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A NOTE ON THE STRENGTH CHARACTERISTICS OF SMALL-SCALE CONCRETE WITH SPECIAL AGGREGATES

By

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A Report on a Research Project
Sponsored by
THE NATIONAL SCIENCE FOUNDATION
Research Grant GK-1894

UNIVERSITY OF ILLINOIS
URBANA, ILLINOIS
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1. INTRODUCTION

1.1 Object and Scope

The ratio of the modulus of rupture to compressive strength for small-scale concrete is usually considerably higher than that for ordinary concrete. The high modulus of rupture creates problems in lightly reinforced test specimens if cracking affects the phenomena under study.

The tests described in this report were conducted to investigate the influence of various aggregates and time on the tensile strength of small-scale concrete with respect to its compressive strength. A total of 165 2 x 4-in. cylinders and 83 2 x 2 x 8-in. beams were tested. Thirteen different mixes were used with the coarse aggregate provided by pebbles, birdshot, and glass beads, in addition to ordinary sand-cement-water mixes with and without air-entrainment. In certain mixes the coarse aggregate was coated with graphite or silicone.

1.2 Outline of Tests

The mixes were designated as follows.

Mix	Type of Substitute Aggregate or Admixture	Type of Aggregate Coating
1	Gap Graded Pebbles	None
2	Glass Beads	None
3	Birdshot	None
4	None (Regular)	None
5	Air-entraining Agent	None
1G	Gap Graded Pebbles	Graphite
2G	Glass Beads	Graphite
3G	Birdshot	Graphite
1S	Gap Graded Pebbles	Silicone
2S	Glass Beads	Silicone
3S	Birdshot	Silicone

In addition to the above mixes, two batches of regular mix were used to conduct a series of tests on the same batch of concrete at various intervals over a period of 48 days. The purpose of these tests was to investigate the variation in the compressive and tensile strengths of the small-scale concrete with age. The two batches were designated TST-A and TST-B.

1.3 Acknowledgments

This report was written by J. E. Barry, Research Assistant in Civil Engineering, under the direction of Dr. M. A. Sozen, Professor of Civil Engineering, as a special problem in partial fulfillment of the requirements for a Master of Science Degree in Civil Engineering. This study was supported by the National Science Foundation Grant GK 1894. The work was conducted at the Structural Research Laboratory of the Department of Civil Engineering, University of Illinois, Urbana.

The author wishes to acknowledge Dr. H. K. Hilsdorf, Professor of Civil Engineering, and A. E. Fiorato, Research Assistant in Civil Engineering, for their helpful advice. Appreciation is due to J. D. Spencer, Research Assistant in Civil Engineering for his continual assistance, and to Mrs. Barbara J. Williamson for typing the report.

2. MATERIALS

2.1 Concrete

Mix 4 represented the "basic" small-scale concrete mix. The mix proportions were similar to those for other mixes routinely used in model studies in the laboratory. A fine lake sand and Wabash River sand were combined to form the aggregate. Sieve analysis for the fine lake sand and the Wabash River sand are shown in Fig. 2.1 and 2.2. The aggregate was air dried before use.

Atlas type III portland cement was used with a water/cement ratio of 0.7 by weight. The mix proportions by weight are presented in Table 1. Eleven batches weighed approximately 35 lbs. each, and two batches weighed approximately 100 lbs. each.

2.2 Substitute Aggregates

In addition to the fine and coarse sands mentioned above, adjustments in the mix proportions were made, and three additional aggregates were used. The adjustments made consisted of replacing a portion of the fine lake sand with the additional aggregate. The percentage of replacement of the fine sand was 40 percent and 100 percent depending upon which aggregate substitute was being used.

For the first substitute aggregate, pebbles obtained from Wabash River sand by sieving it through a No. 10 sieve were used. This material, designated "gap graded pebbles", was used to replace 100 percent of the fine lake sand.

Three-millimeter glass beads were used to replace 40 percent of the fine lake sand. The glass beads were obtained through the Kimble

Company, and purchased in one-lb. boxes through the General Chemistry Stores at the University of Illinois.

The final substitute aggregate to be used was American Standard No. 4 chilled lead shot. The lead shot was manufactured by National Lead Company, and purchased through the Civil Engineering Supply Office. A substitution of 40 percent of the fine lake sand was made when the lead shot was used. The substitution was based on the specific gravity of the materials, assuming a specific gravity of 2.7 for the sand. The lead aggregate was called "birdshot".

2.3 Admixture

A neutralized vinsol resin air-entraining agent was added to one regular batch of concrete. Trial batching was conducted in advance of casting the test mixture to produce an air content of 7 to 9-percent. The concrete used for the test specimens contained approximately 8-percent entrained air.

2.4 Aggregate Coatings

A graphite coating solution was produced by mixing equal volumes of concentrated colloidal graphite solution (20-percent solids) and isopropyl alcohol. The mixture was stirred thoroughly, stored in containers and remixed just before using. The concentrated colloidal graphite solution was purchased from the Acheson Colloids Company, Port Huron, Michigan.

The silicone coating was a nonreactive solution having a viscosity of 500 cstks. This material was provided without charge by Union Carbide Corporation.

Only that portion of the aggregate that was substituted for the fine lake sand was coated. The substitute aggregate was washed three times with trichloroethylene and twice with acetone and allowed to dry thoroughly before the coatings were applied. The application of the coatings consisted of dipping the aggregate into the coating solution with the use of a metal screen and allowing the excess fluid to drain away. The coated aggregate was then placed on clean polyethylene sheets and covered to prevent foreign matter from settling on the surface before using. In the case of the graphite coating, the coating was allowed to dry before the aggregate was used.

2.5 Casting and Curing Procedures

All of the 2 x 4-in. cylinder and 2 x 2 x 8-in. beam molds were cleaned and oiled before casting to allow the excess oil to drain away. The molds consisted of solid metal construction. Cylinders were cast in individual forms, while the beam forms were such that six beams could be cast at the same time using the same form.

A twenty quart capacity vertical mixer was used for mixing the small-scale concrete. All of the dry material was placed in the mixing bowl, which was then locked in a stationary position, and the beater speed was set on LOW. The cement and sand was then mixed at a rate of 102 rpm for 60 seconds. After 60 seconds the water was gradually added to the mix as it was being mixed in. If there was any substitute aggregate to be added to the mix, it was added after the water in order to protect the coating (on the coated aggregates) as much as possible. The total mix was mixed for about 2 minutes after the water was added.

The specimen forms were placed on a metal vibrating table either in groups of four cylinders or two beam forms, packed with fresh concrete, and vibrated for approximately 15 seconds. The vibration time varied very little, but less workable concrete was vibrated longer. The vibrating table was equipped with an adjustable eccentricity vibrator and the speed of the vibrator was adjusted by means of an autotransformer. For vibrating the specimens, an eccentricity of 20 percent was used with a setting of 70 on the autotransformer.

Approximately one to two hours after casting, the surface of the specimens was struck off with a wooden block and the beams were troweled. Capping of the cylinders took place at the end of the working day.

The test specimens were removed from the forms the day after casting and wrapped with wet burlap. A covering of polyethylene was used to prevent the burlap from drying out. After six days of moist curing, the specimens were removed from the burlap and air dried in the controlled environment of the Structural Research Laboratory until they were tested.

3. TESTING PROCEDURES

3.1 Test Specimens

Micrometer measurements of the metal cylinder forms indicated an average deviation of no more than 0.025 in. from the 2 in. diameter. Three internal measurements were taken each at the top, middle, and bottom of the cylinder molds. The deviation listed above was the maximum deviation recorded for the average of the three measurements.

A micrometer was also used to measure the width and height of the beam molds. All measurements were within one hundredth of an inch of the specified two inches.

The failure stresses of the concrete mixes were computed using the nominal dimensions of the test specimens. Consideration of the variations in the dimensions of the test specimens had negligible effect on the computed concrete stresses.

3.2 Compression Test

A 60,000-lb. Riehle testing machine was used for testing the concrete specimens. To insure a uniform contact of the upper loading platen with the surface of the specimens, the platen was thoroughly cleaned and lubricated and the cylinders were capped prior to testing.

The compression cylinders were loaded to failure at a rate of approximately 6,000 lbs. per minute. The stress-strain relationship for the concrete was obtained during the compression test with the aid of a 2-in. compressometer. Figure 3.1 is a photograph of a compression cylinder and the compressometer. The compressometer is of aluminum construction and has a mechanical advantage of 2. Readings from a 0.0001 in. dial gage were recorded for each 500 lb. load increment. The dial gage was adjusted to zero at the start of the compression test.

A typical stress-strain curve is shown in Fig. 3.2. Figure 3.3 is a plot of the 12-day initial tangent modulus versus compressive strength for all of the concrete mixes excluding the time series tests.

3.3 Modulus of Rupture Test

A single point loading frame shown in Fig. 3.4 was used to determine the modulus of rupture of the 2 x 2 x 8-in. beams. One of the lower simple supports was stationary while the other was free to roll. The supporting rollers were placed 6 inches from center-to-center. The load was applied through a third roller resting on the top of the beam at the center point of the two support rollers. Before loading, the test frame was carefully centered under the upper platen. The beams were tested to failure in approximately 10 seconds.

3.4 Cylinder Splitting Test

Two loading strips were used to distribute the load along the length of the cylinders during the cylinder splitting tests. The loading strips appeared to be of a compressed fabric similar to pressed cardboard and measured 1/8 x 1 x 8-in. The cylinders were loaded at a rate of approximately 6,000 lbs. per minute.

4. TENSILE STRENGTH AT TWELVE DAYS

4.1 Modulus of Rupture

Individual modulus of rupture test results are plotted in Fig. 4.1 against the average compressive strength of the batch of concrete used in making the specimens for modulus of rupture tests. At an age of twelve days, a trend is indicated for the modulus of rupture to increase with increasing compressive strength. The trend can be approximated by assuming that the modulus of rupture strength is 10 $\sqrt{f'_c}$. The relationship between the modulus of rupture and the compressive strength shown in Fig. 4.1 for small-scale concrete at an age of twelve days is not objectionably higher than the relationship for ordinary concrete.

The modulus of rupture sample means and confidence intervals of the means for the mixes with the uncoated aggregates are presented in Fig. 4.2. The confidence intervals indicate the range within which the average modulus of rupture lies with a probability of 95 percent. The birdshot sample exhibits the largest confidence interval of the mean, however, the confidence interval of the mean for the regular sample is sufficient to include the magnitudes of the mean values for all of the other uncoated aggregate samples. The modulus of rupture sample mean for the regular mix is the median of all of the uncoated aggregate sample means.

On the basis of the results shown in Fig. 4.2, it appears that variations in the type and gradiation of aggregate as well as the option of using air entrainment had no significant effect on the relationship between the modulus of rupture and compressive strength of small-scale concrete. The range of the compressive strengths implies that the uncoated aggregates did not affect the compressive strength significantly: five batches of the same mix would be expected to vary over the range indicated in the figure.

The modulus of rupture sample means and confidence intervals of the means for the mixes with the coated aggregates are presented in Fig. 4.3. The results in this figure indicate that the silicone coating tends to produce a lower modulus of rupture and a lower compressive strength than the graphite coating, when they are used with the same type of aggregate. The silicone coating, being a nondrying fluid, produced a greater slump than the graphite coating. Since the compressive strength depends to some extent on the slump of the concrete, any noticeable change in slump should indicate a corresponding change in compressive strength. The range of the compressive strengths in Fig. 4.3 is greater than would normally be expected and it appears that the silicone coating reduced the concrete compressive strength.

The results of the regular sample are included in Fig. 4.3 for comparison. The mean modulus of rupture for the mixes with the graphite coated aggregates is very close to the mean modulus of rupture for the regular mix. From a comparison of the data for the mixes with graphite coating (solid symbols in the figure) with the mean and confidence interval of the regular mix, it can be concluded that graphite coating had insignificant influence on the modulus of rupture and its scatter, and on the compressive strength of the small-scale concrete.

As in the case of the mixes with uncoated aggregates, the mean modulus of rupture for the regular mix was the median of the means for the mixes with coated aggregates.

4.2 Cylinder Splitting Strength

The individual tensile strengths determined from the cylinder splitting test are plotted against the mean compressive strength of the test mixes in Fig. 4.4. The highest individual strength was obtained from the mix with the uncoated glass beads and the lowest from the mix with the uncoated birdshot. The combined results for all of the mixes are distributed along a curve described by the expression $f_{sp} = 7.5\sqrt{f'_c}$.

The cylinder splitting strength sample means and confidence intervals of the means are presented in Fig. 4.5 for the mixes with the uncoated aggregates and in Fig. 4.6 for the mixes with the coated aggregates. In Fig. 4.5 the tensile strengths from the mix with the birdshot aggregate have so much scatter that it makes the mean dubious. A comparison of the results from the regular mix with the results from the mixes with the gap graded and glass bead aggregates and with air entrainment would indicate that there is no significant effect on the cylinder splitting strength as a result of the various mix alterations.

The results in Fig. 4.6 show that the tensile strength obtained by the cylinder splitting test for the mixes with the coated birdshot aggregates had relatively little scatter. On the other hand, the tensile strengths from the mix with the silicone coated glass bead aggregate had enough scatter to make the value of the mean tensile strength questionable. The substitution of the coated gap graded and glass bead aggregates into the mix resulted in a negligible effect on the splitting strength.

Considering only the ordinates in Fig. 4.6, the mean and the confidence interval of the mean for the mix with silicone coated birdshot appear to be significantly below the corresponding value for the regular mix. However, this difference becomes smaller if the value for the regular mix is modified for the compressive strength. The same tendency can be seen in Fig. 4.3 for the modulus of rupture.

The general conclusion from Fig. 4.6 is that the special mixes used did not reduce appreciably the tensile strength of the small-scale concrete, as measured by the cylinder splitting test, with respect to its compressive strength.

A listing of the material properties of the concrete mixes is presented in Table 2.

5. OBSERVED VARIATION OF CONCRETE STRENGTH WITH TIME

Two series of tests, TST-A and TST-B, were conducted to investigate the variation with time in the compressive and tensile strengths of the small-scale concrete, primarily to determine whether there was a change in the ratio of the modulus of rupture to the compressive strength. The modulus of rupture, splitting strength, and compressive strength of the small-scale concrete (regular mix) were determined at various intervals over a period of 48 days. The strengths of the concrete mixes are listed in Table 3, and the results are presented and discussed in the following sections.

5.1 Compressive Strength

The compressive strength test results for series TST-A and TST-B are shown in Fig. 5.1 and 5.2. Individual test results appear in Fig. 5.1a and 5.2a. Figures 5.1b and 5.2b show the mean compressive strength and the 95-percent confidence interval of the mean versus the age in days after casting.

In both series of tests, the maximum values were indicated by the results obtained at 28 days. At 48 days, the strength was below the 28-day strength in both series of tests. From the available data it would appear that the decrease in strength from 28 to 48 days is significant. However, there is no evidence to indicate that the observed rate of decrease should continue.

5.2 Modulus of Rupture

The results of the modulus of rupture tests are presented in Fig. 5.3 and 5.4 for TST-A and TST-B. For both series of tests, the mean modulus of rupture at an age of 15 days was below the mean modulus of rupture at 12 days. However, the 95-percent confidence intervals of the means at 12 and 15 days suggest a positive but decaying rate of increase in the modulus of rupture with time as represented by the curves in Fig. 5.3 and 5.4. Such a trend would indicate a lower modulus of rupture at 12 days than at 15 days.

The ratio of the mean values of the modulus of rupture to the compressive strength at various test ages are plotted in Fig. 5.7. The plot of the ratio of the modulus of rupture to compressive strength for TST-A in Fig. 5.7 increases almost at a constant rate from a value of 0.14 at 15 days of age to 0.22 at 48 days of age. The corresponding plot for TST-B shows a set of rather erratic test results. The straight broken lines in Fig. 5.7 represent the ratios of the modulus of rupture to the compressive strength for values taken from the representative curves in Fig. 5.1b, 5.2b, 5.3b, and 5.4b. These broken lines appear to have the same slope between 12 and 48 days.

Figure 5.8 presents a plot of the ratio of the modulus of rupture to the square root of the compressive strength versus the age at the time of testing for the results of the two time series tests. The modulus of rupture values increased from approximately 10 $\sqrt{f'_c}$ at 12 days to approximately 15 $\sqrt{f'_c}$ at 48 days.

5.3 Cylinder Splitting Strength

The results of the cylinder splitting tests are presented in Fig. 5.5 and 5.6. The results of TST-A are shown in Fig. 5.5 and indicate an increasing splitting strength with age until 21 days. The two tests conducted after 21 days of age produced a splitting strength of 520 psi, a value below the 21-day strength. The second series of test results, TST-B, plotted in Fig. 5.6, indicate increasing splitting strength until 15 days of age. No further increase was indicated until 28 days. Figure 5.6 shows a maximum test result at 48 days. On the basis of the test results shown in Fig. 5.5 and 5.6, it appears that there was no significant change in the tensile strength determined by the cylinder splitting test for small-scale concrete between the ages of 15 to 48 days.

Ratios of the mean cylinder splitting strength to the compressive strength and to the square root of the compressive strength versus the testing age are plotted in Fig. 5.7 and 5.8. The splitting strength ranged from 0.11 f'_c to 0.12 f'_c for TST-A and 0.11 f'_c to 0.15 f'_c for TST-B. For both series of tests, the splitting strength was essentially constant at a value of approximately $8\sqrt{f'_c}$ over the testing period of 12 to 48 days.

6. SUMMARY AND CONCLUSIONS

The objective of this study was to investigate various means of reducing the flexural strength of small-scale concrete without producing a proportional decrease in the compressive strength so that the ratio of the flexural strength to the compressive strength could be reduced below that of the small-scale concrete that is being used in several model testing projects at the University of Illinois, Urbana.

The study consisted of performing strength tests on concrete specimens in which either a portion of the original aggregate was replaced by larger aggregate (The substitute aggregates used were 3mm glass beads, gap graded sand, and lead birdshot.) or an air-entraining agent was used. For each type of substitute aggregate, tests were conducted with (a) concrete containing the washed substitute aggregate and (b) concretes containing the substitute aggregate coated with graphite and silicone. Also included in the study were two series of tests, using the original small-scale concrete mix, which were performed over a period of 48 days for the purpose of obtaining an indication of the variation of the concrete strength in compression and tension with time.

The entire study was executed using 2 x 4-in. cylinders and 2 x 2 x 8-in. beams.

The conclusions relating to the 12-day tensile strength of the small-scale concretes tested are:

1. The 12-day modulus of rupture could be approximated in terms of the 12-day compressive strength by the expression $f_r = 10\sqrt{f'_c}$.

2. The relationship between the modulus of rupture and compressive strength was not significantly affected by any of the concrete mix variations that were used.

3. Graphite coated aggregate substitutions resulted in basically the same modulus of rupture as the regular aggregate.

4. The 12-day cylinder splitting strength could be approximated in terms of the 12-day compressive strength by the expression $f_{sp} = 7.5\sqrt{f'_c}$.

5. None of the alterations of the concrete mix indicated any significant change in the splitting strength with respect to the compressive strength.

Silicone coating reduced the compressive strength of the concrete but had no effect on the relationship between the tensile and compressive strengths.

The conclusions pertaining to the variation of small-scale concrete strength with time are:

1. Under the same conditions employed in this study, the compressive strength of the small-scale concrete should be near its maximum at 28 days.

2. From 28 to 48 days, there was a slight but significant decrease in compressive strength.

3. Over a period of 48 days, there was a trend for the modulus of rupture to increase with time but at a decreasing rate.

4. A comparison of the trends of the modulus of rupture and the compressive strength indicates that the ratio of the modulus of rupture to the compressive strength was linear with time between 12 and 48 days.

5. Between the ages of 15 to 48 days, there was no significant change in the cylinder splitting strength of the small-scale concrete.

6. Over the testing period of 12 to 48 days, the cylinder splitting strength could be approximated by the expression $f_{sp} = 8\sqrt{f'_c}$.

On the basis of the overall trends observed, it appears that it may be desirable to investigate the effect of the ratio of weights of coarse to fine aggregate. Tests should be conducted with mixes containing larger proportions of coarse aggregate with a noncolloidal graphite coating.

One major trend of the test results should be emphasized: the ratio of the modulus of rupture to the compressive strength increased with time. At 12 days it was approximately $10\sqrt{f'_c}$, not an intolerable value in view of the reduction caused by restrained shrinkage that would be expected in a reinforced specimen. However, at 48 days the modulus of rupture was approximately $15\sqrt{f'_c}$.

TABLE 1

MIX PROPORTIONS BY WEIGHT

Mix	Cement	Fine Sand	Coarse Sand	Gap Graded Pebbles	Glass Beads	Birdshot	Water
1,1G,1S	1		4	1			0.7
2,2G,2S	1	0.6	4		0.4		0.7
3,3G,3S	1	0.6	4			1.68	0.7
4	1	1	4				0.7
5	1	1	4				0.7

TABLE 2

TWELVE-DAY MATERIAL PROPERTIES
OF THE CONCRETE MIXES

Mix	Age Days	f'_c psi	f_{sp} psi	f_r psi	E 10^6 psi
1	12	4530	510	800	3.7+
2	12	4650	550	680	4.0
3	12	4900	470	710	3.5
4	12	5150	540	700	3.7
5	12	4830	530	640	3.75
1G	12	5640	540	770	3.5
2G	12	4920	530	650	3.2
3G	12	4460	450	750	2.5
1S	12	4360	560	720	3.6
2S	12	4020	470	560	3.4
3S	12	3680	430	540+	2.8

f'_c - compressive strength of concrete

f_{sp} - cylinder splitting strength of concrete

f_r - modulus of rupture of concrete

E - initial tangent modulus of deformation of concrete

Values given are the averages of four tests unless otherwise noted.

+Average of three tests

TABLE 3

MATERIAL PROPERTIES OF THE CONCRETES USED IN THE TIME SERIES TESTS

Mix	Age Days	f'_c psi	f_{sp} psi	f_r psi
TST-A	12	3740	430	590
	15	4180	520	570
	21	4510	560	710
	28	4550	520	870
	48	4220	520	940
TST-B	12	3510	420	670
	15	3780	500	640
	21	3590	500	780
	28	4450^{+}	500	830
	48	3730^{+}	550^{+}	950

f'_c - compressive strength of concrete

f_{sp} - cylinder splitting strength of concrete

f_r - modulus of rupture of concrete

Values given are the averages of four tests unless otherwise noted.

$^{+}$Average of three tests

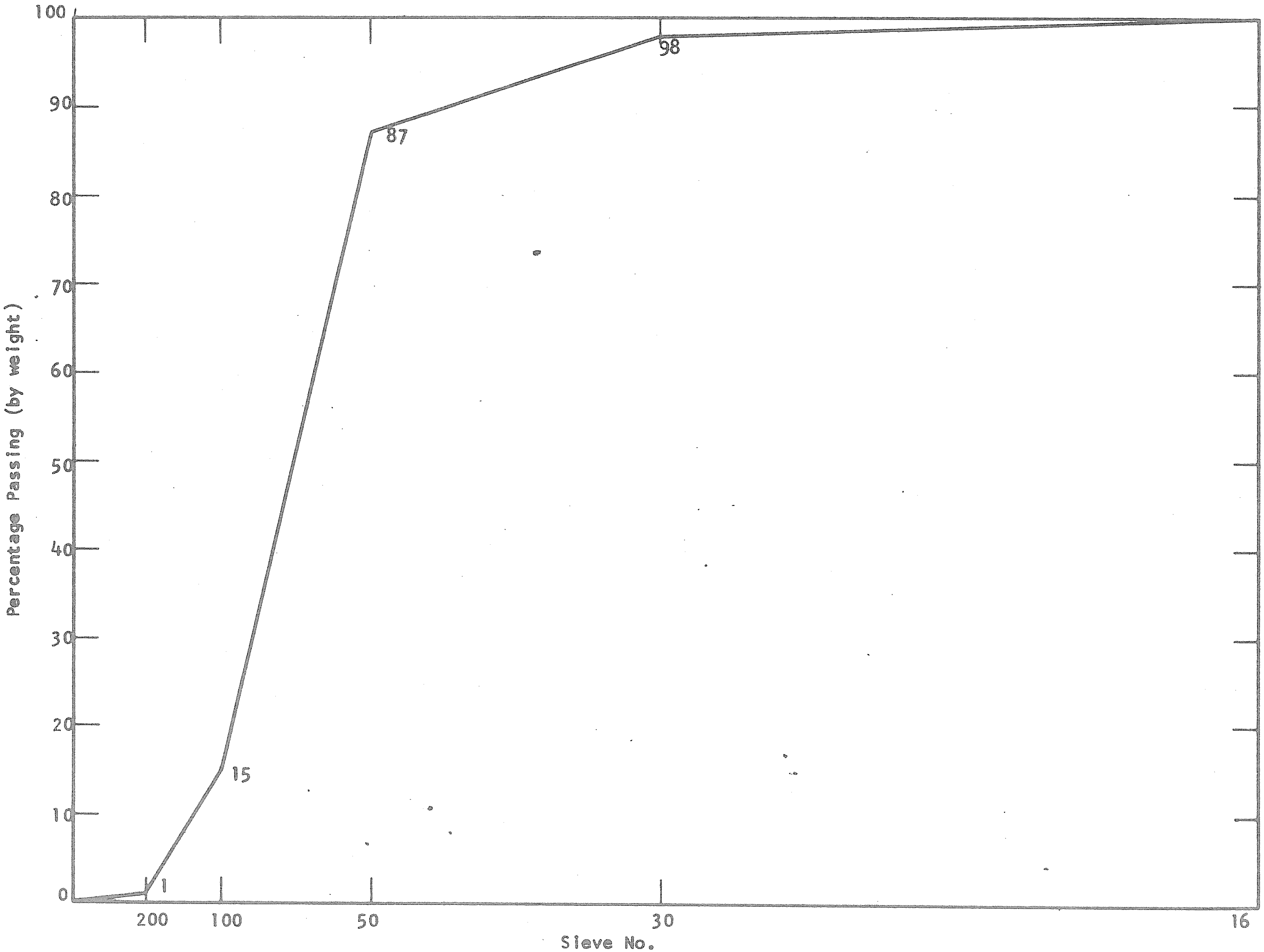


FIG. 2.1 GRADATION OF THE FINE LAKE SAND

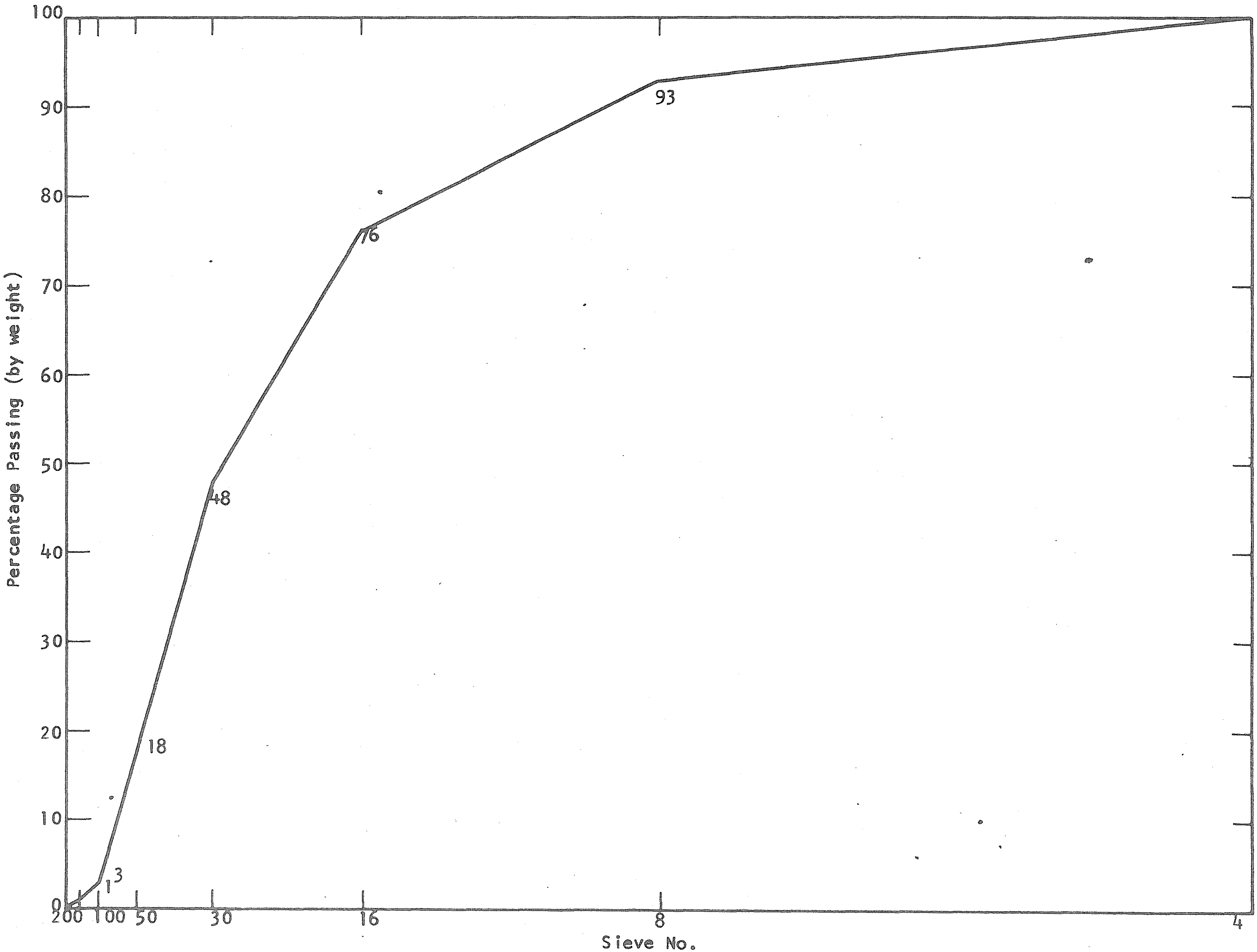


FIG. 2.2 GRADATION OF THE WABASH RIVER SAND

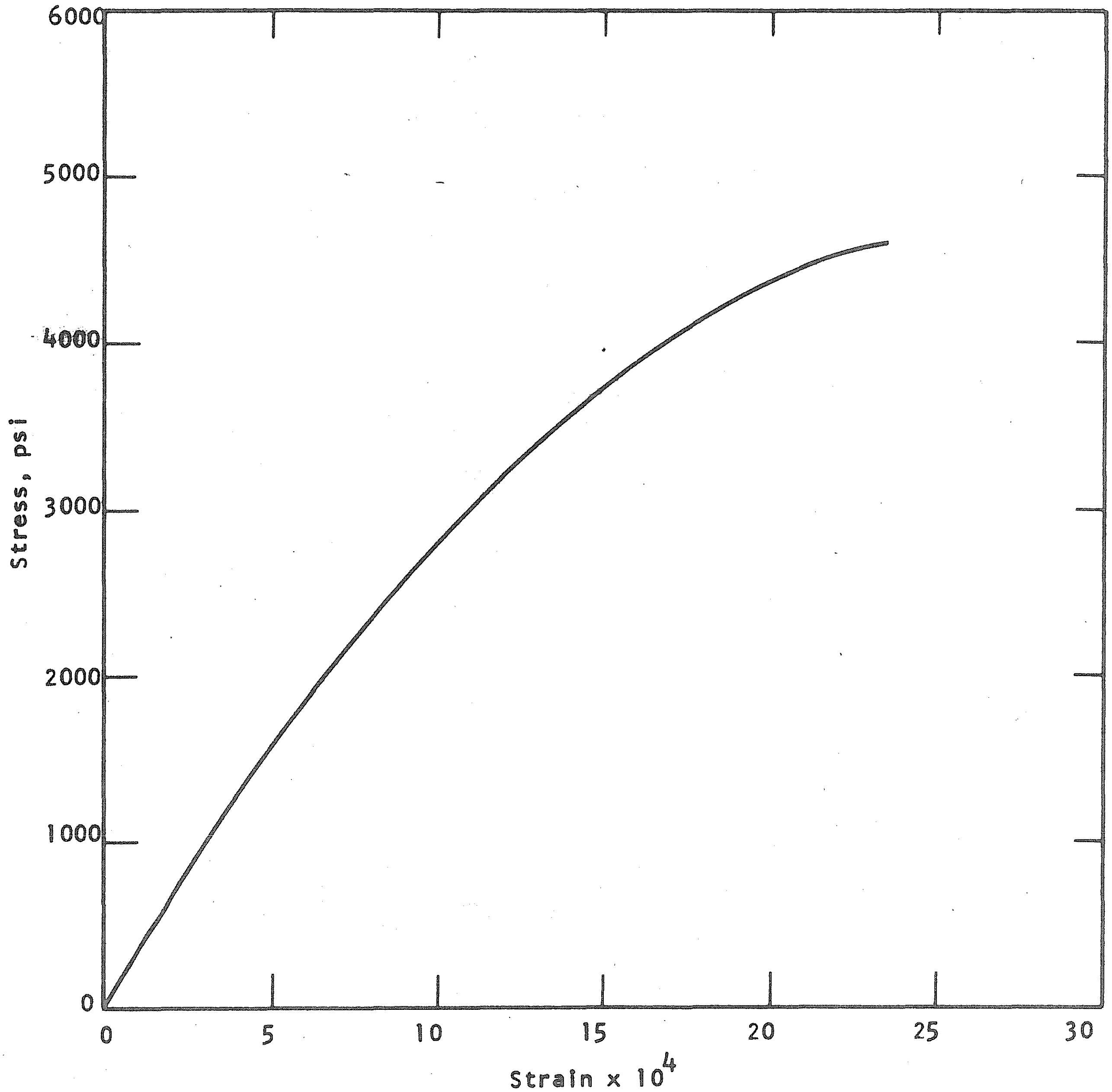


FIG. 3.2 REPRESENTATIVE CONCRETE STRESS-STRAIN CURVE

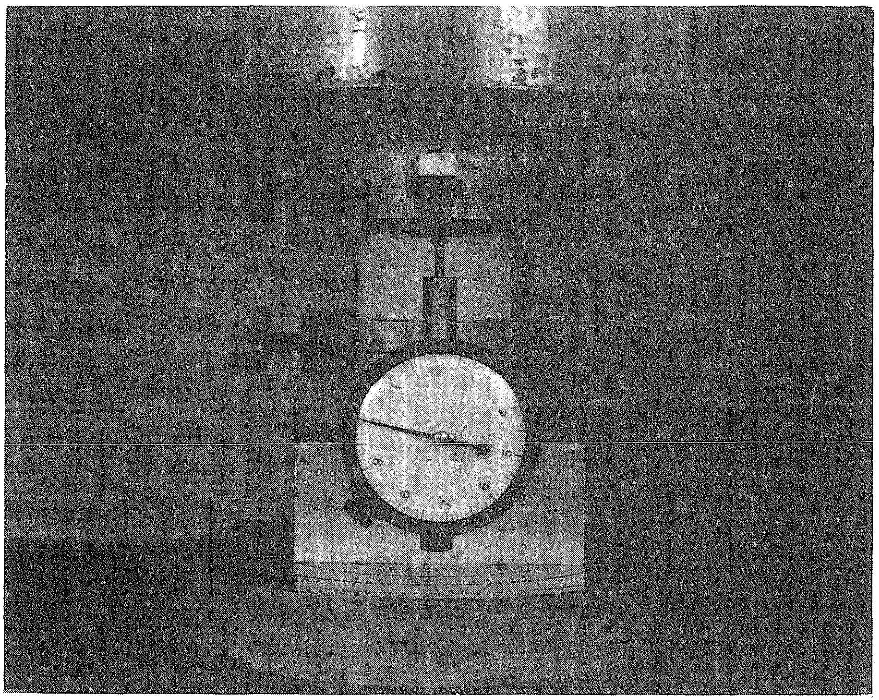


FIG. 3.1 TWO-in. COMPRESSOMETER

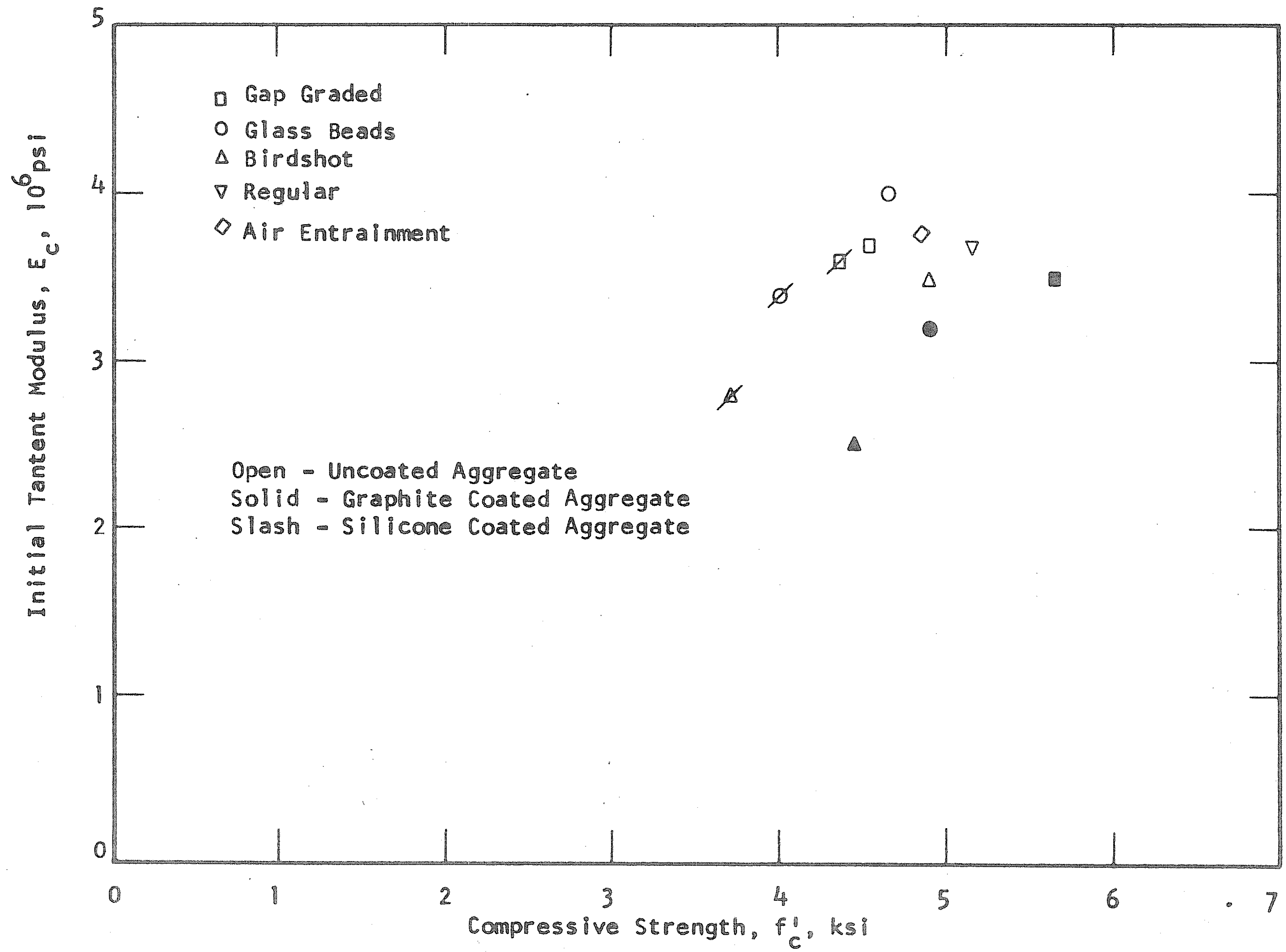


FIG. 3.3 INITIAL TANGENT MODULUS vs COMPRESSIVE STRENGTH FOR THE TWELVE DAY TESTS

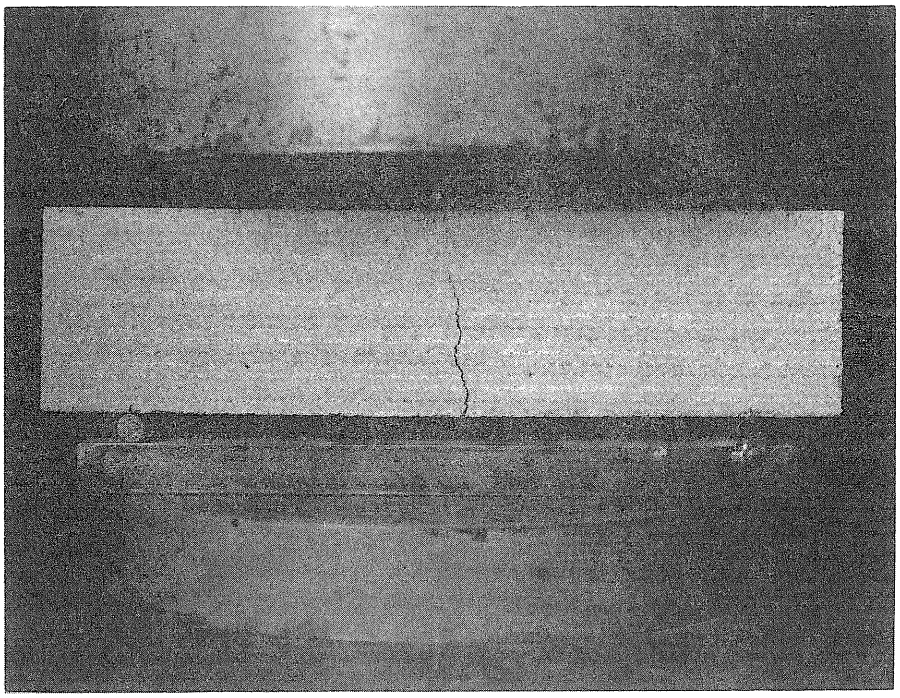


FIG. 3.4 MODULUS OF RUPTURE LOADING FRAME

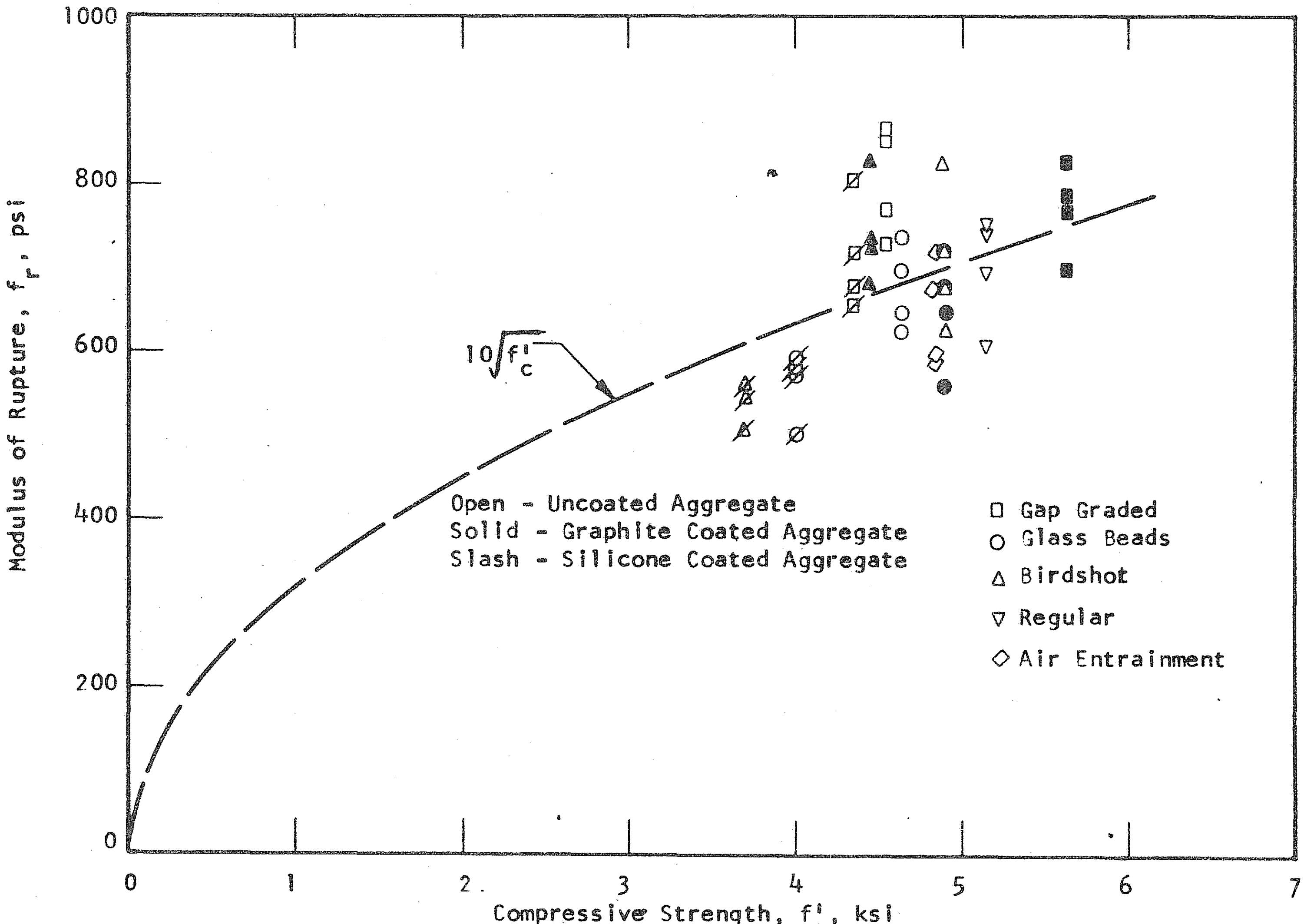


FIG. 4.1 INDIVIDUAL MODULUS OF RUPTURE RESULTS vs COMPRESSIVE STRENGTH AT TWELVE DAYS

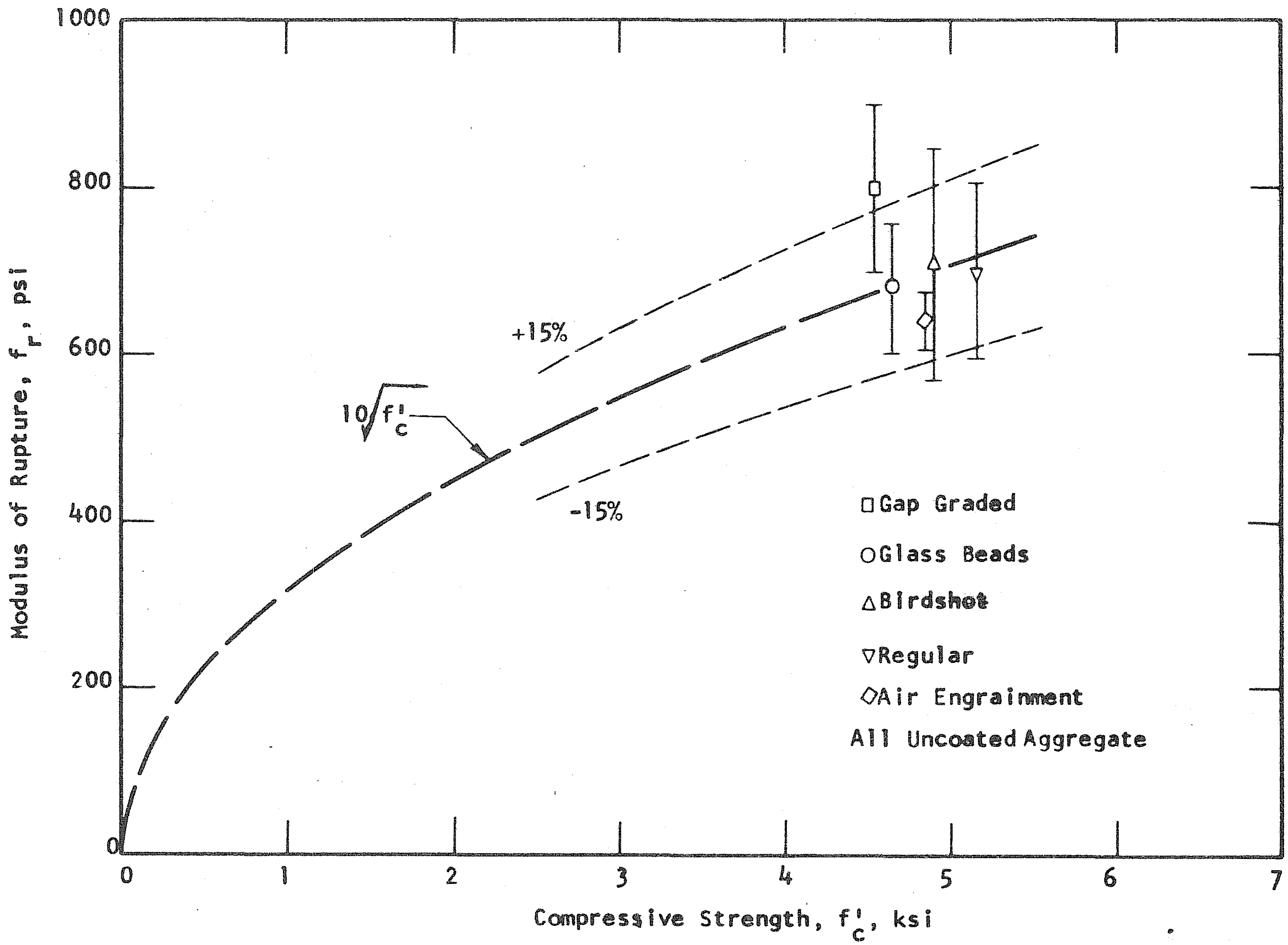


FIG. 4.2 MEAN MODULUS OF RUPTURE AND 95 PERCENT CONFIDENCE INTERVAL OF THE MEAN vs COMPRESSIVE STRENGTH AT TWELVE DAYS FOR CONCRETE MADE WITH UNCOATED AGGREGATE

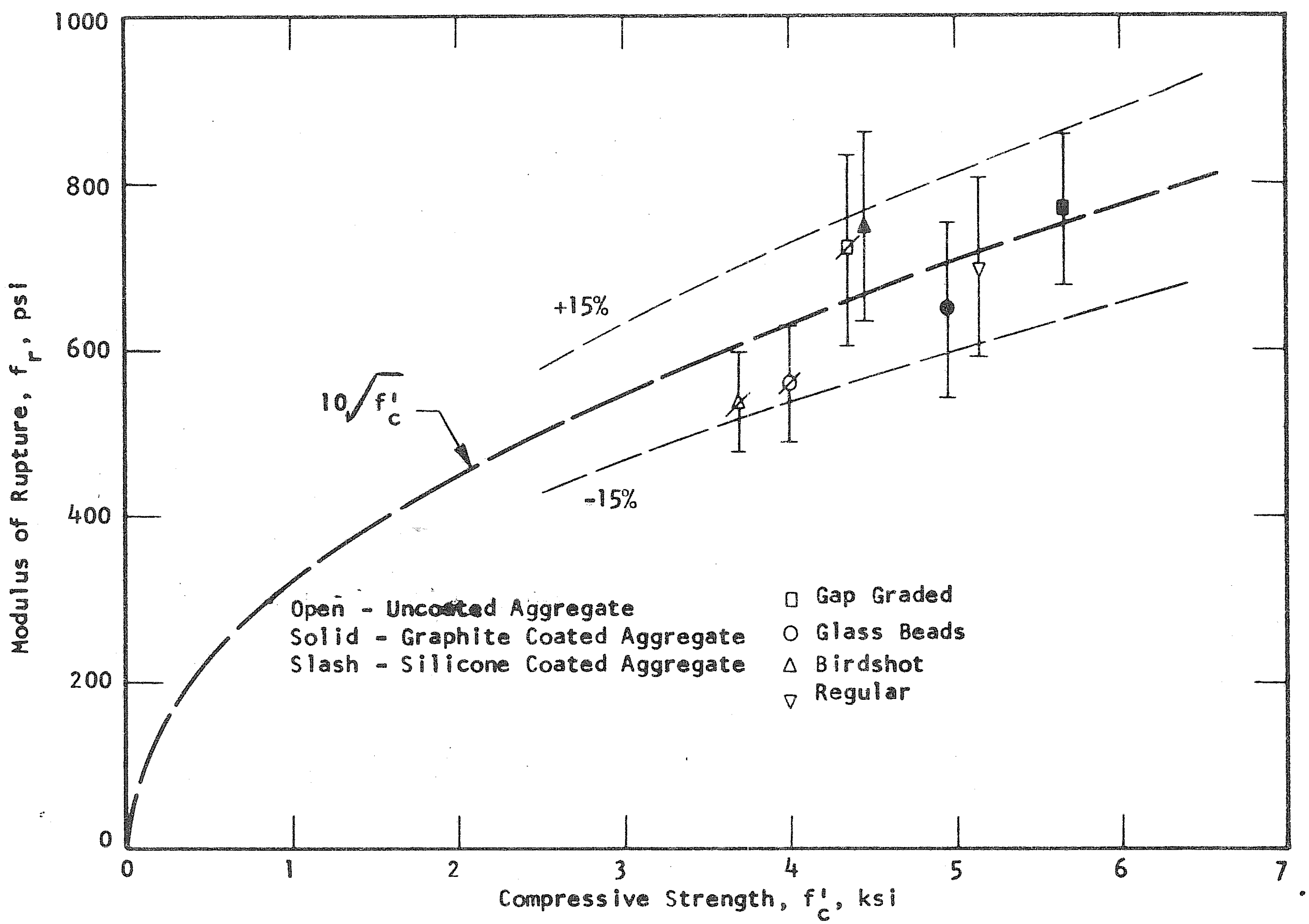


FIG. 4.3 MEAN MODULUS OF RUPTURE AND 95 PERCENT CONFIDENCE INTERVAL OF THE MEAN vs COMPRESSIVE STRENGTH AT TWELVE DAYS FOR CONCRETE MADE WITH COATED AGGREGATE

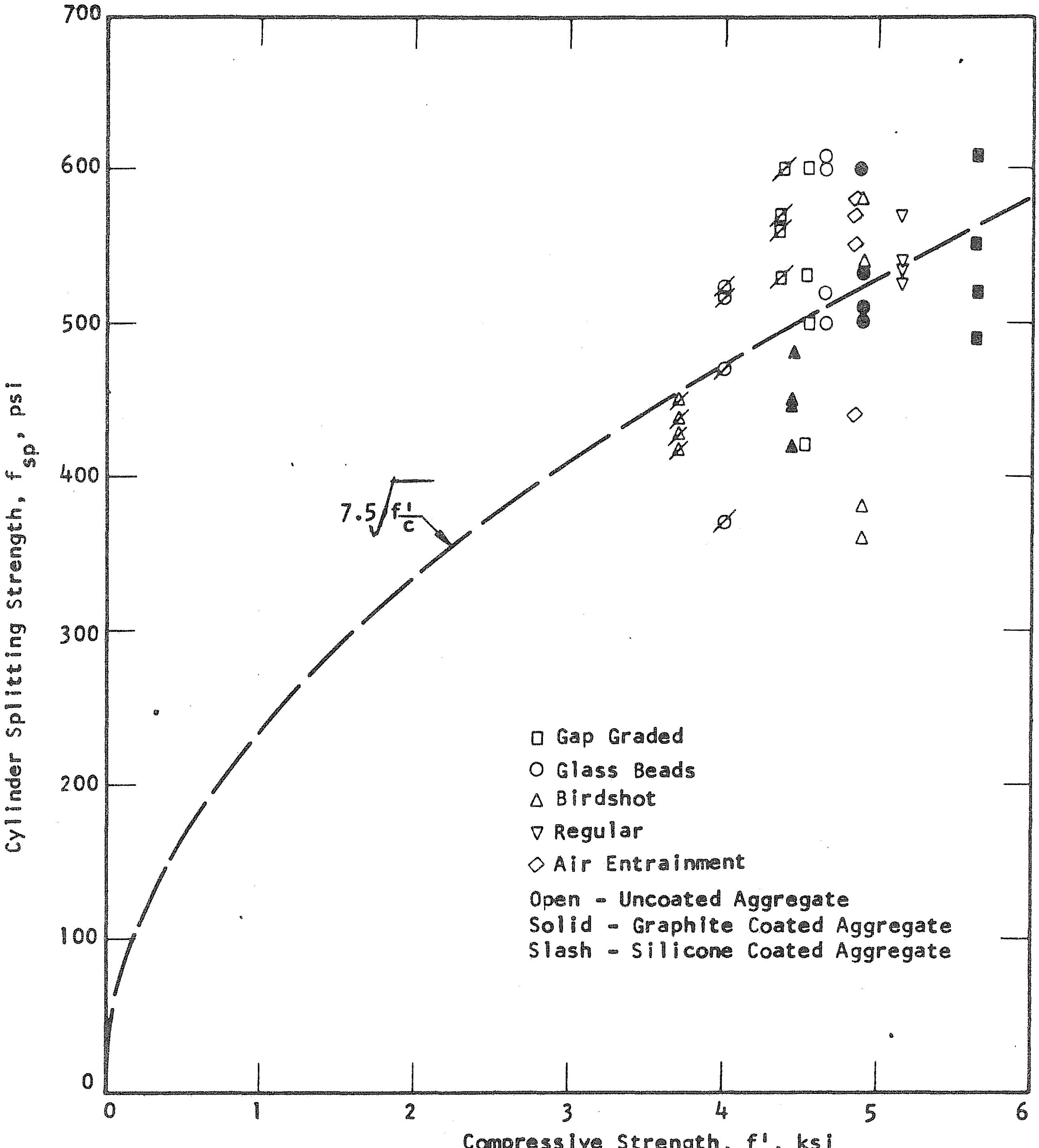


FIG. 4.4 INDIVIDUAL CYLINDER SPLITTING STRENGTH RESULTS vs COMPRESSIVE STRENGTH AT TWELVE DAYS

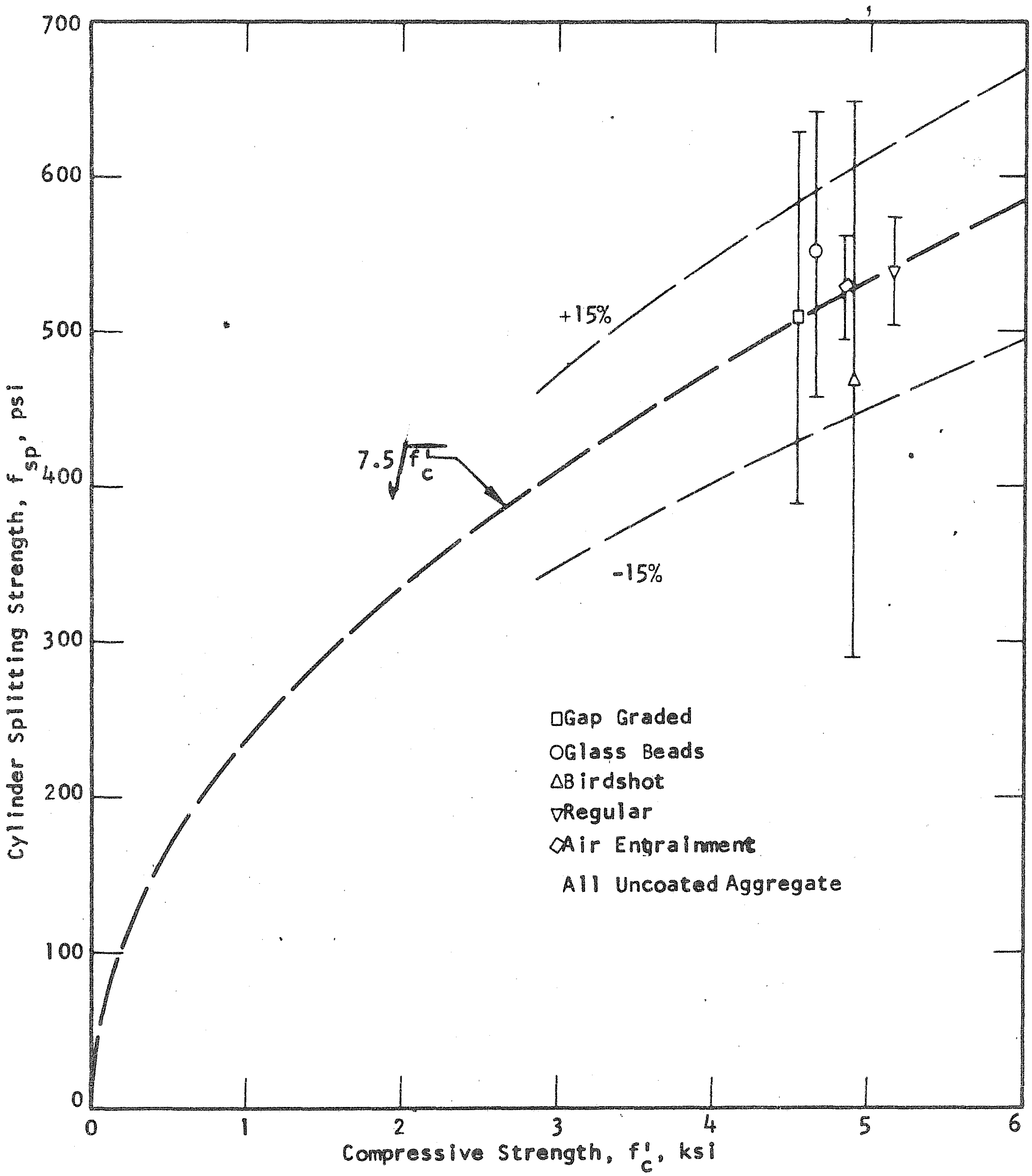


FIG. 4.5 MEAN CYLINDER SPLITTING STRENGTH AND 95 PERCENT CONFIDENCE INTERVAL OF THE MEAN vs COMPRESSIVE STRENGTH AT TWELVE DAYS FOR CONCRETE MADE WITH UNCOATED AGGREGATE

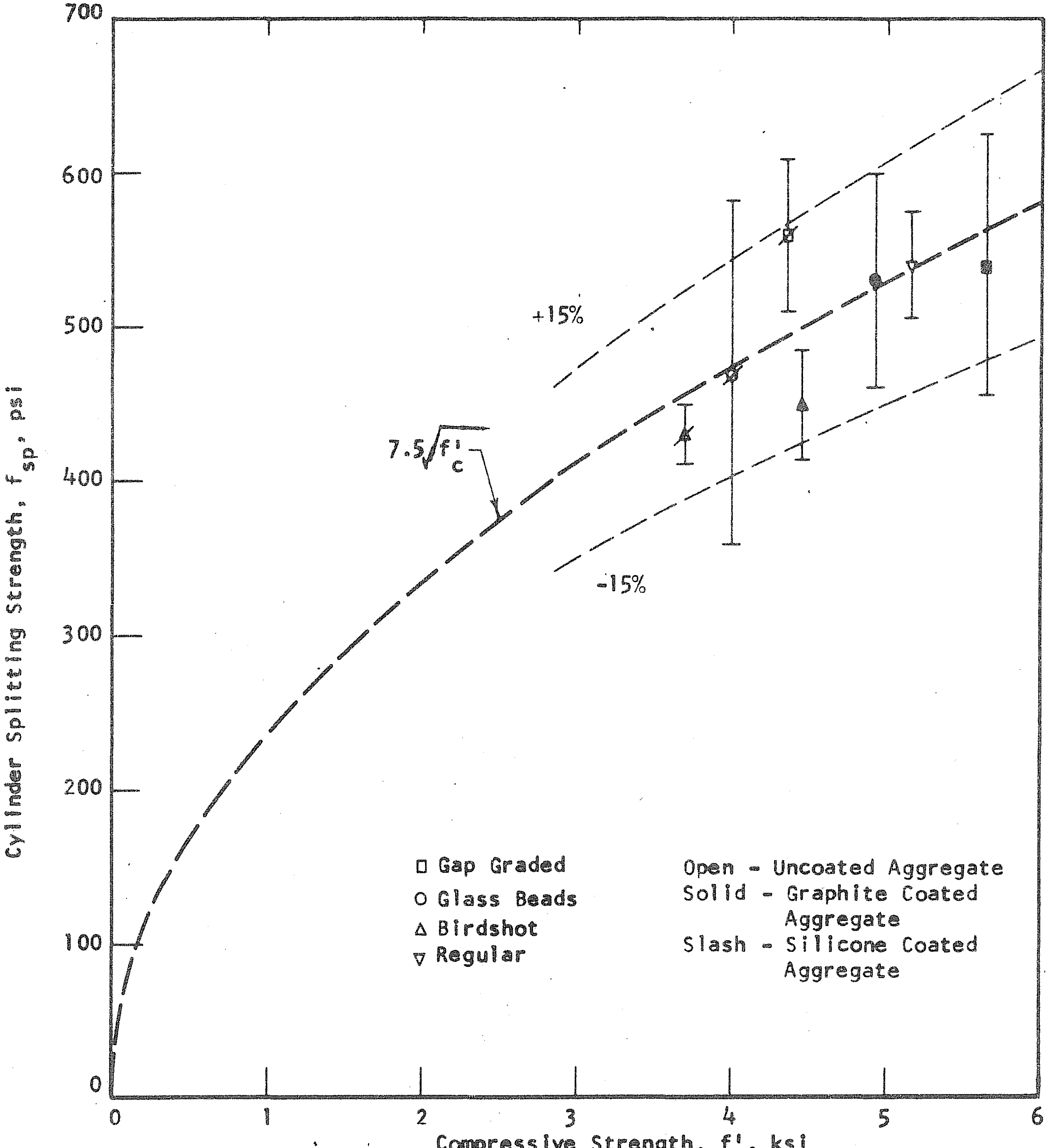


FIG. 4.6 MEAN CYLINDER SPLITTING STRENGTH AND 95 PERCENT CONFIDENCE INTERVAL OF THE MEAN vs COMPRESSIVE STRENGTH AT TWELVE DAYS FOR CONCRETE MADE WITH COATED AGGREGATE

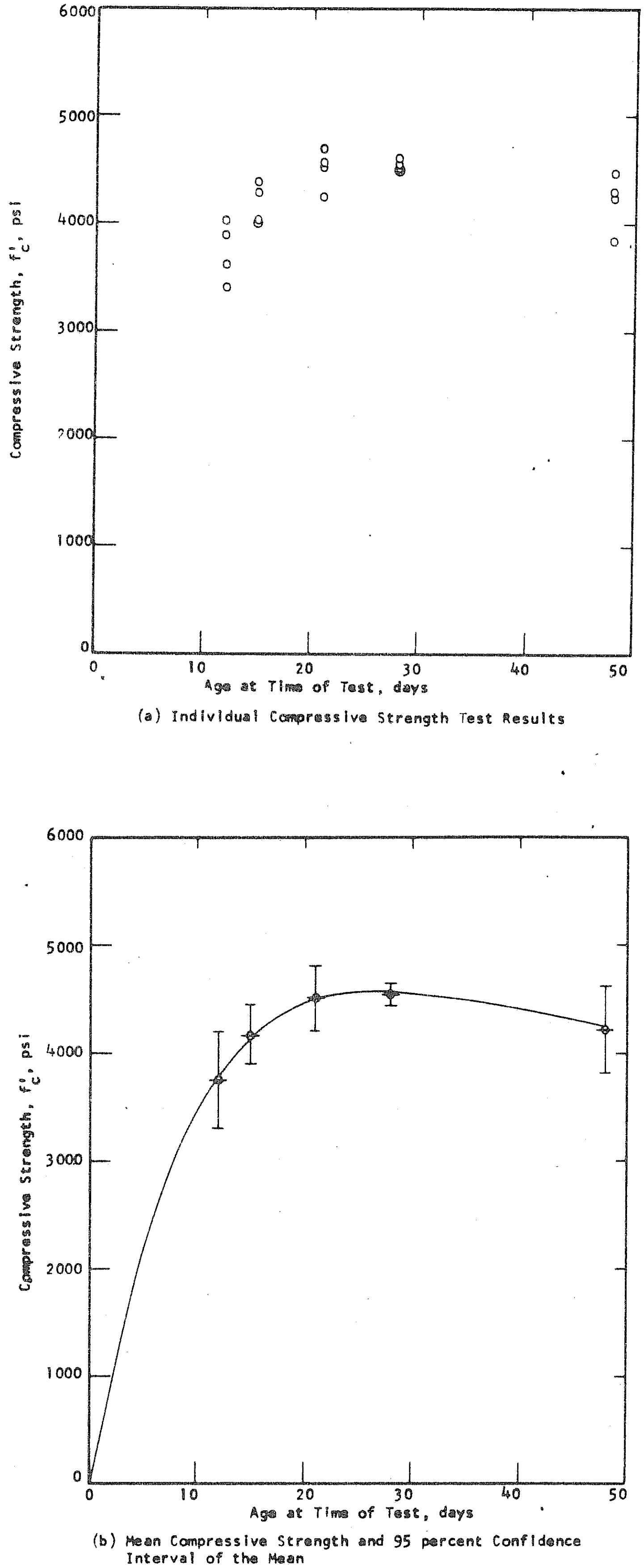
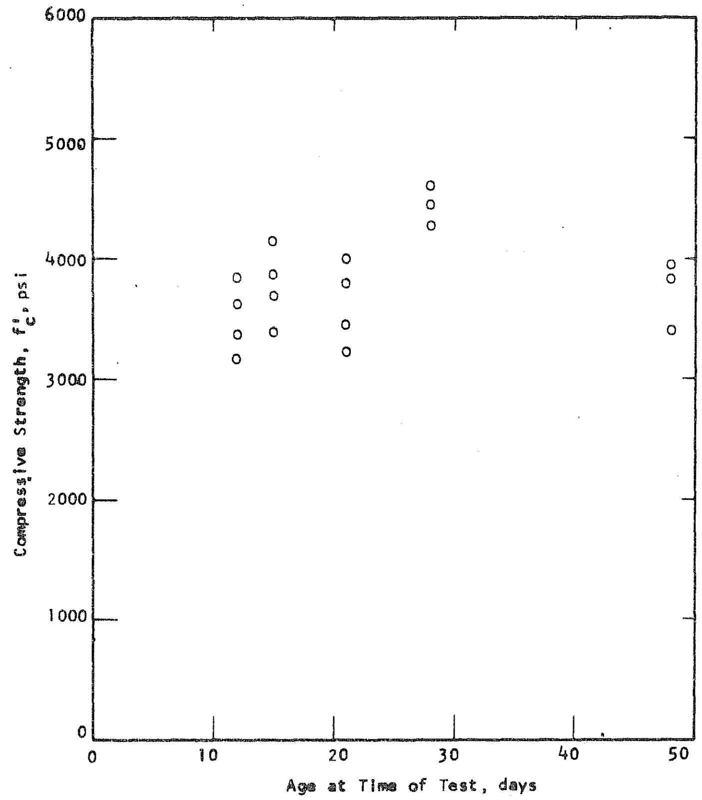
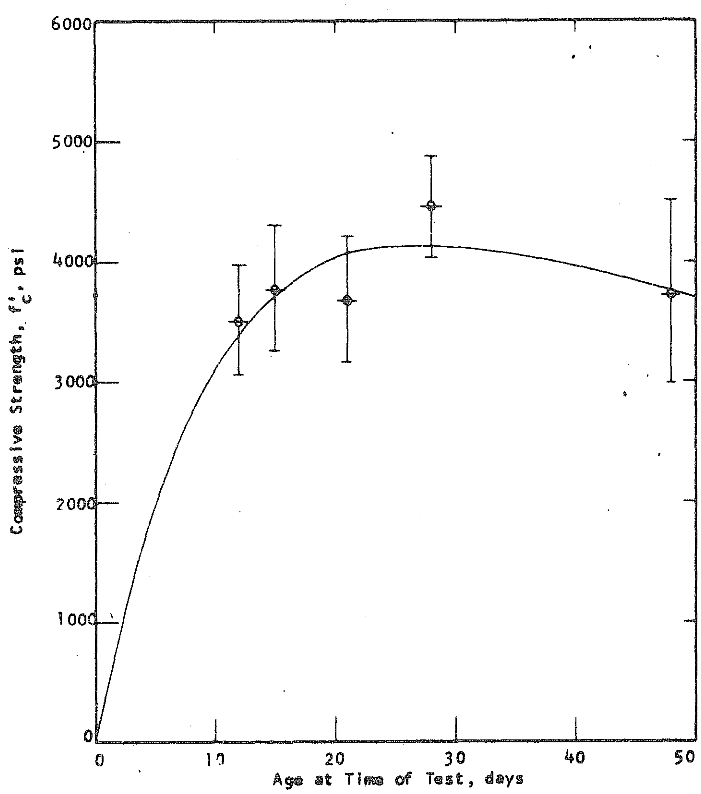


FIG. 5.1 COMPRESSIVE STRENGTH vs THE AGE IN DAYS AFTER CASTING FOR THE TST-A SERIES

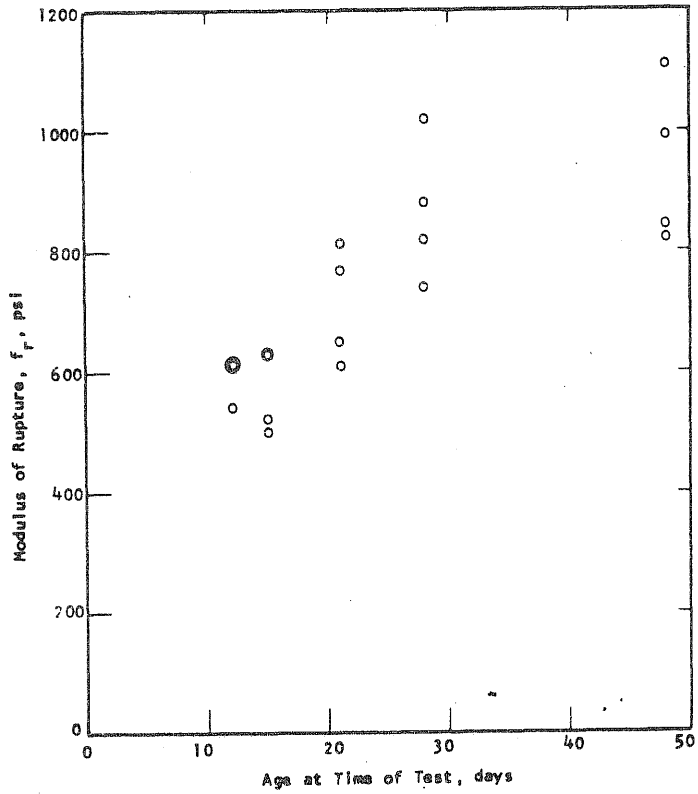


(a) Individual Compressive Strength Test Results

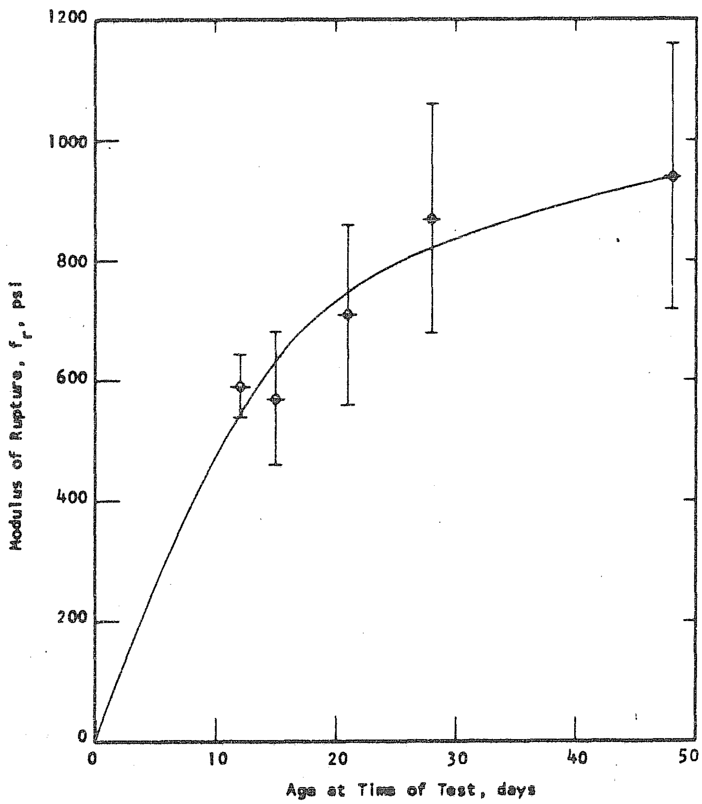


(b) Mean Compressive Strength and 95 percent Confidence Interval of the Mean

FIG. 5.2 COMPRESSIVE STRENGTH vs THE AGE IN DAYS AFTER CASTING FOR THE TST-B SERIES

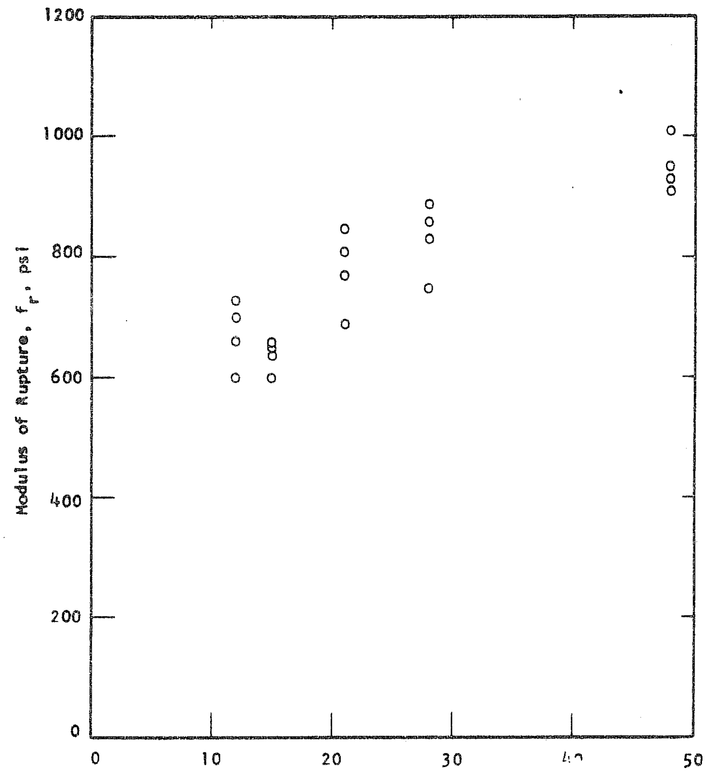


(a) Individual Modulus of Rupture Test Results

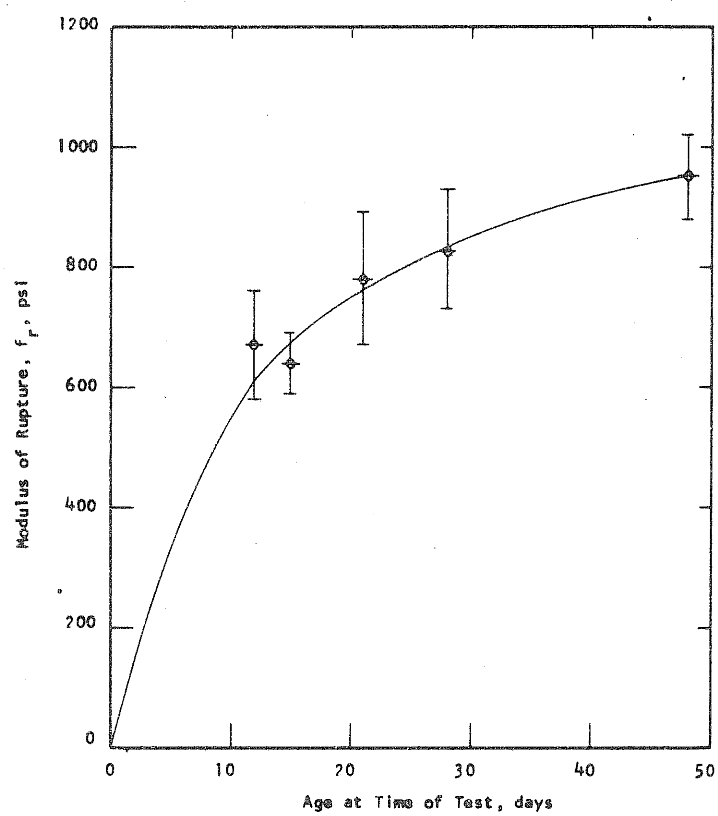


(b) Mean Modulus of Rupture and 95 percent Confidence Interval of the Mean

FIG. 5.3 MODULUS OF RUPTURE vs THE AGE IN DAYS AFTER CASTING FOR THE TST-A SERIES

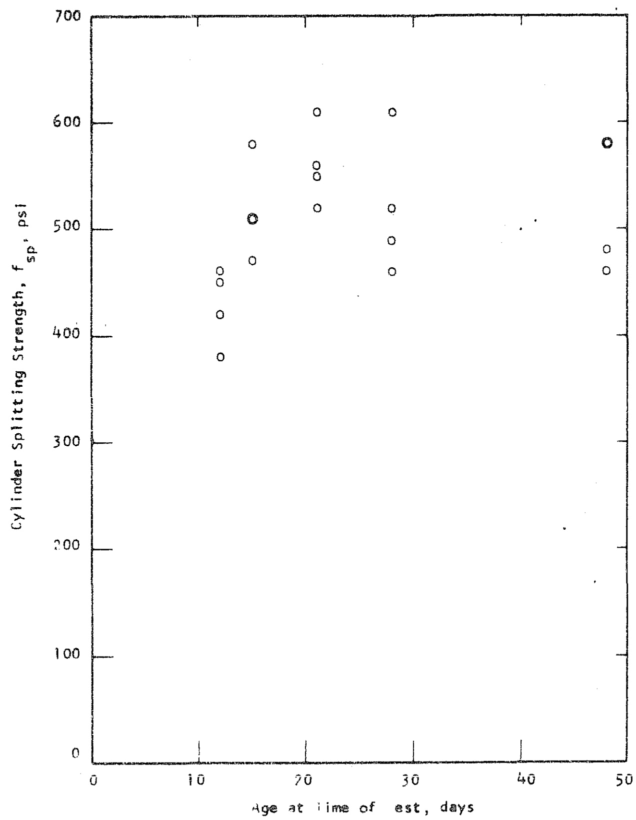


(a) Individual Modulus of Rupture Test Results

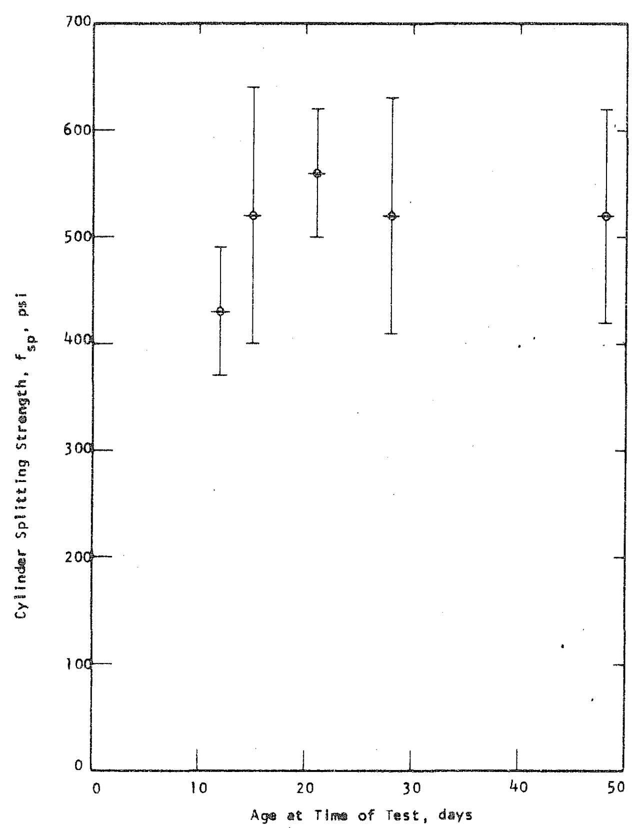


(b) Mean Modulus of Rupture and 95 percent Confidence Interval of the Mean

FIG. 5.4 MODULUS OF RUPTURE VS THE AGE IN DAYS AFTER CASTING FOR THE TST-B SERIES

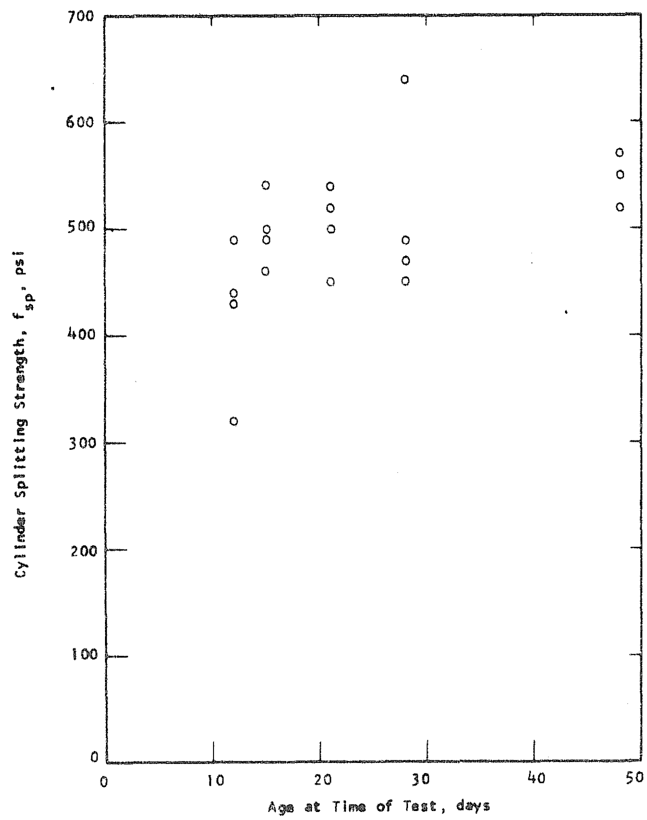


(a) Individual Cylinder Splitting Strength Test Results

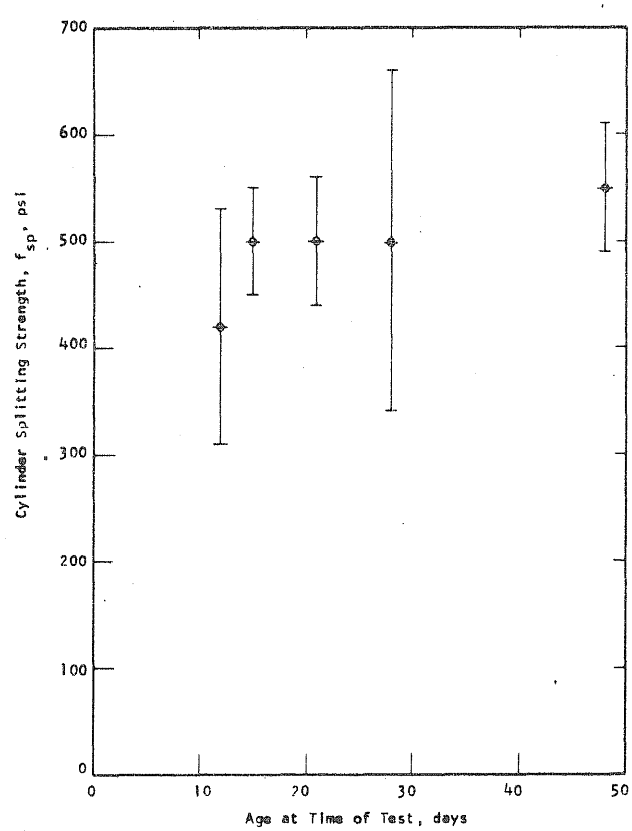


(b) Mean Cylinder Splitting Strength and 95 percent Confidence Interval of the Mean

FIG 5.5 CYLINDER SPLITTING STRENGTH vs THE AGE IN DAYS AFTER CASTING FOR THE TST-A SERIES

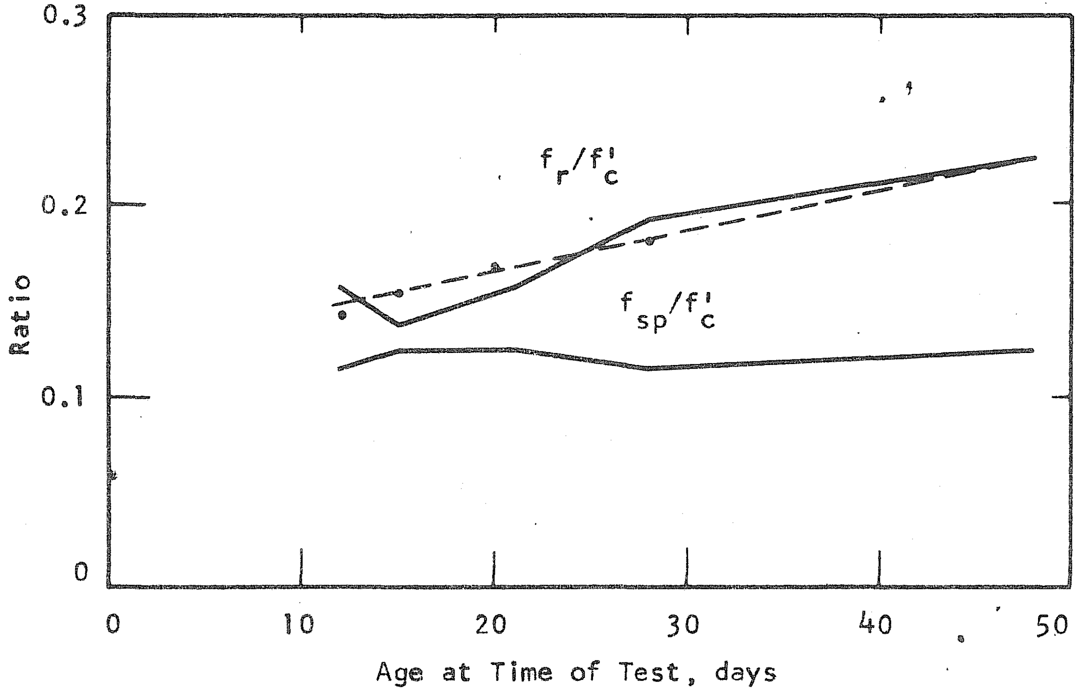


(a) Individual Cylinder Splitting Strength Test Results

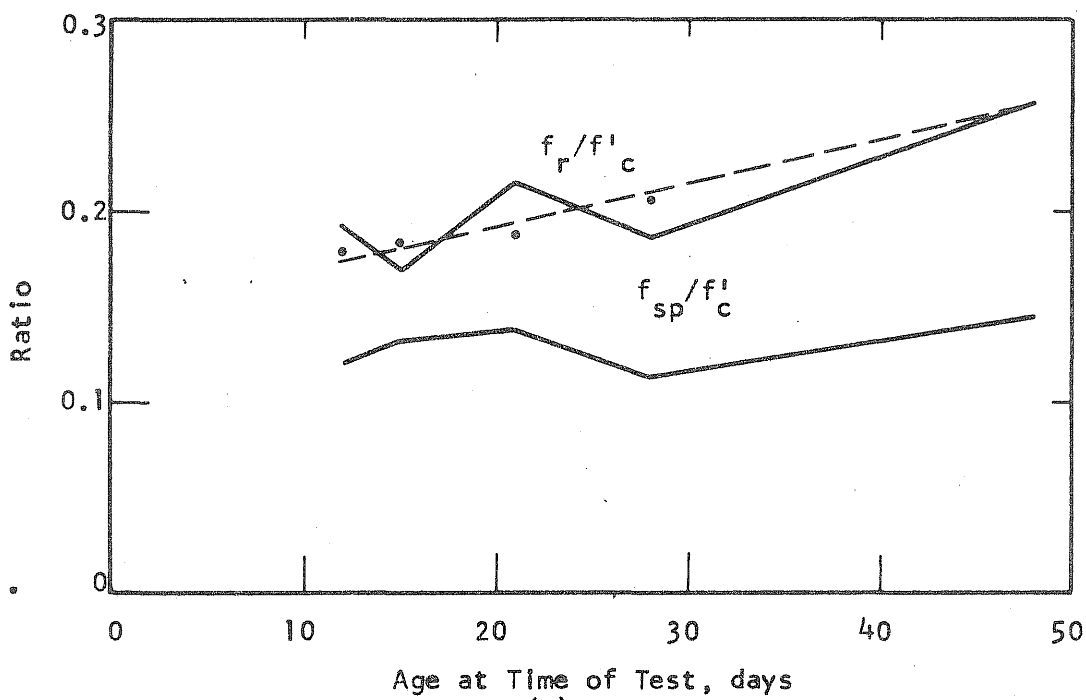


(b) Mean Cylinder Splitting Strength and 95 percent Confidence Interval of the Mean

FIG. 5.6 CYLINDER SPLITTING STRENGTH vs THE AGE IN DAYS AFTER CASTING FOR THE TST-B SERIES

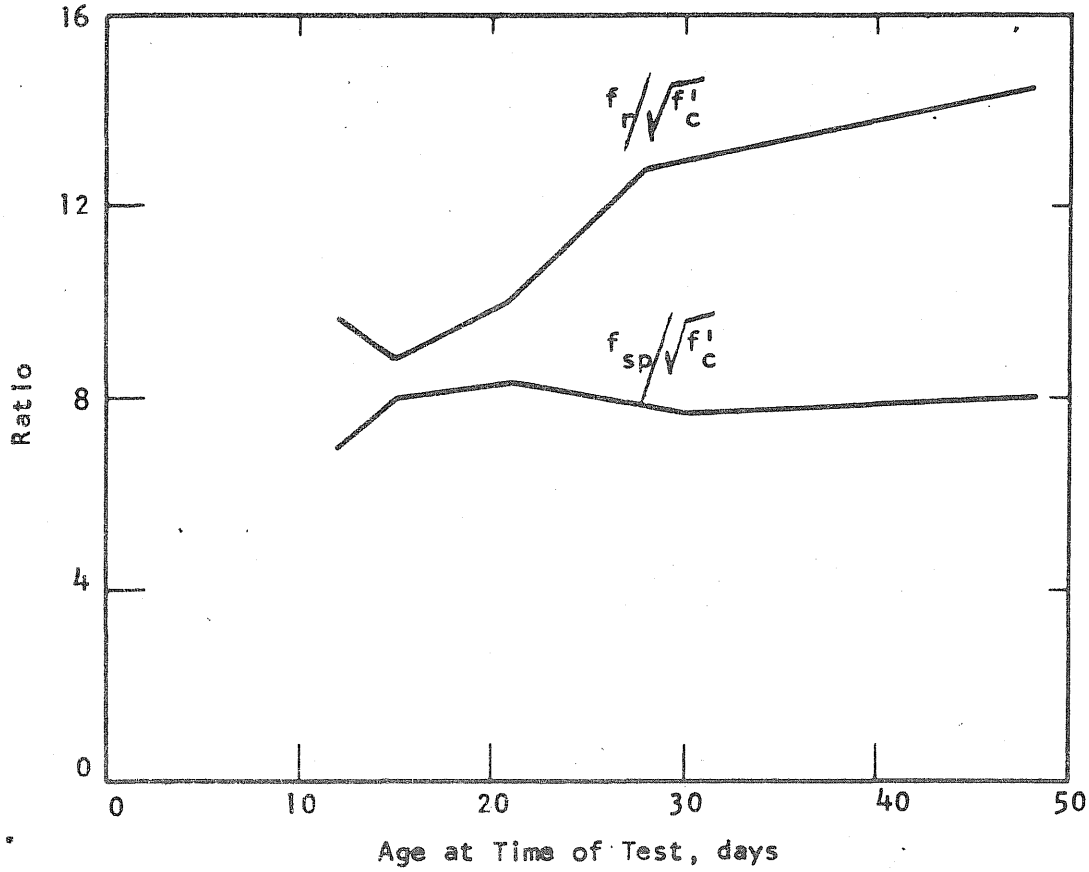


(a) TST-A

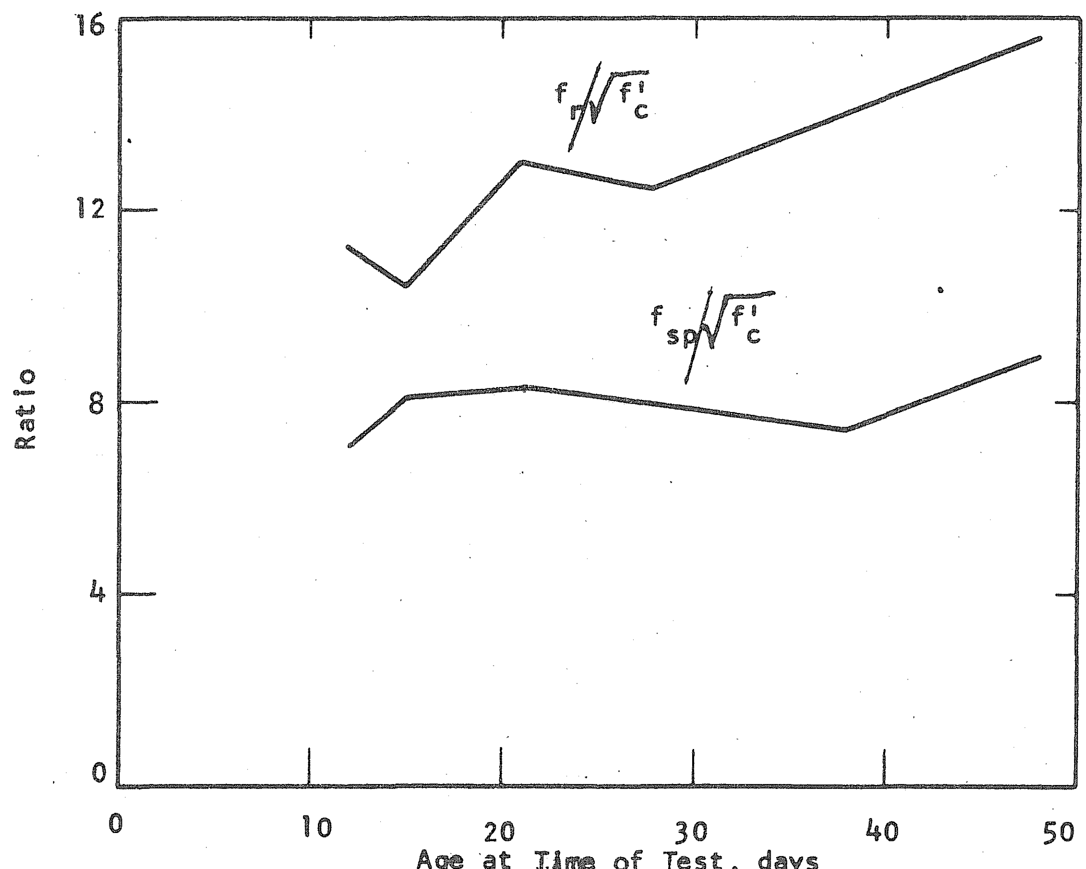


(b) TST-B

FIG. 5.7 A PLOT OF THE RATIOS OF MODULUS OF RUPTURE AND CYLINDER SPLITTING STRENGTH TO THE COMPRESSIVE STRENGTH FOR THE TIME SERIES TESTS



(a) TST-A



(b) TST-B

FIG. 5.8 A PLOT OF THE RATIOS OF MODULUS OF RUPTURE AND CYLINDER SPLITTING STRENGTH TO THE SQUARE ROOT OF THE COMPRESSIVE STRENGTH FOR THE TIME SERIES TESTS