DIVISION OF STRUCTURES AND ENGINEERING SERVICES

TRANSPORTATION LABORATORY

RESEARCH REPORT

ACCELERATED TEST DEVELOPMENT FOR PORTLAND CEMENT CONCRETE

FINAL REPORT (REV.)

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Prepared in Cooperation with the U.S. Department of Transportation,

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16. ABSTRACT

A satisfactory accelerated concrete strength test method has been developed. The method, called "autogenous curing", consists of placing a fresh 6 x 12-inch concrete cylinder in an insulated enclosure for a 48-hour curing period, then testing for compressive strength. The developed 48-hour compressive strengths are 40 to 75 percent of the 28-day standard moist cured compressive strengths. This method can be used for concrete quality control and acceptance.

In the laboratory, a series of tests were designed to determine the magnitude and direction that changes in cement quantity and types, aggregates, temperature, and admixtures would have on the correlation between the 48-hour cure strength and the 28-day standard moist cured strength. Analyses of the data indicated that a new strength correlation curve should be established when any changes are made in the concrete.

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STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF STRUCTURES & ENGINEERING SERVICES
OFFICE OF TRANSPORTATION LABORATORY

April 1976

TL No. 635182
Item No. F-4-23

Mr. C. E. Forbes
Chief Engineer

Dear Sir:

I have approved and now submit for your information this final research project report titled:

ACCELERATED TEST DEVELOPMENT FOR

PORTLAND CEMENT CONCRETE

Study made by . . . . . Roadbed and Concrete Branch

Under the Supervision of . . . . . D. L. Spellman

Principal Investigator . . . . . S. N. Bailey

Co-Investigator . . . . . B. F. Neal

Report Prepared by . . . . . S. N. Bailey

Assisted by . . . . . B. F. Neal

Very truly yours,

George A Hill

GEORGE A. HILL
Chief, Office of Transportation Laboratory

Attachment
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The contents of this report reflect the views of the Transportation Laboratory which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Since the initial distribution of this report in May, 1975, questions have been raised regarding certain aspects of the statistical analyses. At the suggestion of Mr. Howard T. Arni, Materials Division, FHWA, this revised version has been prepared.

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INTRODUCTION

The most commonly accepted measure of concrete "quality" is the 28-day compressive strength. Since the strength is not determined until 28 days after the concrete is produced, the opportunity to make corrective adjustments in mix design if necessary, must wait. This delay at times creates a problem in quality control and specification enforcement. Often decisions must be made to either accept concrete different from that specified, or to remove it, either of which can prove very costly.

Accelerated methods for determining the 28-day strength potential at an early age have been sought for many years. Most accelerated methods attempted have involved hot water or steam since heat accelerates the hydration of portland cement that results in rapid curing of concrete. While these trials resulted in some measure of success, they were never widely accepted. More recently, Ontario[1] reported on an accelerated method referred to as "autogenous cure", so-called because the heat used to accelerate curing is that generated by the hydration process and retained by insulated containers. Advantages of this method are the simple equipment required and the elimination of safety hazards inherent in the hot water or steam methods. The correlation between 48-hour autogenous cured cylinder strengths and 28-day standard moist cured cylinder strengths were judged to be satisfactory. This procedure has now been published as Procedure C in ASTM Designation: C684-74, Standard Method of Making, Accelerated Curing, and Testing of Concrete Compression Test Specimens.

To evaluate the autogenous method, a preliminary series of tests wew made on a paving project. As a result of these tests, three more series of field tests were made, and then a full

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[1]Refers to references at end of report

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scale research project was initiated which included both laboratory and field work. The objectives of the project were to (1) determine the feasibility of an accelerated test for quality control of structural concrete, (2) investigate the feasibility of using the autogenous curing method to predict paving concrete strength potential, and (3) supplement or replace the flexural strength method now used for quality control and for determining when a pavement may be opened to traffic. The need for early knowledge of the adequacy of a paving concrete mix design is just as great as for structural concrete. On paving projects the Contractor places much of the concrete before any flexural strengths are available for evaluation of the concrete.

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CONCLUSIONS

1. The autogenous curing method is a practical accelerated strength test procedure and is feasible for quality assurance of concrete production.

2. A 48-hour to 28-day strength relationship must be developed for each basic mix design.

3. The determination of when traffic can be allowed on new concrete pavement could be made from compressive strength tests of cylinders subjected to the same environmental conditions as the pavement.

4. The use of core strengths or impact hammer results would not be acceptable for determining pavement strength on a routine basis.

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IMPLEMENTATION

It is recommended that the accelerated strength test using autogenous curing be implemented on several large concrete projects in parallel with conventional testing methods. This would not only provide concrete producers and State personnel with valuable information on concrete quality at an early date, but would also provide background to determine feasibility of converting to the accelerated test for quality acceptance. Curing containers and, where needed, testing equipment could be supplied by the Laboratory. Cost to do the additional testing would be small.

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PRELIMINARY STUDY

The purpose of these preliminary tests was to study the possibility of using compressive strengths of cylinders in lieu of the flexural beam test to determine when a pavement could be opened to traffic, and also whether autogenous cured cylinders might be feasible for quality assurance tests. Before a pavement may be opened to traffic, California specifications require that the concrete attain a minimum flexural strength of 550 psi based on beams broken by centerpoint loading.

Testing was carried out on a paving project about 25 miles east of Sacramento. It was thus convenient to bring some of the specimens into the laboratory for controlled curing. For autogenous curing, four cylinders were fabricated once each day for four days. These were placed in an insulated curing box about an hour after sampling and left until tested. Two were tested at 48-hours and two at 10-days. The curing boxes were constructed of 3/4-inch plywood with 2-inches of polyurethane foam for insulation. Each box could hold six cylinders.

For standard compressive strength tests, nine sets of 10 cylinders each were fabricated over a 5-day period. All were left next to the pavement until the morning following fabrication. Of the 10 cylinders, four were cured in the laboratory moist room; two each were tested in the field at ages 10, 14 and 28-days, using a portable testing machine. The lab cured cylinders were tested at age 10 and 14-days.

Beams for contract control are normally cast in sets of three, two sets for each day of paving, then cured and tested at the jobsite. During this study, an additional set of 3 beams was cast for laboratory testing using the third-point loading method. Two of the 3 beams were cured in the moist room for 10 and 14-day breaks and the third was cured in wet sand in the field and tested at 10-days, also with third point loading.

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The strength results are shown in Tables 1a and 1b. All specimens for a given round were cast from one sample taken from a single batch of concrete. Each compressive strength value shown is an average of two cylinders, while each beam strength represents a single break.

Field and Lab Data

The relationship between compressive strengths of 2-day autogenous cured cylinders and those of laboratory or field cured cylinders, appeared to be reasonably consistent. The ratio of 10-day (laboratory cured) to 2-day strengths averaged 2.00 ranging from 1.88 to 2.05. The 14-day (laboratory cured) 2-day ratio was 2.21 ranging from 2.15 to 2.28. The field cured cylinders were considerably lower in strength due, in part at least, to cool curing temperatures. The highs for the testing period did not exceed 70°F and lows approached freezing. The flexural strengths of field cured specimens did not appear to be affected appreciably by the low curing temperatures.

Results of flexural strengths for 10-day field cured specimens show the center point test is approximately 100 psi, or 20 percent, greater than the third point test on the same concrete. This relationship is attributed to the fact that in center point loading the weakest point in the beam may not be at the point of maximum bending moment while in the case of third point loading the bending moment is uniform over the middle third of the beam and the break occurs at the weakest point within that area.

While the testing program left a number of questions unanswered, it did indicate that both objectives -- using autogenous curing to predict strength, and cylinders to replace the beam test -- might be feasible.

Additional Field Tests (Preliminary Study)

To develop further information and verify previous findings, testing was performed on three additional paving projects. The projects were widely scattered around the state and concrete aggregates were of entirely different types from that used on the first project.

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TABLE 1a

Strength Results of Preliminary Testing Program

Round	Compressive Strengths, PSI (Cylinders)						
	Autogenous Cured, Days		Laboratory Cured, Days		Field Cured, Days		
	2	10	10	14	10	14	28
1	1730	2570	3520	3810	2610	3200	3800
2			----	(3170)	(2230)	(2560)	----
3			(3160)	(3590)	(2440)	(2800)	(3230)
4	1790	2870	3610	3840	2670	3000	3520
5	1540	2730	3160	3510	2410	2560	3280
6			(2970)	(3440)	(2520)	(2780)	(3070)
7			(2740)	(3330)	(2320)	(2840)	(3010)
8	1510	2600	2840	3370	2390	2680	3270
9			(2620)	(2950)	(2200)	(2410)	(2780)
*Avg.	1640	2690	3280	3630	2520	2860	3470
Avg. of All	1640	2690	3080	3430	2420	2760	3240

( ) No companion autogenous cured specimens.

* Omits ( ) results.

Note: Each value shown above is the average of two cylinder breaks.

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TABLE 1b

Strength Results of Preliminary Testing Program

Round	Flexural Strengths, PSI					
	Third Point Loading			Center Point Loading		
	Field Cured, 10 Days	Laboratory Cured, Days 10	14	Field Cured, Days 10	14	28
1	600	560	515	---	735	---
2	(505)	(530)	(500)	(635)	(645)	---
3	(530)	(510)	(560)	(620)	(705)	(755)
4	500	610	575	615	625	785
5	535	560	605	665	685	825
6	(540)	(475)	(605)	(680)	(695)	(735)
7	(485)	(485)	(510)	(570)	(625)	(740)
8	470	510	485	620	655	720
9	(450)	(390)	(440)	(520)	(640)	(585)
Avg.*	525	560	545	635	700	775
Avg. of all	515	515	535	615	680	735

Ratio $\frac{\text{Ctr. Pt. Flex. Str (Field Cured)}}{\text{Comp. Str. (Field Cured)}}$ = 10 day $\frac{615}{2420}$ (25.4%), 14 day $\frac{680}{2760}$ (24.6%), 28 day $\frac{735}{3240}$ (22.7%)

( ) No companion autogenous cured specimens.

* Omits ( ) results.

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The testing procedure was essentially that reported above. However, except for the autogenous cured cylinders, all specimens were cured on the job until time to be tested. Both beams and cylinders were then transported to Sacramento (in wet sand) and tested on laboratory testing machines. Contract control beam data were not collected. The test results are shown in Tables 2, 3, and 4.

Ratios of flexural to compressive strengths at various test ages for the aggregates tested are shown on Tables 1 to 4. It can be seen that there is some difference in ratios with different aggregate sources, although with the aggregates tested this difference is not very great. The ratio is reduced as age increases. From existing knowledge of the ratio between flexural and compressive strength it can be stated that the ratio is reduced as the cement content is increased. The explanation for both of these conditions is that compressive strength is influenced to a greater degree by age and cement content than is flexural strength. With the latter strength parameter the aggregate becomes more of a controlling factor in flexural strengths achieved.

From these tests, it appears that for a given concrete mix, the ratio of beam strengths to cylinder strengths, with specimens cured in similar manner, is reasonably constant. Also, the autogenous cured cylinders gave a reasonable estimate of later compressive strength in spite of the varied environmental conditions.

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TABLE 2

Strength Data from Corona Project (PSI)

	Cylinders				Beams**		
Autogenous* Cured, Days	Field Cured, Days				Field Cured, Days		
2 days	10	14	28		10	14	28
1460	2090	2470	2920		500	530	570
1540	2190	2540	2920		480	500	490
1830	2530	3070	3590		500	550	640
1790	2760	2830	3570		540	585	580
1820	2240	2620	3520		590	475	535
1860	2350	2620	2690		540	530	600
1740	2570	2830	3180		530	585	620
1730	2710	2810	2930		540	615	610
2010	2810	3000	3620		560	620	735
2050	2740	3220	3890		---	565	705
1920	2630	2850	3180		---	560	535
1790	2760	2830	3360		---	---	520
Avg. 1800	2530	2810	3280		530	560	595

Ratio $\frac{\text{Third Pt Flex. Str. (Field Cured)}}{\text{Comp. Str. (Field Cured)}}$ = 10 day $\frac{530}{2530}$ (21.0%), 14 day $\frac{560}{2810}$ (19.9%), 28 day $\frac{595}{3280}$ (18.1%)

* Tested at Jobsite
**Third point loading

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TABLE 3

Strength Data from Pleasanton Project

	Cylinders			Beams**		
Autogenous* Cured, Days	Field Cured, Days			Field Cured, Days		
2 days	10	14	28	10	14	28
2100	2830	3290	4130	510	565	790
2100	2770	3150	4240	575	615	760
1960	2650	3250	3940	555	625	725
1840	2990	3230	4060	580	635	765
1860	2560	3250	3800	535	660	750
1980	2830	2930	3600	525	700	750
1890	2790	3000	3780	525	580	820
1890	2650	3550	4280	465	600	575
1840	2860	3150	4290	535	580	645
1770	----	2850	4100	630	560	690
1800	----	2810	4210	600	580	675
Avg. 1910	2750	3140	4030	545	605	725

	10 day	14 day	28 day
Ratio $\frac{\text{Third Pt. Flex. Str. (Field Cured)}}{\text{Comp. Str. (Field Cured)}}$	$\frac{545}{2750}$	$\frac{605}{3140}$	$\frac{725}{4030}$
	(19.8%)	(19.3%)	(18.0%)

*Tested at Jobsite
**Third Point Loading

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TABLE 4

Strength Data from Boron Project

	Cylinders			Beams**		
Autogenous* Cured, Days	Field Cured, Days			Field Cured, Days		
2 days	10	14	28	10	14	28
	Aggregate A					
1710	2950	3410	3650	475	580	675
1680	3180	3360	3750	535	590	590
1640	2880	3360	3600	545	595	640
1640	2630	3230	3900	530	590	615
1780	2790	3010	4060	505	635	620
1730	2740	3220	3500	575	540	650
2080	2790	3070	3980	580	640	620
2060	2860	3480	3850	620	555	715
Avg.1790	2850	3270	3790	545	590	640

	10 day	14 day	28 day
Ratio - Third Pt. Flex. Str (Field Cured) / Comp. Str. (Field Cured)	545/2850	590/3270	640/3790
	(19.1%)	(18.0%)	(16.9%)

	Aggregate B					
1440	2810	2950	3750	495	510	590
1470	2850	2910	3590	470	535	590
1890	2650	3020	3180	465	505	610
1890	2510	2860	3200	485	555	560
Avg.1670	2710	2940	3430	480	525	590

	10 day	14 day	28 day
Ratio - Third Pt. Flex. Str. (Field Cured) / Comp. Str. (Field Cured)	480/2710	525/2940	590/3430
	(17.7%)	(17.9%)	(17.2%)

*Tested at Jobsite
**Third point loading

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RESEARCH STUDY

Equipment

The initial autogenous cure testing was performed with existing insulated curing boxes which held several cylinders. From the Ontario report and correspondence with Virginia researchers, it was considered advisable to use individual containers with more positive seals to retain heat.

To check on heat retention characteristics, three different sizes of boxes were made in the laboratory shop. Each had a plywood shell, but the poured polyurethane foam insulation was constructed xo 3, 4, and 5 inches in minimum thickness. The containers were constructed in half sections for ease in handling cylinders. Two adjustable clamps were attached for holding the two portions together and a soft foam layer was used between the two halves xo provide more positive seals.

Tests were made on each container to determine heat loss. The additional heat retained was minimal using 4 and 5 inches of insulation. The box with 3 inches of insulation had heat loss well within the limitations recommended by Ontario and Virginia, and was considered adequate and preferable to the more bulky containers. Thirty of these containers were then constructed for conducting concrete testing. Steps in construction of the container are shown in Figures 1 through 6 in Appendix A.

Laboratory Study of Factors Affecting Accelerated Tests

For this study at least five parameters were considered to have some effect on the relationship between 48-hour autogenous cured and 28-day standard moist cured cylinders. Based on California needs, the following selections were made. These were considered the minimum number of variables necessary to evaluate each parameter.

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Factors to Study		Variables	
1.	Aggregate Quality	(6)	2 low, 2 medium, and 2 high (strength producing)
2.	Type of Cement	(3)	Types II, III, and II Prestress*
3.	Cement Factors	(3)	5, 6, and 7-1/2 sack/cu yd
4.	Admixtures	(3)	A water-reducing agent, an air-entraining agent, and a control containing no admixture
5.	Temperature of Fresh Concrete	(3)	50°F, 70°F, and 90°F

To conduct a factorial experiment with the above parameters and the necessary replications, was not considered practical. However, two Latin square experiments were designed which did include all the variables. Latin square A was an evaluation of:

1. Three aggregates of low, medium, and high strength producing properties.

2. Three cement types - Type II, III, and II Prestress*.

3. Three fresh concrete temperatures - 50°, 70°, and 90°F.

Latin square B was an evaluation of:

1. Three aggregates (different from A) of low, medium, and high strength producing properties.

2. Three admixtures - a water-reducer, an air-entraining agent, and a control.

3. Three cement contents of 5, 6, and 7-1/2 sacks per cubic yard.

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The experimental block design for Latin squares A and B are shown on Figure 1. For each block, a random mixing schedule was followed and included replication for each mix. Four cylinders were fabricated from each batch of concrete mix; two for autogenous curing, and two for 28-day moist curing. The compressive strength test results are shown on Figures 2 and 3, and also the data are plotted on Figures 4 and 5 for Latin squares A and B respectively. For each round of tests, a separate analysis was made on the 48-hour autogenous and the 28-day moist cured strength test results. In addition, an analysis was made on the strength ratio factor of the 28-day to 48-hour strength.

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*"Type II Prestress" is California's designation for cement used primarily by prestress and concrete pipe plants to obtain higher early strengths. The cement meets Type II requirements but is more finely ground than that normally used in pavements and structures.

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EXPERIMENT DESIGN

Latin Square A

Cement Types	Relative Aggregate Strength		
	Low	Medium	High
II	50°F	70°F	90°F
III	70°F	90°F	50°F
II Prestress	90°F	50°F	70°F

Latin Square B

Admixture	Relative Aggregate Strength		
	Low	Medium	High
Water-Reducing Set-Retarding (R)	5 sk/cu yd	6 sk/cu yd	7-1/2 sk/cu yd
None Control (N)	6 sks/cu yd	7-1/2 sk/cy	5 sks/cu yd
Air entraining (A)	7-1/2 sk/cy	5 sk/cy	6 sk/cy

Figure 1

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LATIN SQUARE "A" RESULTS
Compressive Strength, psi

$$\frac{\text{28-day Moist Cured, psi}}{\text{48-hour Autogenous Cured, psi}} = \text{Strength Ratio}$$

	Cement Types	Relative Aggregate Strength Quality		
		Low	Medium	High
Round 1	II	50°F	70°F	90°F
		$\frac{4180}{1835} = 2.28$	$\frac{4920}{2480} = 1.98$	$\frac{5370}{2535} = 2.12$
	III	70°F	90°F	50°F
		$\frac{4745}{3380} = 1.60$	$\frac{5655}{3970} = 1.42$	$\frac{6165}{3370} = 1.83$
	II Pre.	90°F	50°F	70°F
		$\frac{4435}{2775} = 1.60$	$\frac{6295}{4430} = 1.42$	$\frac{5290}{3355} = 1.58$
Round 2	II	50°F	70°F	90°F
		$\frac{4375}{1660} = 2.63$	$\frac{5240}{2360} = 2.22$	$\frac{5195}{2470} = 2.10$
	III	70°F	90°F	50°F
		$\frac{4750}{3295} = 1.44$	$\frac{5795}{4150} = 1.40$	$\frac{5970}{4390} = 1.36$
	II Pre.	90°F	50°F	70°F
		$\frac{4170}{2770} = 1.53$	$\frac{6140}{3780} = 1.62$	$\frac{5395}{3260} = 1.66$

II Pre = Type II - Prestress (Calif. Specs.)

Figure 2

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LATIN SQUARE "B" RESULTS
Compressive Strength, psi

$$\frac{\text{28-day Moist Cured, psi}}{\text{48-hour Autogenous Cured, psi}} = \text{Strength Ratio}$$

	Admixtures	Relative Aggregate Strength Quality: Low	Medium	High
Round 1	Water-reducing and Set Retarding	5-sk/cy $\frac{3550}{1600} = 2.22$	6-sk/cy $\frac{6475}{3910} = 1.66$	7-1/2 sk/cy $\frac{7435}{5115} = 1.45$
	None (Control)	6-sk/cy $\frac{3465}{1710} = 2.03$	7-1/2 sk/cy $\frac{6235}{3630} = 1.72$	5-sk/cy $\frac{4780}{1765} = 2.71$
	Air Entraining	7-1/2 sk/cy $\frac{3950}{2400} = 1.64$	5-sk/cy $\frac{4575}{1835} = 2.49$	6-sk/cy $\frac{4715}{2350} = 2.01$
Round 2	Water-reducing and Set Retarding	5-sk/cy $\frac{3460}{1345} = 2.57$	6-sk/cy $\frac{6665}{8835} = 1.74$	7-1/2 sk/cy $\frac{7020}{5300} = 1.33$
	None (Control)	6 sk/cy $\frac{3765}{1590} = 2.37$	7-1/2 sk/cy $\frac{6545}{3675} = 1.78$	5-sk/cy $\frac{4555}{1720} = 2.65$
	Air Entraining	7-1/2 sk/cy $\frac{3880}{2330} = 1.66$	5-sk/cy $\frac{3805}{1630} = 2.33$	6-sk/cy $\frac{4610}{2170} = 2.12$

Figure 3

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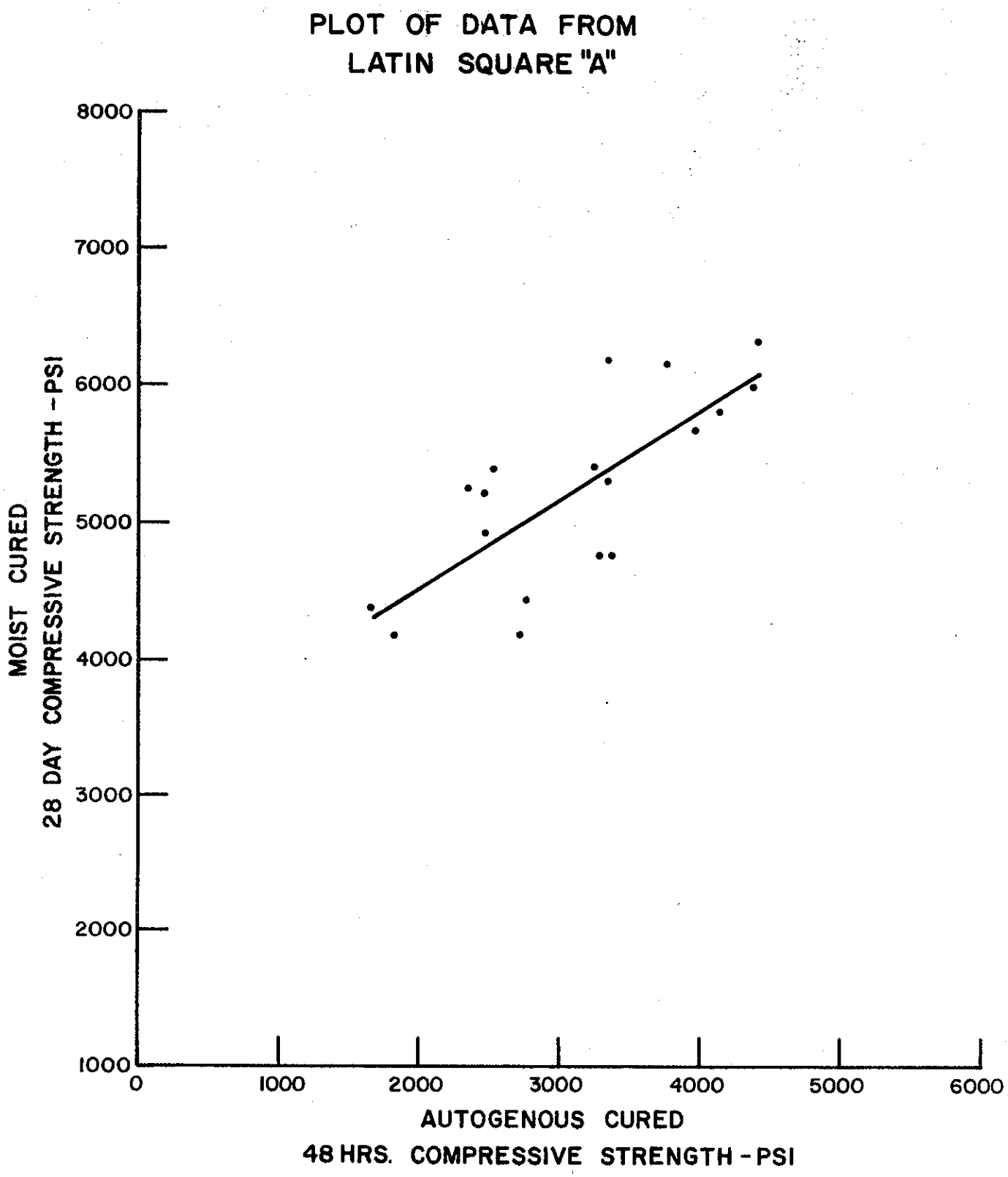

Fig. 4

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PLOT OF DATA FROM
LATIN SQUARE "B"

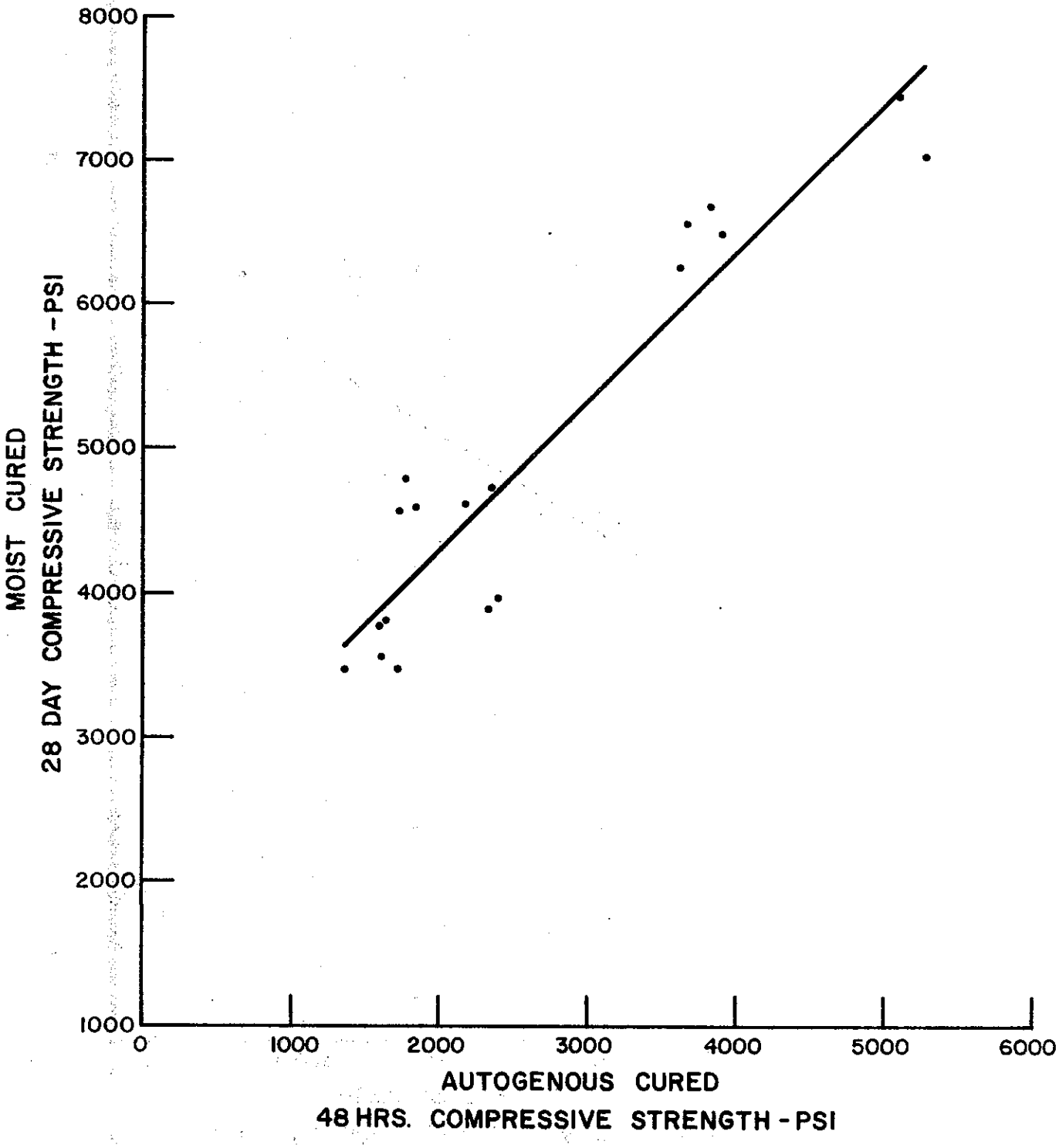

 Fig. 5

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The results of the analysis can be found in Appendix B and are summarized in Table 5.

For the Latin Square analysis those parameters for which a significant effect was detected in the data analyzed are identified by the magnitude of the "F" ratio. In our case, which involved only two degrees of freedom for each variable, the F ratio would have to be 19 or larger to indicate significance at the 5 percent level. In Table 5 the following results are indicated:

> Cement type was significant for the 48-hour cure in Round 2 but not in Round 1, and in neither round for the 28-day cure.
>
> Aggregate quality was significant in Latin Square A for both curing conditions in Round 2 but for neither curing condition in Round 1. In Latin Square B, aggregate quality was significant for both rounds for the 28-day cure but for neither for the 48-hour cure.
>
> Temperature of the mix was not significant in any of the four cases.
>
> Cement content was significant in all four cases.
>
> Admixtures were significant in both rounds for the 28-day cure but in neither round for the 48-hour cure.

It is present practice by some Resident Engineers to use early normally cured strength test results to estimate the ultimate 28-day strength. This estimation or prediction of the 28-day strength is made by an established or assumed strength ratio

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Table 5

Summary of Latin Square Analysis of Variance
(Individual 48-hr. Autogenous Cured and 28-day Moist Cured Concrete)

Compressive Strength
X - Significant at the 5% level; 0 - Not Significant at the 5% level

Latin Square A

	Cement Types II, III & II-P		Aggregates; Fair, Good and Excellent		Temperature 50°, 70°, and 90°F	
	48-hour Cure	28-day Cure	48-hour Cure	28-day Cure	48-hour Cure	28-day Cure
Round 1	F = 6.22 0	F = 2.72 0	F = 2.74 0	F = 9.36 0	F = .06 0	F = 1.72 0
Round 2	F = 112.71 X	F = 5.44 0	F = 33.15 X	F = 32.54 X	F = 3.28 0	F = 3.76 0

Latin Square B

	Cement Content, 5 Sk/CY 6 Sk/CY, and 7-1/2 Sk/CY		Aggregates; Fair, Good and Excellent		Admixtures; Water Rdcr. Air Entraining and None	
	48-hour Cure	28-day Cure	48-hour Cure	28-day Cure	48-hour Cure	28-day Cure
Round 1	F = 30.03 X	F = 22.46 X	F = 14.60 0	F = 49.85 X	F = 16.39 0	F = 18.59 X
Round 2	F = 24.79 X	F = 97.12 X	F = 11.45 0	F = 124.77 X	F = 11.96 0	F = 71.91 X

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between the early and later tests. Considering the ratio between the 28-day strength and the 48-hour autogenous cured strength as a factor by which this prediction could be made and analyzing this ratio in Latin squares A and B, it could possibly give some insight of how these parameters affect the strength ratio. The computer analysis is summarized in Table 6. Here it may be seen again that the temperature is not significant at the 5% level and cement content is significant at the 5% level.

In Tables 5 and 6 where there are differences between Round 1 and Round 2 as to the parameters being significant or not significant, it may be attributed to the variations in the materials themselves. This indicates some doubt and suggests that a new strength relation curve should be established when the aggregate source is changed or when admixtures are used.

Table 7 and Figure 6 show results of 4 sets of tests in which water-cement ratio was varied from 0.4 to 0.7. Cement type and source, aggregate source and slump were held constant. The amount of sand in each mix was adjusted to attain the same volume. Cement content varied from 7 sacks per cubic yard (w/c 0.4) to 4 sacks per cubic yard (w/c 0.7). As seen in Figure 6, the variation between actual data points and the strength relation regression line is small in comparison with that shown in Figures 4 and 5. This experiment verified the conclusions from the Latin Square analysis which indicated that varying only the cement content, or water-cement ratio, would not change the strength relationship between 48-hour autogenous cured specimens and 28-day moist cured specimens.

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Table 6

Summary of Latin Square Analysis of Variance
(28-day Concrete Strength Prediction from Ratio of 48-hr
Autogenous Cured and 28-day Moist Cured Cylinders)

Latin Square A

X - Significant at the 5% Level
O - Not significant at the 5% Level

	Cement Types II, III & II-P	Aggregates; Fair, Good and Excellent	Temperature 50°, 70°, and 90°F
Round 1	F = 17.73 O	F = 2.17 O	F = 1.48 O
Round 2	F = 21.32 X	F = .65 O	F = .87 O

Latin Square B

	Cement Content: 5 Sk/CY, 6 Sk/CY and 7-1/2 Sk/CY	Aggregates; Fair, Good and Excellent	Admixtures: Water Reducer, Air Entrainment, and None
Round 1	F = 2071.50 X	F = 33.02 X	F = 395.73 X
Round 2	F = 29.69 X	F = 2.29 O	F = 5.19 O

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Table 7

Range in Compressive Strengths Due to Different W/C Ratios

Series	W/C Ratio	2-day cure	2-day Avg. S_2	28-day Avg. S_{28} (All Moist, Room Curing)	S_{28}/S_2
TP1-1	0.5	Outside Inside	2400 2300	5000	2.08 2.15
TP1-2	0.5	Outside Inside	2500 2670	5320	2.11 1.99
TP2-1	0.6	Outside Inside	2180 2340	4820	2.21 2.06
TP2-2	0.6	Outside Inside	2160 2050	4670	2.16 2.28
TP3-1	0.4	Outside Inside	3370 3670	5960	1.77 1.62
TP3-2	0.4	Outside Inside	3650 3590	5880	1.61 1.64
TP4-1	0.7	Outside Inside	1450 1240	3510	2.42 2.83
TP4-2	0.7	Outside Inside	1580 1510	3640	2.30 2.41
Average $\overline{X}$			2419.4	4850	2.10

Note: Inside temperature was Lab, 73±3°F.

Outside temperature varied from 49° to 93°F

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PLOT OF DATA
DIFFERENT W/C RATIOS

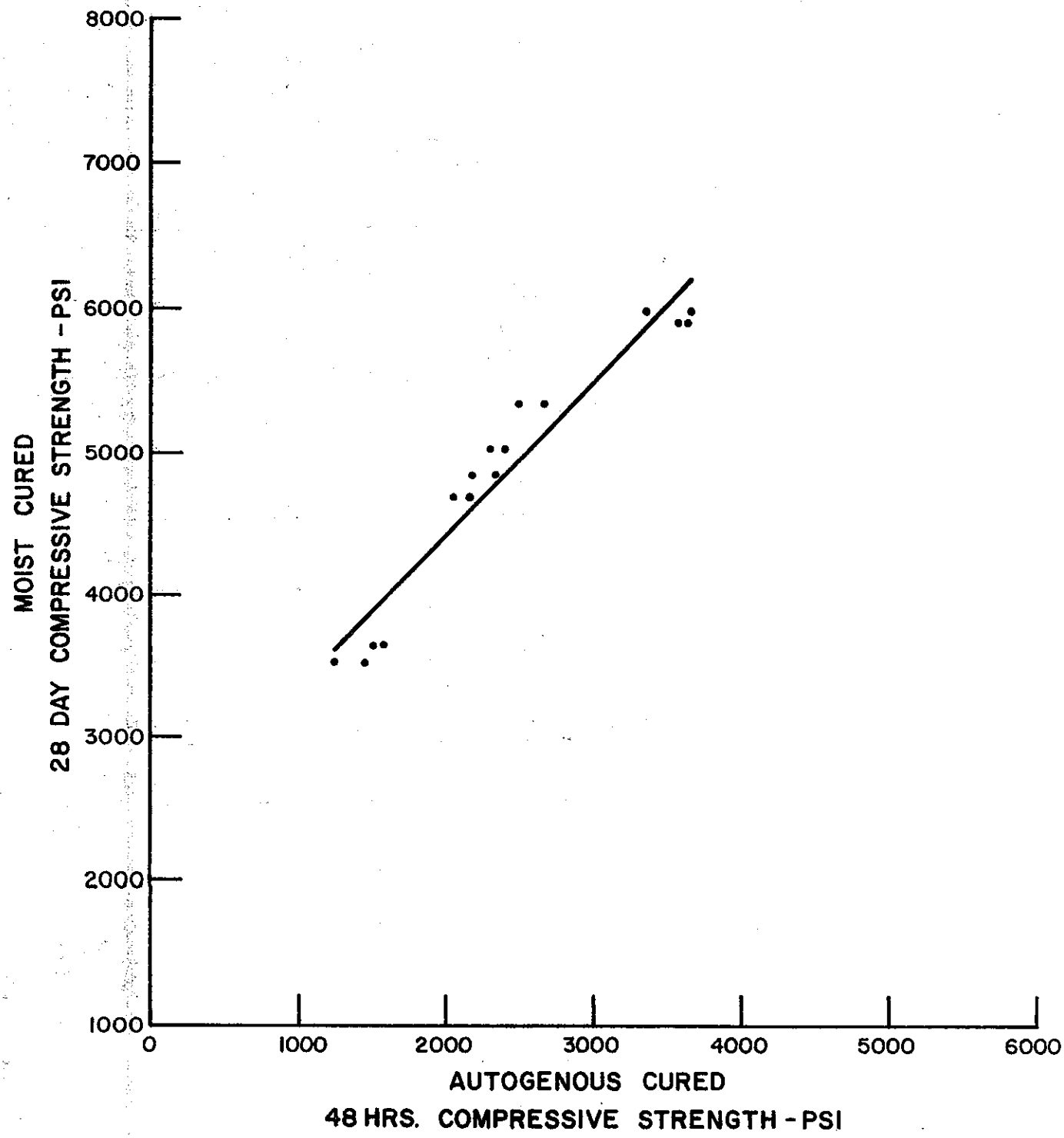

Fig. 6

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Field Tests - (Using Laboratory Personnel)

After the completion of the laboratory study, the next phase of this investigation was to go to the field and perform the tests under job conditions. For the first phase, the laboratory personnel who conducted the laboratory series made the cylinders and performed the tests in the field. This series consisted of eight separate days of sampling and testing from six separate projects throughout the state. Two of the projects were used twice. During the course of the day, six batches of concrete were sampled. Four cylinders, two for 48-hour autogenous cure and two for 28-day moist cure were cast from each batch sampled. In addition, at some locations, two additional sets of cylinders were also cast from each batch and placed in wet sand and in a shaded area for a 10-day curing period in the field. During this period, the cylinders were left in their sheet metal molds with the lids sealed with tape. These cylinders were made for five of the eight projects to serve as a means of collecting additional data for considering the feasibility of changing from the present beam test requirement to concrete cylinder strength test. These cylinder strengths could then be used to determine when the pavement had gained sufficient strength to be opened to traffic. The test data developed during this study is shown in Table 8 and plotted on Figure 7.

The prime purpose of the field study was to verify the equipment and technique in the field on different projects under various working conditions. A secondary purpose was to obtain data that represented many different types of concrete materials. As may be expected, from what was found in the laboratory experiments when different aggregates, cements, and admixtures are used, a greater scatter would exist around any strength relationship line developed from these data. This may be seen on Figure 7 which has magnitudes of variation from the prediction line of the actual data point upwards to 1000 psi. This again verified the fact that an individual strength relationship curve should be established for a specific concrete mix. The relationship should be re-established whenever the mix design parameters are significantly changed.

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PLOT OF FIELD DATA
(LABORATORY PERSONNEL)

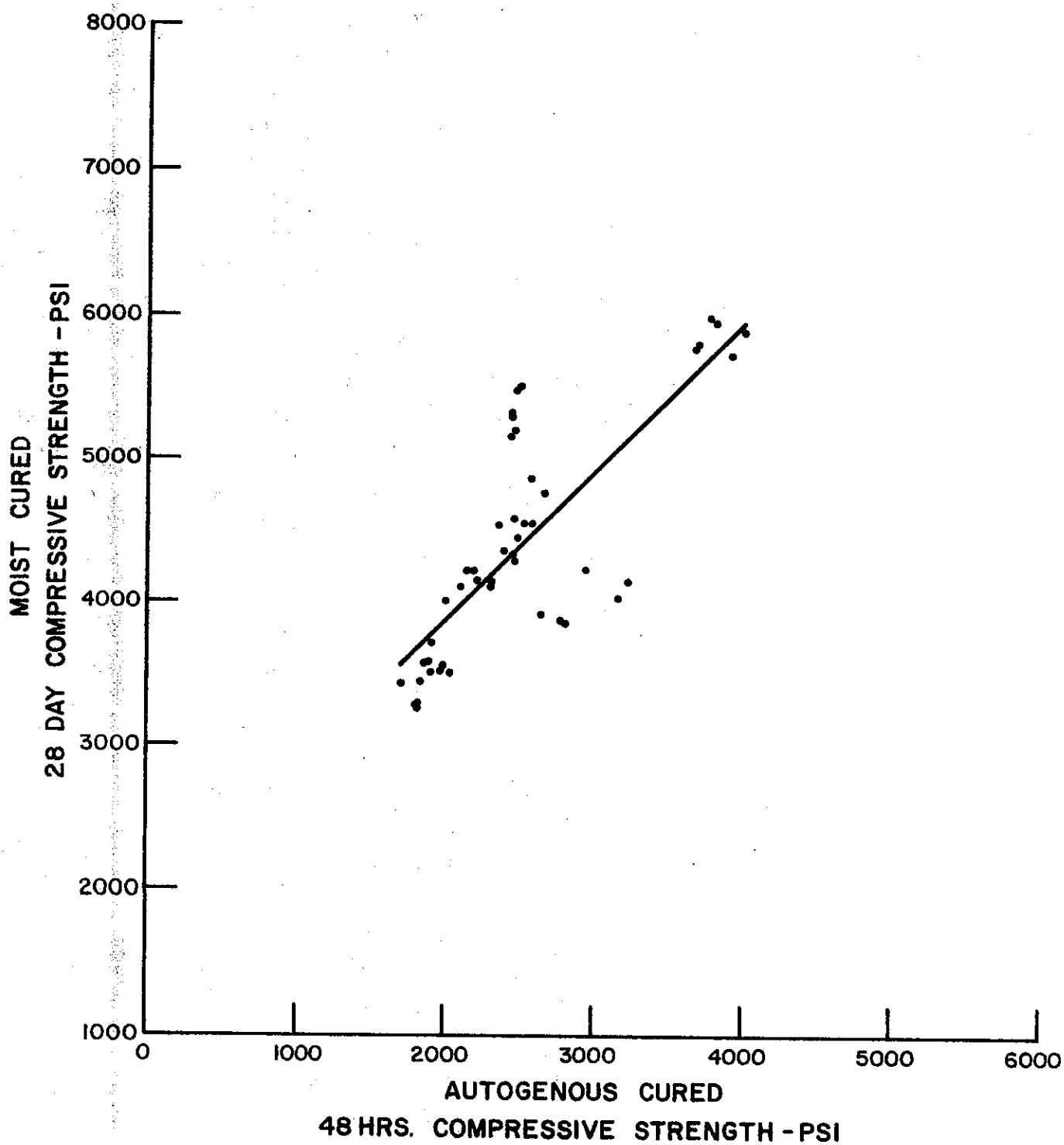

Fig. 7

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Table 8

Field Test Data
(Laboratory Personnel)

Project Number	Autogenous Cure, 48-hours*	Wet Sand 10-day*	Shade 10-day*	Moist Cure 28-day
1	2540	3590	3480	4420
Sacto.,	2480	3380	3150	4430
I-80	2460	3450	3250	4310
	2300	3100	3040	4100
	2100	2970	3020	4090
	2000	2960	2960	3960
Average	2320	3240	3150	4220
2	2570	3530	3550	4850
Sacto.,	2350	3380	3140	4520
I-80	2380	3200	3270	4340
	2470	3110	2940	4280
	2210	3120	3060	4140
	2570	3410	3140	4530
Average	2430	3290	3180	4440
3	2460			5460
Davis,	2440			5300
I-80	2430			5190
	2440			5260
	2490			5430
	2460			5180
Average	2450			5303
4	3780			5980
Riverbank,	3820			5940
Rte. 108	4010			5870
	3950			5700
	3680			5760
	3700			5790
Average	3820			5840
5	1980			3540
Woodland,	1900			3490
I-5	1880			3580
	1800			3270
	1810			3240
	1820			3430
Average	1870			3430
6	2020	3010	2800	3480
Woodland,	1680	2460	2260	3410
I-5	1910	2750	2630	3700
	1800	2690	2700	3290
	1960	2720	2470	3500
	1860	2610	2640	3570
Average	1870	2710	2580	3490
7	3160	3370	3450	4020
San Diego	2810	3220	3210	3850
I-805	3290	3590	3550	4140
	2780	3110	3010	3870
	2950	3470	3370	4220
	2650	3170	3020	3900
Average	2940	3320	3270	4000
8	2460	3190	3290	4560
Shasta,	2310	3030	3140	4120
I-5	2660	3430	3440	4750
	2530	3430	3390	4530
	2140	3020	2870	4210
	2190	3050	2860	4210
Average	2380	3190	3170	4400

*Left in can molds until day tested.

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An analyses of these field data obtained under this phase of the work is shown in Table 9 for each of the 8 projects. The equation which relates the 48-hour and 28-day strength was developed in the form $y = mx + b$. This is shown in the column of Y. The difference between the calculated and actual 28-day strength is analyzed as a source of error. By squaring these differences and summing the squares, it is possible to compute a standard deviation of the errors with two degrees of freedom.

Field Tests (Using Field Personnel)

As a means to verify that the test procedure and equipment were satisfactory for use on state projects by field personnel, a test series was arranged for a relatively large on-going project (the Stockton Crosstown Viaduct). This project had concrete placements spanning seeral months. All the materials and equipment needed to conduct the autogenously cured tests were provided to the field forces. This included a portable testing machine, capping materials, a capping plate, and autogenous curing insulated boxes. Normally, cylinders from the field are forwarded to the laboratory for moist curing and testing; this same procedure was followed for the 28-day test. Over a period of several months the data shown in Table 10 were collected and were analyzed by the same method used for the field data in Table 9. Since these data were collected over a long period of time, it must be expected to include some variations due to materials. The standard deviation of the difference between the actual test results and the strength curve for this series was determined to be 252 psi. Table 10 includes only the 6-sk/cu yd concrete. Table 11 includes the same data shown in Table 10, 6sks/cu yd as well as concrete consisting of 6-1/4 sks/cu yd with a water-reducing admixture, and a 7-sk/cu yd concrete.

Analyzing these data in Table 11 by considering the difference between the actual 28-day compressive strength and the calculated 28-day compressive strength results in a standard deviation of 294 psi.

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Table 9

Field Test Data (Lab Personnel)

Comparison of the difference (ε) between the actual 28-day compressive strength ($\bar{Y}28D$) and the calculated 28-day compressive strength ($\hat{Y}$) from the 48-hr autogenously cured, accelerated compressive strength (X_{48H})

	Actual Strength				
	X_{48H}	Y_{28D}	$\hat{Y}$	$\varepsilon = Y_{28D} - \hat{Y}$	ε^2
Sacramento I-80	2540	4420	4404	16	256
	2480	4420	4355	65	4225
$\hat{Y}_{28D} = 2299 + .8288X_{48H}$	2460	4310	4338	-28	784
	2300	4100	4206	-106	11236
Rotated Axis m = 1	2100	4090	4040	50	2500
$\hat{\hat{Y}}_{28D} = 1904 + (1)X$	2000	3960	3957	3	9
Sacramento I-80	2570	4850	4634	216	46656
	2350	4520	4343	177	31329
$\hat{Y}_{28D} = 1240 + 1.321X_{48H}$	2380	4340	4383	-48	1849
	2470	4280	4502	-222	49284
Rotated Axis m = 1	2210	4135	4159	-24	576
$\hat{\hat{Y}}_{28D} = 2017 + (1)X$	2570	4530	4634	-104	10816
Davis, I-80	2460	5460	5337	123	15129
	2400	5300	5256	44	1936
$\hat{Y}_{28D} = 4698 + 4.079X_{48H}$	2430	5190	5215	-25	625
	2440	5260	5256	4	16
Rotated Axis m = 1	2480	5430	5419	11	121
$\hat{\hat{Y}}_{28D} = 2851 + (1)X$	2460	5180	5337	-157	24649
Riverbank, Rte. 108	3780	5980	5840	140	19600
	3820	5935	5840	95	9025
$\hat{Y}_{28D} = 5877 - .01X_{48H}$	4010	5870	5837	33	1089
	3950	5700	5838	-138	19044
Rotated Axis m = 1	3680	5760	5841	-81	6561
$\hat{\hat{Y}}_{28D} = 2016 + (1)X$	3700	5790	5840	-50	2500
Woodland, I-5	2020	3480	3565	-85	7225
	1680	3410	3397	13	169
$\hat{Y}_{28D} = 2568 + .4937X_{48H}$	1910	3700	3511	189	35721
	1800	3290	3456	-166	27556
Rotated Axis m = 1	1960	3500	3535	-35	1225
$\hat{\hat{Y}}_{28D} = 1619 + (1)X$	1860	3570	3486	84	7056
Woodland, I-5	1980	3540	3607	-67	4489
	1900	3490	3480	10	100
$\hat{Y}_{28D} = 478 + 1.508X_{48H}$	1880	3580	3449	131	17161
	1800	3270	3322	-52	2704
Rotated Axis m = 1	1810	3240	3338	-98	9604
$\hat{\hat{Y}}_{28D} = 1560 + (1)X$	1820	3430	3354	76	5776
San Diego, I-805	3160	4020	4092	-72	5184
	2810	3850	3945	-95	9025
$\hat{Y}_{28D} = 2766 + .4197X_{48H}$	3290	4140	4147	-7	49
	2780	3870	3933	-63	3969
Rotated Axis m = 1	2950	4220	4004	216	46656
$\hat{\hat{Y}}_{28D} = 1060 + (1)X$	2650	3900	3878	22	484
Shasta, I-5	2460	4560	4487	73	5329
	2310	4120	4317	-197	38809
$\hat{Y}_{28D} = 1697 + 1.1345X_{48H}$	2660	4750	4714	36	1296
	2520	4530	4555	-25	625
Rotated Axis m = 1	2140	4210	4124	86	7396
$\hat{\hat{Y}}_{28D} = 2017 + (1)X$	2190	4210	4181	29	841
Totals = $\Sigma\varepsilon$				+2	498264
Averages $\frac{\Sigma\varepsilon}{48}$				.04	
Standard Deviations	$\frac{\Sigma\varepsilon^2}{48-2}$				104

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Table 10

Field Test Data (Field Personnel)

Comparison of the difference (ε) between the actual 28-day compressive strength (Y_{28D}) and the calculated 28-day compressive strength ($\hat{Y}$) from the 48-hr autogenously cured accelerated compressive strength (X_{48H}). One type concrete only.

	X_{48H}	$\hat{Y}_{28D}$	$\hat{Y}$*	$\varepsilon = Y_{28D} - \hat{Y}$	ε^2
Stockton Cross	2360	4450	4548	-98	9604
Town Viaduct	2010	3760	4095	-334	111556
	2000	4110	4081	29	841
All data from	2210	4750	4353	397	157609
6-sk/cy	2530	4550	4768	-218	47524
concrete	2490	4890	4716	174	30276
	2470	4760	4690	70	4900
$\hat{Y}_{28D} = 1490 +$	2580	5110	4833	277	76729
$1.296X_{48H}$	2090	4410	4198	212	44944
	2100	3920	4211	-291	84681
	2280	4480	4444	36	1296
	2820	4890	5144	-254	64516

Avg $\varepsilon = 0$ $\Sigma\varepsilon^2 = 634{,}476$

Average	AV	2330	4510	4510
Standard Deviation	σ	257	410	333
Coeff. of Variation	V	11%	9%	7%

$$\sigma_\varepsilon = \frac{\Sigma\varepsilon^2}{n-2} = \frac{634{,}476}{12-2} = \sigma_\varepsilon = 252 \text{ psi}$$

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Table 11

Field Test Data (Field Personnel)

Comparison of the difference (ε) between the actual 28-day compressive strength (Y_{28D}) and the calculated 28-day compressive strength ($\hat{Y}$) from the 48-hour autogenously cured accelerated compressive strength (X_{48H}) (all concrete).

	X_{48H}	Y_{28D}	$\hat{Y}$	$\varepsilon = Y_{28D}-\hat{Y}$	ε^2
Stockton Cross	2360	4450	4511	-61	3721
Town Viaduct	2010	3760	4134	-374	139876
	2000	4110	4123	-13	169
Data consists	2210	4750	4350	400	160000
of the	2530	4550	4694	-144	20736
following:	2490	4890	4651	239	57121
	2470	4760	4630	130	16900
6 sks/cy	2580	5110	4748	362	131044
6-1/4 sk/cy	2090	4410	4220	190	36100
with water	2100	3920	4231	-311	96721
reducer	2280	4480	4425	55	3025
admixture	2820	4890	5007	-117	13689
7 sk/cy	2720	4750	4899	-149	22201
	2520	4560	4684	-124	15376
	2660	5100	4835	265	70225
	3470	5655	5707	-52	2704
	3280	5290	5503	-213	45369
	3760	5830	6020	-190	36100
	3630	5740	5880	-140	19600
	4120	6170	6408	-238	56644
	3945	6690	6219	471	221841
	3455	5600	5690	-91	8281
	4800	7410	7141	269	72361
	6010	8590	8445	145	21025
	5660	8330	8067	263	69169
	5450	7490	7841	-351	123201
	5320	7480	7701	-221	48841
Average	3290	5510	5510	Mean ε = 0	$\Sigma\varepsilon^2$ = 2,163,340
σ	1220	1337	1315		
V	37%	24%	24%		

$$\sigma_\varepsilon = \frac{\Sigma\varepsilon^2}{n-2} = \frac{2163340}{27-2} = 294 \text{ psi}$$

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DISCUSSION

The objectives of this study were to develop test procedures which would provide (1) a means of predicting 28-day compressive strength from results of short time (48-hour) tests; (2) a method of monitoring the quality of concrete produced throughout a project, and (3) the development of a procedure which might be used to replace the present flexure beam test which is used as a control for concrete pavement.

The results of this study indicate that the accelerated autogenous curing test is a practical method for predicting the 28-day compressive strength of concrete from 48-hr tests. Figure 8 shows a plot of all the data developed by Laboratory personnel, one hundred data points, from which the regression line or strength curve was drawn. An inspection of the large scatter of these actual data points about the line reflects the difference in the various concretes used in this set of tests. Whereas the line does give a trend and possibly an indication of the 28-day strength from the accelerated test, it is far from exact and would not be of much use for a particular concrete. The large scatter of data points would make this method unacceptable for general application. This study showed the scatter of data points about the strength curve can be made much smaller by keeping the concrete materials constant.

The tentative method adopted by ASTM Designation C684 (Procedure C), for making and accelerating curing of concrete compressive test specimens provides an adequate procedure that could be used for specifying and using the autogenous test method. Equipment developed in this study complies with requirements of the ASTM method and could be used to evaluate concrete produced in the field.

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COMPOSITE PLOT OF TEST DATA

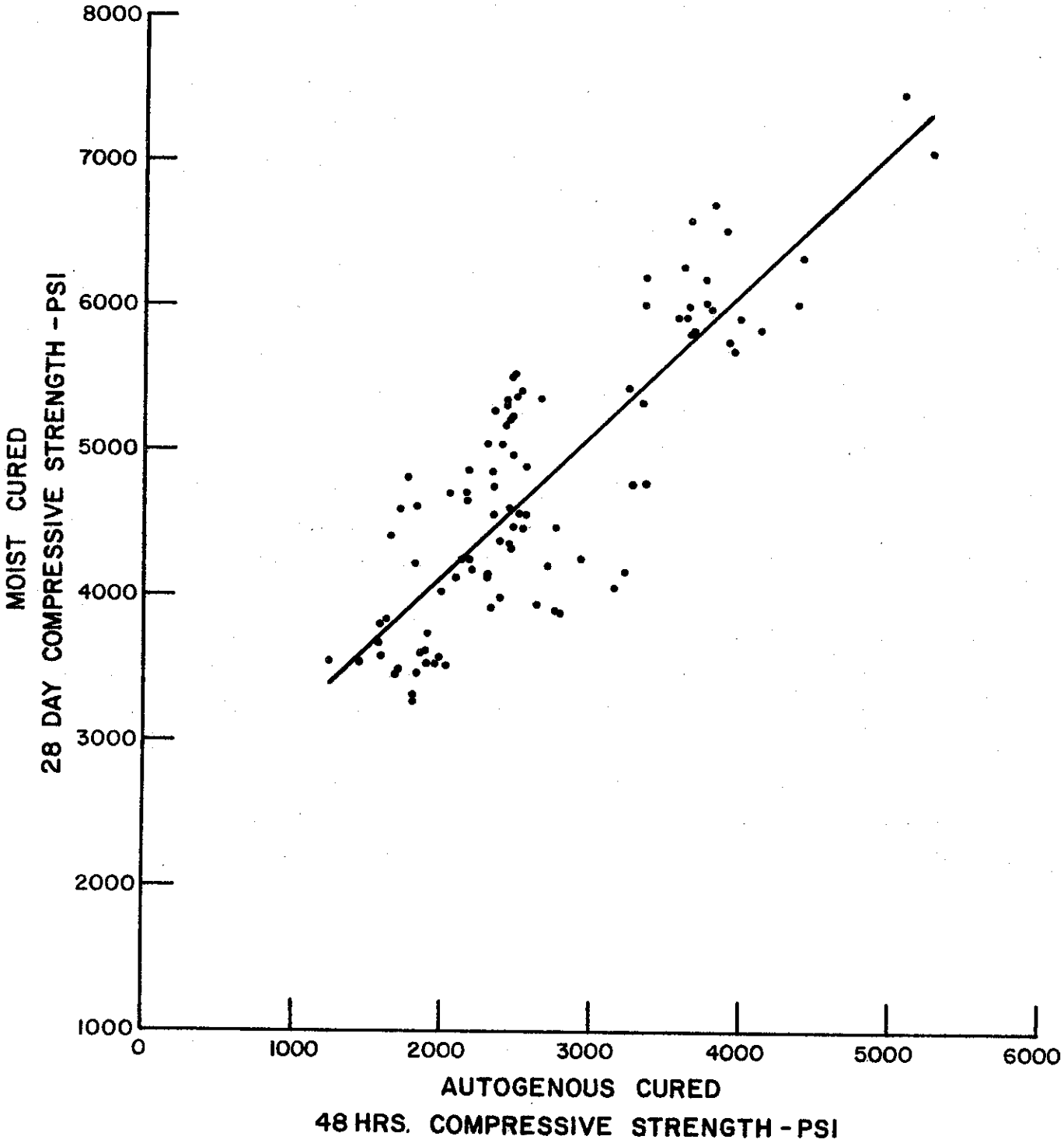

Fig. 8

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Other possibilities investigated for replacing the beam flexural strength tests for pavements were impact hammer readings and compressive strength tests of cores. The impact hammer readings taken on concrete at various ages had such wide variations they were considered completely unacceptable. Cores taken from projects 6 and 7 were broken at age 10 days and compared to strength data from test cylinders made in the same general area. Results are shown in Tables 12 and 13. The large variation found in the core strengths themselves indicate that this method would not be reliable enough to be acceptable. The relationship between cores and cylinders has been studied by many researchers with no conclusive results. Core strengths are affected by the interaction of aggregate and cement paste at the exposed surface of the cores. The properties of aggregate surface texture, shape, bond of aggregate to paste, and volume change of individual particles, can be factors causing wide differences in compressive strengths of cores and cylinders of the same concrete. Differences in curing conditions constitute another large variable.

Of the methods investigated, the compressive strength as determined from field-cured cylinders is the only test judged as an acceptable test method to replace the beam flexural strength test. The two advantages of cylinder testing in lieu of beam testing are: (1) the cylinder test is more reproducible than the beam test, and (2) fabricating and handling of cylinders is easier than making and testing beams.

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Table 12

Comparison of Core Strengths to Cylinder Strengths

Project 6

Area	Cores* psi at 10-days	Cylinders - psi** 2-day Autogenous Cured	10-day, Wet Sand	10-day, Shade	28-day Moist Cure
1	3220 3580 3540 3780 4180 3580				
Avg. =	3650	1860	2740	2530	3450
σ =	318				
2	3380 3110 3220 3180 3300 3420				
Avg. =	3270	1860	2720	2670	3500
σ =	120				
3	3380 3420 3420 3300 3180				
Avg. =	3340	1910	2670	2560	3540
σ =	102				
Avg. of all =	3340	1880	2710	2580	3490
σ AV =	180				

*5-inch diameter - corrected to L/D of 2
** Average of 2 cylinders per test

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Table 13

Comparison of Core Strengths to Cylinder Strengths

Project 7

Area	Cores* psi at 10-days	Cylinders - ** 2-day Autogenous Cured	10-day, Wet Sand	10-day, Shade	28-day Moist Cure
1	3410				
	2810				
	2950				
	3390				
	3550				
	3440				
Avg. =	3260	2910	3270	3240	3960
σ =	301				
2	3610				
	2920				
	2330				
	5040				
	3160				
	3930				
Avg. =	3500	3030	3410	3380	4000
σ =	937				
3	3660				
	2920				
	3520				
	3680				
	3550				
	4330				
Avg. =	3610	2870	3290	3190	4040
σ =	450				
Avg. of All =	3450	2930	3320	3270	4000
σ AV =	563				

*5-inch diameter - corrected to L/D of 2
** 2 cylinders per test result

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4. Newlon, Howard H., Jr., "Autogenous Accelerated Curing of Concrete Cylinders", Part V, Virginia Highway Research Council.

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APPENDIX A

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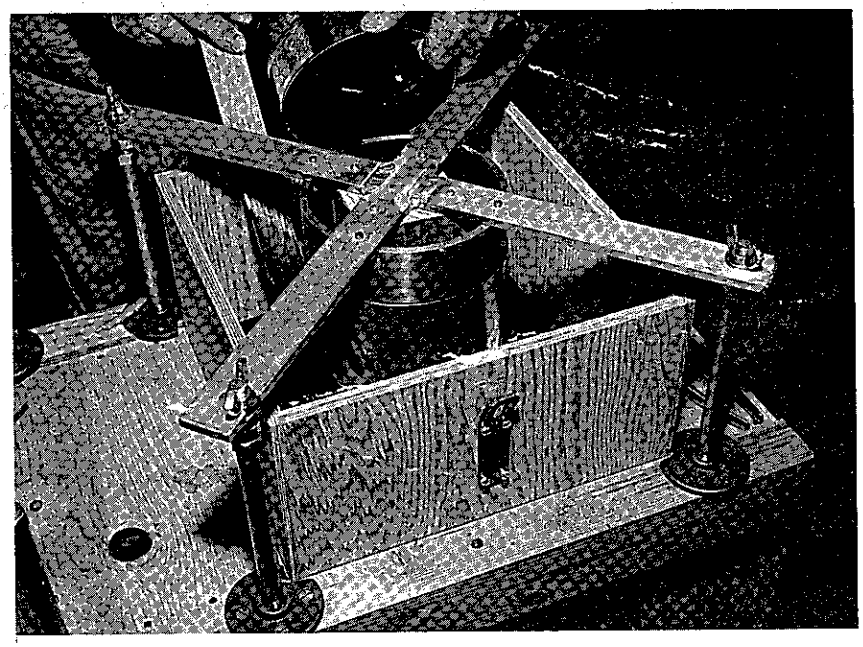

Figure 1

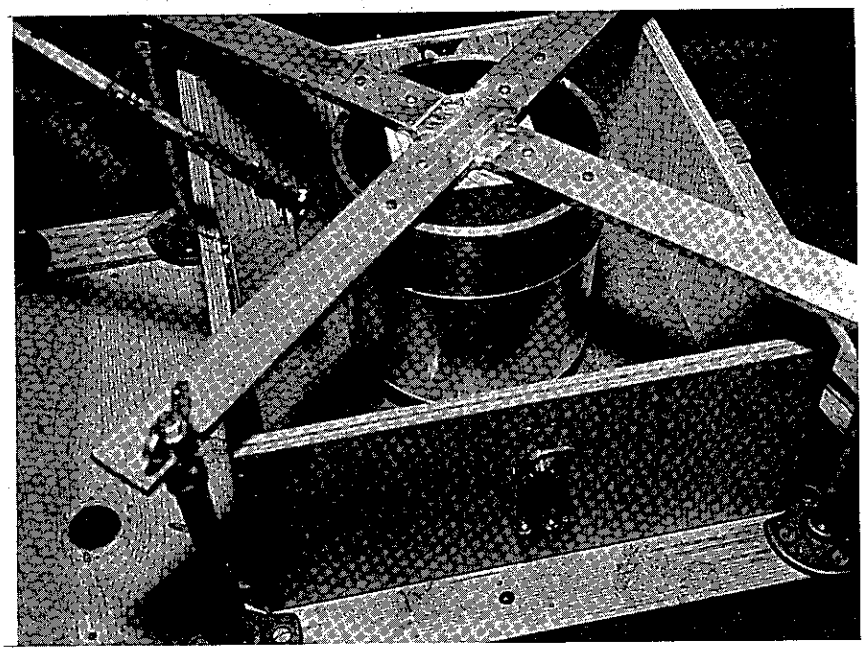

Figure 2
Pouring polyurethane into shell

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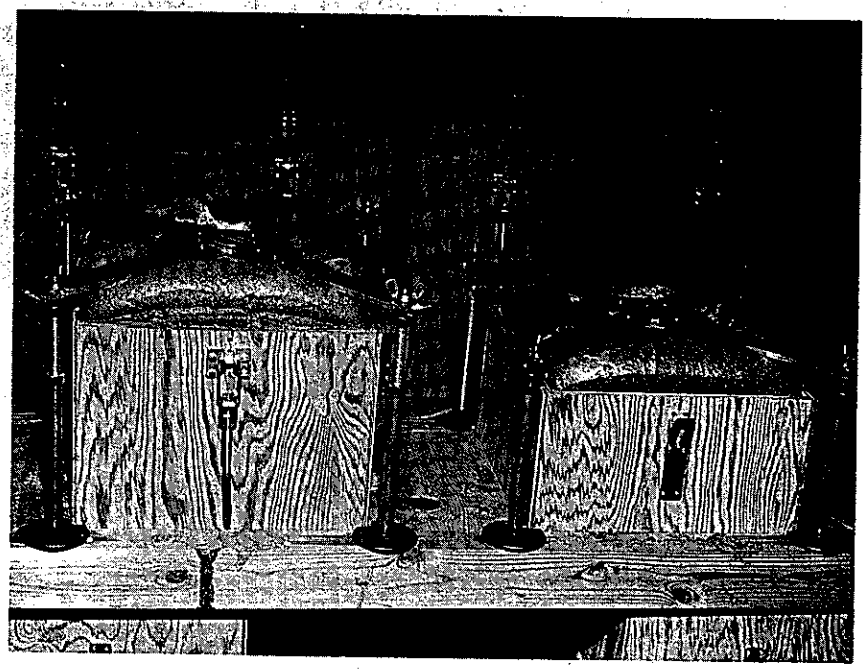

Figure 3

Polyurethane poured and cured

Figure 4

Removing excess polyurethane

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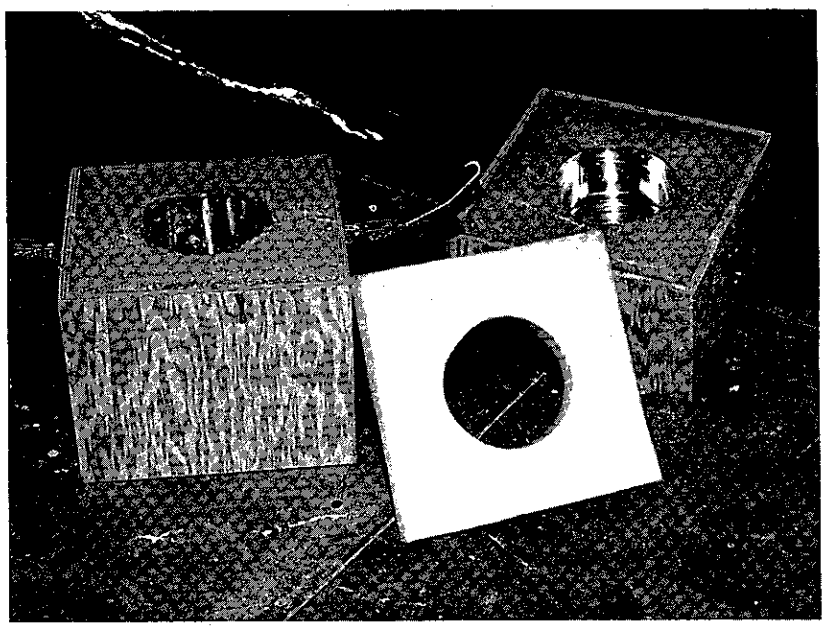

Figure 5 - Finished Container Parts

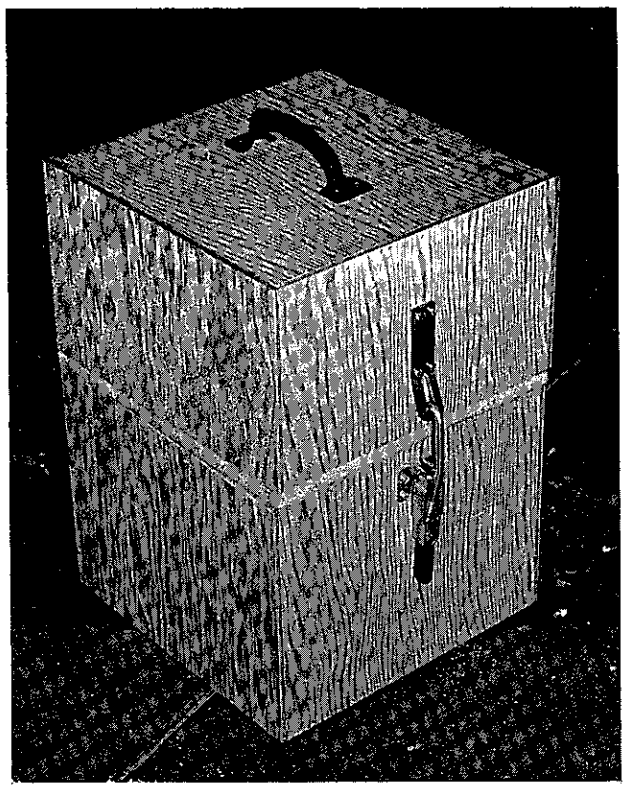

Figure 6

Completed Assembly

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APPENDIX B

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LATIN SQUARE ANALYSIS OF VARIANCE

48 HOURS - A ROUND 1- TEMPERATURE

TREATMENT LEVEL	AGGREGATE	* * * M E A N S * * * CEMENT TYPE	TEMPERATURE
1	2.66000E+03	2.28233E+03	3.20867E+03
2	3.62600E+03	3.57033E+03	3.07067E+03
3	3.08600E+03	3.51933E+03	3.09267E+03

GRAND MEAN = 3.12400E+03

SOURCE OF VARIATION	SUMS OF SQUARES	DEG. OF FREEDOM	MEAN SQUARES	F RATIO
AGGREGATE	1.40625E+06	2	7.03124E+05	2.7413
CEMENT TYPE	3.19173E+06	2	1.59587E+06	6.2218
TEMPERATURE	3.30000E+04	2	1.65000E+04	.0643
RESIDUAL	5.12994E+05	2	2.56497E+05	
TOTAL	5.14397E+06	8		

LATIN SQUARE ANALYSIS OF VARIANCE

48 HOURS - A ROUND 2 - TEMPERATURE

TREATMENT LEVEL	AGGREGATE	* * * M E A N S * * * CEMENT TYPE	TEMPERATURE
1	2.55967E+03	2.16400E+03	3.27733E+03
2	3.43000E+03	3.94567E+03	2.97100E+03
3	3.37400E+03	3.25400E+03	3.11533E+03

GRAND MEAN = 3.12122E+03

SOURCE OF VARIATION	SUMS OF SQUARES	DEG. OF FREEDOM	MEAN SQUARES	F RATIO
AGGREGATE	1.42375E+06	2	7.11876E+05	33.1504
CEMENT TYPE	4.84084E+06	2	2.42042E+06	112.7130
TEMPERATURE	1.40914E+05	2	7.04568E+04	3.2810
RESIDUAL	4.29483E+04	2	2.14742E+04	
TOTAL	6.44845E+06	8		

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LATIN SQUARE ANALYSIS OF VARIANCE

28 DAY - A ROUND 1 - TEMPERATURE

TREATMENT LEVEL	AGGREGATE	* * * M E A N S * * * CEMENT TYPE	TEMPERATURE
1	4.45333E+03	4.82333E+03	5.54667E+03
2	5.62333E+03	5.52167E+03	4.98500E+03
3	5.60833E+03	5.34000E+03	5.15333E+03

GRAND MEAN = 5.22833E+03

SOURCE OF VARIATION	SUMS OF SQUARES	DEG. OF FREEDOM	MEAN SQUARES	F RATIO
AGGREGATE	2.70313E+06	2	1.35156E+06	9.3571
CEMENT TYPE	7.87593E+05	2	3.93797E+05	2.7263
TEMPERATURE	4.98493E+05	2	2.49247E+05	1.7256
RESIDUAL	2.88886E+05	2	1.44443E+05	
TOTAL	4.27810E+06	8		

LATIN SQUARE ANALYSIS OF VARIANCE

28 DAY - A ROUND 2 - TEMPERATURE

TREATMENT LEVEL	AGGREGATE	* * * M E A N S * * * CEMENT TYPE	TEMPERATURE
1	4.43167E+03	4.93667E+03	5.49500E+03
2	5.72500E+03	5.50500E+03	5.12833E+03
3	5.52000E+03	5.23500E+03	5.05333E+03

GRAND MEAN = 5.22556E+03

SOURCE OF VARIATION	SUMS OF SQUARES	DEG. OF FREEDOM	MEAN SQUARES	F RATIO
AGGREGATE	2.89919E+06	2	1.44960E+06	32.5374
CEMENT TYPE	4.84895E+05	2	2.42447E+05	5.4419
TEMPERATURE	3.35129E+05	2	1.67564E+05	3.7611
RESIDUAL	8.91034E+04	2	4.45517E+04	
TOTAL	3.80832E+06	8		

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LATIN SQUARE ANALYSIS OF VARIANCE

48 HOURS - B ROUND 1 - CEMENT CONTENT

TREATMENT LEVEL	* * * M E A N S * * * AGGREGATES	ADMIXTURES	SKS. CEM.
1	1.90467E+03	3.54333E+03	1.73433E+03
2	3.12567E+03	2.37000E+03	2.65800E+03
3	3.07867E+03	2.19567E+03	3.71667E+03

GRAND MEAN = 2.70300E+03

SOURCE OF VARIATION	SUMS OF SQUARES	DEG. OF FREEDOM	MEAN SQUARES	F RATIO
AGGREGATES	2.87133E+06	2	1.43566E+06	14.6075
ADMIXTURES	3.22331E+06	2	1.61165E+06	16.3982
SKS. CEM.	5.90358E+06	2	2.95179E+06	30.0337
RESIDUAL	1.96565E+05	2	9.82825E+04	
TOTAL	1.21948E+07	8		

LATIN SQUARE ANALYSIS OF VARIANCE

48 HOURS - B ROUND 2 - CEMENT CONTENT

TREATMENT LEVEL	* * * M E A N S * * * AGGREGATES	ADMIXTURES	SKS. CEM.
1	1.75600E+03	3.49333E+03	1.56633E+03
2	3.04733E+03	2.32900E+03	2.53233E+03
3	3.06467E+03	2.04567E+03	3.76933E+03

GRAND MEAN = 2.62267E+03

SOURCE OF VARIATION	SUMS OF SQUARES	DEG. OF FREEDOM	MEAN SQUARES	F RATIO
AGGREGATES	3.38044E+06	2	1.69022E+06	11.4558
ADMIXTURES	3.53168E+06	2	1.76584E+06	11.9683
SKS. CEM.	7.31653E+06	2	3.65826E+06	24.7946
RESIDUAL	2.95085E+05	2	1.47543E+05	
TOTAL	1.45237E+07	8		

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LATIN SQUARE ANALYSIS OF VARIANCE

28 DAYS - B ROUND 1 - CEMENT CONTENT

TREATMENT LEVEL	* * * M E A N S * * * AGGREGATES	ADMIXTURES	SKS. CEM.
1	3.65500E+03	5.82100E+03	4.30167E+03
2	5.76167E+03	4.82667E+03	4.88600E+03
3	5.64533E+03	4.41433E+03	5.87433E+03

GRAND MEAN = 5.02067E+03

SOURCE OF VARIATION	SUMS OF SQUARES	DEG. OF FREEDOM	MEAN SQUARES	F RATIO
AGGREGATES	8.41298E+06	2	4.20649E+06	49.8557
ADMIXTURES	3.13740E+06	2	1.56870E+06	18.5924
SKS. CEM.	3.79150E+06	2	1.89575E+06	22.4686
RESIDUAL	1.68746E+05	2	8.43732E+04	
TOTAL	1.55106E+07	8		

LATIN SQUARE ANALYSIS OF VARIANCE

28 DAYS - B ROUND 2 CEMENT CONTENT

TREATMENT LEVEL	* * * M E A N S * * * AGGREGATES	ADMIXTURES	SKS. CEM.
1	3.70233E+03	5.71633E+03	3.94067E+03
2	5.67167E+03	4.95500E+03	5.01333E+03
3	5.39567E+03	4.09833E+03	5.81567E+03

GRAND MEAN = 4.92322E+03

SOURCE OF VARIATION	SUMS OF SQUARES	DEG. OF FREEDOM	MEAN SQUARES	F RATIO
AGGREGATES	6.82182E+06	2	3.41091E+06	124.7785
ADMIXTURES	3.93143E+06	2	1.96571E+06	71.9100
SKS. CEM.	5.30998E+06	2	2.65499E+06	97.1251
RESIDUAL	5.46715E+04	2	2.73357E+04	
TOTAL	1.61179E+07	8		

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LATIN SQUARE ANALYSIS OF VARIANCE (28-day/48 hrs. Strength Ratio)

ROUND 1 - TEMPERATURE - A

TREATMENT LEVEL	* * * M E A N S * * * AGGREGATE	CEMENT TYPE	TEMPERATURE
1	1.76267	2.12800	1.84567
2	1.60967	1.55400	1.65500
3	1.84200	1.53233	1.71367

GRAND MEAN = 1.73811

SOURCE OF VARIATION	SUMS OF SQUARES	DEG. OF FREEDOM	MEAN SQUARES	F RATIO
AGGREGATE	8.36803E-02	2	4.18402E-02	2.1673
CEMENT TYPE	6.84763E-01	2	3.42381E-01	17.7355
TEMPERATURE	5.72182E-02	2	2.86091E-02	1.4820
RESIDUAL	3.86097E-02	2	1.93049E-02	
TOTAL	8.64271E-01	8		

LATIN SQUARE ANALYSIS OF VARIANCE

ROUND 2 - TEMPERATURE - A

TREATMENT LEVEL	* * * M E A N S * * * AGGREGATE	CEMENT TYPE	TEMPERATURE
1	1.86867	2.31900	1.87200
2	1.74767	1.39933	1.77333
3	1.70567	1.60367	1.67667

GRAND MEAN = 1.77400

SOURCE OF VARIATION	SUMS OF SQUARES	DEG. OF FREEDOM	MEAN SQUARES	F RATIO
AGGREGATE	4.29736E-02	2	2.14868E-02	.6548
CEMENT TYPE	1.39924	2	6.99620E-01	21.3209
TEMPERATURE	5.72360E-02	2	2.86180E-02	.8721
RESIDUAL	6.56275E-02	2	3.28138E-02	
TOTAL	1.56508	8		

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LATIN SQUARE ANALYSIS OF VARIANCE (28-day/48-Hrs. Strength Ratio)

ROUND 1 - ADDITIVE B

TREATMENT LEVEL	* * * M E A N S * * * AGGREGATE	ADDITIVE	CEMENT Content
1	1.96200	1.77567	2.47200
2	1.95533	2.14833	1.89533
3	2.05500	2.04833	1.60500

GRAND MEAN = 1.99079

SOURCE OF VARIATION	SUMS OF SQUARES	DEG. OF FREEDOM	MEAN SQUARES	F RATIO
AGGREGATE	1.86275E-02	2	9.31373E-03	33.0216
ADDITIVE	2.23228E-01	2	1.11614E-01	395.7255
CEMENT CONT.	1.16853	2	5.84264E-01	2071.4968
RESIDUAL	5.64098E-04	2	2.82049E-04	
TOTAL	1.41095	8		

LATIN SQUARE ANALYSIS OF VARIANCE

ROUND 2 - ADDITIVE B

TREATMENT LEVEL	* * * M E A N S * * * AGGREGATE	ADDITIVE	CEMENT Content
1	2.20200	1.87900	2.51667
2	1.95000	2.26467	2.07600
3	2.03067	2.03900	1.59000

GRAND MEAN = 2.06089

SOURCE OF VARIATION	SUMS OF SQUARES	DEG. OF FREEDOM	MEAN SQUARES	F RATIO
AGGREGATE	9.93584E-02	2	4.96792E-02	2.2880
ADDITIVE	2.25257E-01	2	1.12628E-01	5.1872
CEMENT CONT.	1.28909	2	6.44544E-01	29.6852
RESIDUAL	4.34253E-02	2	2.17127E-02	
TOTAL	1.65713	8		

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LEAST SQUARES LINEAR REGRESSION ANALYSIS

LATIN SQUARE A

REGRESSION EQUATION: Y=3241.64+.635748*X

NUMBER OF OBSERVATIONS	= 18
STD. ERROR OF Y ON X	= 460.821
INDEX OF DETERMINATION	= .580023
COEFF. OF CORRELATION	= .761593

SOURCE	SS	DF	MS	F
REGRESSION	.469251E7	1	.469251E7	22.0974
RESIDUAL	.33977E7	16	.212356E6	
TOTAL	.809021E7	17		

VAR.	MEAN	VARIANCE	STD. DEV.
X	3122.78	.682945E6	826.405
Y	5226.94	.475895E6	689.851

	STD. ERROR	95% CONFIDENCE LIMITS	
YINTCPT	436.078	2317.19	4166.1
SLOPE	.135243	.349041	.922455

REGRESSION EQUATION: Y=3241.64+.635748*X

X-ACTUAL	Y-ACTUAL	Y-CALC
1830	4180	4405.06
1660	4370	4296.99
3380	4750	5390.47
3295	4750	5336.43
2775	4435	5005.85
2720	4170	4970.88
2480	4920	4818.3
2360	5240	4742.01
3970	5655	5765.56
4150	5795	5880
4430	6295	6058.01
3780	6140	5644.77
2535	5370	4853.27
2470	5195	4811.94
3370	6165	5384.12
4390	5970	6032.58
3355	5290	5374.58
3260	5395	5314.18

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LEAST SQUARES LINEAR REGRESSION ANALYSIS

LATIN SQUARE B

REGRESSION EQUATION: Y=2249.59+1.02233*X

NUMBER OF OBSERVATIONS = 18
STD. ERROR OF Y ON X = 481.826
INDEX OF DETERMINATION = .882717
COEFF. OF CORRELATION = .93953

SOURCE	SS	DF	MS	F
REGRESSION	.279568E8	1	.279568E8	120.422
RESIDUAL	.37145E7	16	.232156E6	
TOTAL	.316713E8	17		

VAR.	MEAN	VARIANCE	STD. DEV.
X	2662.89	.157346E7	1254.38
Y	4971.94	.186301E7	1364.92

	STD. ERROR	95% CONFIDENCE LIMITS	
YINTCPT	272.839	1671.19	2827.99
SLOPE	.931617E-1	.824833	1.21983

LATIN SQUARE B **KK1**

REGRESSION EQUATION: Y=2249.59+1.02233*X

X-ACTUAL	Y-ACTUAL	Y-CALC
1600	3550	3885.32
1345	3462	3624.63
1713	3465	4000.84
1590	3765	3875.1
2402	3950	4705.23
2332	3880	4633.67
3913	6475	6249.97
3835	6665	6170.23
3630	6235	5960.65
3675	6545	6006.66
1835	4575	4125.57
1632	3805	3918.04
5118	7438	7481.88
5300	7022	7667.94
1768	4780	4057.07
1722	4555	4010.05
2350	4718	4652.07
2172	4610	4470.09

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LEAST SQUARES LINEAR REGRESSION ANALYSIS

COMP. STRENGTHS (CHANGE IN WATER-CEMENT RATIO)

REGRESSION EQUATION: Y=2281.23+1.06312*X

NUMBER OF OBSERVATIONS = 16
STD. ERROR OF Y ON X = 246.005
INDEX OF DETERMINATION = .927329
COEFF. OF CORRELATION = .962979

SOURCE	SS	DF	MS	F
REGRESSION	.108115E8	1	.108115E8	178.648
RESIDUAL	.847259E6	14	60518.5	
TOTAL	.116588E8	15		

VAR.	MEAN	VARIANCE	STD. DEV.
X	2416.25	.637718E6	798.573
Y	4850	.777253E6	881.62

	STD. ERROR	95% CONFIDENCE LIMITS	
YINTCPT	201.788	1848.42	2714.03
SLOPE	.795397E-1	.892523	1.23372

COMP. STRENGTHS KK

REGRESSION EQUATION: Y=2281.23+1.06312*X

X-ACTUAL	Y-ACTUAL	Y-CALC
2400	5000	4832.72
2300	5000	4726.41
2500	5320	4939.04
2670	5320	5119.77
2180	4820	4598.84
2340	4820	4768.94
2160	4670	4577.57
2050	4670	4460.63
3370	5960	5863.95
3670	5960	6182.89
3650	5880	6161.63
3590	5880	6097.84
1450	3510	3822.76
1240	3510	3599.5
1580	3640	3960.96
1510	3640	3886.54

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LEAST SQUARES LINEAR REGRESSION ANALYSIS

TABLE 9 **(FIELD DATA - LAB PERSONNEL)**

REGRESSION EQUATION: Y=1805.38+1.03015*X

NUMBER OF OBSERVATIONS	= 48
STD. ERROR OF Y ON X	= 505.698
INDEX OF DETERMINATION	= .614016
COEFF. OF CORRELATION	= .783592

SOURCE	SS	DF	MS	F
REGRESSION	.187133E8	1	.187133E8	73.1759
RESIDUAL	.117636E8	46	.255731E6	
TOTAL	.30477E8	47		

VAR.	MEAN	VARIANCE	STD. DEV.
X	2509.79	.375194E6	612.53
Y	4390.83	.648446E6	805.262

	STD. ERROR	95% CONFIDENCE LIMITS	
YINTCPT	310.929	1179.51	2431.25
SLOPE	.120425	.787745	1.27255

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LEAST SQUARES LINEAR REGRESSION ANALYSIS

GRAND TOTAL **(ALL DATA)**

REGRESSION EQUATION: Y=2168.2+.969037*X

NUMBER OF OBSERVATIONS	= 100
STD. ERROR OF Y ON X	= 516.219
INDEX OF DETERMINATION	= .719603
COEFF. OF CORRELATION	= .848294

SOURCE	SS	DF	MS	F
REGRESSION	.670216E8	1	.670216E8	251.505
RESIDUAL	.261153E8	98	.266482E6	
TOTAL	.931369E8	99		

VAR.	MEAN	VARIANCE	STD. DEV.
X	2632.72	.72094E6	849.082
Y	4719.4	.940776E6	969.936

	STD. ERROR	95% CONFIDENCE LIMITS	
YINTCPT	168.948	1832.93	2503.47
SLOPE	.611036E-1	.847779	1.09029

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LEAST SQUARES LINEAR REGRESSION ANALYSIS

GRAND TOTAL

REGRESSION EQUATION: Y=2168.2+.969037*X

X-ACTUAL	Y-ACTUAL	Y-CALC
1830	4180	3941.53
1660	4370	3776.8
3380	4750	5443.54
3295	4750	5361.17
2775	4435	4857.27
2720	4170	4803.98
2480	4920	4571.41
2360	5240	4455.12
3970	5655	6015.27
4150	5795	6189.7
4430	6295	6461.03
3780	6140	5831.16
2535	5370	4624.71
2470	5195	4561.72
3370	6165	5433.85
4390	5970	6422.27
3355	5290	5419.32
3260	5395	5327.26
2400	5000	4493.89
2300	5000	4396.98
2500	5320	4590.79
2670	5320	4755.53
2180	4820	4280.7
2340	4820	4435.74
2160	4670	4261.32
2050	4670	4154.72
3370	5960	5433.85
3670	5960	5724.56
3650	5880	5705.18
3590	5880	5647.04
1450	3510	3573.3
1240	3510	3369.8
1580	3640	3699.28
1510	3640	3631.44
1600	3550	3718.66
1345	3462	3471.55
1713	3465	3828.16
1590	3765	3708.97
2402	3950	4495.82
2332	3880	4427.99
3913	6475	5960.04
3835	6665	5884.45
3630	6235	5685.8
3675	6545	5729.41
1835	4575	3946.38

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1632	3805	3749.67
5118	7438	7127.73
5300	7022	7304.09
1768	4780	3881.45
1722	4555	3836.88
2350	4718	4445.43
2172	4610	4272.95
2550	4420	4639.24
2480	4430	4571.41
2460	4310	4552.03
2310	4100	4406.67
2100	4090	4203.17
2000	3990	4106.27
2570	4850	4658.62
2350	4520	4445.43
2390	4340	4484.2
2470	4280	4561.72
2210	4140	4309.77
2570	4530	4658.62
2470	5460	4561.72
2440	5300	4532.65
2430	5140	4522.96
2440	5270	4532.65
2490	5480	4581.1
2460	5180	4552.03
3780	5980	5831.16
3820	5940	5869.92
4010	5870	6054.03
3930	5710	5976.51
3680	5760	5734.25
3700	5790	5753.63
1980	3540	4086.89
1900	3490	4009.37
1890	3580	3999.68
1800	3270	3912.46
1810	3240	3922.15
1830	3430	3941.53
2030	3480	4135.34
1690	3410	3805.87
1910	3700	4019.06
1810	3290	3922.15
1960	3500	4067.51
1860	3570	3970.61
3170	4020	5240.04
2810	3850	4891.19
3240	4140	5307.88
2780	3860	4862.12
2950	4220	5026.86
2650	3900	4736.14
2460	4570	4552.03
2310	4120	4406.67
2660	4750	4745.84
2530	4530	4619.86
2140	4210	4241.94
2190	4210	4290.39

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