DESIGN AND EVALUATION OF HIGH STRENGTH CONCRETE FOR GIRDERS

Final Report

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Research Report No. FHWA/LA-80/138

State Project No. 736-04-67

Research Project No. 79-2C(B)

Louisiana HPR 0010(003)

Conducted By
LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT
Research and Development Section
In Cooperation with
U. S. Department of Transportation
FEDERAL HIGHWAY ADMINISTRATION

MAY 1980

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METRIC CONVERSION CHART

To convert U.S. units to metric units (SI), the following conversion factors should be noted:

Multiply U.S. Units	By	To Obtain Metric Units
inches (in)	2.5400	centimeters (cm)
feet (ft)	0.3048	meters (m)
yards (yds)	0.9144	meters (m)
square inches (in^2)	6.4516	square centimeters (cm^2)
square feet (ft^2)	0.0929	square meters (m^2)
square yards (yd^2)	0.8361	square meters (m^2)
cubic inches (in^3)	16.3871	cubic centimeters (cm^3)
cubic feet (ft^3)	0.0283	cubic meters (m^3)
cubic feet (ft^3)	28.3168	liters (l)
cubic yards (yd^3)	0.7646	cubic meters (m^3)
pounds (lbs)	0.4536	kilograms (kg)
pounds (lbs)	453.592	grams (g)
gallons (gal)	3.7854	liters (l)
pounds per square inch (p.s.i.)	0.0703	kilograms per square centimeter (kgs/cm^2)

ABSTRACT

A research study was initiated to establish mix designs, and to make, test and evaluate concrete in a strength range of 6500 psi. This study included both laboratory and field evaluations. This high strength concrete is required for the newly designed prestressed girders on the elevated portion of the Westbank Expressway construction project in the New Orleans area.

The scope of the study was to make concrete mixes in the laboratory using a partial factorial, with three cement contents, two coarse aggregates and three fine-to-coarse aggregate ratios. The mixes showing the best properties and highest compressive strengths were repeated for several test repititions to determine if these strengths could be obtained consistently. The concrete using limestone did consistently make the high strengths, while concrete using pea gravel did not consistently make the high strengths.

With these results in hand, field trials were begun at a casting yard first, with a preliminary field trial on a normal production run of prestressed girders, where such a compressive strength was not necessarily needed. The reason for this trial was to see if the particular concrete mix would present any field problems and to get some idea of the strengths obtained in a field production mode using steam and air curing for the concrete. This was successful; however, a pea gravel concrete mix did not give the required high strengths.

Later, the final field trials included pouring six dummy girders (exact 8 ft. long sections of the newly designed girder) using a concrete design with 8.0 bags of cement per cubic yard, two of the girders using limestone coarse aggregate, two others using regular Class A gravel coarse aggregate and, finally, two using small size pea gravel coarse aggregate. The primary purpose was to evaluate the flowability and vibration of the concrete, the consistency of the mixes and closeness of this steel, resulting in the possibility of honeycombing or voids in the concrete and problems with the finish of the girders.

The prime conclusion reached on this research study was that high strength concrete (minimum compressive strength of 6,500 psi) can be obtained in a production mode. Also ASTM #7 stone gradation limestone coarse aggregate is the best material of the several tested for acquiring consistent high strengths in these mixes. The prime recommendations set forth from the study were (1) a set of guide specifications with the changes in the Class P(M) specifications in the form of special provisions (found in the Appendix), to the construction project and, finally, (2) that both gradation limestone and the regular Class A gravel coarse aggregate be considered as alternates for this concrete.

After all the pours were made and all the strength results were recorded, a set of guide specifications were written following the observations and recommendations formulated during the study.

These guide specifications were given to the consulting engineers for their use in submitting a package of plans and specifications to the Department for review and approval. This is the beginning of the implementation process on this project.

IMPLEMENTATION

Recommendations for specifications for high strength concrete for the newly designed prestressed girders on the Westbank Expressway construction project are in the process of being implemented. The recommended changes to the Class P(M) specifications by special provisions on this project have been given to the consulting engineers. They will, in turn, present a package of plans and specifications to the Department for review and approval. The implementation will be accomplished on this construction project.

A follow-up will be made on the actual field construction strengths on the West Bank Expressway construction project for any upgrading, modification, etc. of the Standard Specifications.

INTRODUCTION

The Louisiana Department of Transportation and Development has in its bridge design plans a new design for a high strength prestressed girder to be used on the elevated portion of the West Bank Expressway, State Project No. 700-09-19. In order to have this girder produced and used, the Department had to determine if the required high strength concrete could be consistently obtained.

A research study was, therefore, introduced to investigate the possibility of achieving this high strength in concrete under certain specified conditions. Research was required for the design and use of high strength concrete, particularly under Louisiana conditions and using local, or easily obtainable, satisfactory aggregate. The effect of these conditions and aggregate on this type concrete was to be determined.

PURPOSE AND SCOPE

The purpose of this research study was to make, test and evaluate concrete mix designs that should be capable of consistently producing high strength concrete. These concrete mix designs were to be made under certain constraints and specifically designed to obtain high strength. The concrete strengths were to be verified in the field and then guide specifications, specifically for concrete for the new design high strength girders on the West Bank Expressway, were to be recommended. The laboratory strength goal was set at 7500 psi compressive strength after 28-days of moist curing, in order to assure that a field f'c strength of 6500 psi could be obtained under a combination of steam and air curing at 28-day age, or earlier if possible.

The scope of the study was to make concrete mixes in the laboratory using a partial factorial, with three cement contents, two coarse aggregates, three aggregate ratios of fine aggregate (FA) to coarse aggregate (CA) and mixes both with and without air; to test concrete cylinders for 28-day compressive strengths after 28-day moist curing, to evaluate results and to recommend suitable mix designs for field trials. After field trails, an evaluation of all compressive strength results and other contributing information was to be made, and recommendations for the implementation of specifications for concrete for high strength concrete girders were to be made.

The principal constraint of the effort was to achieve higher strength mechanically (aggregates) and through cement controls <u>not</u> to use added strength enhancers like super water reducers or polymers.

METHODOLOGY

Prior to this structured research project, several attempts were made by others to obtain high strength concrete resuls, using La. DOTD regular specification gravel and also using small size pea gravel with various mix designs and normal water reducers. These attempts were very limited and were not successful.

The research study described herein consisted of three phases: Phase I was the laboratory testing and mix design phase; Phase II was the preliminary casting and field testing phase, when a plan change was made for casting some prestressed concrete girders for a state construction project using a recommended high strength concrete mix design; and Phase III was the final casting and field testing phase, when "dummy" girders were cast under the same conditions as would normally be present when casting the actual full-sized girders, using several types of coarse aggregate with the several recommended mix designs. "Dummy" girders, herein referred to, are girders with actual cross-sectional dimensions, steel requirements and ties, but only eight feet in length, thus giving the same problems in pouring the concrete, vibration of the concrete and the flowability of the concrete, but on a smaller scale.

Phase I, Laboratory Phase -

Two coarse aggregates were included in the study to be tested, a pea gravel basically passing the 1/2-in. screen and retained on the No. 4 screen and a crushed limestone of the same gradation. Three cement contents, 7.5, 8.0 and 8.5 bags cement per cubic yard, and three aggregate ratios, (FA/CA) 36-64, 40-60 and 45-55, were included in the study variables. A partial factorial was used because there were some mixes in the block diagram, primarily those with air-entrainment that were not included. The slump range aimed for in all the mixes was 2-3 inches. The assumed air content range for the mixes without air-entrainment was 1.5-3.0%, while that assumed for the mixes with air-entrainment was 2.5-5.0%. An approximate water-cement ratio of 0.36, as determined from a literature search, was used as a guide with normal water reducing admixtures being used on all mixes.

A partial factorial block diagram for the mix designs that were tested in this study is shown below in Table 1.

TABLE 1

PARTIAL FACTORIAL BLOCK DIAGRAM

MIX DESIGNS

	"Pea" Gravel Passing 1/2", Retained No. 4, 2"-3" Slump, Water Reducer					
Cement Content, Bags/cu.yd.	Aggregate Ratio FA-36 CA-64		Aggregate Ratio FA-40 CA-60		Aggregate Ratio FA-45 CA-55	
	No Air*	Air**	No Air*	Air**	No Air*	Air**
7.5	Mix		Mix		Mix	
8.0	Mix	Mix	Mix	Mix	Mix	
8.5	Mix		Mix	Mix	Mix	
	Limestone Passing 1/2", Retained No. 4, 2"-3" Slump, Water Reducer					
Cement Content, Bags/cu.yd.	Aggregate Ratio FA-36 CA-64		Aggregate Ratio FA-40 CA-60		Aggregate Ratio FA-45 CA-55	
	No Air*	Air**	No Air*	Air**	No Air*	Air**
7.5	Mix		Mix		Mix	
8.0	Mix	Mix	Mix	Mix	Mix	
8.5	Mix		Mix	Mix	Mix	

*No air, non-entrained air, from 2% to 3%.
**Air, air-entrained air, from 4% to 5%.

Plastic concrete tests were made for slump, air content and unit weight determinations. Six 6 in. x 12 in. concrete cylinders were cast for each mix for compressive strength breaks at 28-day age. Half of the cylinders were molded on a vibrating table, while the other half were molded by rodding according to ASTM: C-192. All specimens were moist cured in the 100% relative humidity room for 28 days, then tested for 28-day compressive strengths as by ASTM: C-39. Comparisons were made for results obtained on the vibrated cylinders against results obtained on the rodded cylinders. Results and comparisons of vibrated and rodded cylinders were inconsistent, and no definite conclusions could be discerned; therefore, no further mention of vibrated cylinders will be made in this report, nor reflected in the Tables or Figures. No further work was done with vibrated cylinders.

After completion of the testing on the factorial block diagram mixes, several mixes that appeared to give the best strength results were chosen to run repetitive mixing and testing for 28-day strengths. These mixes were run on consecutive days for four days, and results were compared for repetitive values and also compared to previous results.

Phase II, Preliminary Field Phase -

In order to determine if these strength values and proper workability could be obtained in a field pour, a plan change was instituted for the casting of twenty-four (24) Type III prestressed concrete girders for use on a construction project. This project was State Project No. 829-12-09, Gibson-Raceland Highway (La. 653 over U.S. 90), State Route 653, Lafourche Parish.

Specification changes for the experimental pours of Class P concrete, high strength concrete, cast at the Mandeville, Louisiana prestress plant were as given below:

All physical requirements of the existing specifications for Class P concrete will be met. In addition, the following requirements will also be met:

1. Normal water reducers only will be allowed. No air entrainment nor other admixtures are to be used including super plasticizers.
2. Type 1, Type 1(B) or Type II cement can be used as is the present allowance for Class P concrete.
3. The minimum cement content shall be eight bags of cement per cubic yard.
4. The maximum water content shall be 32.5 gallons per cubic yard with an allowable slump range of two inches minimum to four inches maximum.
5. The Departments presently specified fine aggregate shall be used. The Department's normally specified coarse aggregate shall be deleted and the following gradation substituted therefor.

Sieve Size	Percent Passing
3/4"	100
1/2"	90 - 100
3/8"	40 - 70
No. 4	0 - 15
No. 8	0 - 5

6. All acceptance testing will be done by construction personnel in conformance to existing sampling requirements. However, no statistical lot averaging shall be done for the four experimental pours."

Six girders were cast for each of four separate pours. Research personnel molded eighteen 6 in. x 12 in. concrete cylinders for each pour, with three being molded from each girder. Of these three cylinders made from each girder, two were made in steel molds, while the other one was made in an approved cardboard mold as data was desired concerning the possible effect of cylinder molds on strength. An air content determination and a unit weight were made on each pour, and slump tests were made at intervals on each pour.

The twelve cylinders made in steel molds were steam cured as for the girder line, then after a detensioning compressive strength was obtained, the remaining cylinders were air cured as for the girder line. Four cylinders made in steel molds were broken for the detensioning break, four more cylinders were broken at varying times, from six to seventeen days, depending on when it was thought that an ultimate strength could be obtained, that is, the 5000 psi Class P requirement for strength. The remaining four cylinders made in steel molds were air cured until the 28-day age, then broken for 28-day strength results.

The six cylinders made in cardboard molds were brought back to the laboratory and moist cured in the 100% relative humidity room. Three cylinders were broken at the time of the ultimate strength breaks for the cylinders in the steel mods, and the remaining three cylinders were broken at 28 days.

Construction inspection personnel also made cylinders and these cylinders were broken for acceptance of the girder for the state project. All results were compared for strength values at the varying ages and for strength gain or time of required strength acquisition. A comparison of strengths was made between steel molded cylinders (steam and air cured) and cardboard molded cylinders (moist cured). The strength comparisons can be found in Table 7 on page 20.

Phase III, Final Field Phase -

Again, as in Phase II, in order to determine if these high strength values, proper aggregate, adequate slump and proper workability could be obtained in production mode on the proposed design girders, a letter agreement was negotiated for some experimental concrete pours.

A "dummy" girder steel form was designed, fabricated and set up to manufacture six (6) separate girders in a production mode, as explained in the letter agreement quoted below.

The pertinent part (first six paragraphs) of the letter agreement between the Department and Prestressed Concrete Products Co., Inc. of Mandeville, Louisiana is given below:

> Prestressed Concrete Products Co., Inc. agrees to undertake casting at our plant of experimental test girders of the section and type proposed for State Design Project 700-09-19, West Bank Expressway, using experimental high strength concrete. The basic scope of the work is to cast approximately six short representative girder sections using three aggregates (regular Class A gravel, pea gravel, and fine limestone coarse aggregates) with each different aggregate's concrete being cast at two water contents or consistencies. Each girder segment is to be approximately eight feet in length and contain approximately four cubic yards of concrete. Each girder segment is to be cast in accordance with the two plan sheets attached for the full girder section with each segment being that portion of the girder approximately twenty feet from the girder end and containing stirrups at nine-inch maximum spacing. Each girder segment is to be full size except for length and will contain all reinforcing steel and strands of the proper size, location and spacing.

Steel girder forms will be reusable and similar to the permanent metal forms projected to be used in the full sized, production casting. Girder forms will remain the property of Prestressed Concrete Products Co., Inc. Concrete girder casting, curing and handling will be done in such a manner as to simulate actual line casting conditions and practices. We understand that the Department may require the cast girder segments to be turned or moved for inspection or study, and they may be stored at our plant for an extended period of time.

Normal Louisiana Department of Transportation and Development inspection procedures shall be followed concerning forming, re-steel and strand placement, casting, densification, and form removal. No detensioning or form removal strengths are required. Form removal shall be accomplished after concrete cures to the satisfaction of Prestressed Concrete Products Co., Inc. and the Department.

Concrete shall meet the requirements of the specifications attached (two pages). There will be no strength requirements for the experimental concrete mixes used; however, research strength cylinders will be made by departmental personnel on each girder segment cast. Two cores of each girder segment shall be taken by Prestressed Concrete Products Co., Inc. for testing by the Department in accordance with the specifications attached.

Reinforcing strands shall be pulled taut to an extent that will not allow strand sagging or displacement during concrete placement and densification. Internal and external vibration shall be used for densification in such a manner as to best simulate full length form conditions.

All work shall be completed in a timely manner. Mobilization will require about a month to secure the materials and build the forms. The six initial girder segments shall be cast within a three-week calendar time after mobilization and instructions to proceed. Any additional girder segments required will be done as expeditiously as possible.

Six (6) "dummy" girders were poured, two (2) using small size (ASTM #7 stone gradation) limestone coarse aggregate at two different slump values, two (2) using regular Class A gravel, again, at two different slump values and, finally, two (2) using pea gravel (ASTM #7 stone gradation) at two different slump values.

For each girder poured, research personnel made six (6) 6 in. x 12 in. concrete cylinders molded in steel forms and three (3) 6 in. x 12 in. concrete cylinders in approved cardboard molds. Of these, two (2) steel molded cylinders and one (1) cardboard molded cylinders were broken at an early age for deternsioning (ranging from 39-42 hours), 7 days and 28 days.

For each girder, Department inspection personnel made seven (7) 6 in. x 12 in. concrete cylinders molded in steel forms. Generally, one (1) cylinder was broken at the same early age as the research cylinders for detensioning (39-42 hours), two (2) at 7 days, two (2) at 14 days and two (2) at 28 days. All strength results were compared; however, ultimate strength values were the main comparisons made, with the time required to reach design strength also noted. All these strength results can be found in Table 8 on page 24.

Other items under investigation were the flowability of the concrete, the slump ranges of concrete that were needed, the appearance of the girders after the forms were removed, the amount or extent or air voids or honeycombing noted after the forms were removed and the size and type of coarse aggregate used, with the resulting strengths noted.

DISCUSSION OF RESULTS

The strength of portland cement concrete is dependent on several factors, major of which are the water-cement ratio, the size and type of aggregate, the type of additives or admixtures, the type, amount and quality of the cement and the strength of the aggregate.

The design strength, f'c, of the new design high strength girders ranges up to 6500 psi; therefore, it was deemed advisable to establish a higher target strength value of 7500 psi, principally on the initial laboratory testing phase. Aside from being able to achieve the high strength, consistency was also a principal requirement.

Phase I, Laboratory Phase -

High strength and uniformity, or consistency, in 28-day strength results were the principal aims of the laboratory phase of this study. From the strength results in the following tables, several designs were chosen on which to run repetitive mixes in order to determine if consistent high strengths could be obtained. The highest strength mixes (non air-entrained) for each type aggregate were selected to run the repetitive tests, with an additional small size pea gravel mix selected at a different fine to coarse aggregate ratio.

Tables 2, 3, 4 and 5 give all the laboratory test results. A water reducer was added to all the mixes, and all concrete cylinders were cured in the moist room for 28 days.

TABLE 2

Test Results-Factorial
Pea Gravel

Cement content, bags/cu.yd.	Agg. Ratio (FA/CA)	Air Content, %	Slump, in.	Unit Wt., lbs./cu.ft.	Water-cement ratio	28 day Compressive strength, psi**
7.5	36/64	2.3	2 3/4	146.8	0.37	6290
7.5	40/60	2.6	2 3/4	146.8	0.37	6472
7.5	45/55	3.0	2 3/4	146.0	0.37	6456
8.0	36/64	2.0	2 3/4	148.0	0.37	7105
8.0*	36/64	4.4*	2	144.0	0.37	5824*
8.0	40/60	2.3	2 1/2	147.6	0.37	6318
8.0*	40/60	5.1*	2 3/4	143.2	0.35	5774*
8.0	45/55	2.5	2	147.6	0.36	7364
8.5	36/64	2.1	2 1/2	147.2	0.34	6970
8.5	40/60	2.3	3	147.2	0.34	7076
8.5*	40/60	4.8*	3 1/4	141.6	0.36	5743*
8.5	45/55	2.4	3 1/4	147.2	0.35	6705

*Entrained air
**Averages of All Cylinders, Rodded and Vibrated

TABLE 3

Test Results-Factorial

Small Limestone

Cement content, bags/cu.yd.	Agg. Ratio (FA/CA)	Air Content, %	Slump, in.	Unit Wt., lbs./cu.ft.	Water-cement ratio	28 day Compressive strength, psi**
7.5	36/64	1.7	3	150.4	0.40	6755
7.5	40/60	2.3	3 1/4	149.6	0.38	6843
7.5	45/55	2.6	2 1/4	150.4	0.38	7092
8.0	36/64	1.9	2 3/4	151.2	0.38	6986
8.0*	36/64	5.2*	2 3/4	146.4	0.36	7247*
8.0	40/60	2.3	2 1/4	150.4	0.38	7056
8.0*	40/60	5.1*	2 1/4	146.8	0.35	7206*
8.0	45/55	3.0	3	149.6	0.38	7190
8.5	36/64	2.0	2 3/4	151.2	0.36	7792
8.5	40/60	1.9	2 3/4	150.0	0.36	7880
8.5*	40/60	4.4*	2	148.0	0.34	7406*
8.5	45/55	2.2	2	150.0	0.36	7630

*Entrained air
**Averages of All Cylinders, Rodded and Vibrated

TABLE 4

Test Results-Repetitive Mix Series

Pea Gravel

Pour no.	Cement content, bags/cu.yd.	Agg. Ratio (FA/CA)	Air Content, %	Slump, in.	Unit Wt., lbs./cu.ft.	Water-cement ratio	28 day Compressive strength, psi*
Ref.	8.0	45/55	2.5	2	147.6	0.36	7191
1	8.0	45/55	2.8	2 3/4	146.0	0.37	5810
2	8.0	45/55	2.7	3 1/4	145.6	0.37	5595
3	8.0	45/55	2.7	1 3/4	146.0	0.37	6192
4	8.0	45/55	2.8	3	145.6	0.37	6160
Ref.	8.5	40/60	2.3	3	147.2	0.34	7049
1	8.5	40/60	2.3	2 1/4	146.8	0.34	5764
2	8.5	40/60	2.3	1 3/4	146.4	0.34	5797
3	8.5	40/60	2.3	2	146.4	0.34	5742
4	8.5	40/60	2.4	2 1/2	146.0	0.34	5617

*Average of Rodded Cylinders

TABLE 5

Test Results-Repetitive Mix Series

Small Limestone

Pour no.	Cement content, bags/cu.yd.	Agg. Ratio (FA/CA)	Air Content, %	Slump, in.	Unit Wt., lbs./cu.ft.	Water-cement ratio	28 day Compressive strength, psi*
Ref.	8.5	40/60	1.9	2 3/4	150.0	0.36	7980
1	8.5	40/60	1.9	2 1/2	149.6	0.36	7441
2	8.5	40/60	1.9	2 3/4	150.0	0.36	7927
3	8.5	40/60	1.9	2 3/4	149.6	0.36	7913
4	8.5	40/60	2.0	2 1/2	150.0	0.36	7768

*Average of Rodded Cylinders

In the laboratory phase of the study, there were some limitations placed on the mix designs. The first limitation was that super water reducers would not be used; however, it was felt that a plain water reducer was needed to lower the water-cement (w/c) ratio, thus increasing the strength. A second limitation was thought necessary, that is, to limit the size of the coarse aggregate; therefore a gradation essentially passing the 1/2-in. screen and retained on the No. 4 screen was used in all the laboratory mixes. This gradation closely approaches the ASTM Stone Size No. 7. A third limitation was that there would be no air-entrained admixture used; however, several mixes with air-entrainment were run to determine the effect and strengths that would be obtained.

A target slump of 2-3/4 in. was set, along with a water-cement ratio of 0.36. Slumps did range from 2 in., to 2-1/4 in., and only three mixes varied more than 1/2 in. from this guide range value. Water-cement ratios ranged from 0.34 to 0.37 on the pea gravel mixes and 0.34 to 0.40 on the small limestone mixes. An average of 2.5% air content on non-entrained air mixes and 4.8% air content on air-centrained mixes was obtained in these laboratory mixes.

Looking at Tables 2 and 3 on pages 12 and 13, which give the test results obtained on the first mixes for the block diagram or partial factorial, there were a few inconsistencies on some of the strength results.

Looking at Table 2 on page 12, one can readily see that the pea gravel mixes with air-entrainment had low compressive strengths (below the f'c design strength, 6500 psi, for the largest girders) averaging around 5800 psi. However, looking at Table 3, the small limestone mixes with air-entrainment had high strengths and strengths equal to the limestone mixes without air, much higher than the f'c design strength. These limestone mixes with air averaged approximately 7300 psi. Therefore, a preliminary conclusion can be reached that limestone mixes can give the high strengths, even with air-entrainment while pea gravel mixes will not give this high strength.

Disregarding the mixes with air-entrainment, and looking at Table 6 on page 18 for non-air mixes, one can see that compressive strengths of all limestone mixes exceed those of the pea gravel mixes. Also, all the limestone mixes generally exceeded the design f'c strength of 6500 psi. The 8.5 bag limestone mix exceeded the targeted laboratory standard for strength of 7500 psi. However, when looking at the pea gravel mixes, six of the nine mixes exceeded the design f'c strength of 6500 psi, but none of the mixes exceeded the laboratory target for strength of 7500 psi. These results are from the original factorial mixes that were run. Here pea gravel mixes do not appear to be capable of necessary high strengths, however it was felt repetitive mixes needed to be run to see what strengths would be obtained.

Three individual mixes were selected to run repetitive series of mixes to check the consistency of strength results. Generally these mixes were chosen due to their having the highest strengths for each type of aggregate. These results are also shown at the bottom of Table 6. One can see that the pea gravel mixes gave consistent results, but were very much lower than the original mixes in strength and were far under the design f'c strength of 6500 psi. However, the 8.5 bag limestone mix also gave consistent results, averaging 7761 psi, which compares with the original mix strength of 7980 psi for rodded cylinders from the factorial.

Figures 1 and 2 in the Appendix show strength comparisons for the different aggregate ratios at increasing cement contents. In Figure 1 for the pea gravel mixes, there appears to be a peak, or limiting cement content, of 8.0 bags per cubic yard, while in Figure 2 for the limestone mixes, there are steady increases in strength for increasing cement contents.

This concluded the laboratory phase of the study. It was found that high strength concrete mixes could be designed; however, most likely, limestone aggregate will have to be used. Regular Class A gravel concrete mixes were not made in Phase I, but later in Phase III. From this point the research project went into the preliminary field phase.

TABLE 6

Test Results
Non-Air Mixes, Factorial & Series
(Rodded Cylinder Averages Only)

Coarse Aggregate	Cement Content bags/cu.yd.	Aggregate Ratio (FA/CA) 36/64	40/60	45/55
Pea Gravel	7.5	6133 psi 2 3/4" slump 2 3/4% air	6564 psi 2 3/4" slump 2.6% air	6440 psi 2 3/4" slump 3.0% air
	8.0	6843 psi 2 3/4" slump 2.0% air	6372 psi 2 1/2" slump 2.3% air	*7191 psi 2" slump 2.1% air
	8.5	7014 psi 2 1/2" slump 2.1% air	*7049 psi 3" slump 2.3% air	6720 psi 3 1/4" slump 2.4% air
Small Limestone	7.5	6525 psi 3" slump 1.7% air	6625 psi 3 1/4" slump 2.3% air	7350 psi 2 1/4" slump 2.6% air
	8.0	7079 psi 2 3/4" slump 1.9% air	7085 psi 2 1/4" slump 2.3% air	7120 psi 3" slump 2.4% air
	8.5	7615 psi 2 3/4" slump 2.0% air	*7980 psi 2 3/4" slump 1.9% air	7762 psi 2" slump 2.2% air

*Repetitive Series Run

Repetitive
Series Test Results

Coarse Aggregate	Cement Content bags/cu.yd.	Aggregate Ratio (FA/CA)	Compressive Strengths, psi 1	2	3	4	Avg.
Pea Gravel	8.0	45/55	5810	5595	6160	6192	5939
Pea Gravel	8.5	40/60	5617	5742	5797	5764	5730
Small Limestone	8.5	40/60	7913	7927	7768	7441	7761

Phase II, Preliminary Field Phase -

Preliminary field test data from Phase II is given in Table 7, on page 20, which includes cylinder compressive strength values at varying ages and the fresh concrete test properties such as slumps, unit weights and air contents.

As one can see from the data in Table 7 and from the strength gain curves in Figures 3, 4, 5 and 6 in the Appendix, all of the moist cured cylinders (cardboard molds) had lower compressive strengths than the comparable steam and air cured cylinders (steel molds). However, the moist cured cylinders showed good increasing strength values at 14 and 28-day ages, while the comparable steam and air cured cylinders tended to show a decrease from the 14 to the 28-day strength value, causing a hump on the strength gain curves. Cause for this occurrence is not known, however this condition seems to happen often at prestressed plants, where there is steam curing and later air curing on cylinders.

Steel molded cylinders will give higher strength values that comparable cardboard molded cylinders; however, it is hard to isolate the difference in strength between steam and air cured cylinders and moist cured cylinders, especially if these conditions are combined with the steel mold and cardboard mold conditions. Principal strength values that were analyzed were the steel molded, steam and air cured cylinders' compressive strengths. The cardboard molded moist cured cylinder strength values were only compared with the original laboratory strength values for the appropriate mix design. Laboratory strengths for repetitive tests averaged 5939 psi and the field strength values averaged 5170 psi at 28 days, thus showing a decrease in strength of approximately 800 psi. The steam and air cured steel molded cylinders had ultimate strength values averaging about 5927 psi. One can see that all of these values were lower than the f'c design strength of 6500 psi, which reinforces the conclusion that the small size pea gravel concrete mixes will not give the required consistent high strength.

TABLE 7

Preliminary Field Test Data

Pour No.	Testing For	Age, days	Average Compressive Strength, psi R&D steam & air cured	R&D moist cured	DOTD steam & air cured	Fresh Concrete Test Data
	Detensioning	39(hrs.)	5155	-	4916	Slump-3 1/2"
1	Shipping	6	6190	4570	5677	Unit Wt.-146.4
	28 day	28	6175	5595	-	lbs./ft.^{3}
						air content-2.0%
	Detensioning	63(hrs.)	5049	-	4492	Slump-2 3/4"
2	Shipping	17	5713	4596	5659	Unit Wt.-146.5
	28 day	28	4919	4847	-	lbs./ft.^{3}
						air content-2.0%
	Detensioning	39(hrs.)	4934	-	4881	Slump-2 3/4"
3	Shipping	13	5863	4726	5836	Unit Wt.-146.2
	28 day	28	5546	5091	-	lbs./ft.^{3}
						air content-2.1%
	Detensioning	4	5182	-	5518	Slump-3"
4	Shipping	13	5942	4641	5451	Unit Wt.-145.7
	28 day	28	5276	5139	-	lbs./ft.^{3}
						air content-2.4%

*Note: (m) moist cured, (D) DOTD steam & air cured. All the compressive strength results in this table are the averages of several cylinders, varying up to four (4). All the concrete cylinders were steam cured, then air cured, except for those marked (m), which were moist cured.

Slumps ranged from 2-3/4 in. to 3-1/2 in., unit weights ranged from 145.7 to 146.5 lbs./cu. ft. and the air contents ranged from 2.0% to 2.4%. Field test properties were all in the accepted target range of values. The workability of the mix was satisfactory as noted through visual inspection of the pours. However, the untimate strength values were lower than the f'c design strength of 6500 psi for the largest girder. Aside from this lack of projected necessary strength, the prime aim of this phase of the study was obtained, that is to determine if a satisfactory, workable mix could be poured on a production mode using the small size aggregate and a satisfactory strength value could be obtained in an acceptable length of time.

Phase III, Final Field Phase -

Strength results obtained in this phase of the study were more than adequate. In addition, useful information was discovered concerning placement of the concrete, vibration, finishing, the types of aggregate that may be used with confidence in these girders and the slumps needed for this type of pour.

Strengthwise, one can see from Table 8 on page 24 and Figures 7-12 in the Appendix that useful compressive strength results were obtained. Pours 1 and 2, with small limestone, resulted in the highest strengths obtained averaging around 9,100 psi at 28 days and reaching the f'c strength of 6500 psi in about 2 days or less.

Pours 3 and 4, with regular Class A gravel, resulted in slightly lower strengths but were more than adequate. Compressive strengths at 28 days averaged around 8200 psi with the f'c strength of 6500 psi being reached in approximately 2 days.

Pours 5 and 6, with small size (pea) gravel, generally resulted in the lowest of these strengths. Compressive strengths at 28 days averaged around 7500 psi with the f'c strength of 6500 psi being reached in approximately 6-12 days. Although these results were reached in this phase satisfactorily, laboratory and field results previously indicated that mixes with pea gravel give strengths that are inconsistent and genrally too low to be relied on.

Slumps and air contents for all the pours were generally in the range of the assumed values, which were 2-3 in. for the slumps and 3.0% for the air contents (non air-entrained). Flowability and ease of operation were noted as being very satisfactory in all the pours.

A principal concern noted beforehand had been whether the concrete could be vibrated through the close spacing between the steel in these forms without causing honeycombing or voids and still achieving bond to the steel. The amount and type of vibration were studies and external vibration under the forms and internal vibration in the forms were decided upon. In all the pours, only surface depressions in the finish were noted after the forms were removed.

Figures 15-21 in the Appendix give various views of the so-called "dummy" girders before, during and after pouring the concrete. In some views, one can see the amount of steel in the forms the close spacing of the steel, along with various views showing the surface depressions in the finishes and a view of the external vibrator under the forms. Some views show the 8-foot "dummy" girders as finished products. All of these finished products came out satisfactorily in appearance and high strength obtained, in addition to providing valuable information for casting.

Although research effort was concentrated on cement contents of 7.5, 8.0 and 8.5 bags per cubic yard for limestone mixes and 8.0 bags per cubic yard for Class A gravel mixes, 6500 psi strengths should be obtainable for mixes of 7.0 bags or better under the Class P(M) specifications.

TABLE 8

Final Field Test Data

Girder Pour No.	Cylinder Compressive Strength, psi (steel molds)				Core Compressive Strength, psi	Field Test Properties
	Detensioning	7 days	14 days	28 days		
	42 hrs.				51 days	
#1	R-6437	R-8135	I-8736	R-7792	I-9158	slump-3"
Ls	R-6579	R-7958	I-8630	R-7827	I-9736	air-3.1%
10/10/79	I-6331	I-7888		I-9197		
		I-7958		I-8807		
	41 hrs.				46 days	
#2	R-7286	R-8099	I-8842	R-7986	I-10268	slump-2 1/4"
LS	R-7039	R-8382		R-7279	I-9752	air-2.3%
10/15/79	I-6544	I-8241		I-9090		
10/15/79	I-6968	I-8418		I-9338		
	42 hrs.				43 days	
#3	R-6048	R-7746	I-8042	R-6802	I-7736	slump-2 3/4"
Reg. Gr.	R-5624	R-8205	I-7711	R-6961	I-7111	air-2.8%
10/18/79	I-6331	I-7878		I-8276		
		I-7993		I-7852		
	40 hrs.				38 days	
#4	R-5588	R-6367	I-8458	R-6643	I-9220	slump-2 1/4"
Reg. Gr.	R-5906	R-7145	I-8276	R-5866	I-8799	air-2.3%
10/23/79	I-6826	I-7817		I-8276		
		I-7701		I-8488		
	42 hrs.				32 days	
#5	R-5624	R-6614	I-6720	R-5230	I-8064	slump-2 1/2"
Pea Gr.	R-5553	R-6437	I-6649	R-5053	I-7439	air-2.6%
10/29/79	I-5376	I-5836		I-6791		
		I-6225		I-6473		
	39 hrs.				30 days	
#6	R-6083	R-6614	I-6897	R-5945	I-9064	slump-2 3/4"
Pea Gr.	R-5836	R-7144	I-7321	R-6254	I-9439	air-2.7%
10/31/79	I-5624	I-6826		I-7640		
		I-6649		I-7428		

NOTE: R = research's cylinder
I = inspector's cylinder

CONSLUSIONS

The following conclusions have been derived from information and test results obtained on this research project:

1. High strength concrete (minimum compressive strength of 6500 psi) can be consistently obtained in a production mode for use in the long prestressed girders for the West Bank Expressway construction project.
2. The high strength mixes have good consistency using either of two types of coarse aggregates, an ASTM #7 stone gradation limestone and a regular Class A gravel.
3. A third coarse aggregate, a small size pea gravel, does not consistently or practically meet the requirements for high strength and has been eliminated by the Department's Design Section from consideration for the West Bank Expressway construction project.
4. A slump range of 2-4 in. appears to be the ideal production range for the workability of the concrete while still producing adequate high strength concrete.
5. Present specifications for Class P(M) concrete are adequate with a few revisions, as presented in the R & D special provisions, shown in the Appendix.
6. The water content successfully used in this research effort, both in laboratory and field, was a maximum of 4.1 gallons per sack of cement, resulting in a maximum water cement (w/c) ratio of 0.36.
7. Lower compressive strength results were obtained in concrete using air-entrained admixtures, as shown in Table 2 on page 12, for pea gravel mixes and generally is true for most concrete mixes; therefore, use of air in the recommended high strength concrete should be discouraged.

RECOMMENDATIONS

The following recommendations from this research effort are presented as follows:

1. A set of preliminary revisions to Class P(M) specifications, in the form of special provisions, is found in the Appendix of this report and is recommended for consideration by the consulting engineers, for their package presentation of the West Bank Expressway construction project to the Department for review and approval.
2. ASTM #7 stone gradation limestone is recommended as the best coarse aggregate material to use in these concrete mixes in order to obtain the necessary high strength consistently for the girders on this construction project.
3. Class A gravel is recommended as an alternate for coarse aggregate in this high strength concrete.
4. The use of small size pea gravel for the coarse aggregate in this concrete is not recommended.
5. Normal water reducers should be specified for use in high strength concrete on this construction project.
6. Air-entrained admixtures are not recommended for use in this concrete.
7. A slump range of 2-4 in. is recommended for workability of concrete for these girders.
8. A water-cement (w/c) ratio of 0.36 is recommended for use in this high-strength girder construction.

BIBLIOGRAPHY

1. ACI Manual of Concrete Practice, "Part 1, Materials and Properties of Concrete Construction Practices and Inspection Pavements and Slabs," ACI Publication, 1979.
2. ACI Manual of Concrete Practice, "Part 3, Products and Processes," ACI Publication, 1978.
3. A. M. Neville, Properties of Concrete, John Wiley and Sons, N.Y., Printed in Great Britain, 1973, 686 pages.
4. Concrete Manual, A Water Resources Technical Publication, Eighth Edition, U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado, 1975, 676 pages.
5. Shu-T'ien Li and Hsin-Hsiu Kuo, Concrete Bridge Design, Part 1, Significant Attributes and Mix Design Methods, "High-Quality, High-Strength Concrete, It's Significant Attributes Mix Design and Application to Bridge Members and Piles," pp. 1100-1144.
6. Significance of Tests and Properties of Concrete and Concrete-Making Materials, ASTM Special Technical Publication 169B, Sponsored by ASTM Committee C-9, American Society of Testing and Materials, Philadelphia, Pa., Printed in Baltimore, Md., December 1978, 872 pages.

APPENDIX

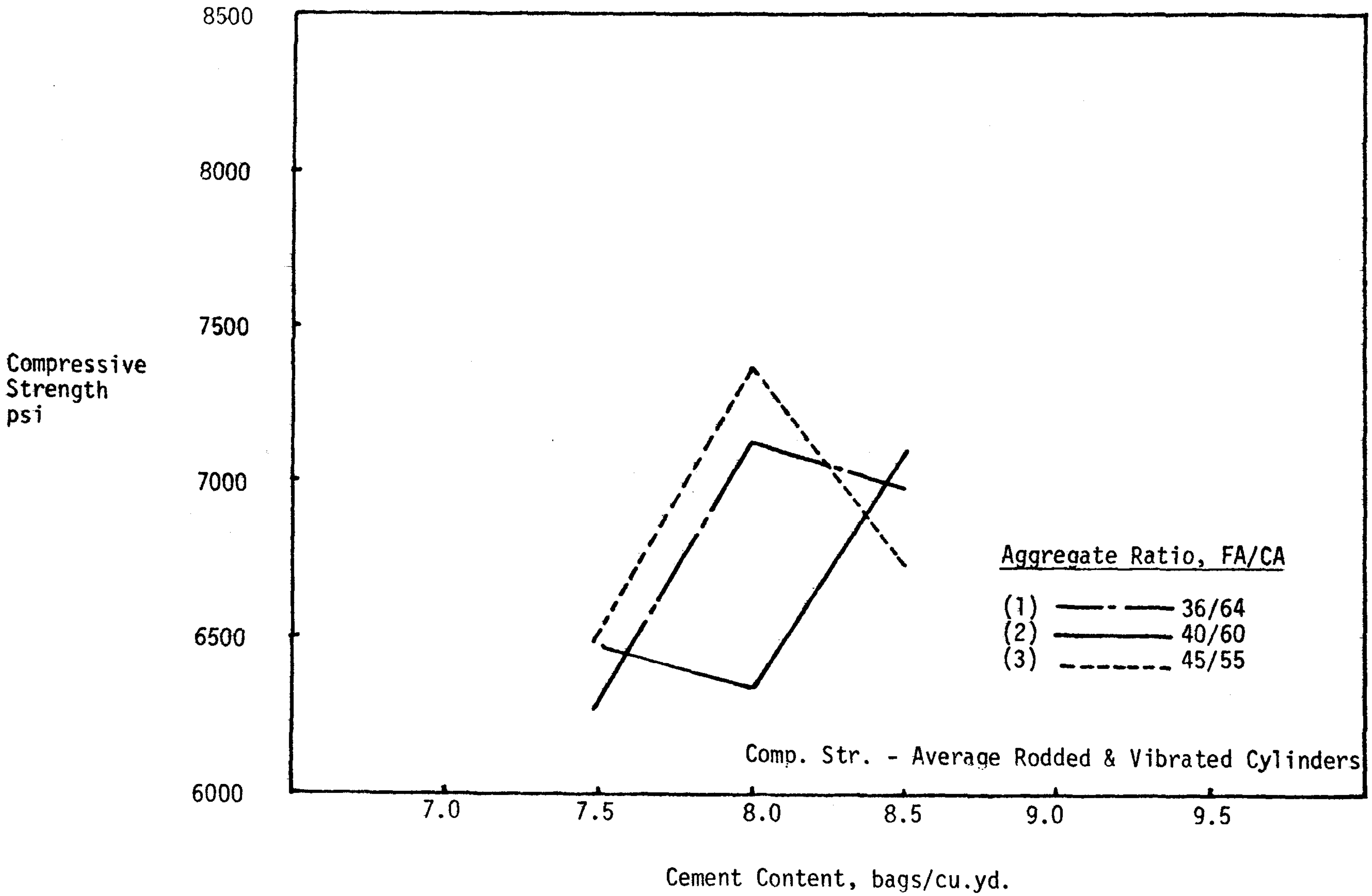


FIGURE 1

Compressive Strength vs. Cement Content
Pea Gravel Mixes

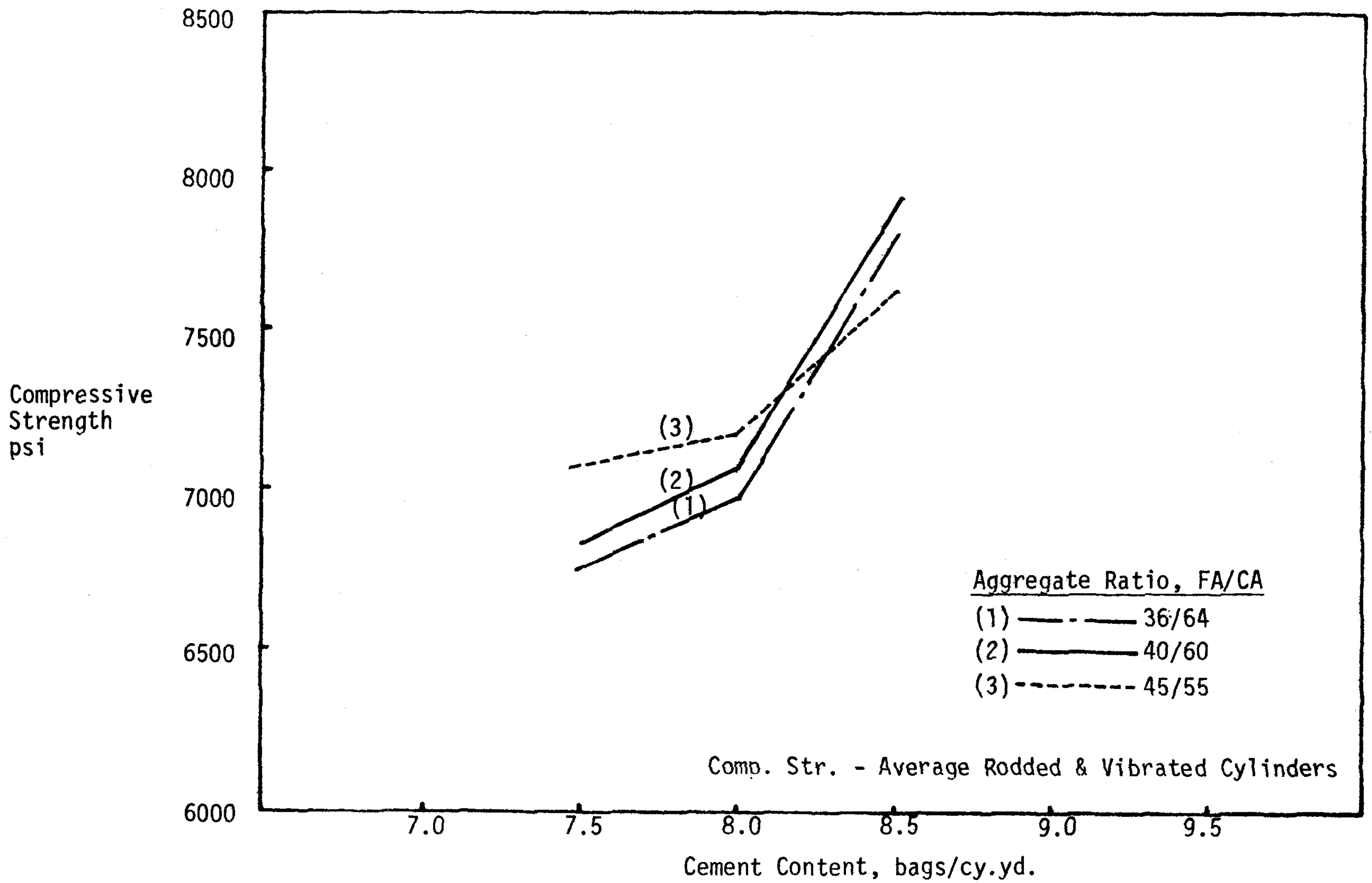


FIGURE 2

Compressive Strength vs. Cement Content
Limestone Mixes

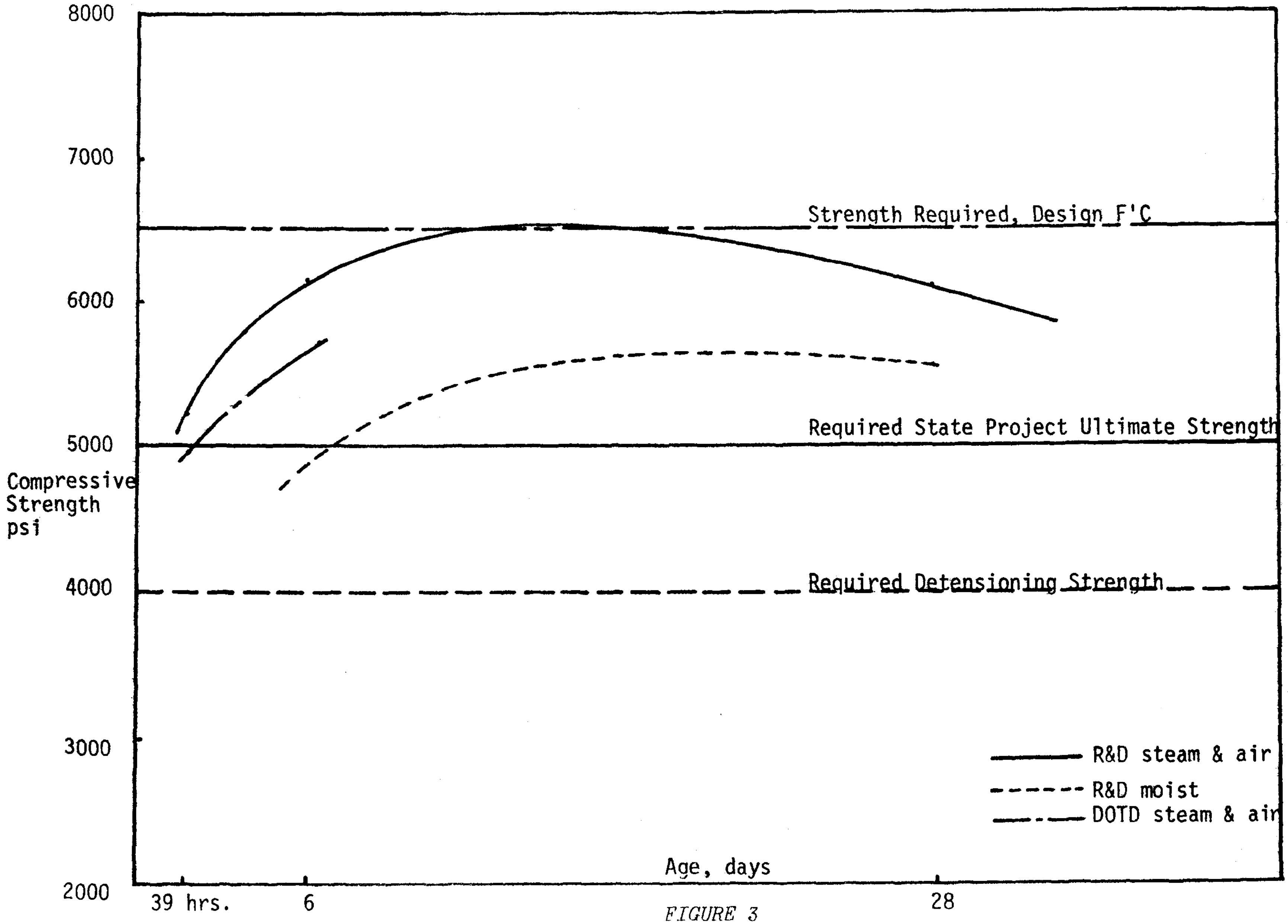


FIGURE 3

Compressive Strength vs. Age
Phase II, Pour No. 1

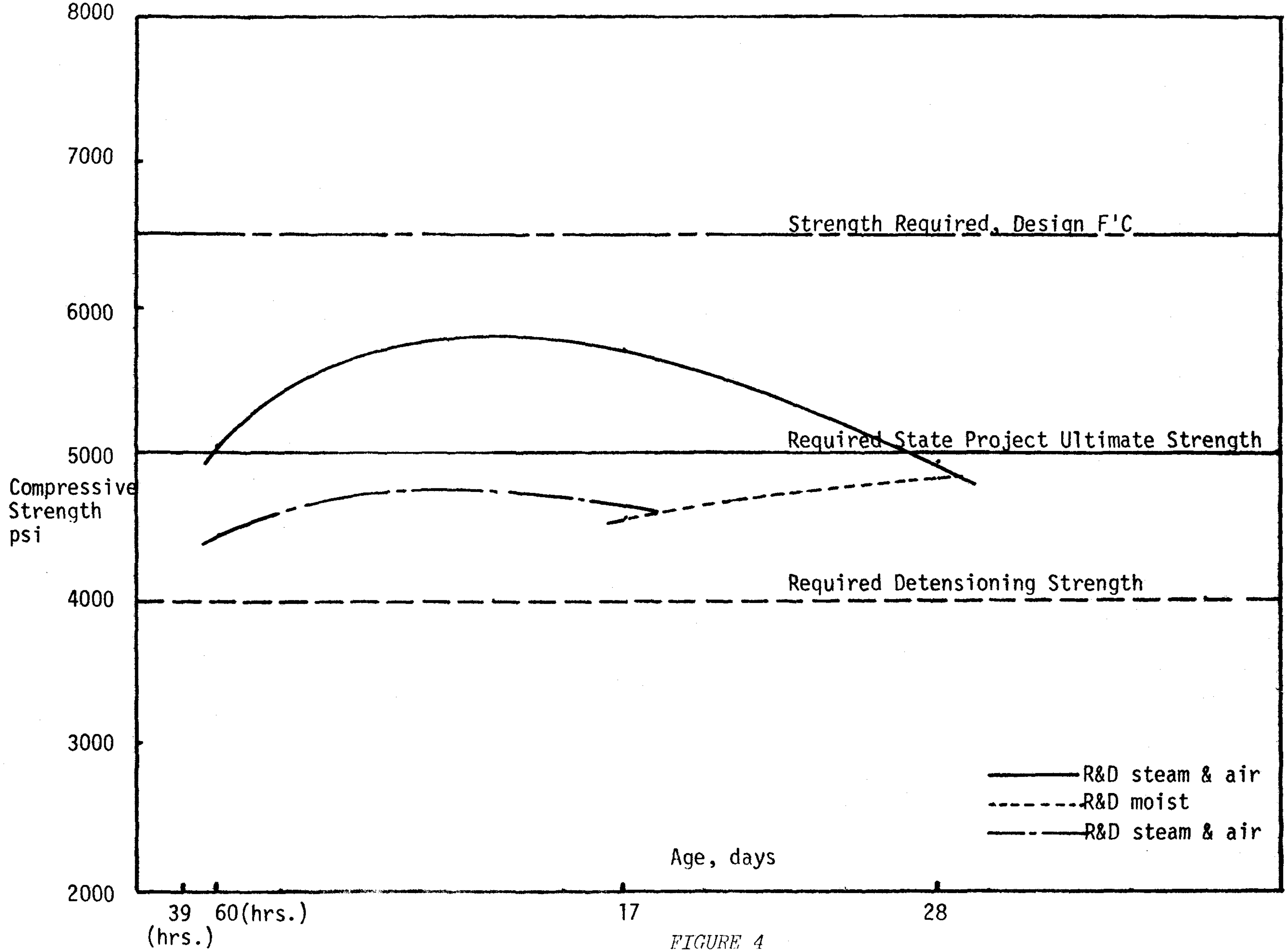


FIGURE 4

Compressive Strength vs. Age
Phase II, Pour No. 2

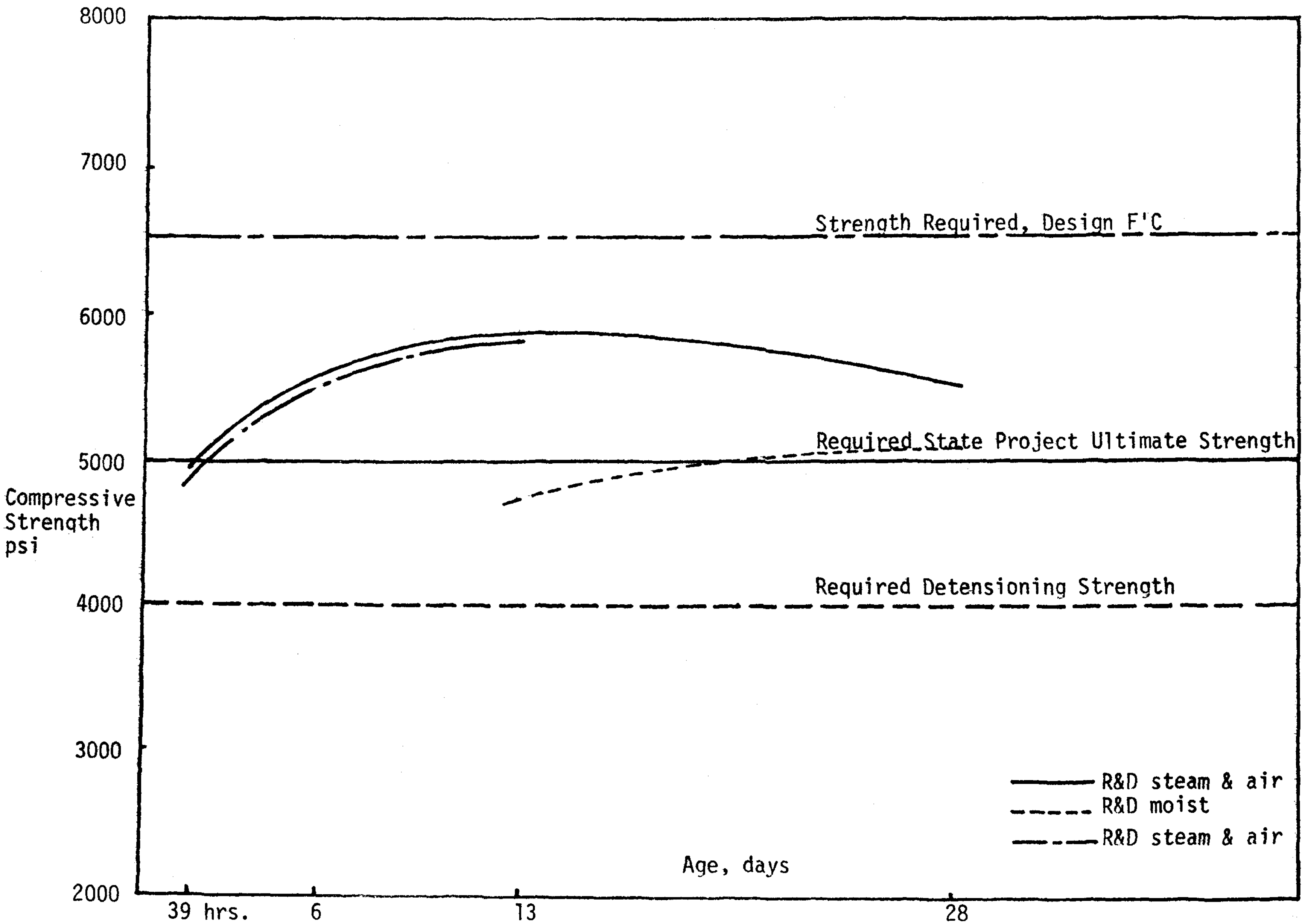


FIGURE 5

Compressive Strength vs. Age
Phase II, Pour No. 3

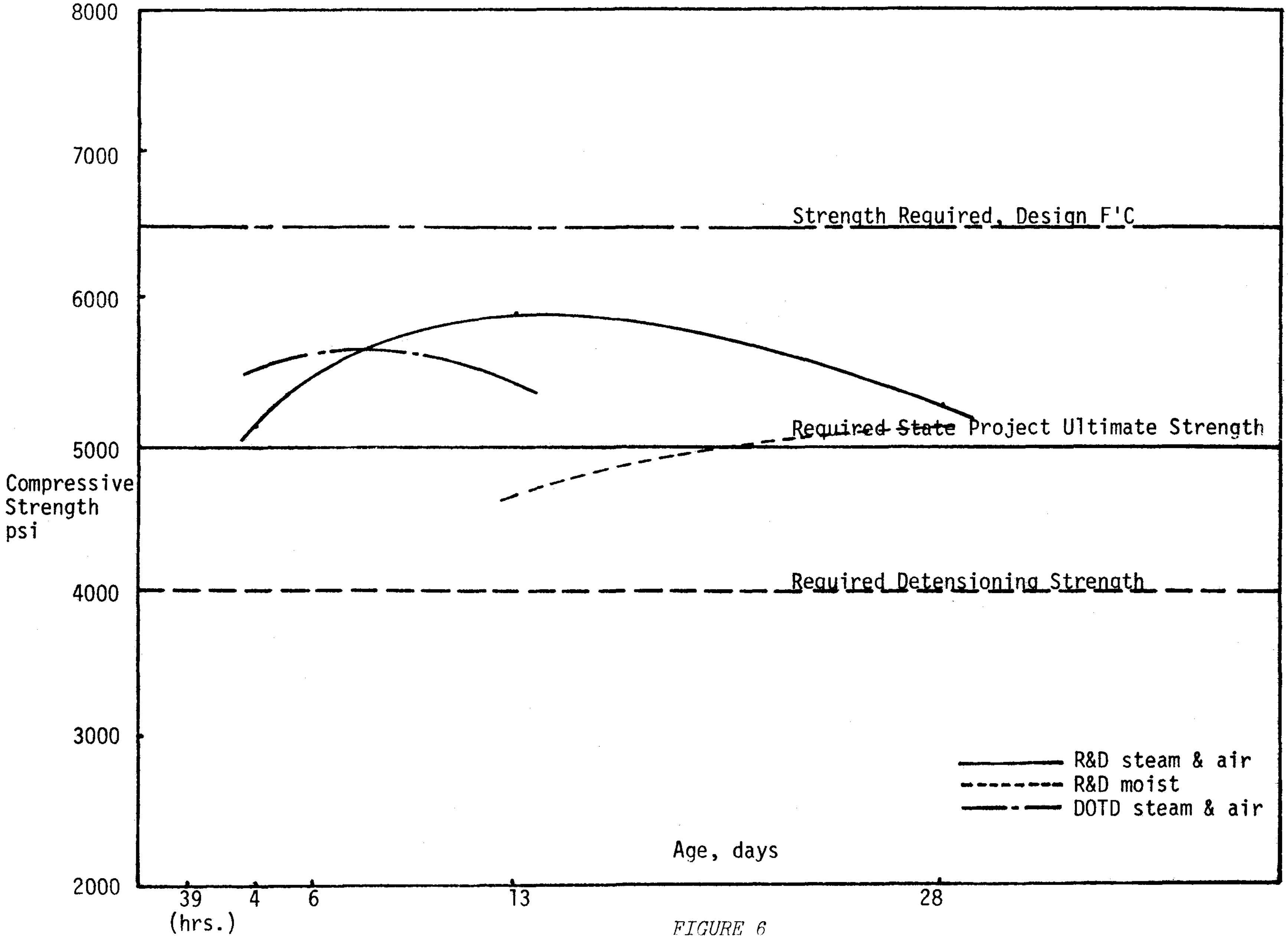


FIGURE 6

Compressive Strength vs. Age
Phase II, Pour No.4

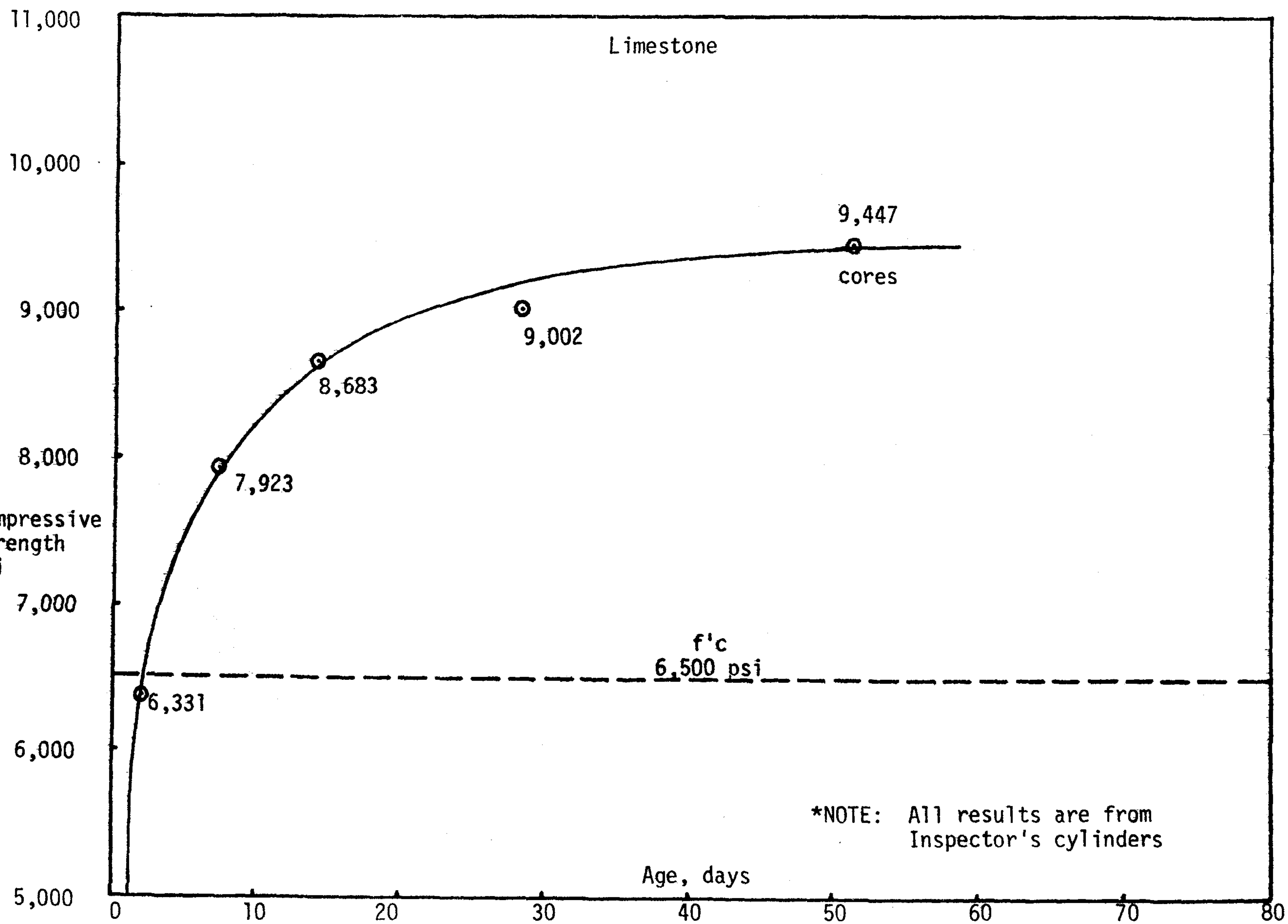


FIGURE 7

Compressive Strength vs. Age
Phase III, Pour No. 1

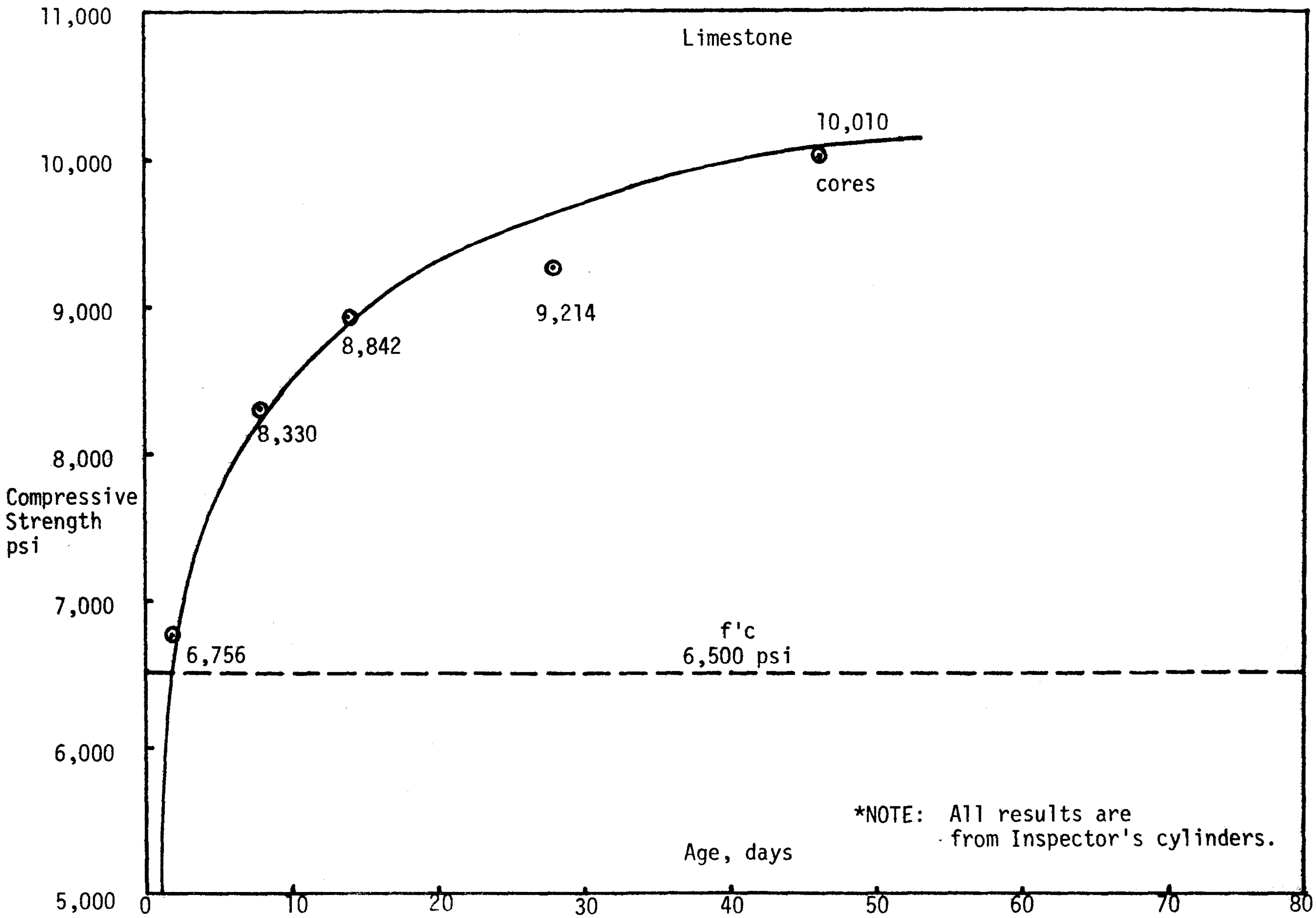


FIGURE 8

Compressive Strength vs. Age
Phase III, Pour No. 2

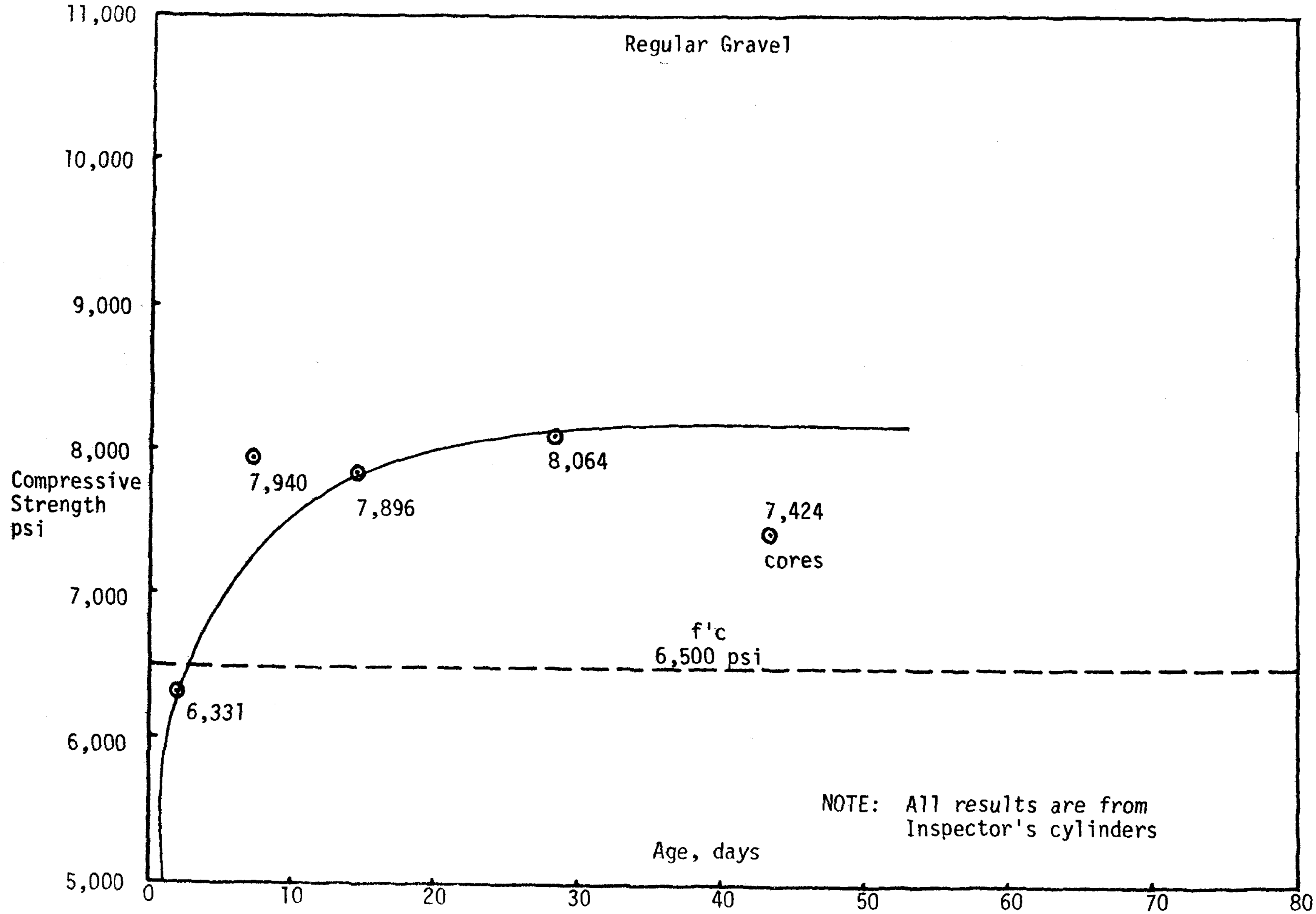


FIGURE 9

Compressive Strength vs. Age
Phase III, Pour No. 3

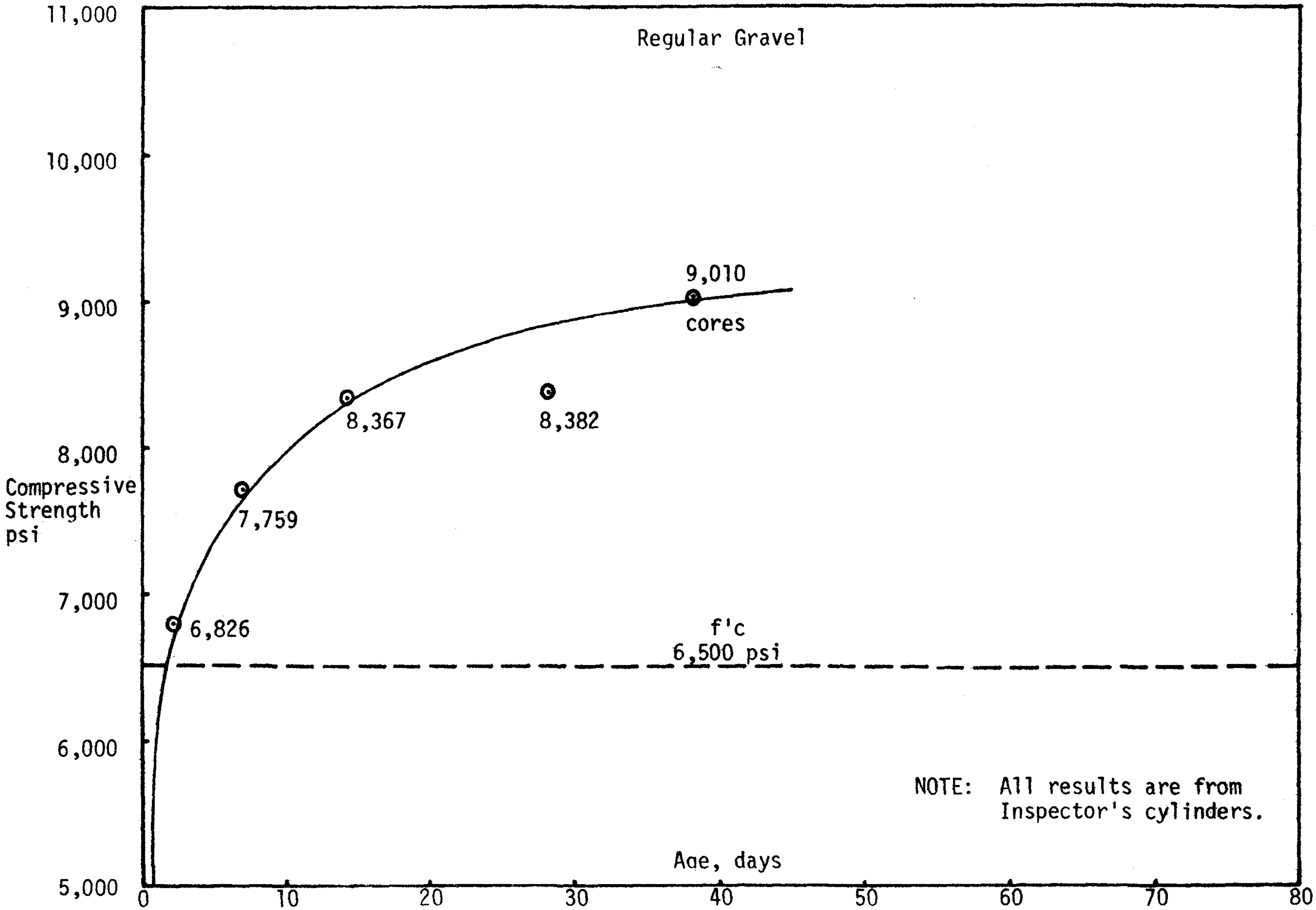


FIGURE 10

Compressive Strength vs. Age
Phase III, Pour No. 4

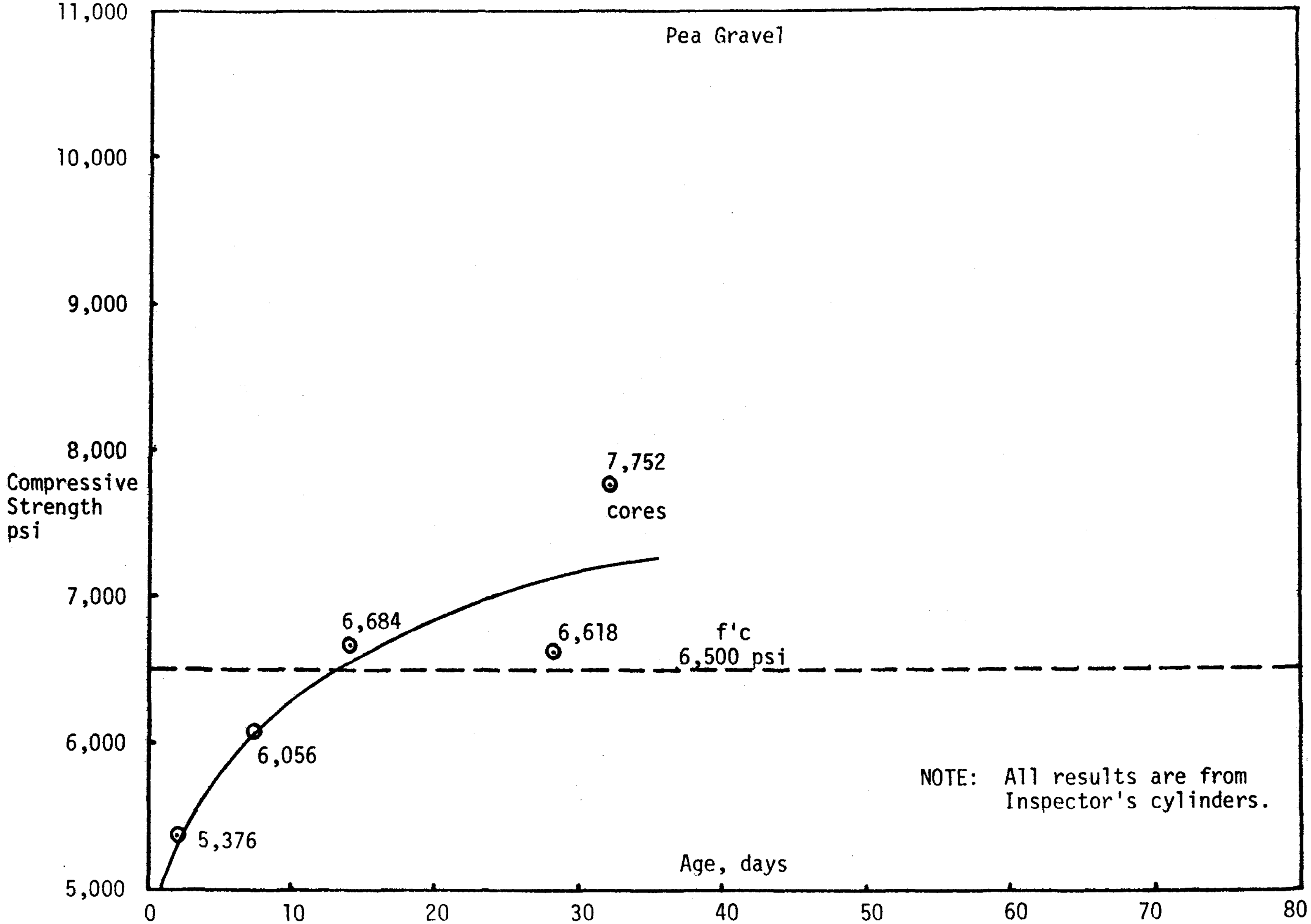


FIGURE 11

Compressive Strength vs. Age
Phase III, Pour No. 5

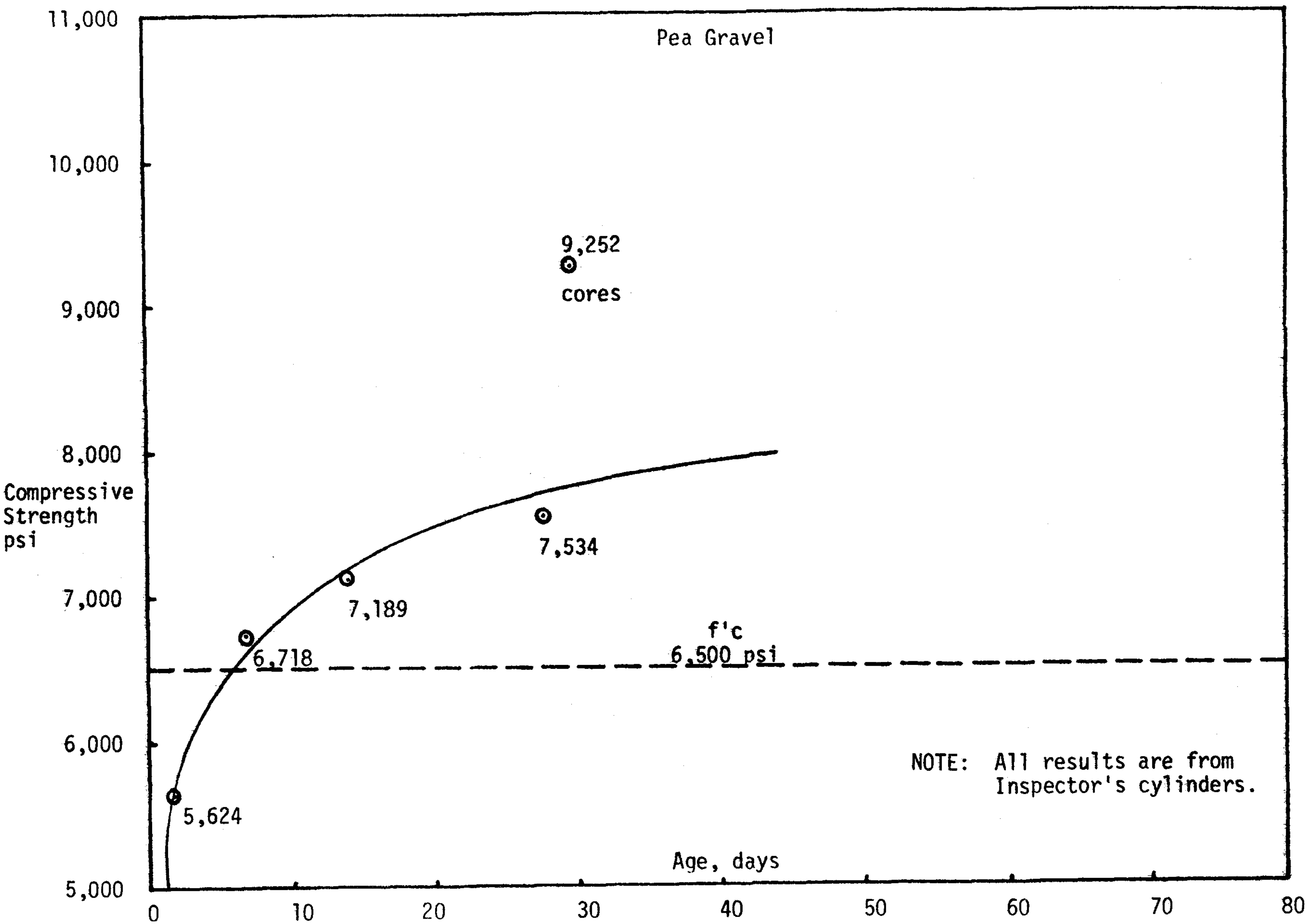
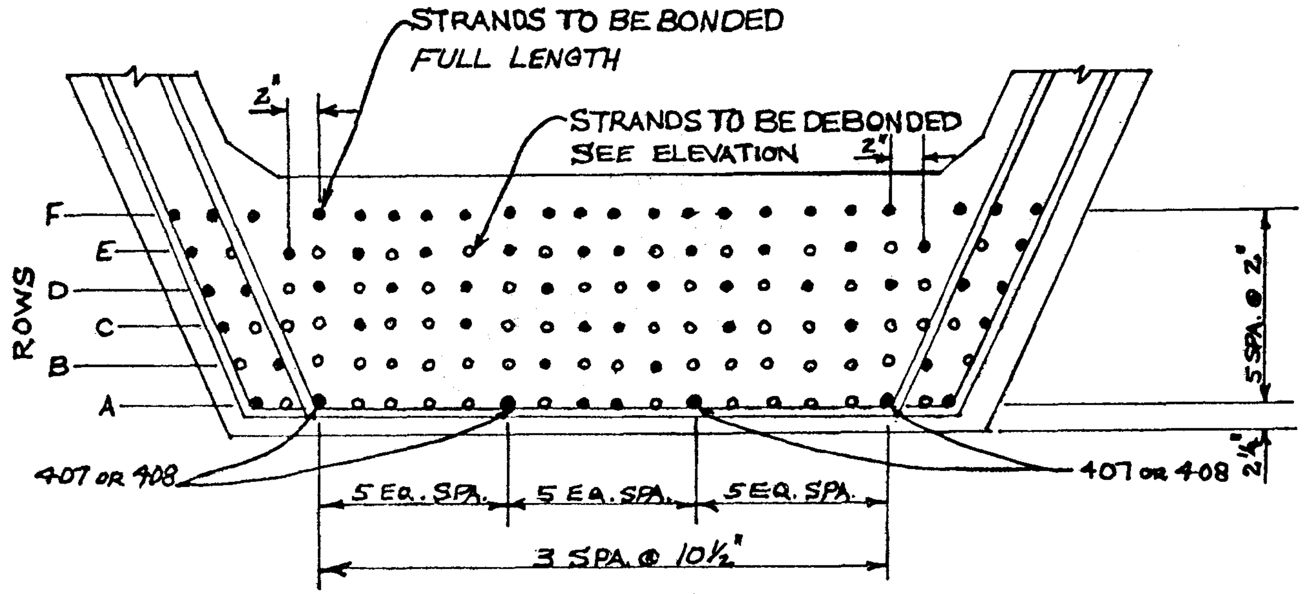


FIGURE 12

Compressive Strength vs. Age
Phase III, Pour No. 6

HIGH STRENGTH CONCRETE GIRDERS



PRESTRESS STEEL LAYOUT

SCALE: 1½" = 1'0"

124 - ½" ϕ 270K STRANDS

FIGURE 13

Cross Section Prestress Steel

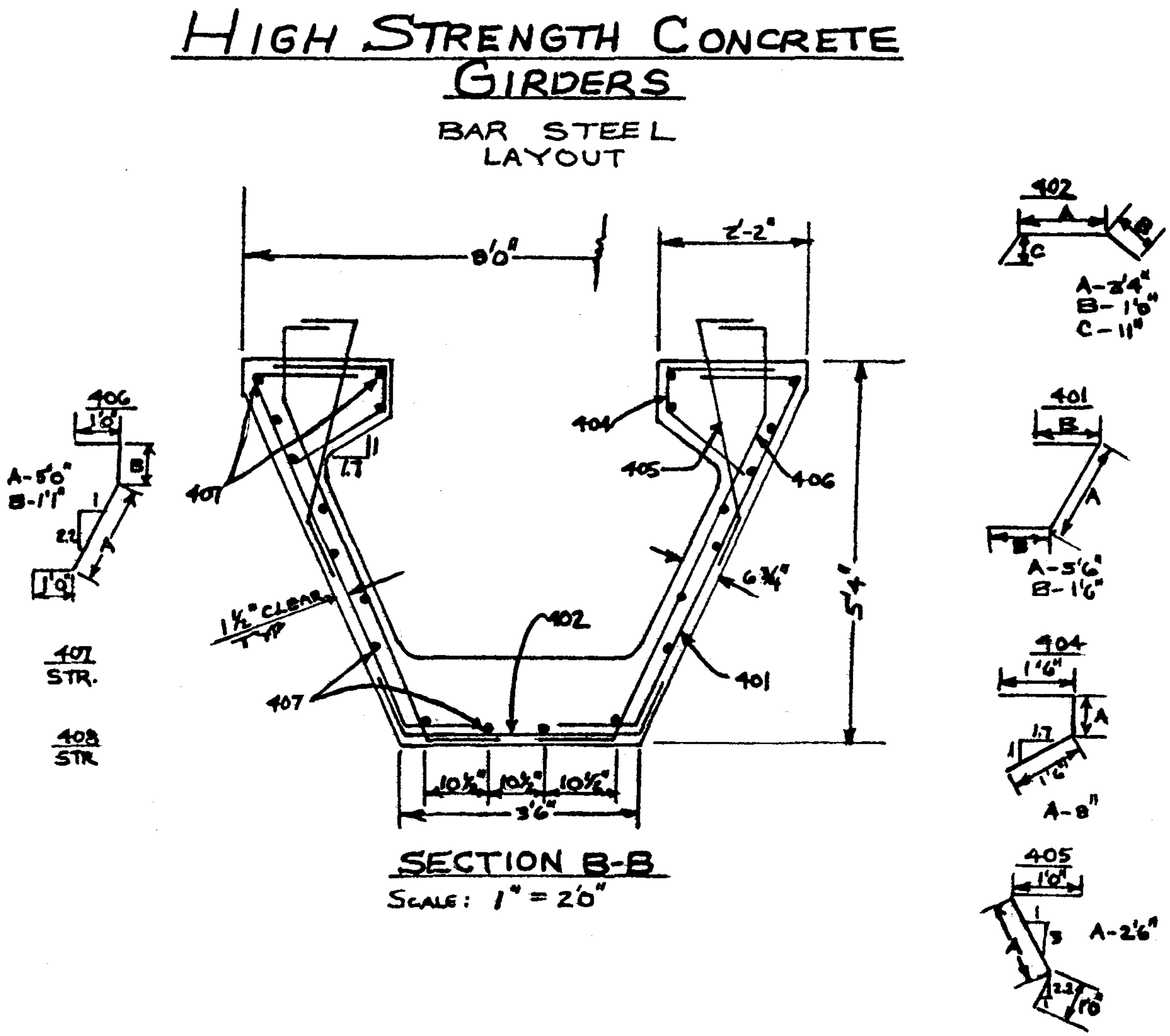


FIGURE 14

Cross Section Bar Steel

PROPOSED
STATE PROJECT NO. 283-09-60
SPECIAL PROVISIONS

PORTLAND CEMENT CONCRETE: Subsection 805.15(d) of the Standard Specifications is amended as follows: Concrete for precast-prestressed girders shall be Class P(M) conforming to Section 901 with the following modifications.

Coarse Aggregate: Limestone coarse aggregate conforming to the following gradation will be permitted.

U.S. Sieve	% Passing (By Weight)
3/4"	100
1/2"	90 - 100
3/8"	40 - 70
No. 4	0 - 15
No. 8	0 - 5

Water-Cement Ratio: The maximum water-cement ratio (gals./sack) shall be 0.36; maximum water content shall be 4.1 gallons per sack of cement; and the allowable slump range shall be 2" to 4".

Admixtures: Approved water-reducing admixtures shall be used. Air-entraining admixtures will not be required. No fly ash, superplasticizers or other admixtures shall be used.

Consolidation: Concrete shall be internally or externally vibrated, or both.

Compressive Strength: Concrete shall be designed, placed, consolidated and cured to attain a minimum 28-day compressive strength of 7000 psi.* The minimum acceptable compressive strength shall be the design compressive strength (f'c) as specified on the plans for each member.

*NOTE: (Added by authors for clarification) The contractor shall furnish a mix design to the Department, for approval, and make a trail batch at the plant site, with cylinders being made, cured and broken in the same manner as acceptance cylinders in a production mode. The design trial batch minimum compressive strength of 7000 psi will be met for mix design approval.

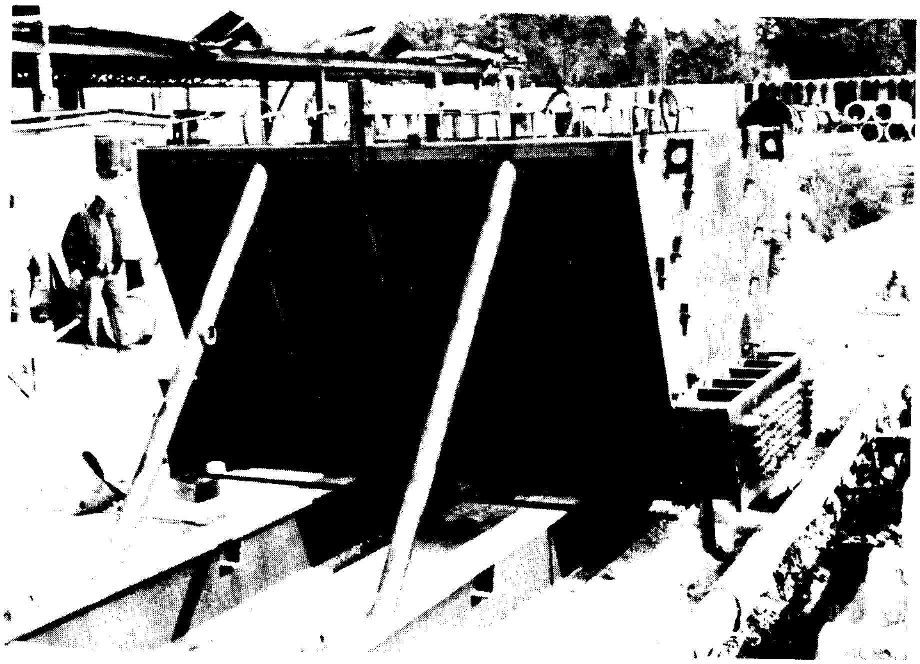


FIGURE 15

"Dummy" Girder
Ready for Pour

FIGURE 16

Bar Steel in Forms

FIGURE 17

Closeup-Surface Irregularities

FIGURE 18

Surface Irregularities after Pour

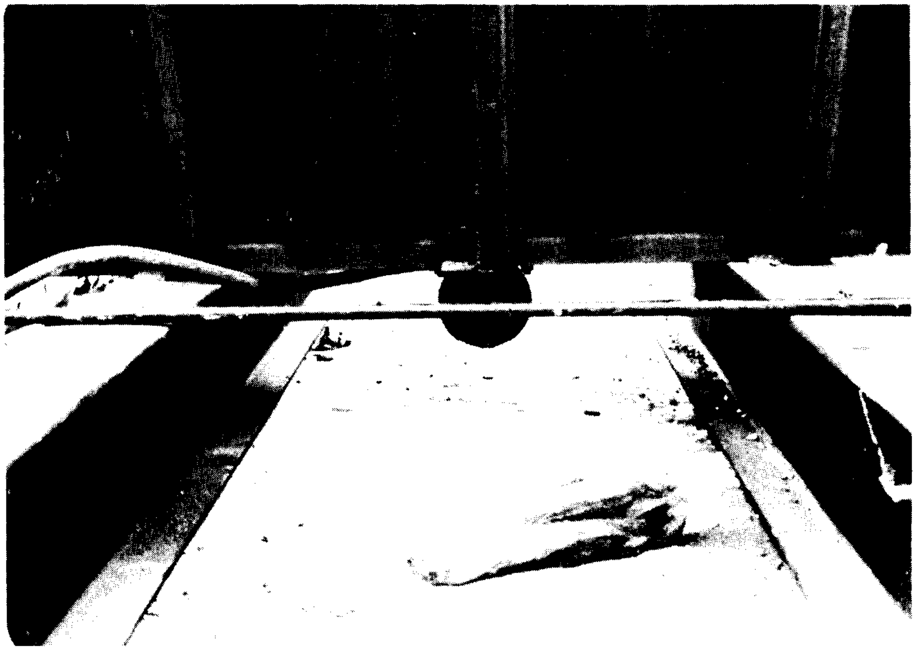


FIGURE 19

Bottom of Form with External Vibrator

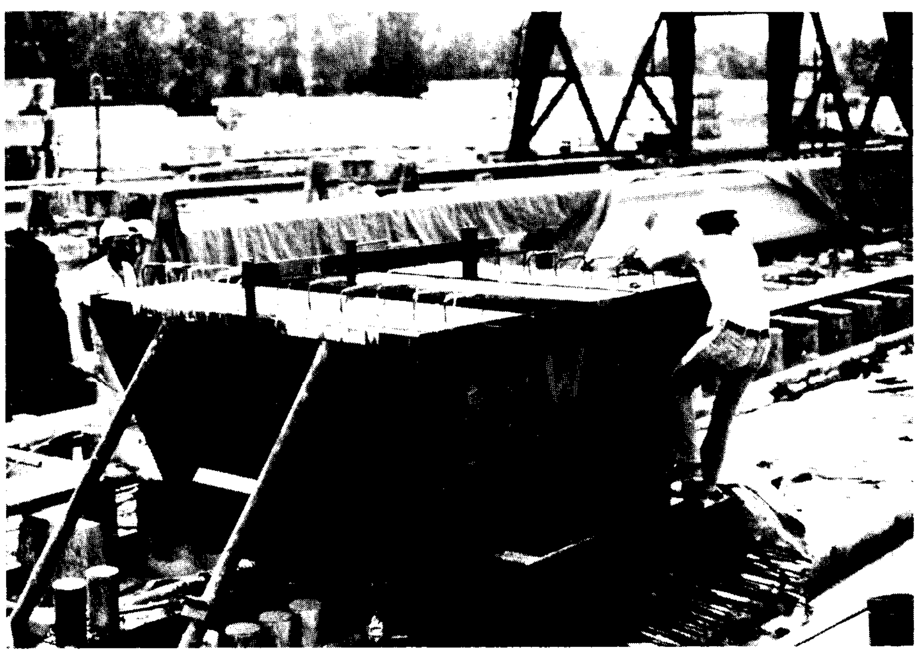


FIGURE 20

View of Finished Pour "Dummy" Girder

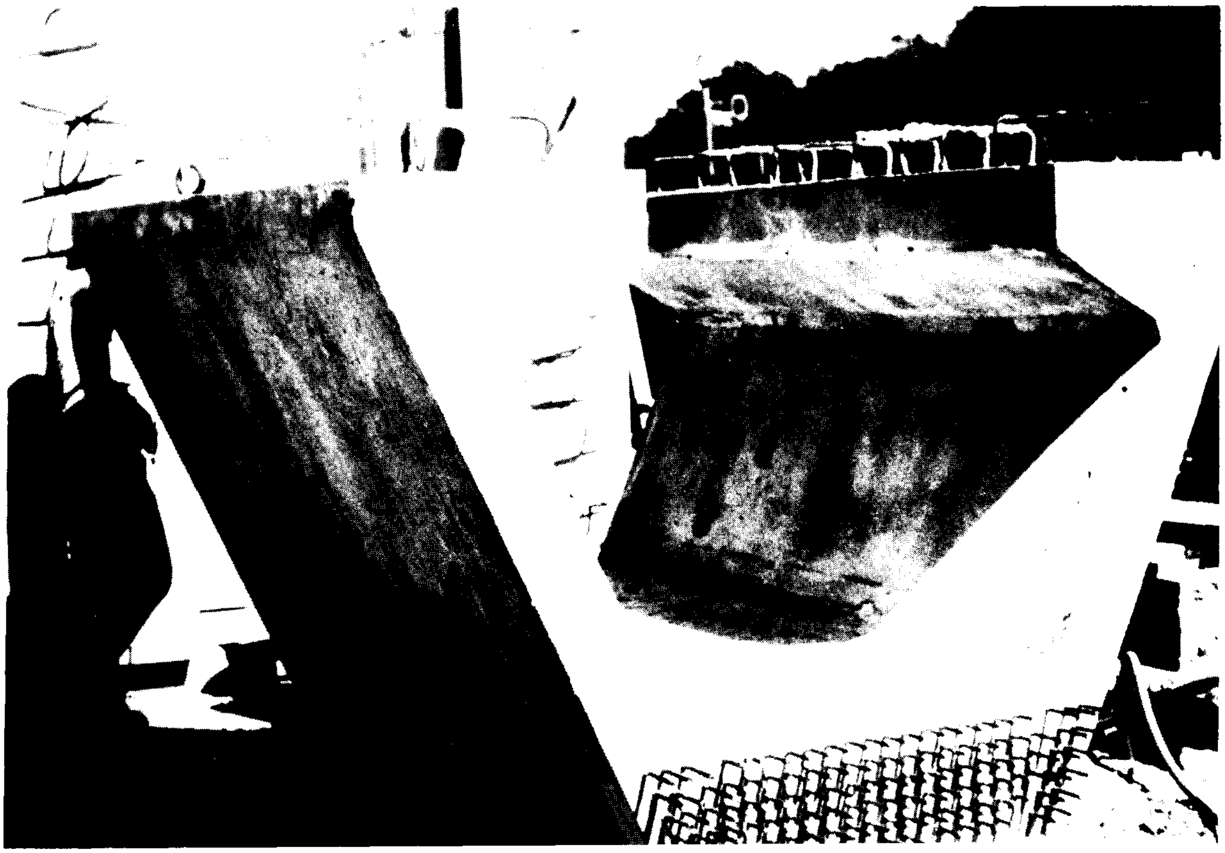


FIGURE 21

View "Dummy" Girder

TABLE 9

Test Results
Vibrated & Rodded Cylinder
Compressive Strengths

Coarse Aggre-gate	Cement Content bags/ cu. yd.	Aggregate Ratio (FA/CA)					
		36/64		40/60		45/55	
		Vibrated	Rodded	Vibrated	Rodded	Vibrated	Rodded
Pea Gravel	7.5	6446 psi	6133 psi	6411 psi	6564 psi	6472 psi	6440 psi
	8.0	7367 psi	6843 psi	6263 psi	6372 psi	7538 psi	7191 psi
	8.5	6926 psi	7014 psi	7102 psi	7049 psi	6690 psi	6720 psi
Small Lime-stone	7.5	6985 psi	6525 psi	7061 psi	6625 psi	6920 psi	7350 psi
	8.0	6902 psi	7079 psi	7026 psi	7085 psi	7261 psi	7120 psi
	8.5	7968 psi	7615 psi	7762 psi	7980 psi	7497 psi	7762 psi

All are non air-entrained concrete mixes.