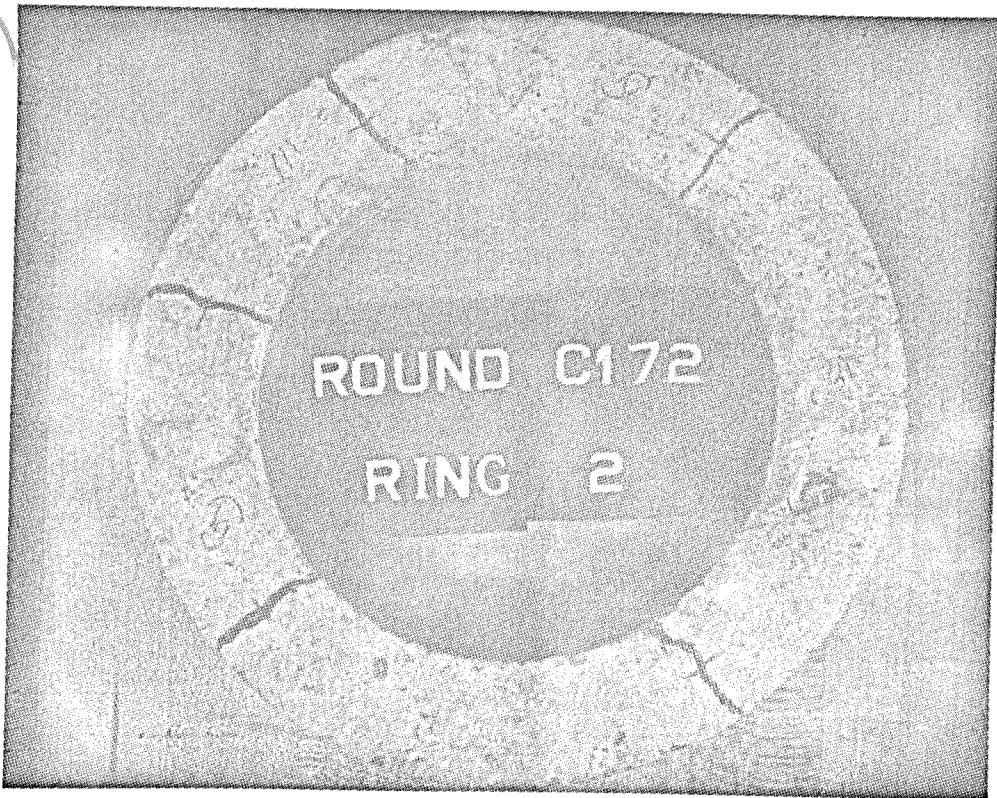
Photograph 3. Concrete rings in testing jigs.



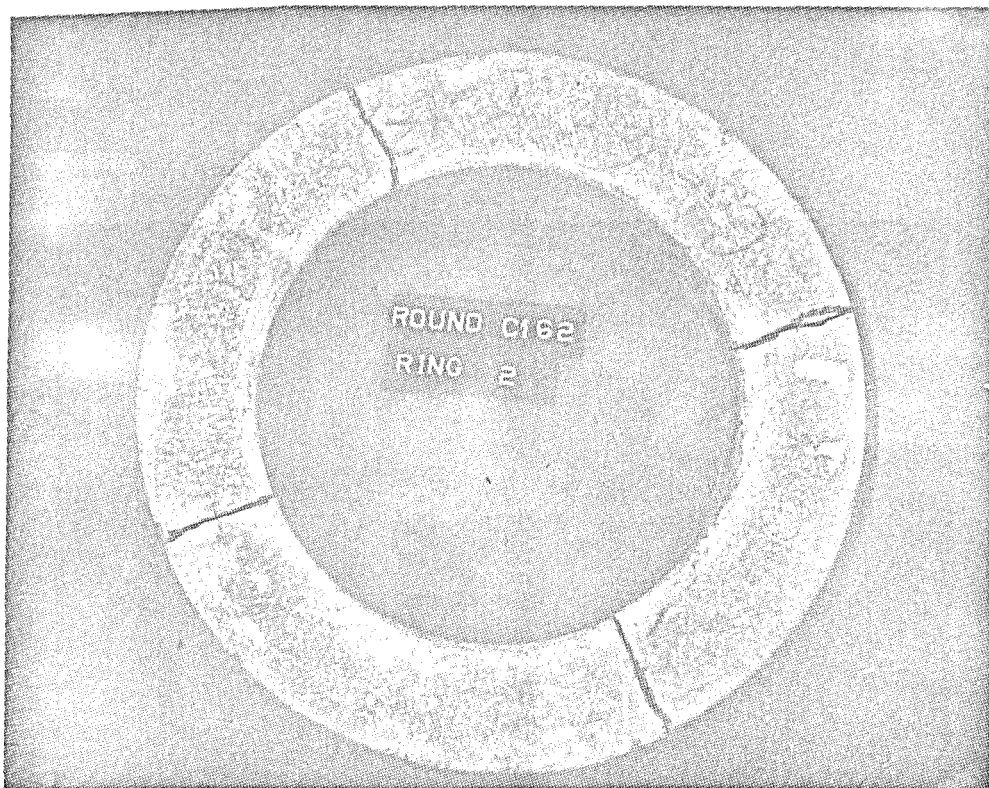
**Photograph 4. Assembled testing jigs.**



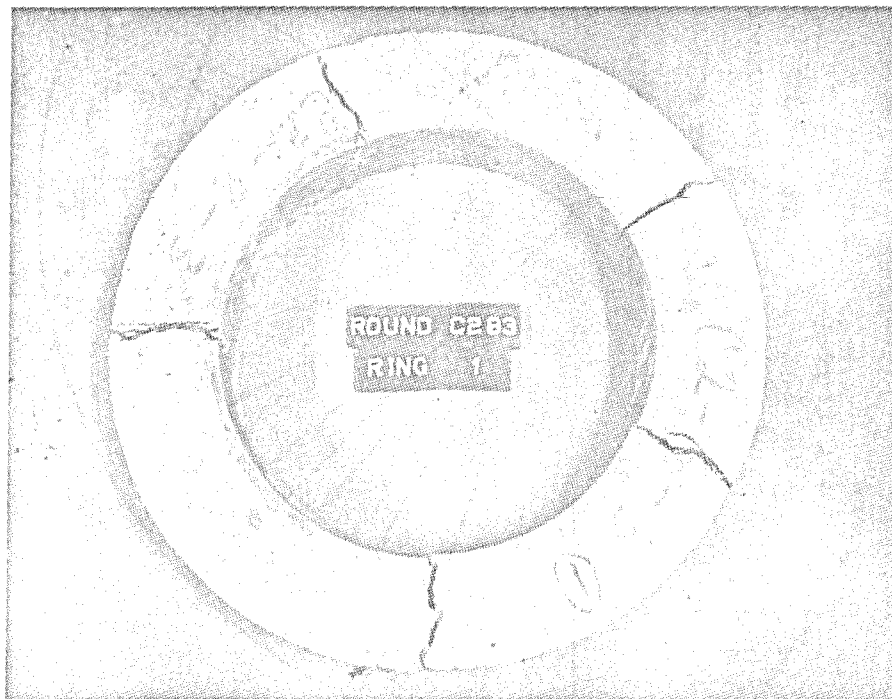
**Photograph 5. Typical failure of 6-in. M series ring.**



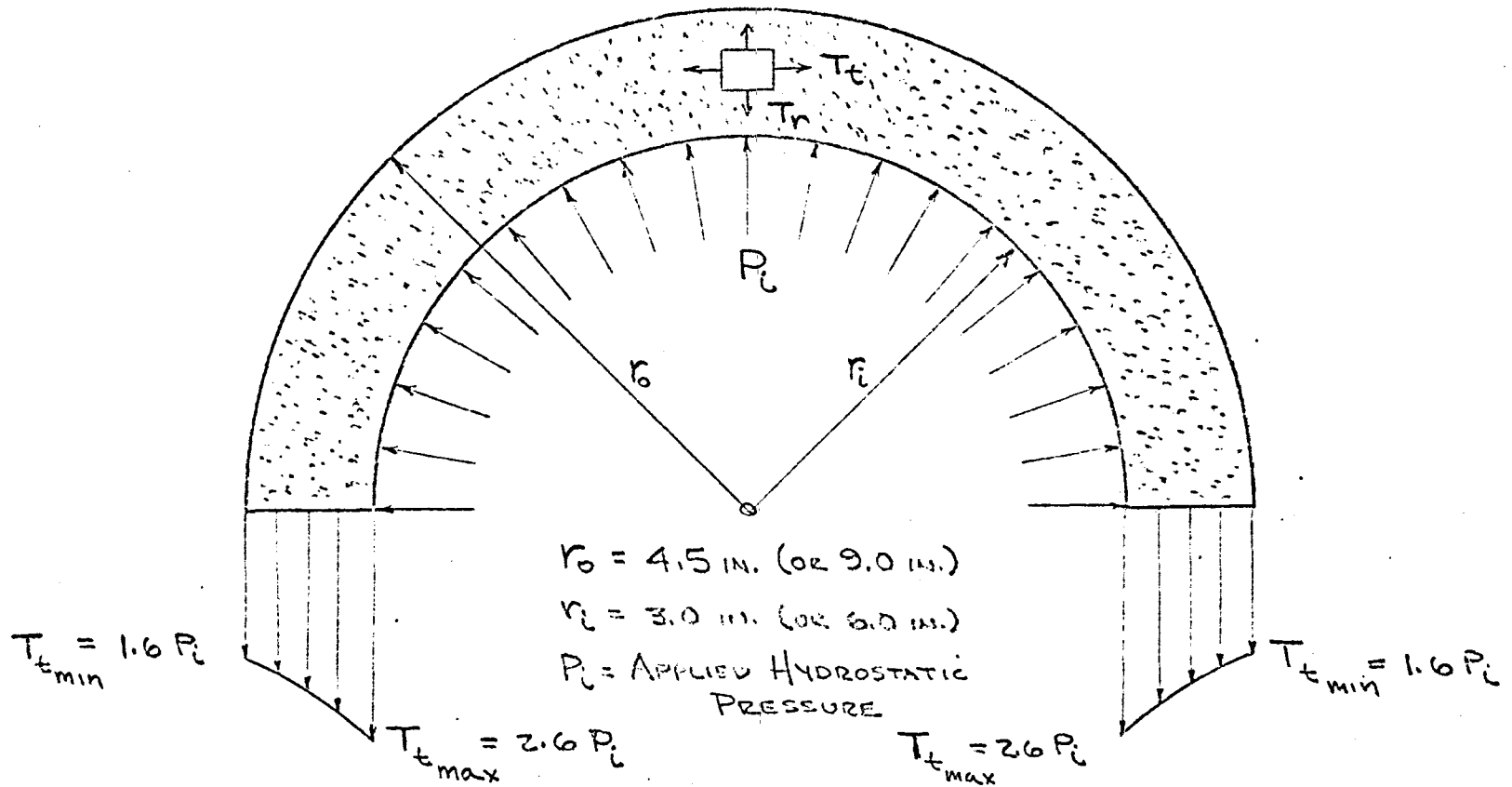
Photograph 6. Typical failure of 6-in. C1 series ring.



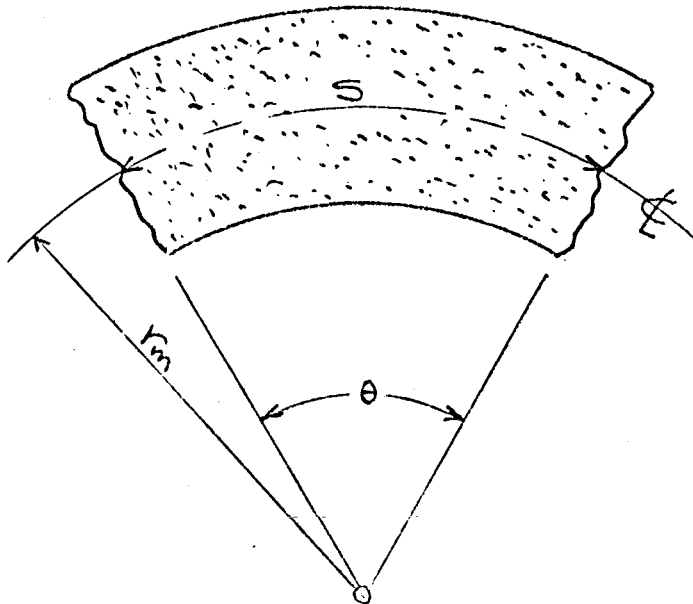
Photograph 7. Typical failure of 12-in. C1 series ring.



Photograph 8. Typical failure of 12-in. C2 series ring.



ASSUMED TANGENTIAL STRESS DISTRIBUTION IN A RING SPECIMEN



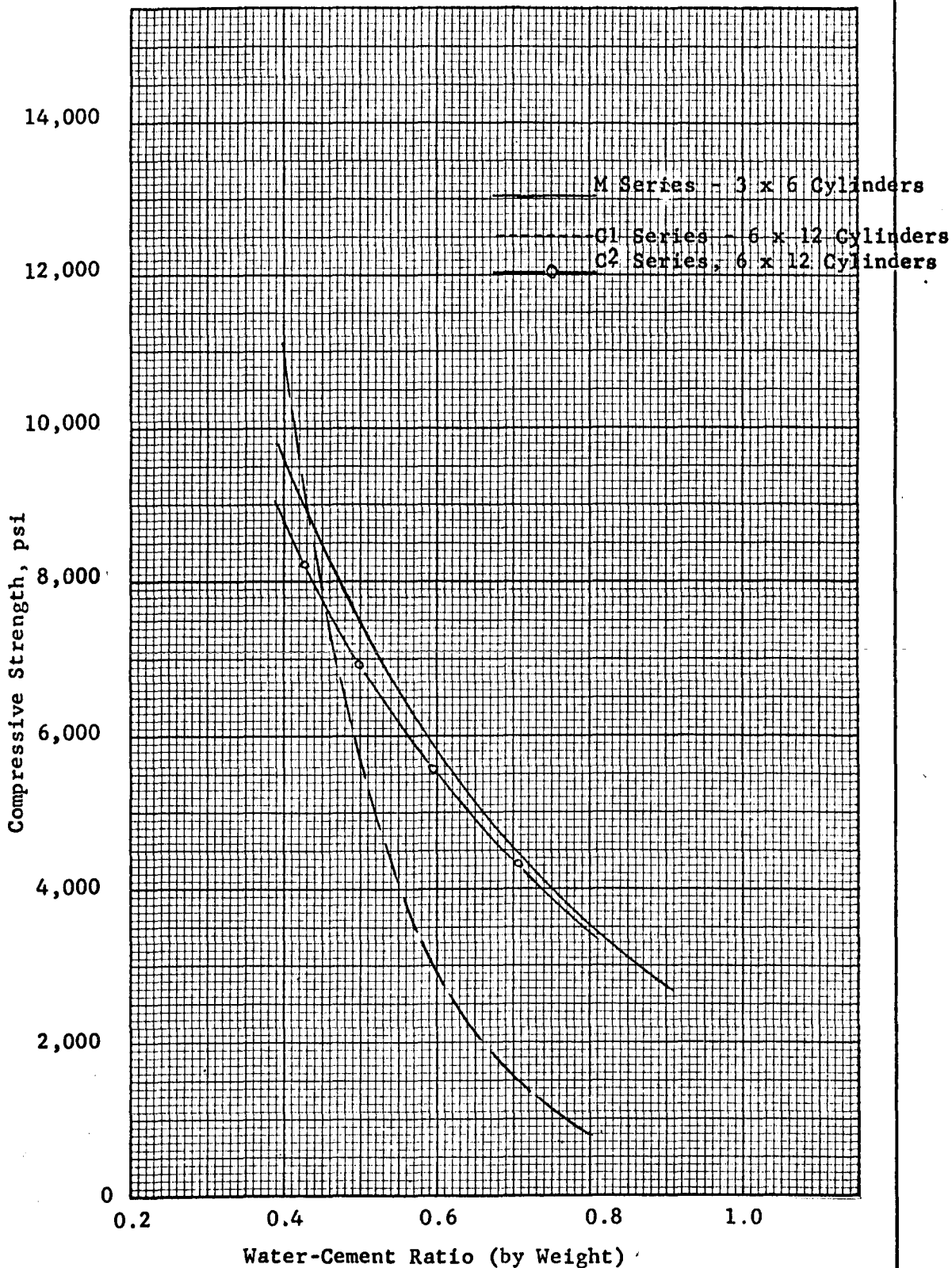
$S$  = ARC LENGTH OF THE CENTERLINE  
OF THE RING PORTION, INCHES

$r_m$  = RADIUS TO THE CENTERLINE OF  
THE RING PORTION, INCHES

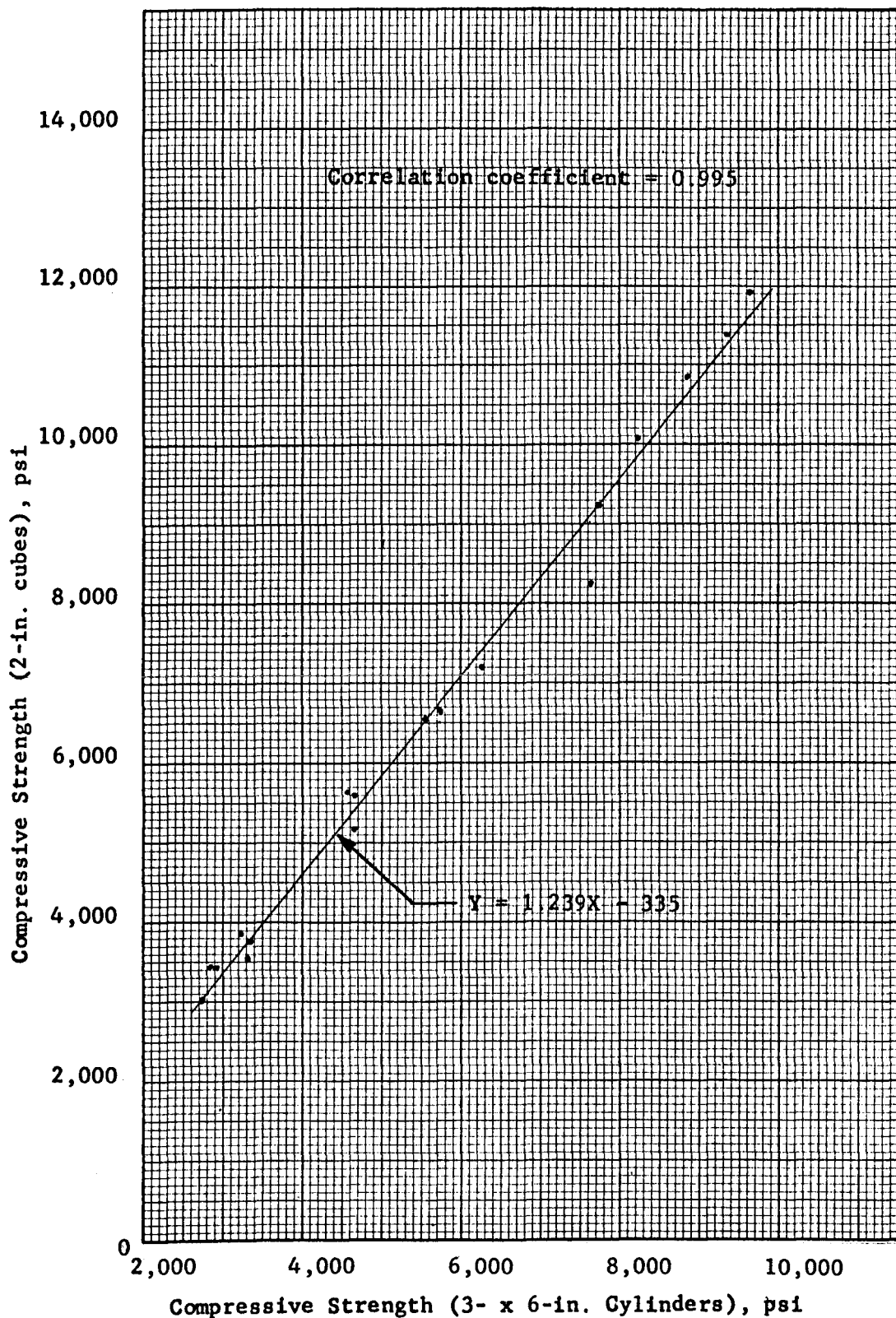
$\theta$  = INTERNAL ANGLE, DEGREES

$$= (57.296) \times \frac{S}{r_m}$$

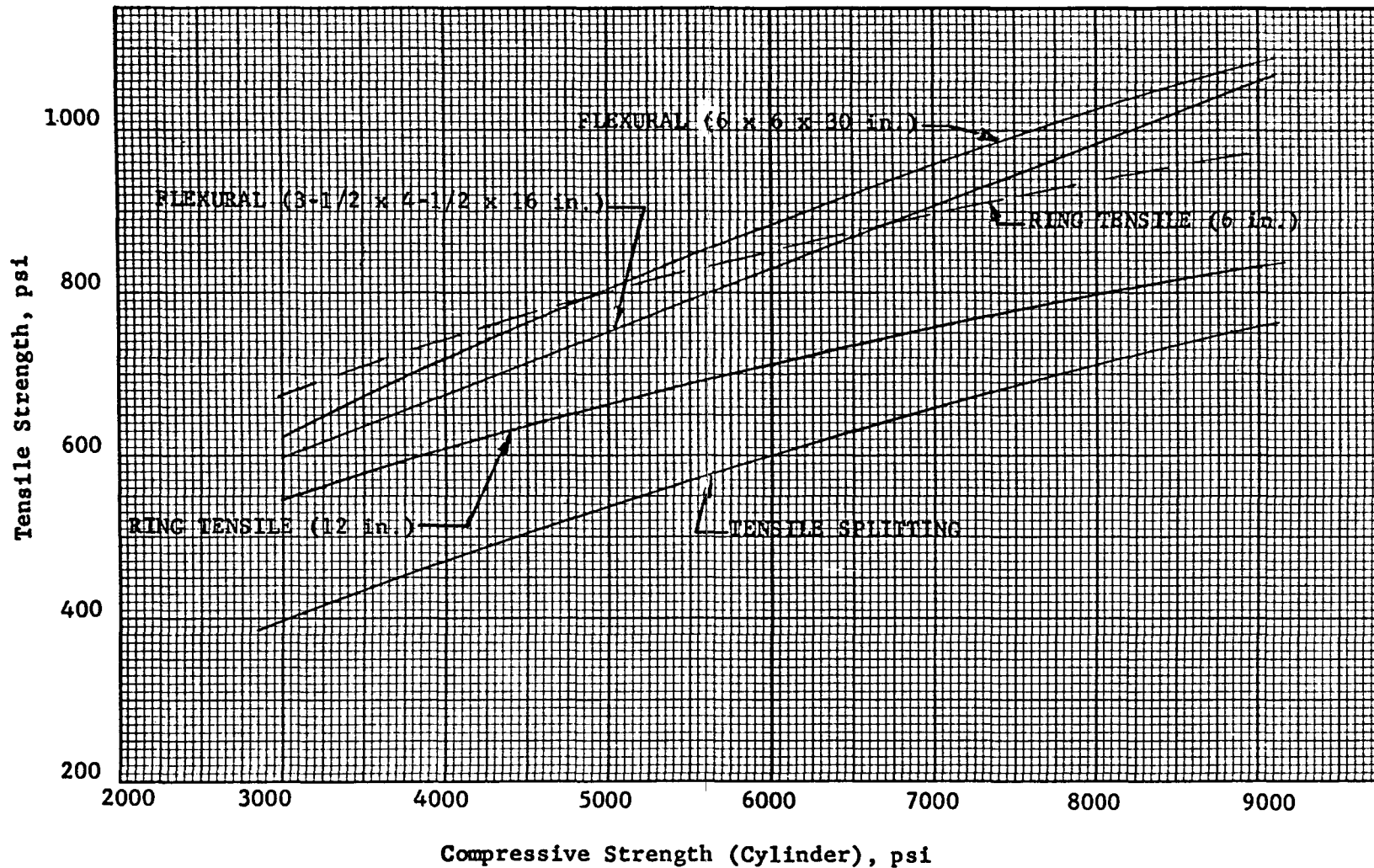
RING PORTION MEASUREMENTS



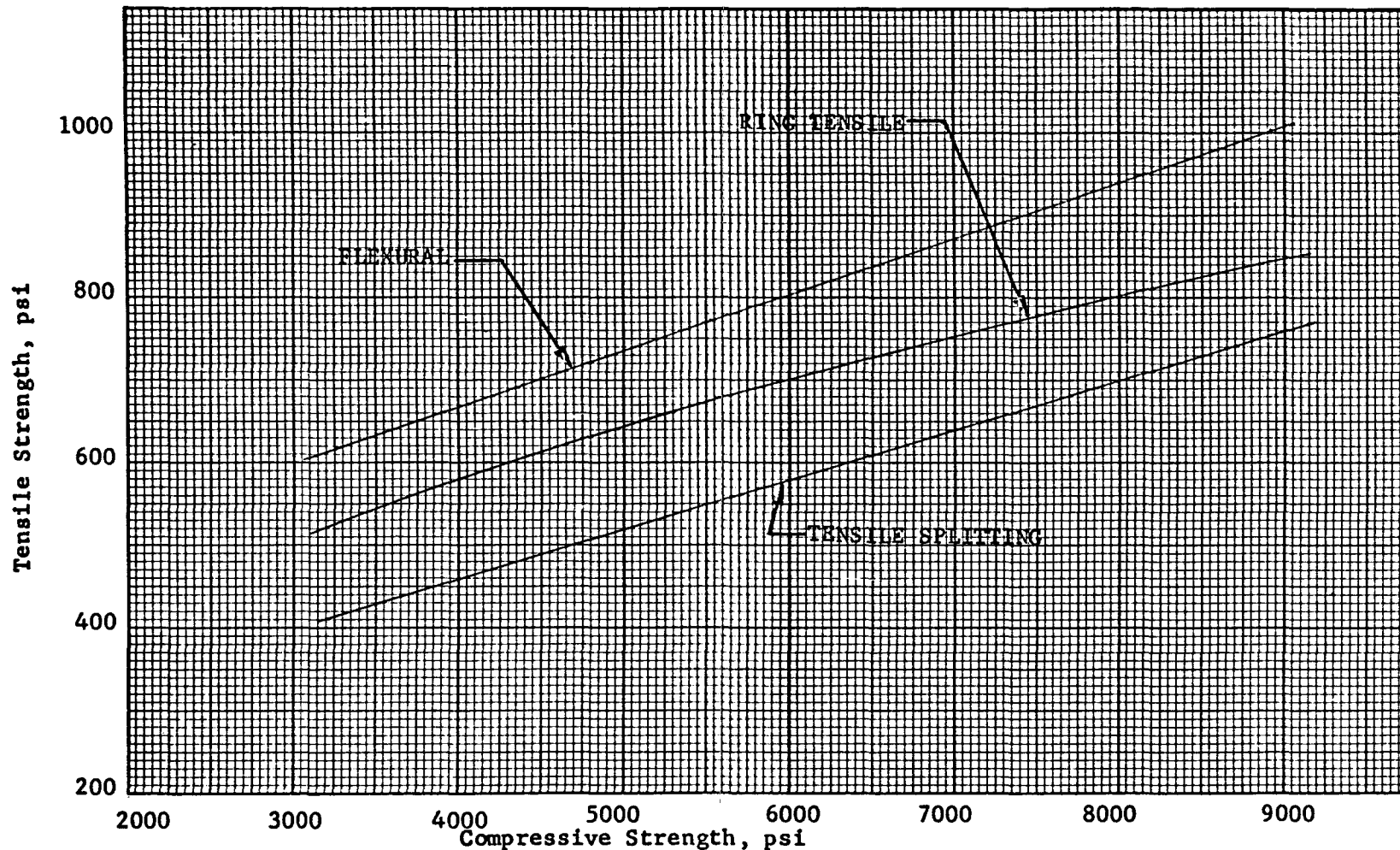
Water-cement ratio vs compressive strength relations for the M, C1, and C2 series cylinders.



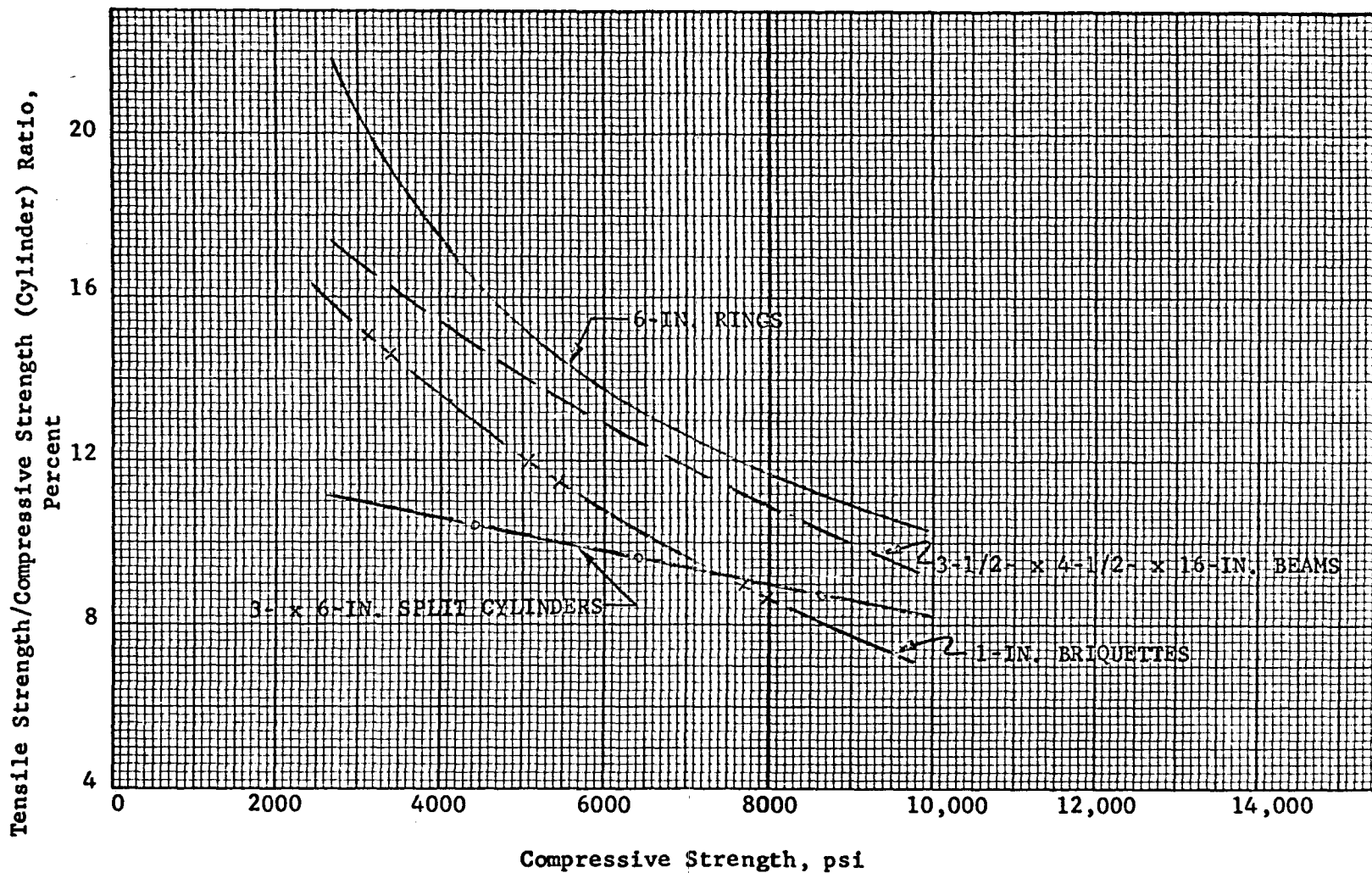
Cylinder strength vs cube strength relation for the M series tests.



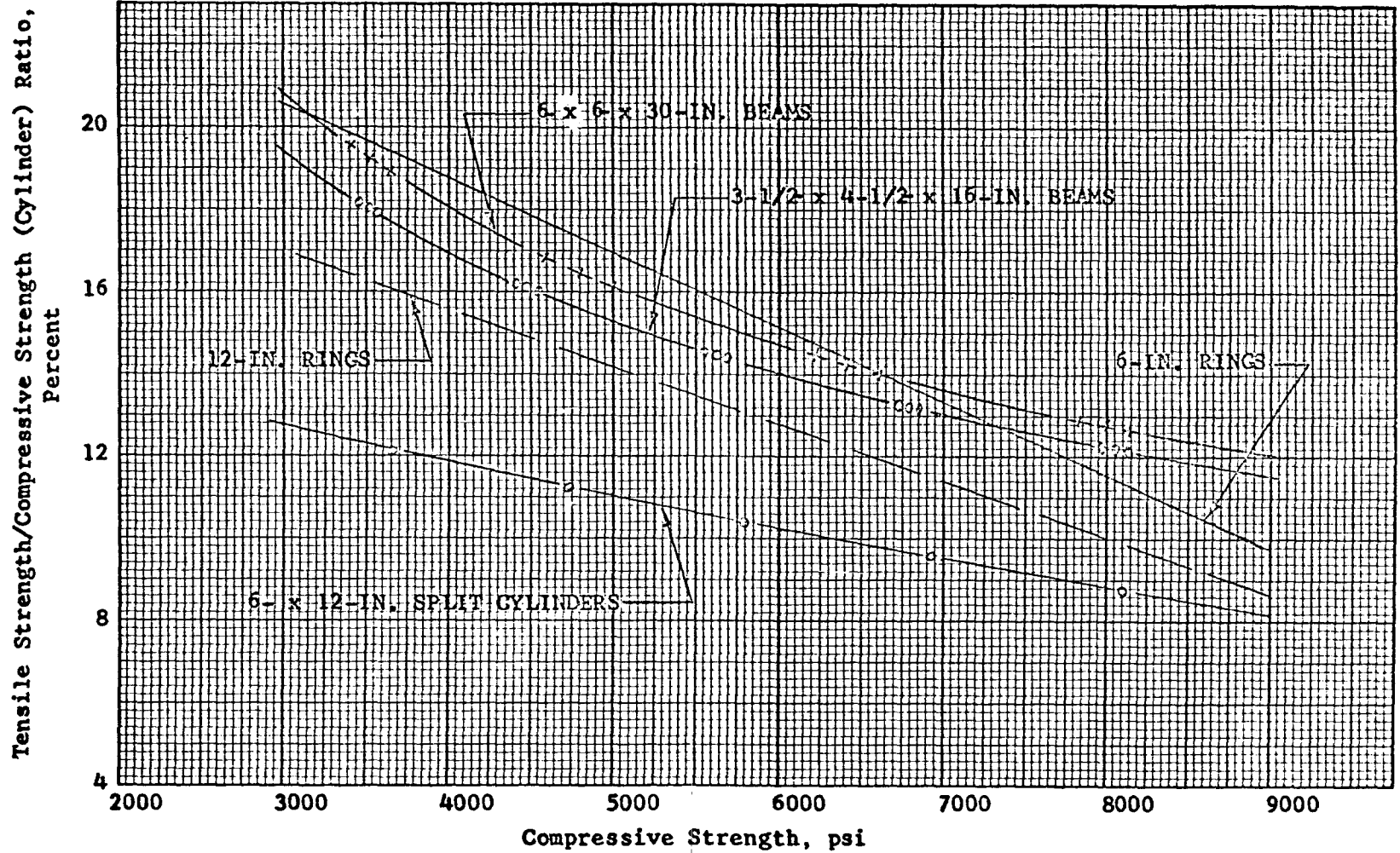
Compressive vs tensile strength relations for CI series tests.



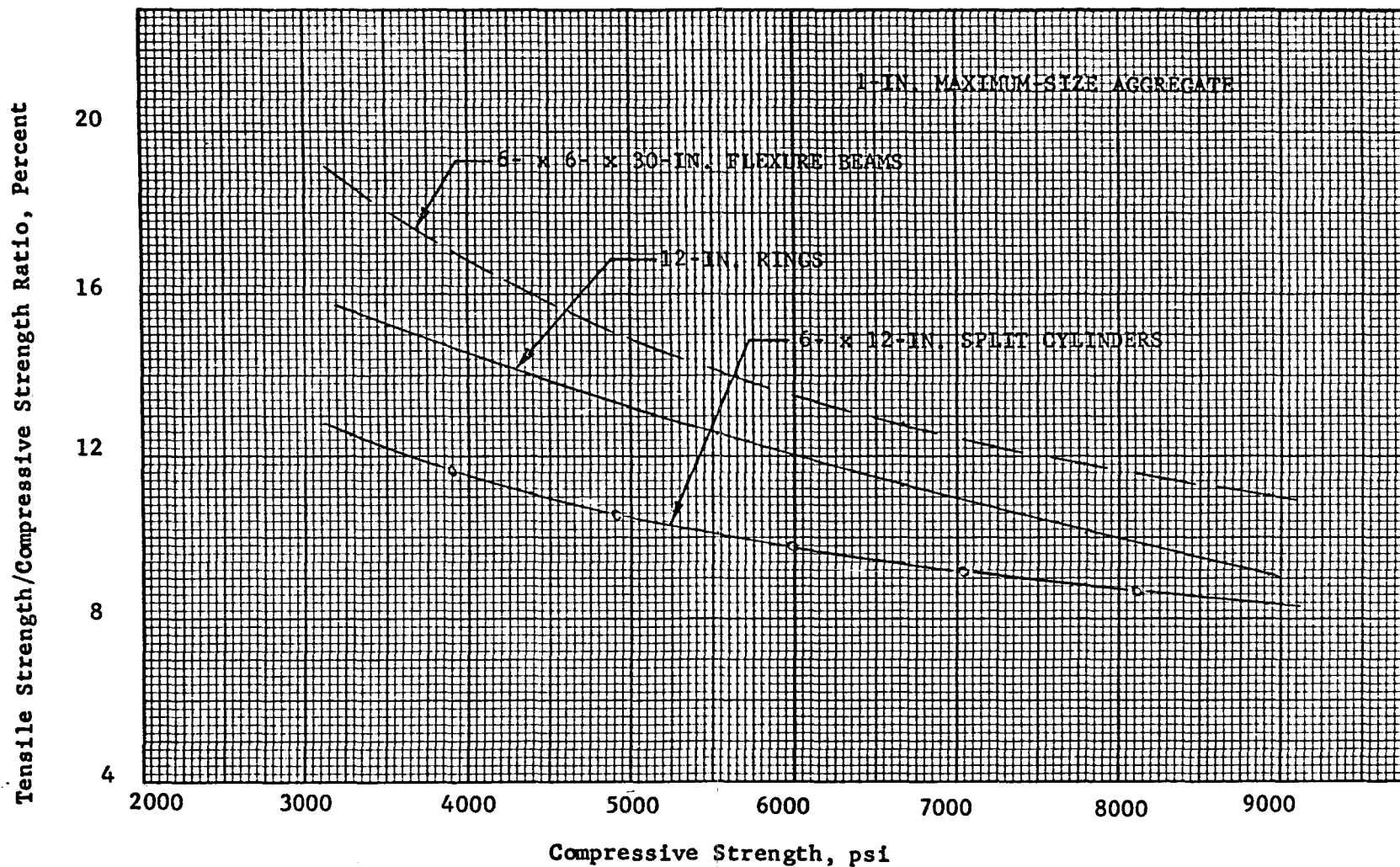
Compressive vs tensile strength relations for the C2 series tests.



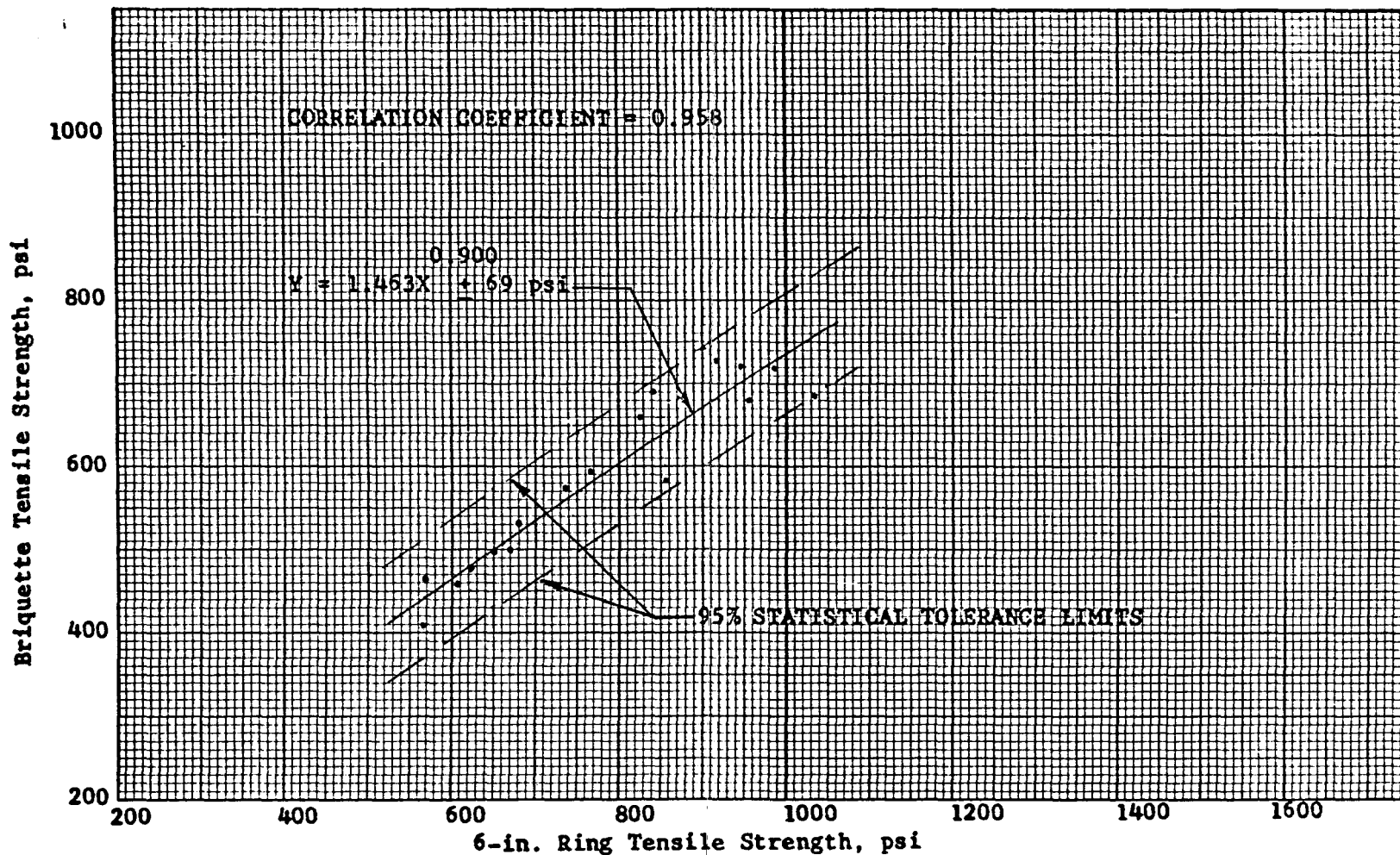
Relation between tensile strength/compressive strength ratio and compressive strength for the M series tests.



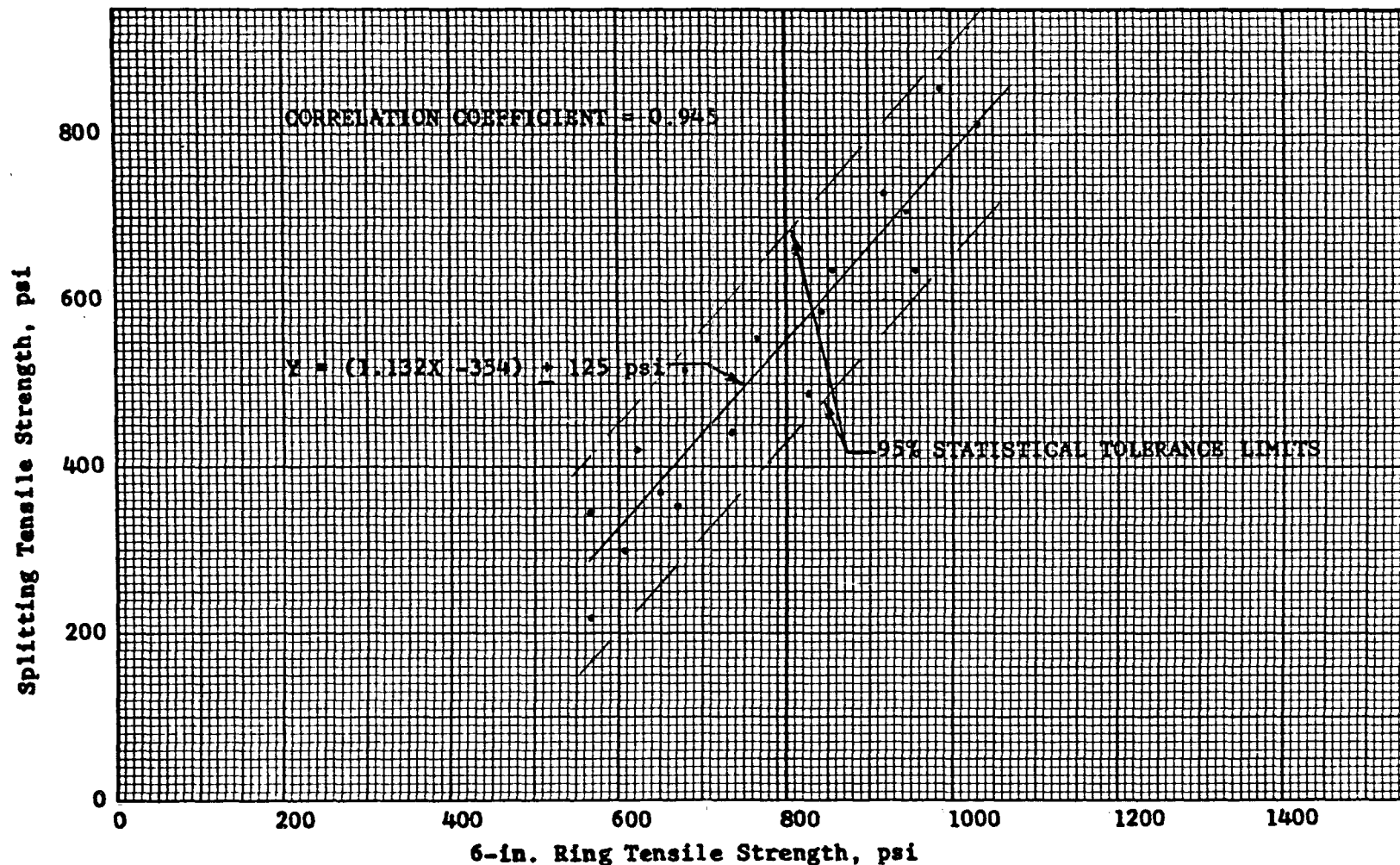
Relation between tensile strength/compressive strength ratio and compressive strength for the C1 series tests.



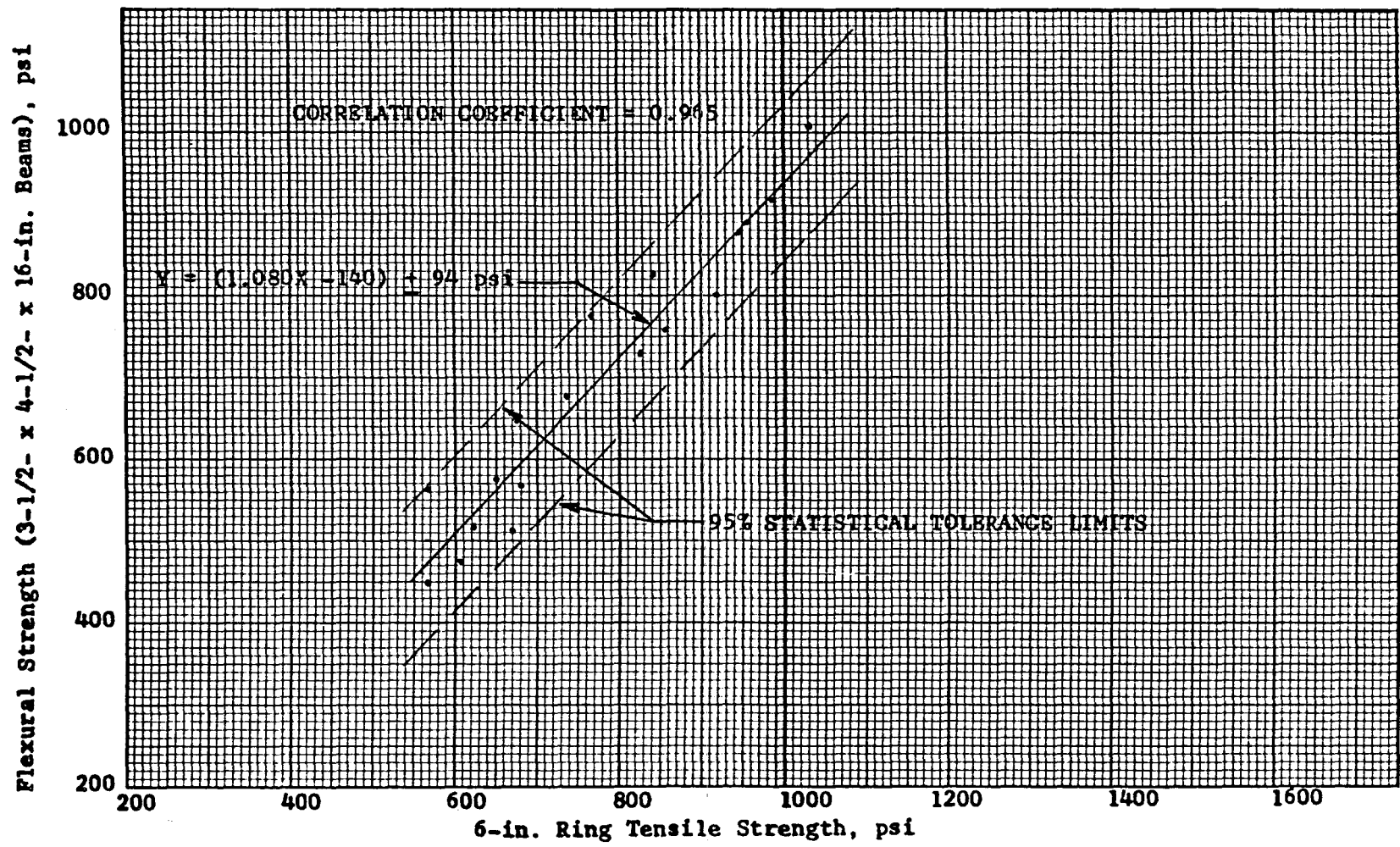
Relation between tensile strength/compressive strength ratio and compressive strength for the C2 series tests.



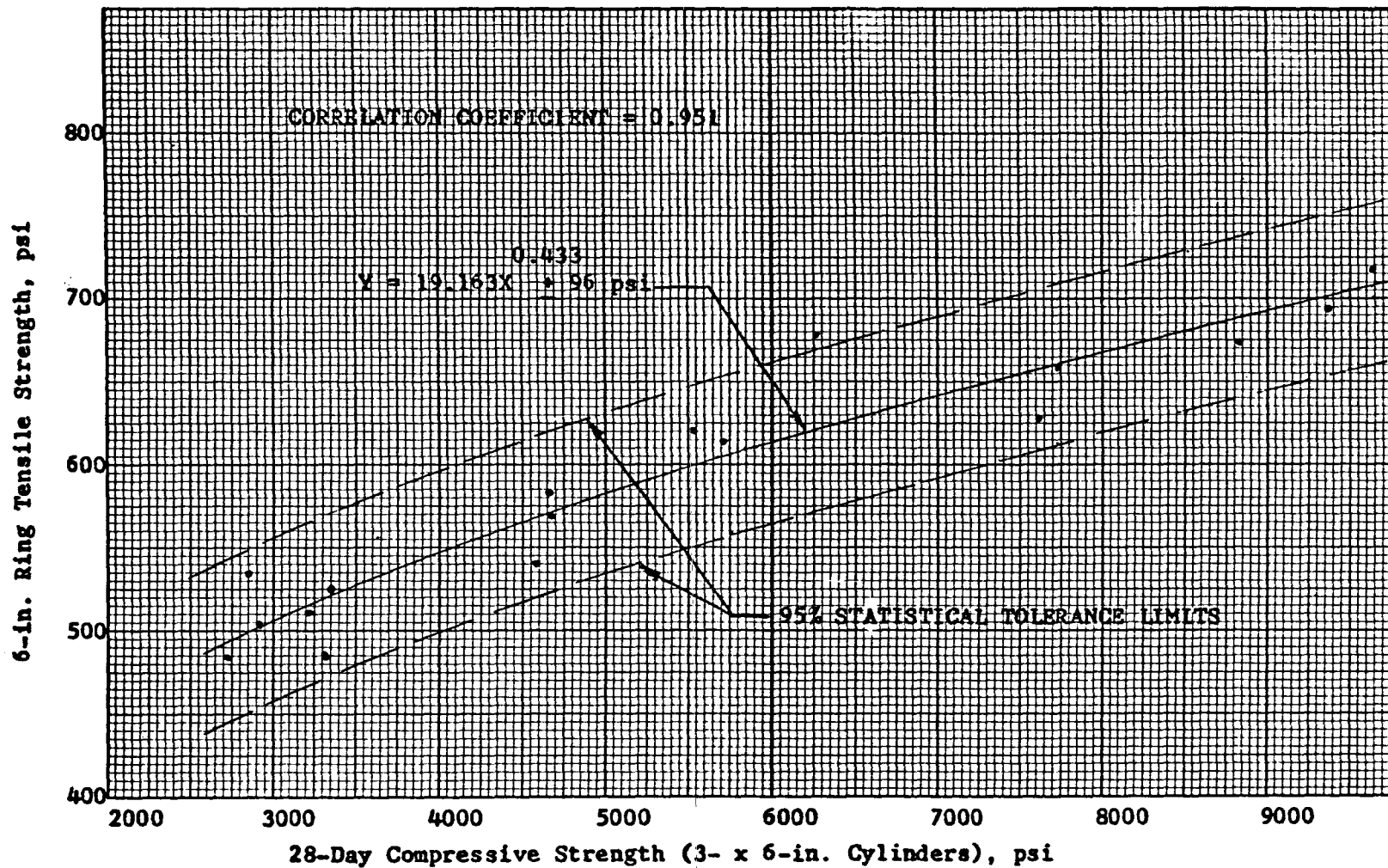
Ring tensile strength vs briquette tensile strength relation for M series test results.



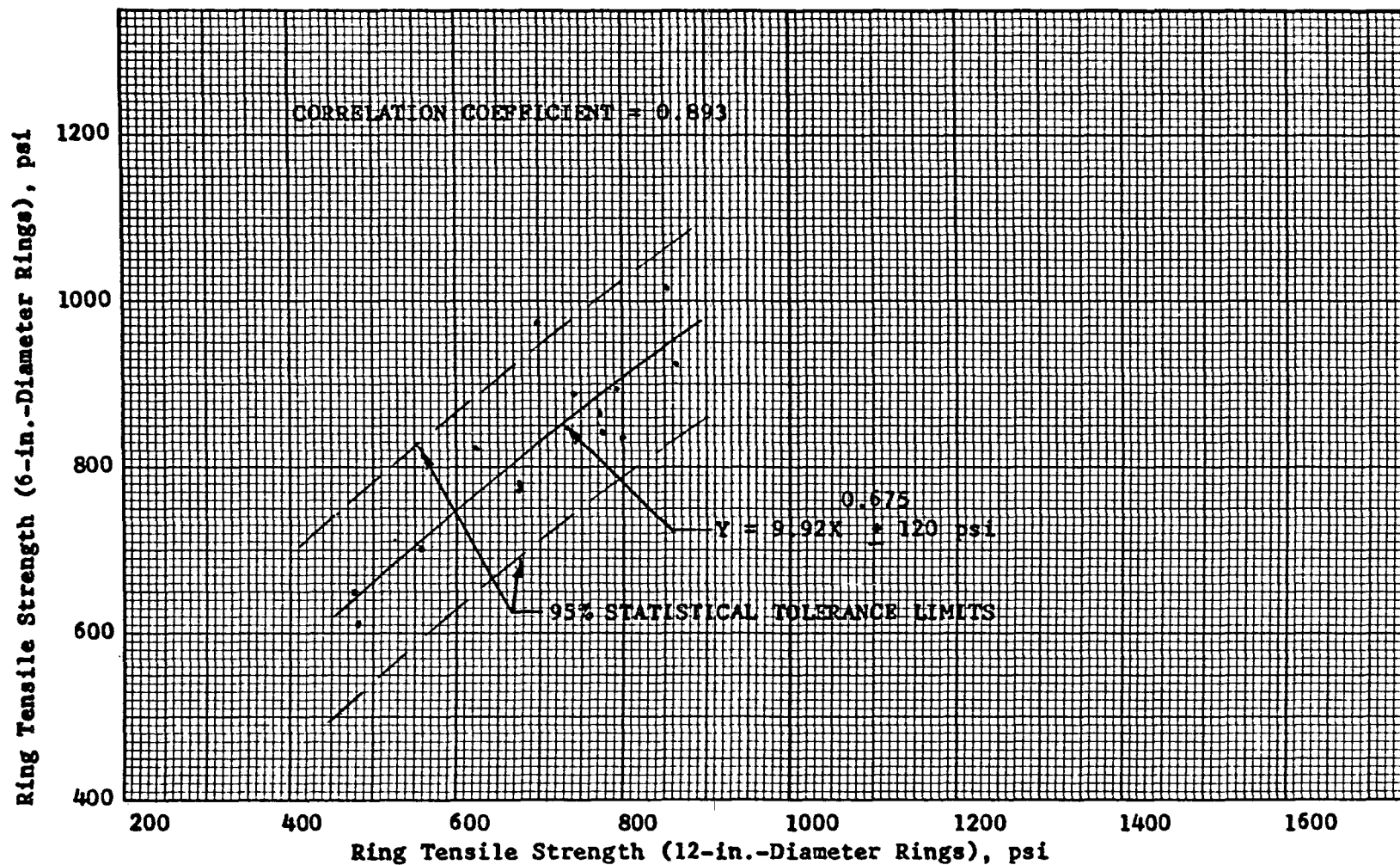
Ring tensile strength vs splitting tensile strength relation for M series test results.



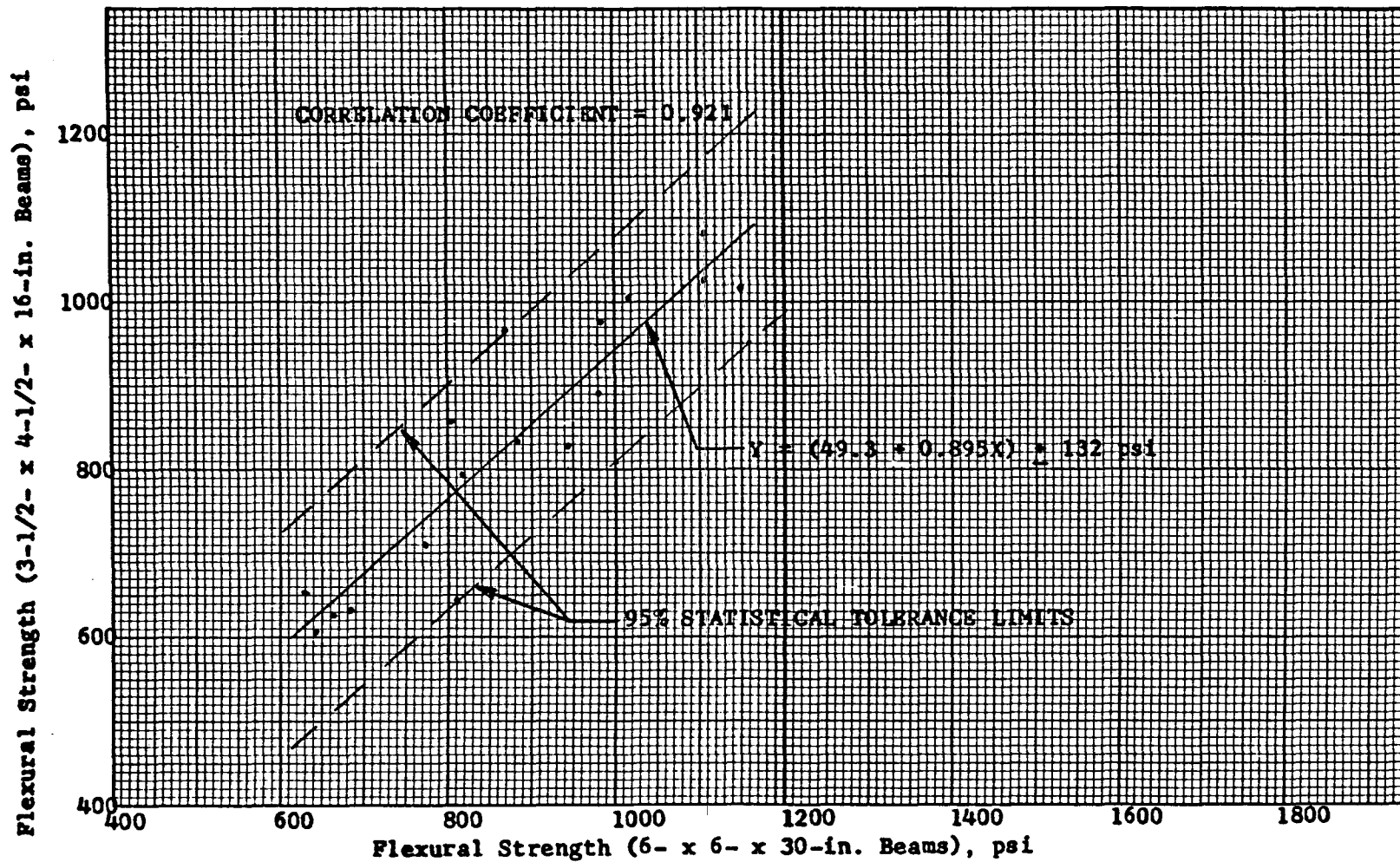
Ring tensile strength vs flexural strength relation for M series test results.



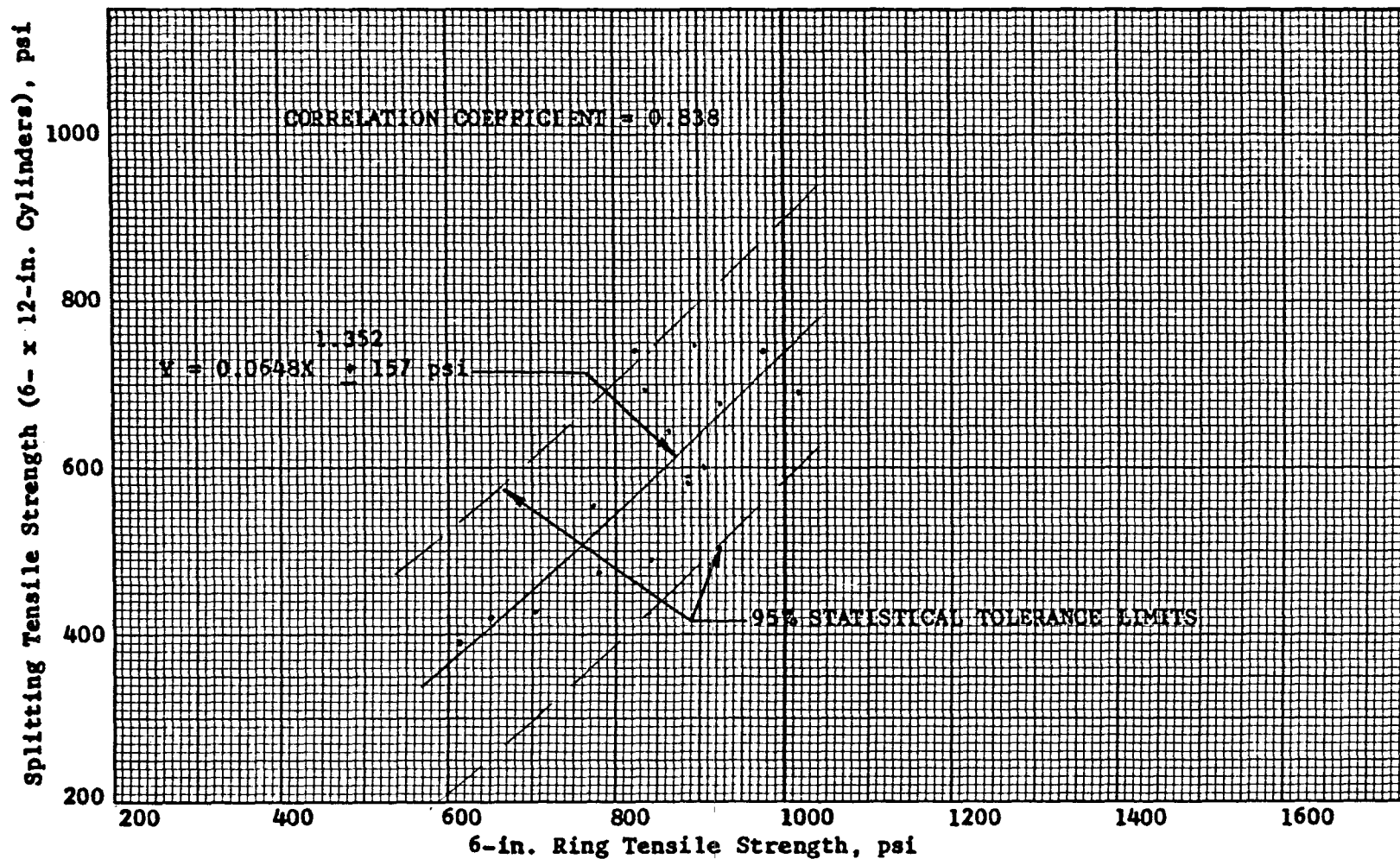
Compressive strength vs 6-in. ring tensile strength relation for M series tests.



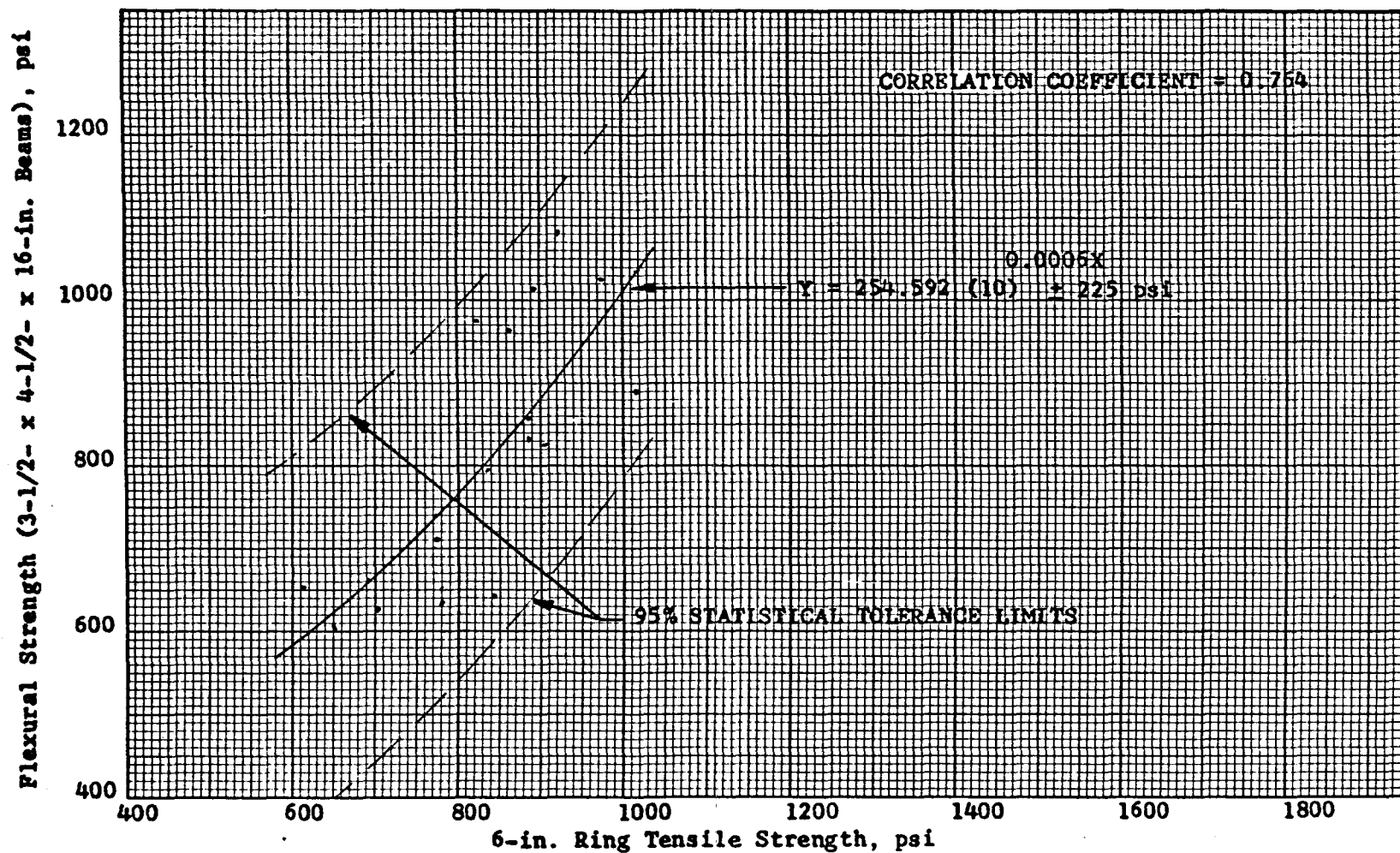
Ring tensile strength relation between 12- and 6-in.-diameter rings  
of the C1 series tests.



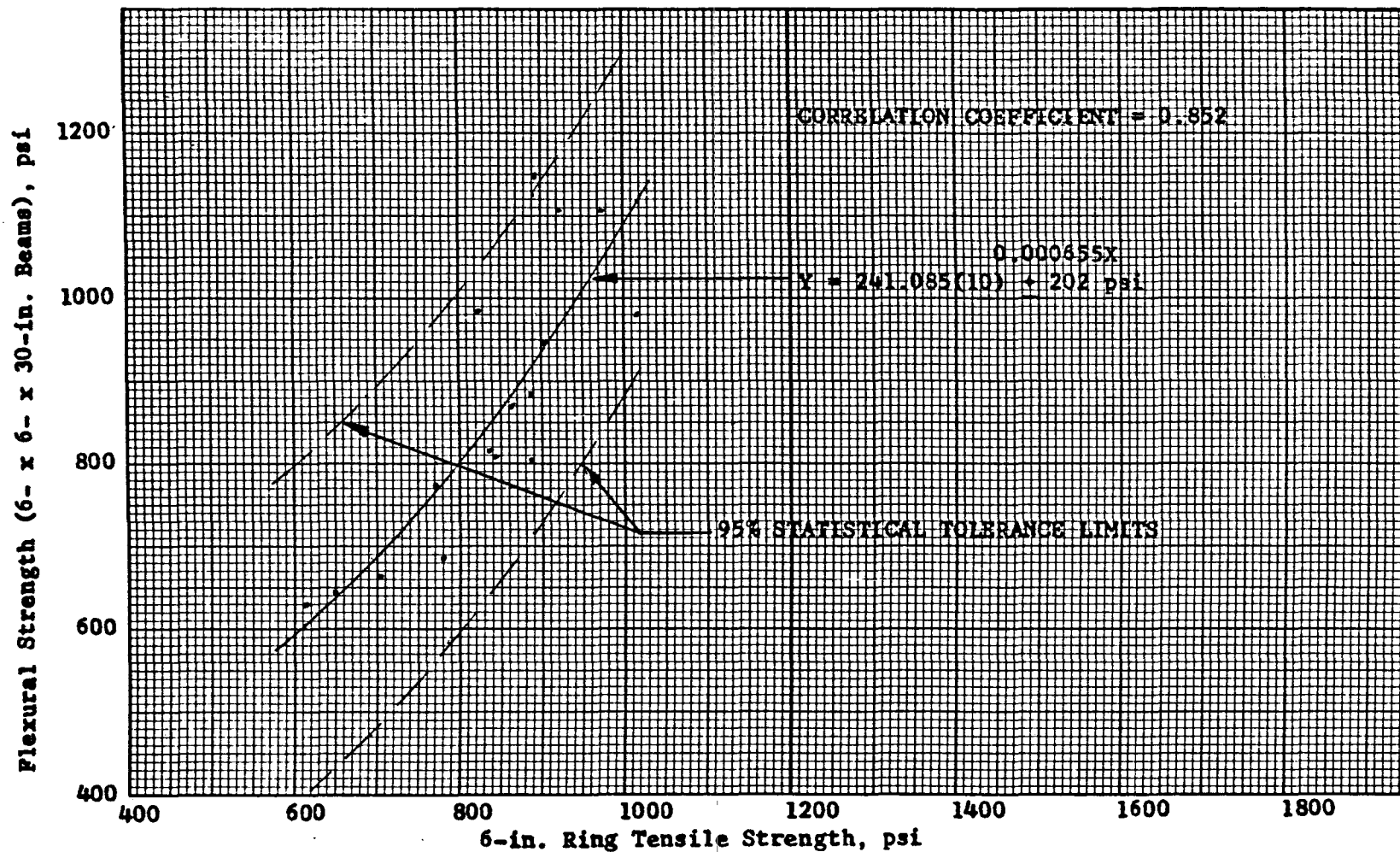
Flexural strength relation between large and small flexure beams from the C1 series.



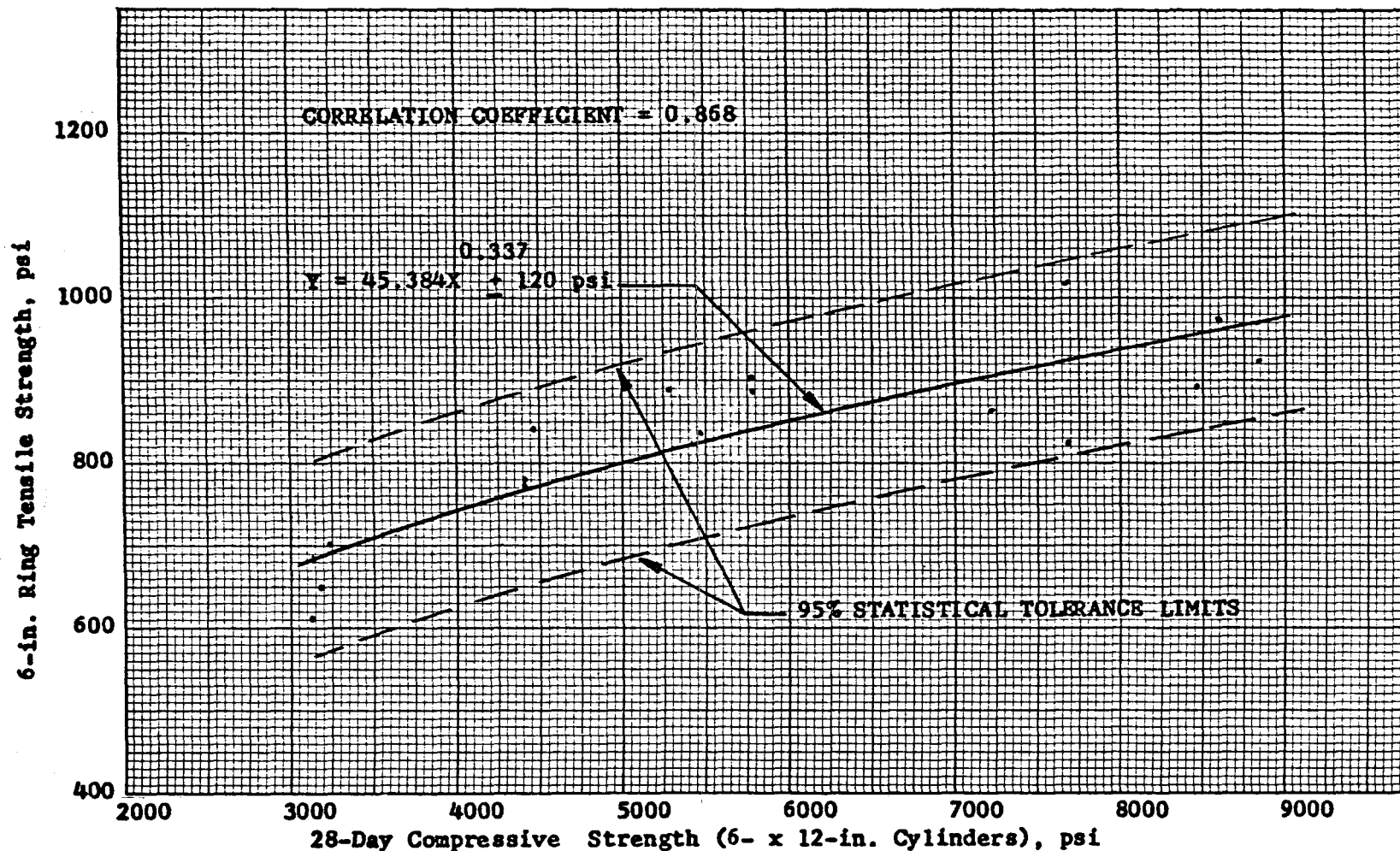
6-in. ring tensile strength vs splitting tensile strength relation  
for C1 series test results.



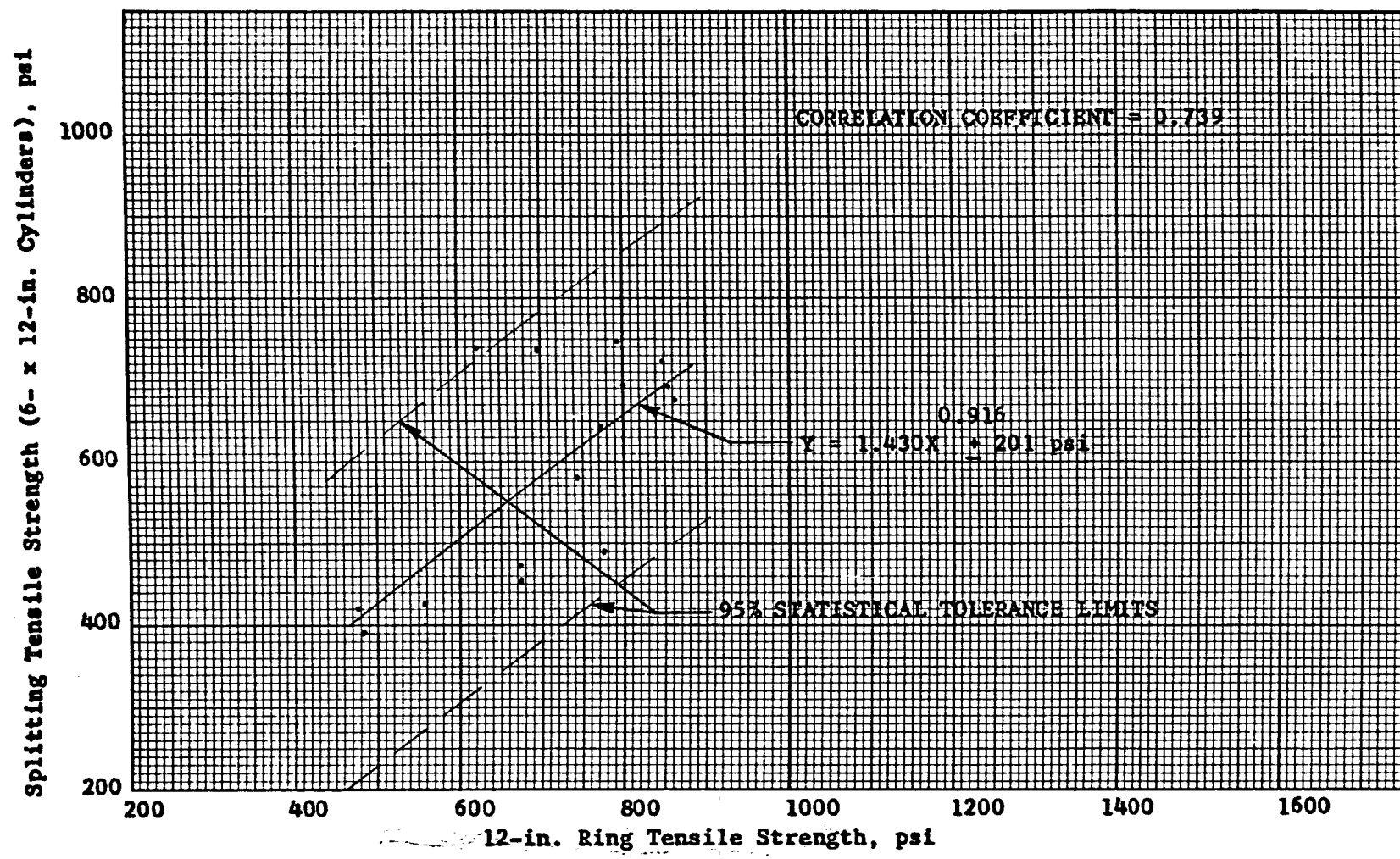
6-in. ring tensile strength vs 3-1/2- x 4-1/2- x 16-in. beam flexural strength relation for C1 series test results.



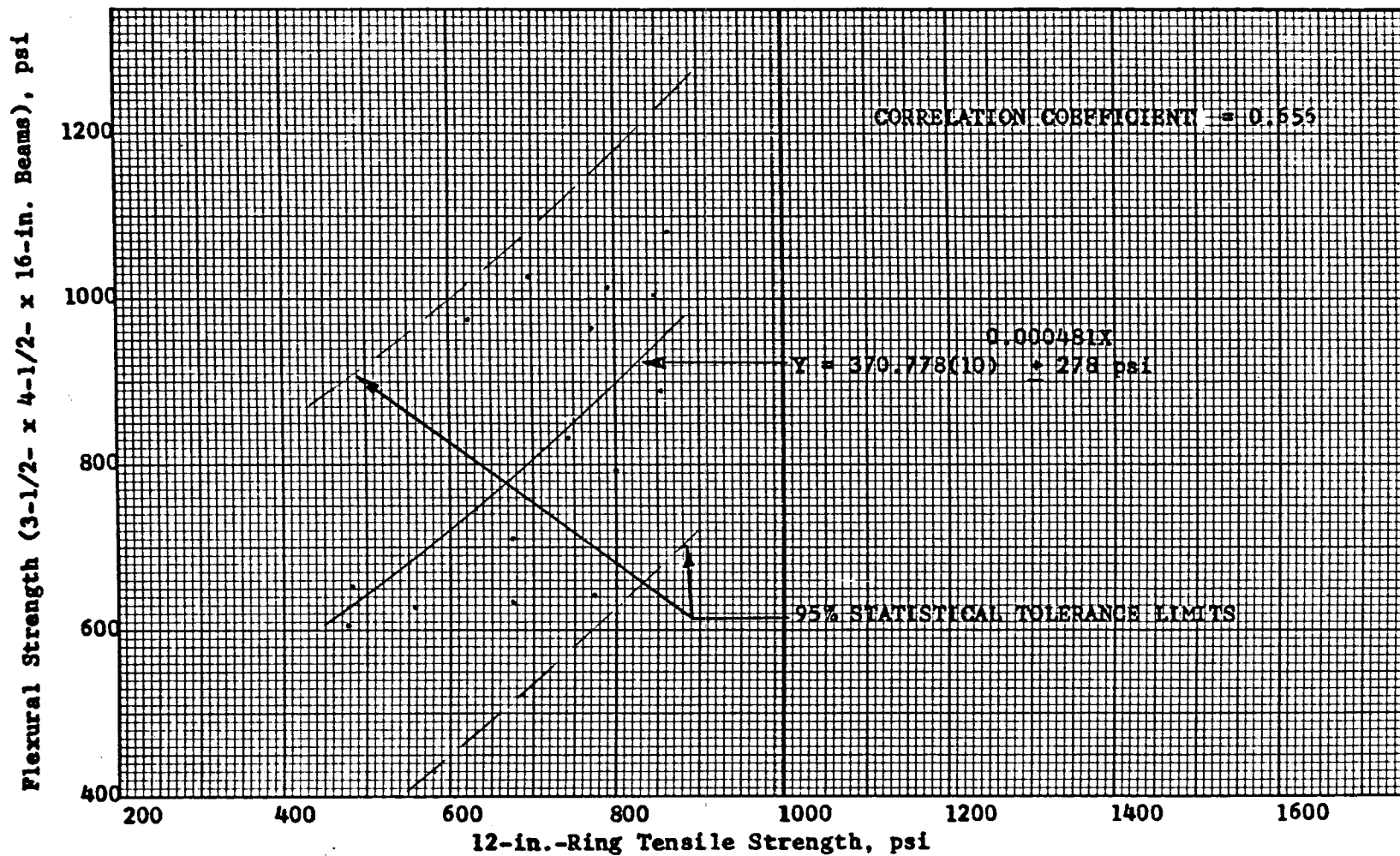
6-in. ring tensile strength vs 6- x 6- x 30-in. beam flexural strength relation for C1 series test results.



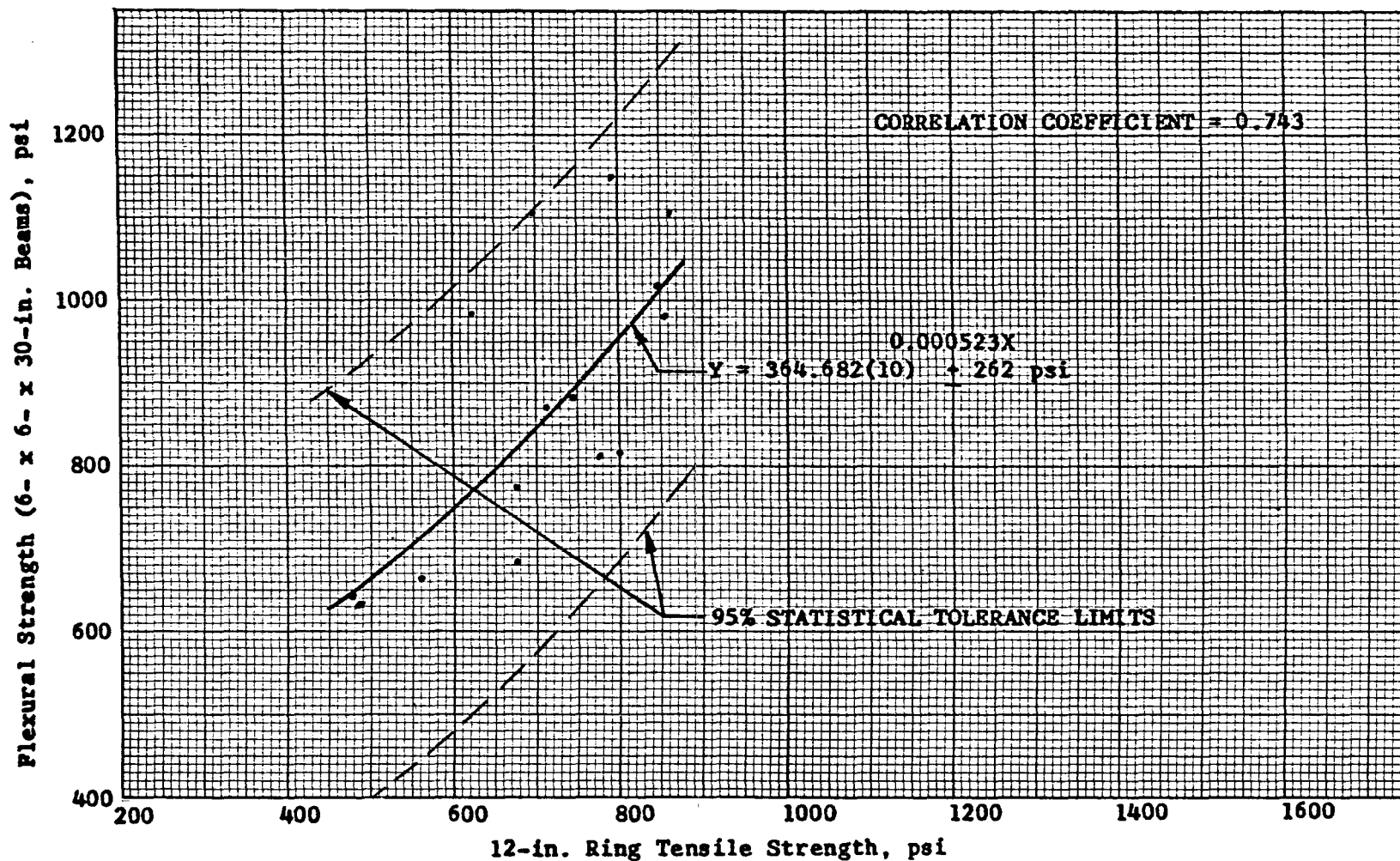
Compressive strength vs 6-in. ring tensile strength for C1 series tests.



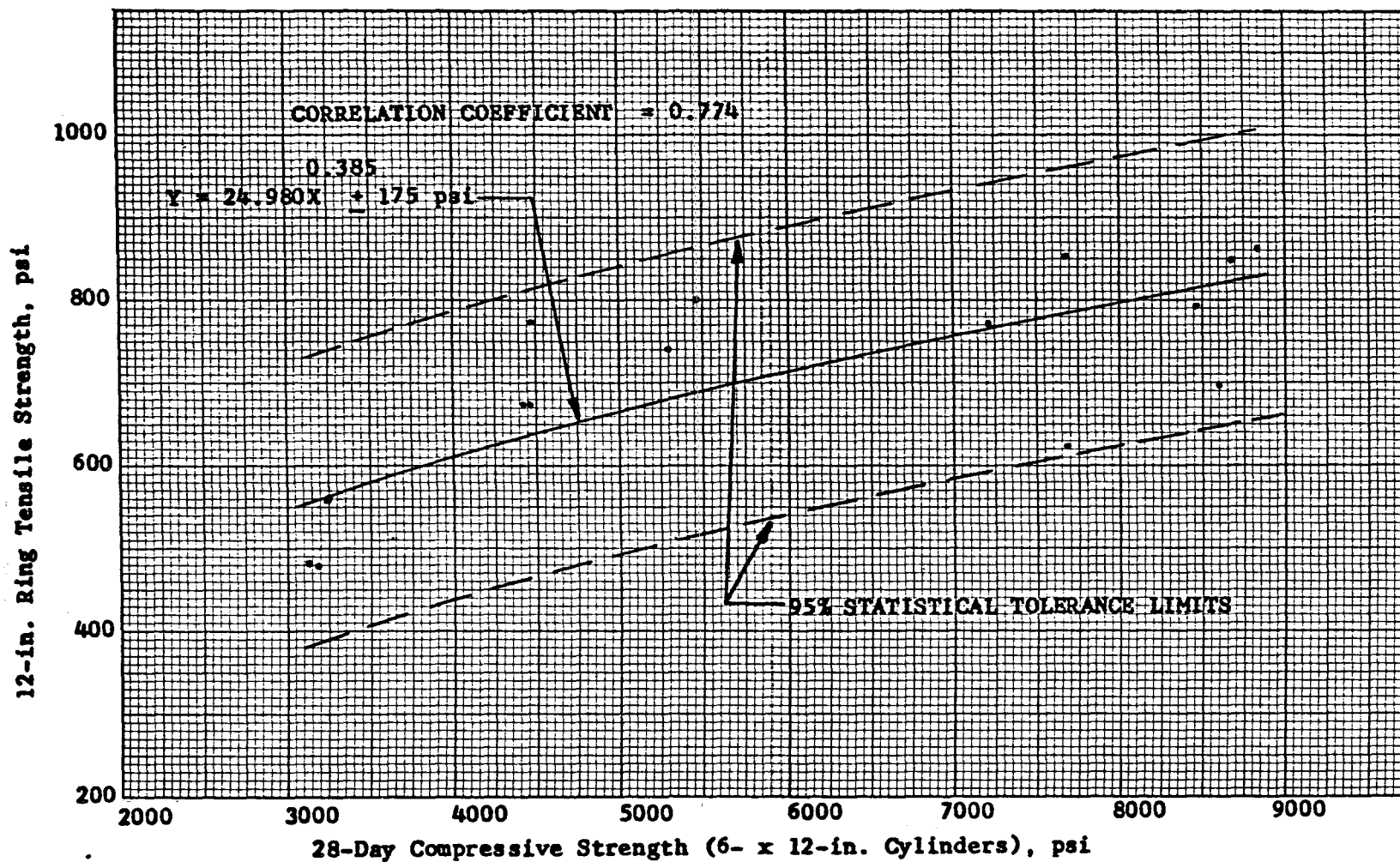
12-in. ring tensile strength vs splitting tensile strength relation for C1 series test results.



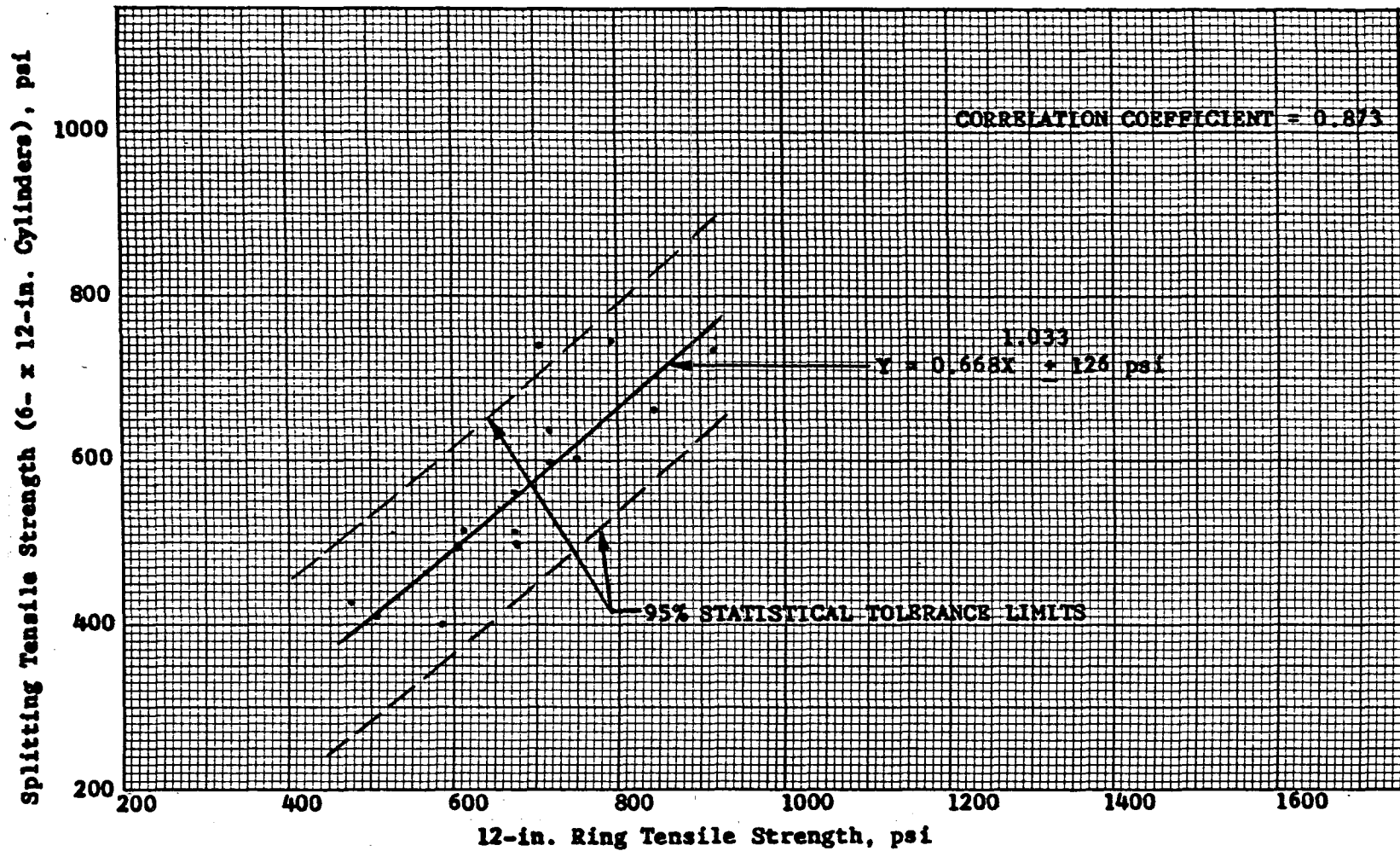
12-in. ring tensile strength vs 3-1/2- x 4-1/2- x 16-in. beam flexural strength relation for C1 series test results.



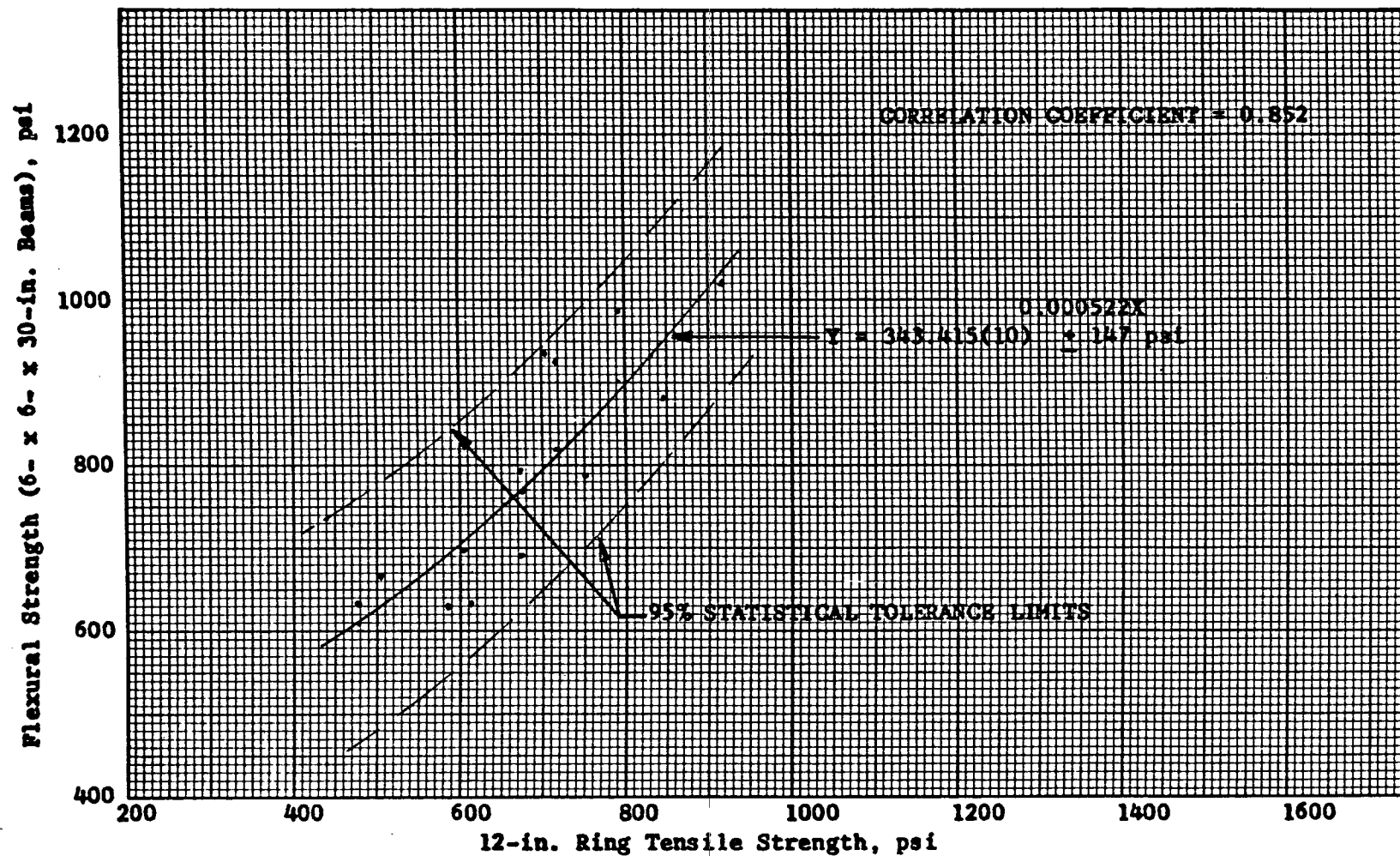
12-in. ring tensile strength vs 6- x 6- x 30-in. beam flexural strength relation for C1 series test results.



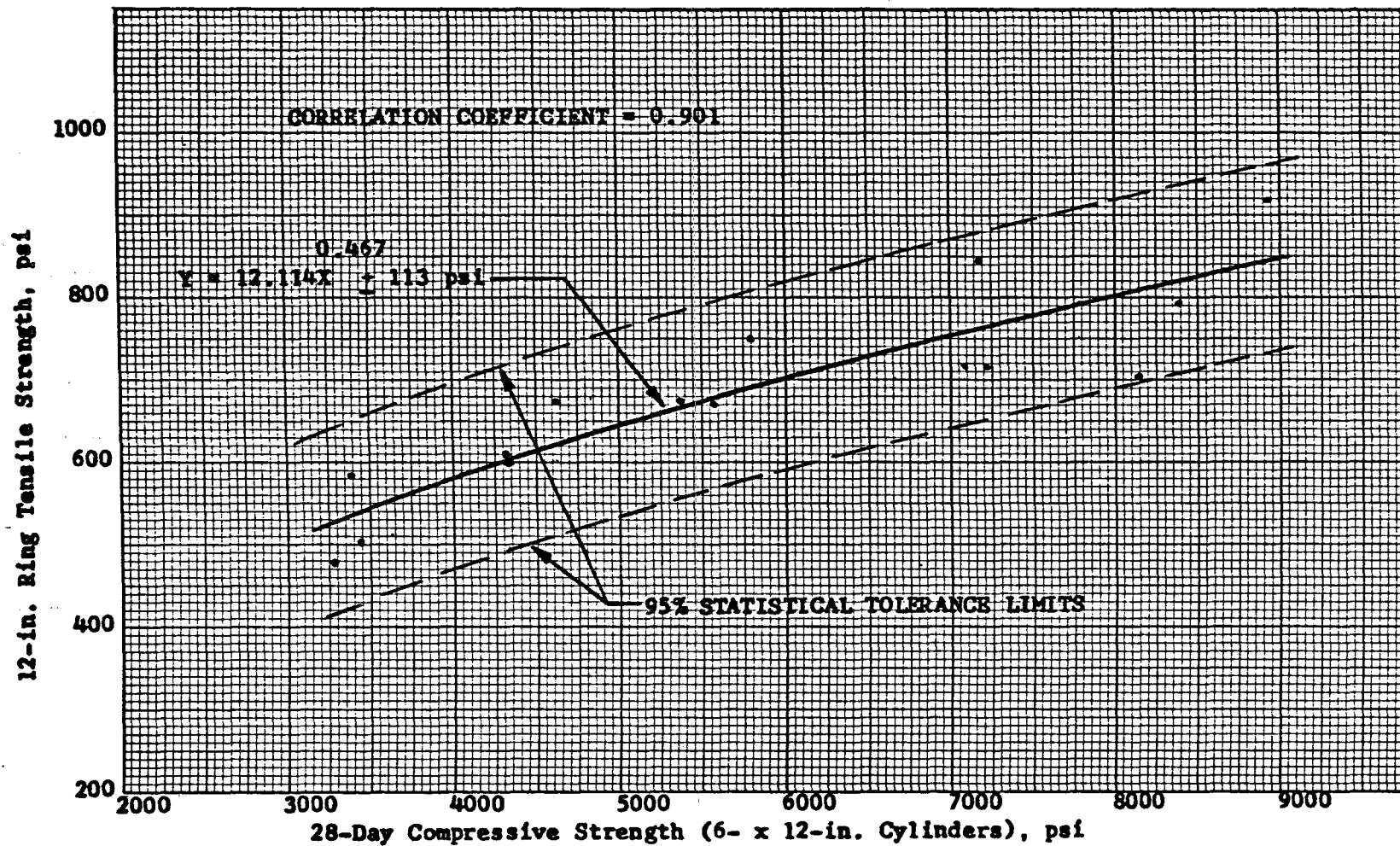
Compressive strength vs 12-in. ring tensile strength for C1 series tests.



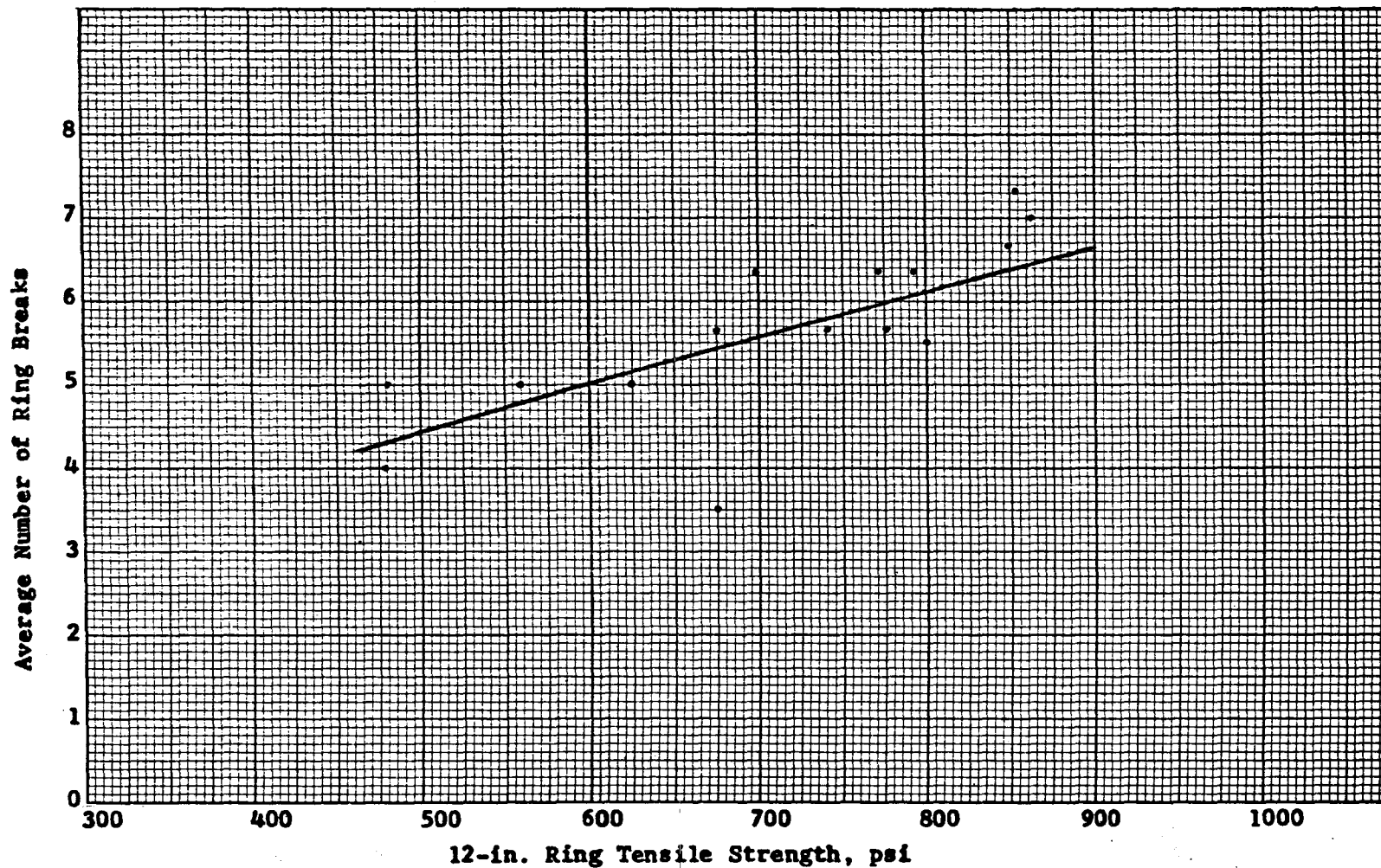
12-in. ring tensile strength vs splitting tensile strength relation for C2 series test results.



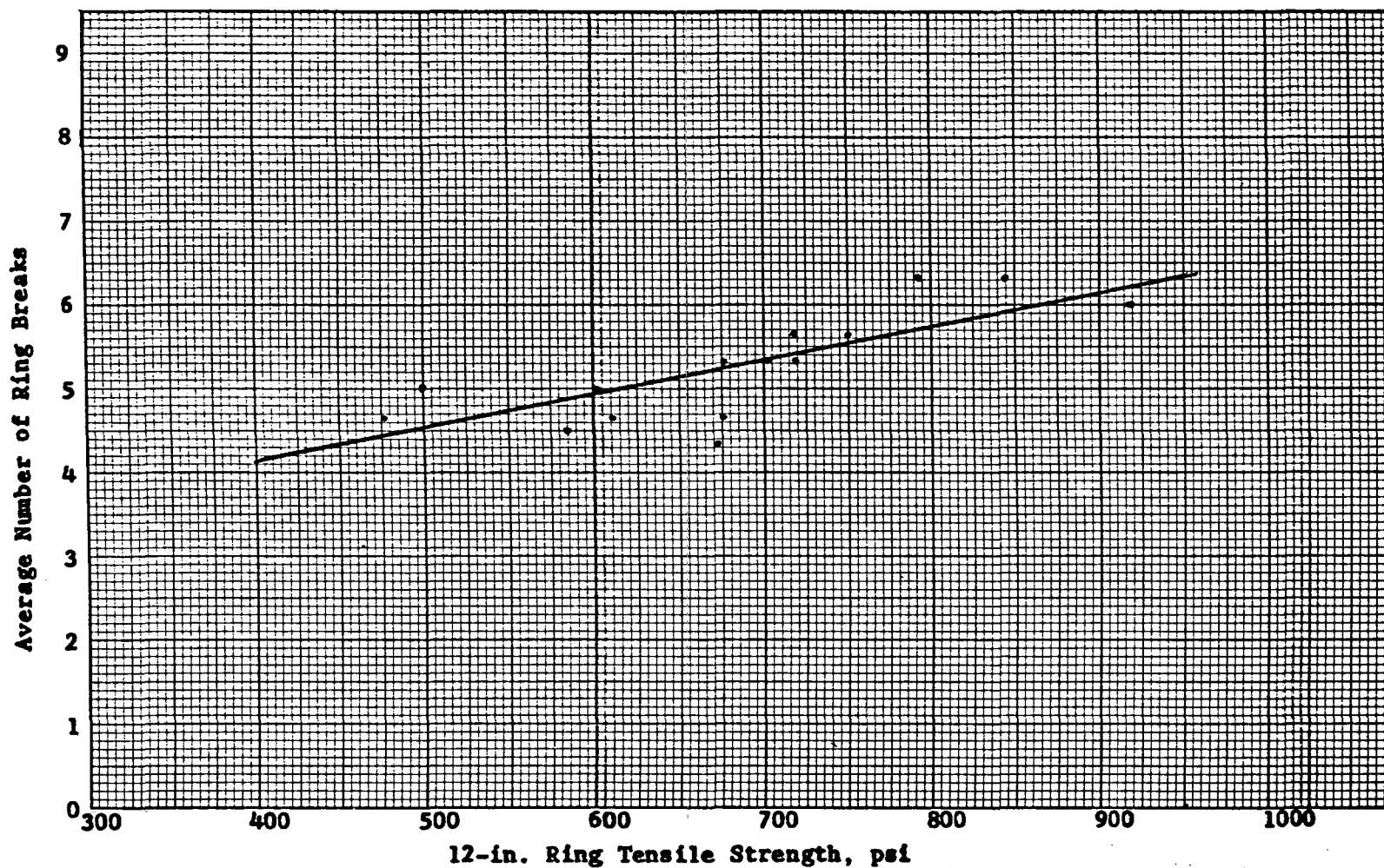
12-in. ring tensile strength vs 6- x 6- x 30-in. beam flexural strength relation for C2 series test results.



Compressive strength vs 12-in. ring tensile strength for C2 series tests.

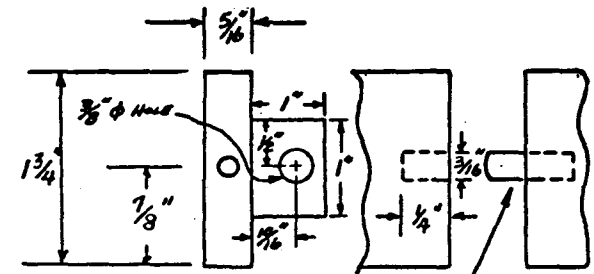
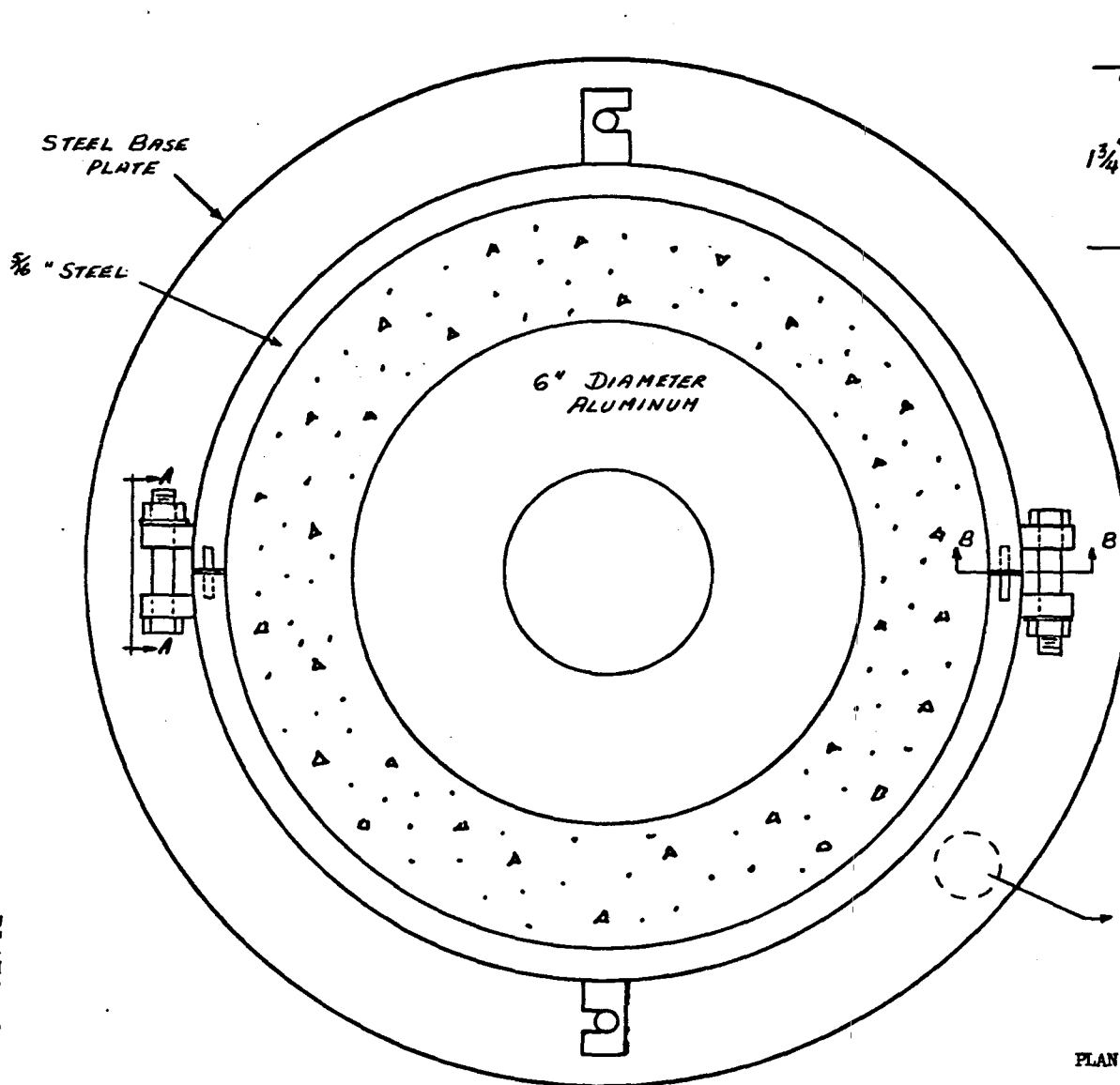


Relation between ring tensile strength and the number of fracture planes in the C1 series 12-in. rings.



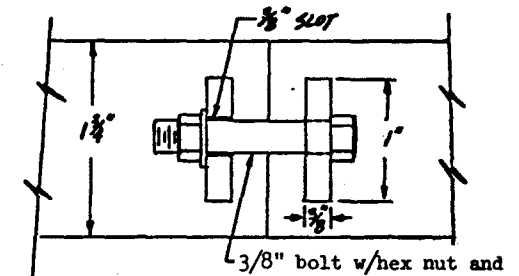
Relation between ring tensile strength and the number of fracture planes in the C2 series 12-in. rings.

## APPENDIX A: CASTING AND TESTING EQUIPMENT



VIEW B-B

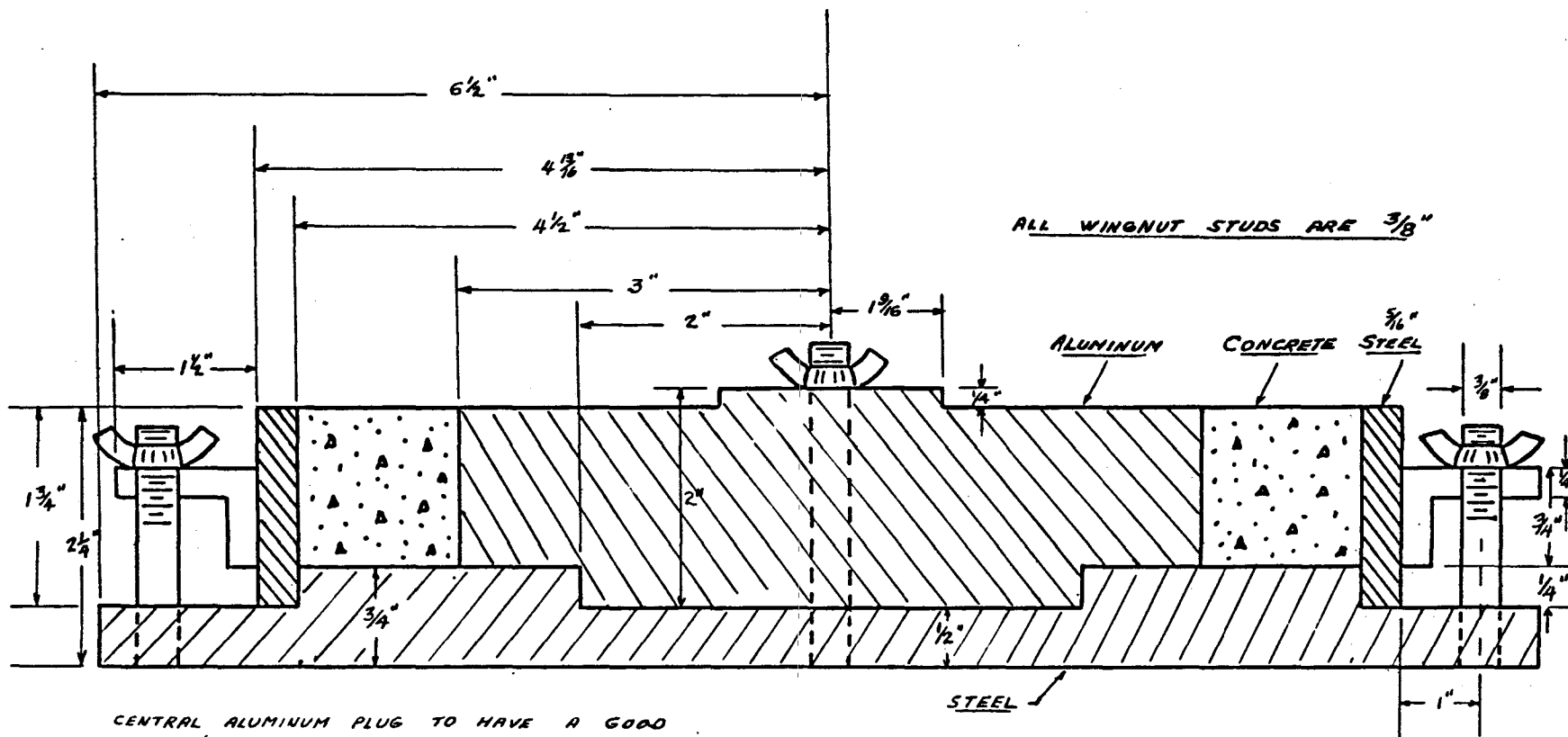
Place pegs in opposite pieces



VIEW A-A

Four feet ( $\phi = 1''$ )  
(Not shown on sectional drawing)

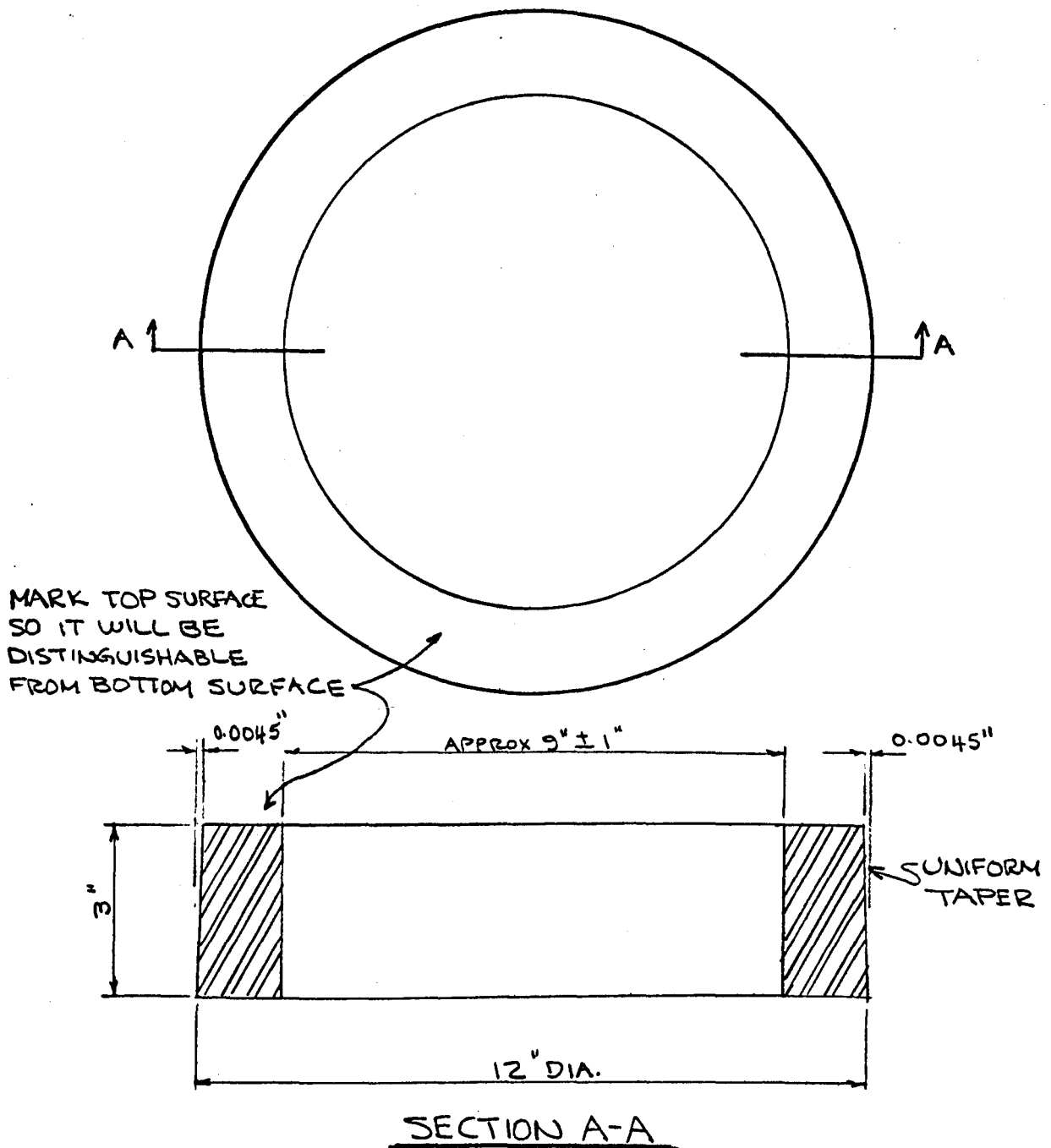
PLAN VIEW OF A MOLD FOR CASTING 6-IN. CONCRETE RINGS



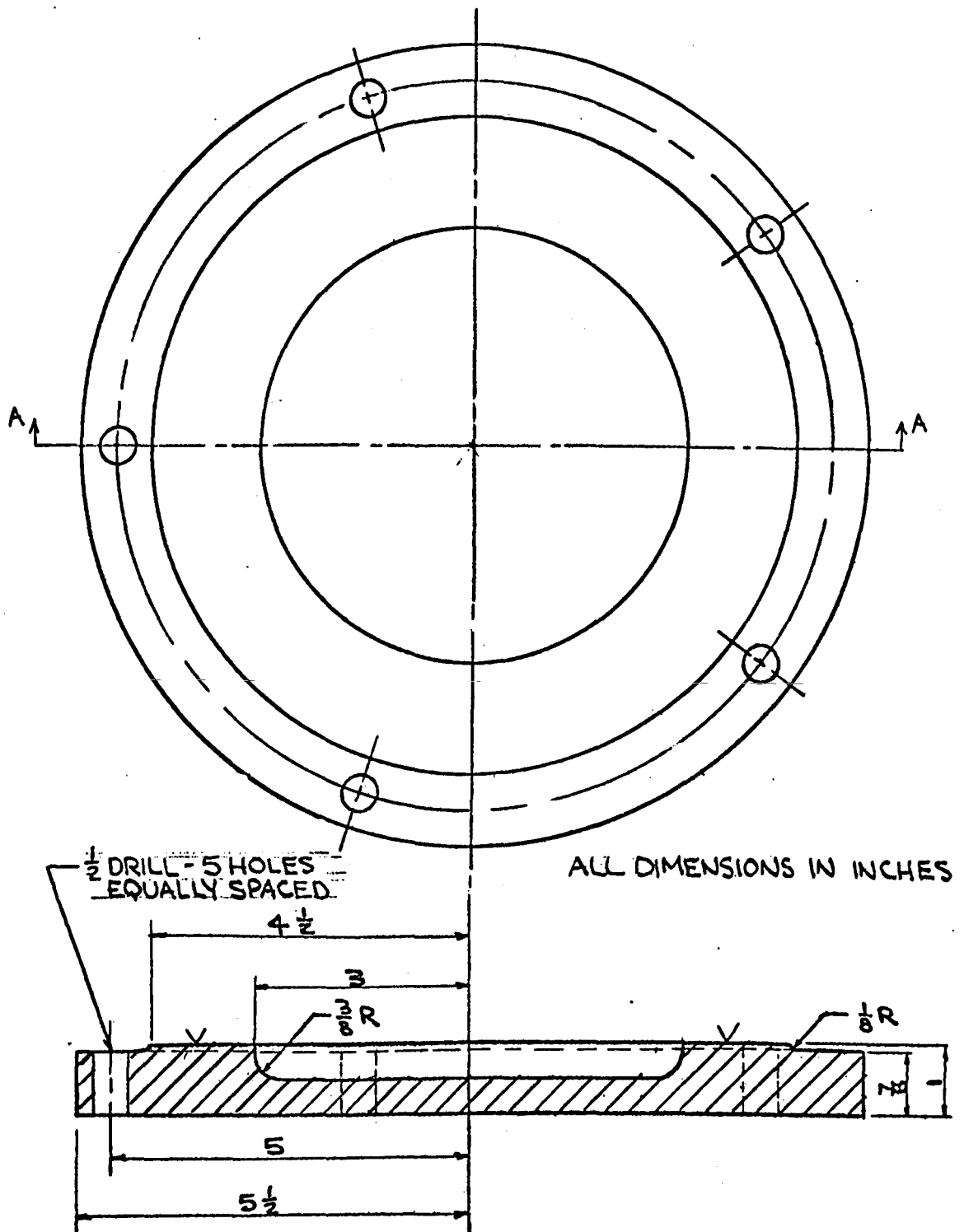
ALL WINGNUT STUDS ARE 3/8"

CENTRAL ALUMINUM PLUG TO HAVE A GOOD SURFACE FINISH AND TO BE 0.0045" SMALLER IN DIAMETER AT THE TOP SURFACE.

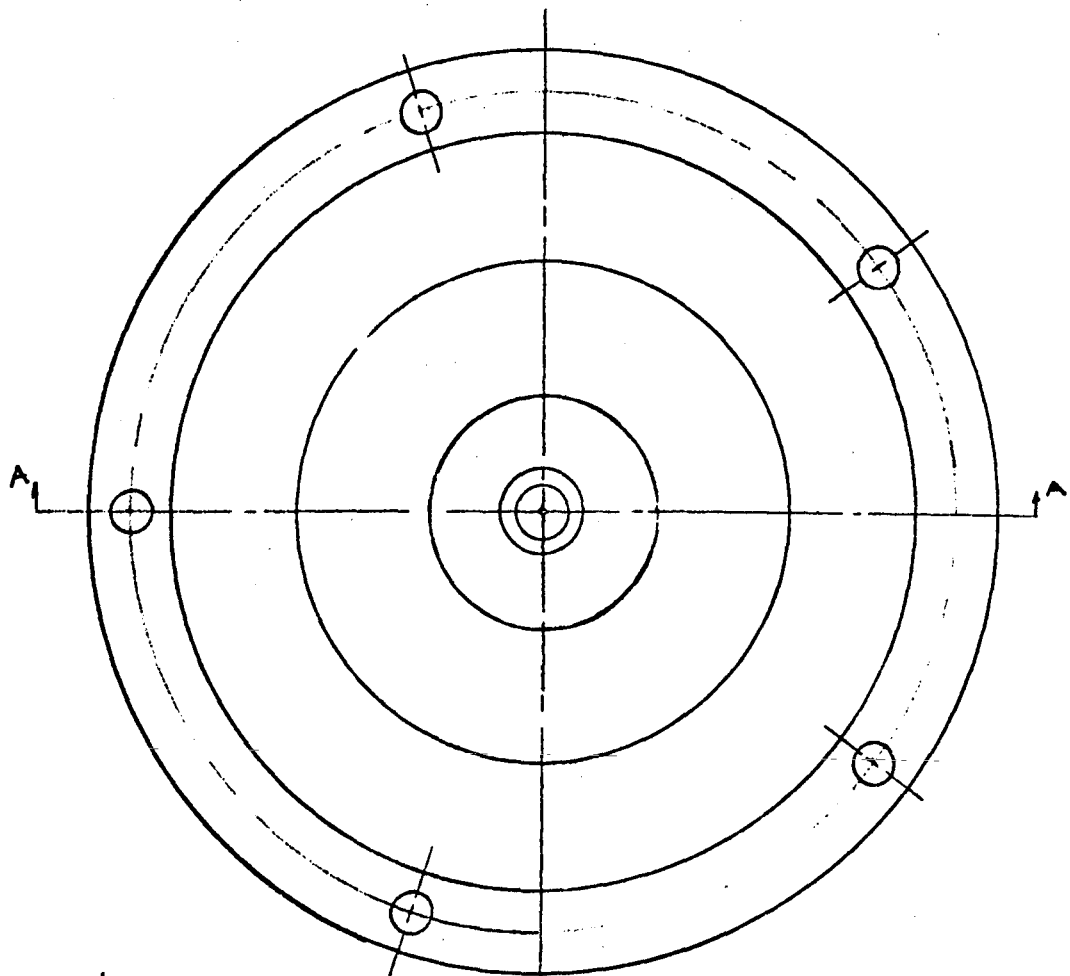
SECTIONAL VIEW OF A MOLD FOR CASTING 6-IN. CONCRETE RINGS



INNER RING OF 12-INCH CONCRETE RING MOLD

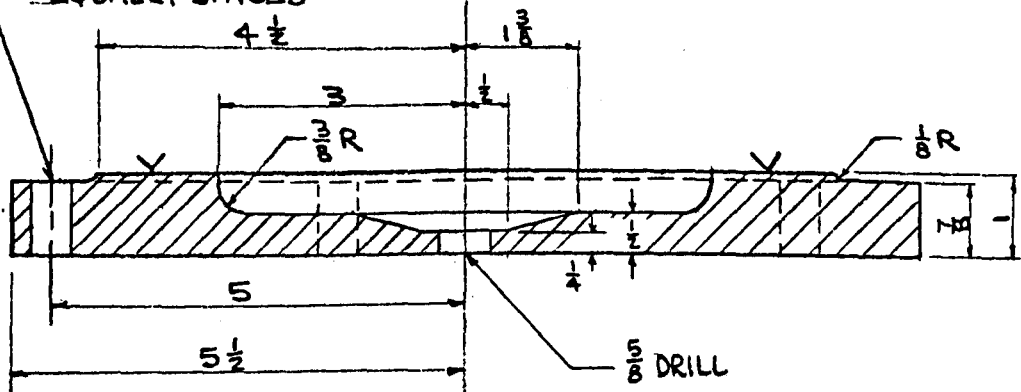


6" RING TESTER - BOTTOM PLATE

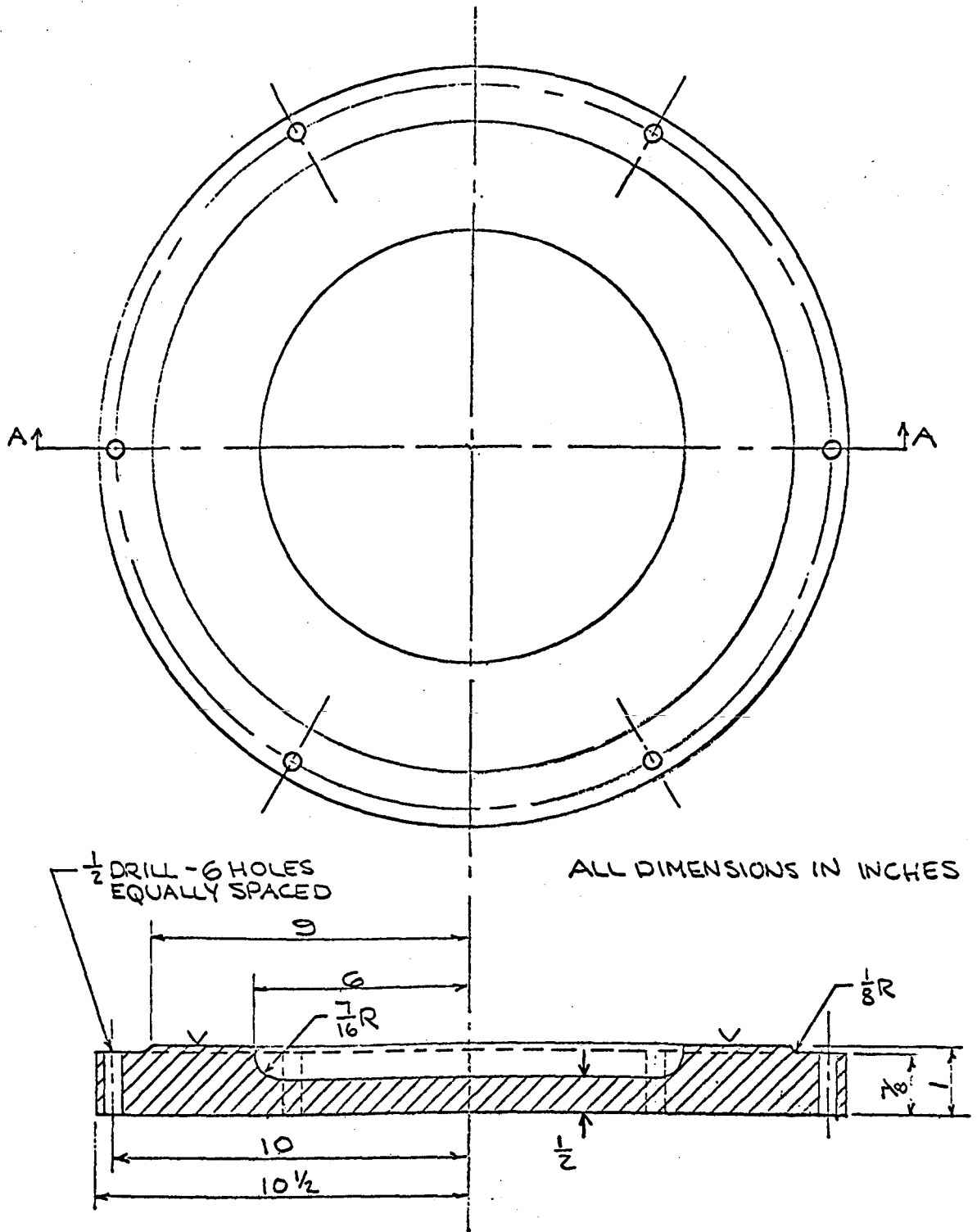


1/2 DRILL - 5 HOLES  
EQUALLY SPACED

ALL DIMENSIONS IN INCHES



6" RING TESTER - TOP PLATE



12" RING TESTER - BOTTOM PLATE



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13. ABSTRACT The investigation consisted of the evaluation of a ring tensile test method for determining a measure of the tensile strength of mortars and concretes. The evaluation was based on the reproducibility and degree of simplicity of the test method. Correlations were made between the ring tensile strength and the cylinder compressive strength and tensile strength values obtained from beam flexural and cylinder splitting tests of sanded mortar, 3/8-in. maximum size aggregate concrete, and 1-in. maximum size aggregate concrete, all made at water-cement ratios (by weight) varying from 0.4 to 0.9. Two sizes of test rings were evaluated: 1.5 in. high by 1.5 in. thick by 6 in. inside diameter and 3 in. high by 3 in. thick by 12 in. inside diameter. The mortar tests used 6-in. rings, the 3/8-in. concrete used both 6- and 12-in. rings, and the 1-in. concrete used only 12-in. rings. A total of ninety-two 6-in. rings and eighty-three 12-in. rings were tested.			

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Unclassified  
Security Classification

14.	KEY WORDS	LINK A		LINK B		LINK C	
		ROLE	WT	ROLE	WT	ROLE	WT
	Concretes Mortars (material) Ring test Tensile strength Tension tests						