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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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DIVISION OF STRUCTURES AND ENGINEERING SERVICES

TRANSPORTATION LABORATORY

RESEARCH REPORT

# ACCELERATED TEST DEVELOPMENT FOR PORTLAND CEMENT CONCRETE

FINAL REPORT (REV.)

CA-DOT-TL-5182-1-75-22

APRIL 1976

75-22

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

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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

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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

---

[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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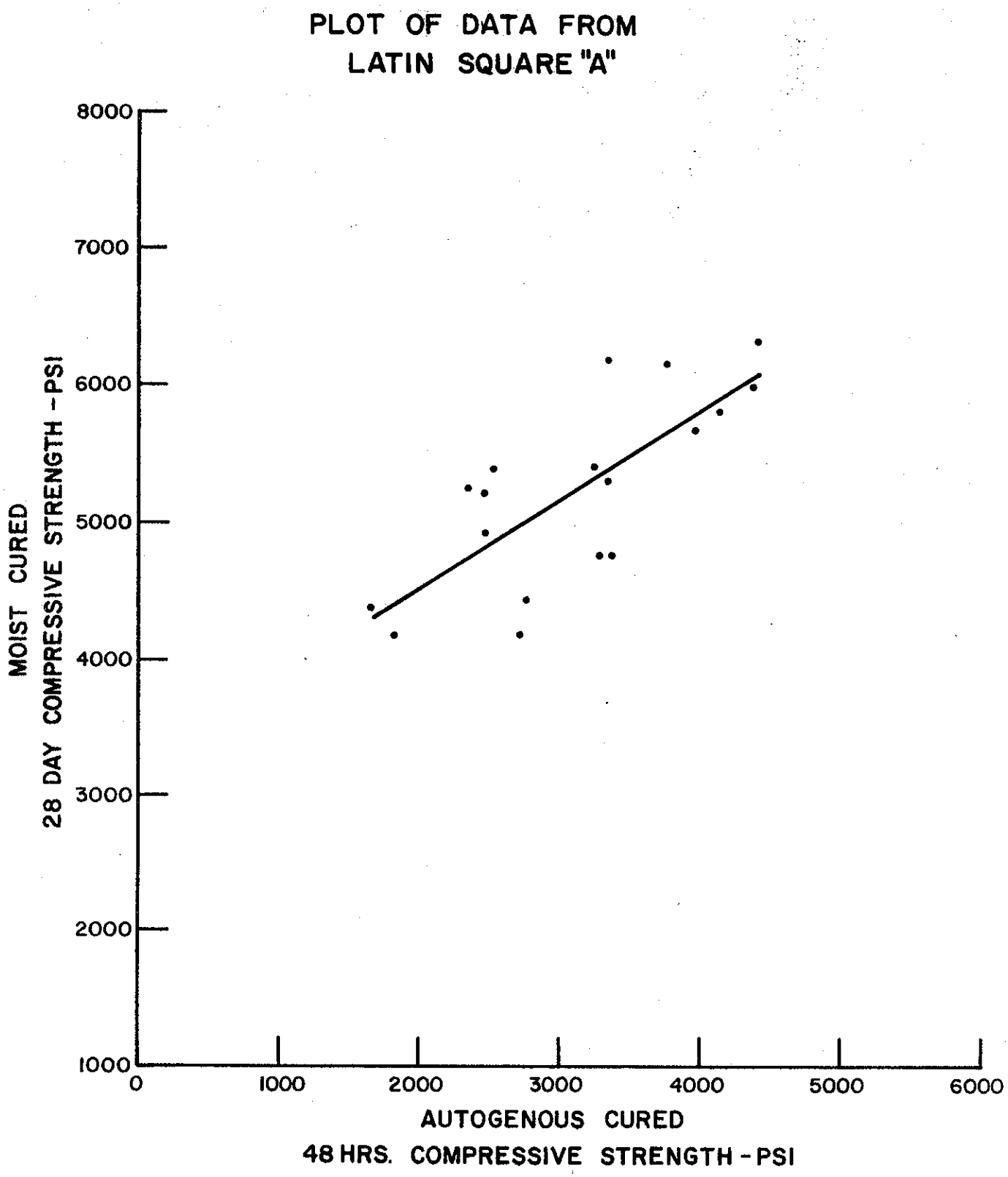


Fig. 4



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PLOT OF DATA FROM
LATIN SQUARE "B"

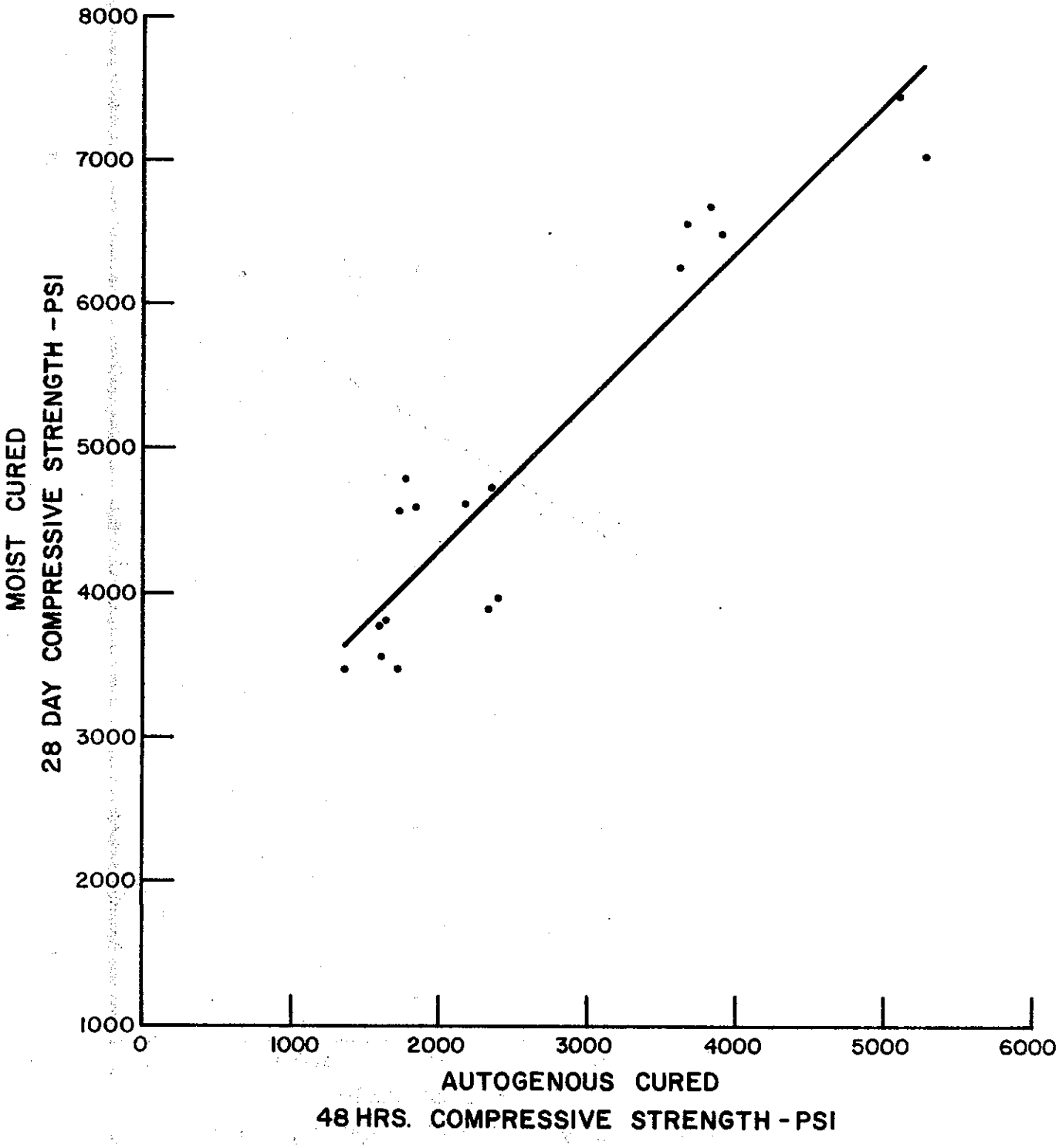


 Fig. 5

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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<br>0 | F = 2.72<br>0 | F = 2.74<br>0 | F = 9.36<br>0 | F = .06<br>0 | F = 1.72<br>0 |
| Round 2 | F = 112.71<br>X | F = 5.44<br>0 | F = 33.15<br>X | F = 32.54<br>X | F = 3.28<br>0 | F = 3.76<br>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<br>X | F = 22.46<br>X | F = 14.60<br>0 | F = 49.85<br>X | F = 16.39<br>0 | F = 18.59<br>X |
| Round 2 | F = 24.79<br>X | F = 97.12<br>X | F = 11.45<br>0 | F = 124.77<br>X | F = 11.96<br>0 | F = 71.91<br>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<br>O | F = 2.17<br>O | F = 1.48<br>O |
| Round 2 | F = 21.32<br>X | F = .65<br>O | F = .87<br>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<br>X | F = 33.02<br>X | F = 395.73<br>X |
| Round 2 | F = 29.69<br>X | F = 2.29<br>O | F = 5.19<br>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<br>Inside | 2400<br>2300 | 5000 | 2.08<br>2.15 |
| TP1-2 | 0.5 | Outside<br>Inside | 2500<br>2670 | 5320 | 2.11<br>1.99 |
| TP2-1 | 0.6 | Outside<br>Inside | 2180<br>2340 | 4820 | 2.21<br>2.06 |
| TP2-2 | 0.6 | Outside<br>Inside | 2160<br>2050 | 4670 | 2.16<br>2.28 |
| TP3-1 | 0.4 | Outside<br>Inside | 3370<br>3670 | 5960 | 1.77<br>1.62 |
| TP3-2 | 0.4 | Outside<br>Inside | 3650<br>3590 | 5880 | 1.61<br>1.64 |
| TP4-1 | 0.7 | Outside<br>Inside | 1450<br>1240 | 3510 | 2.42<br>2.83 |
| TP4-2 | 0.7 | Outside<br>Inside | 1580<br>1510 | 3640 | 2.30<br>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

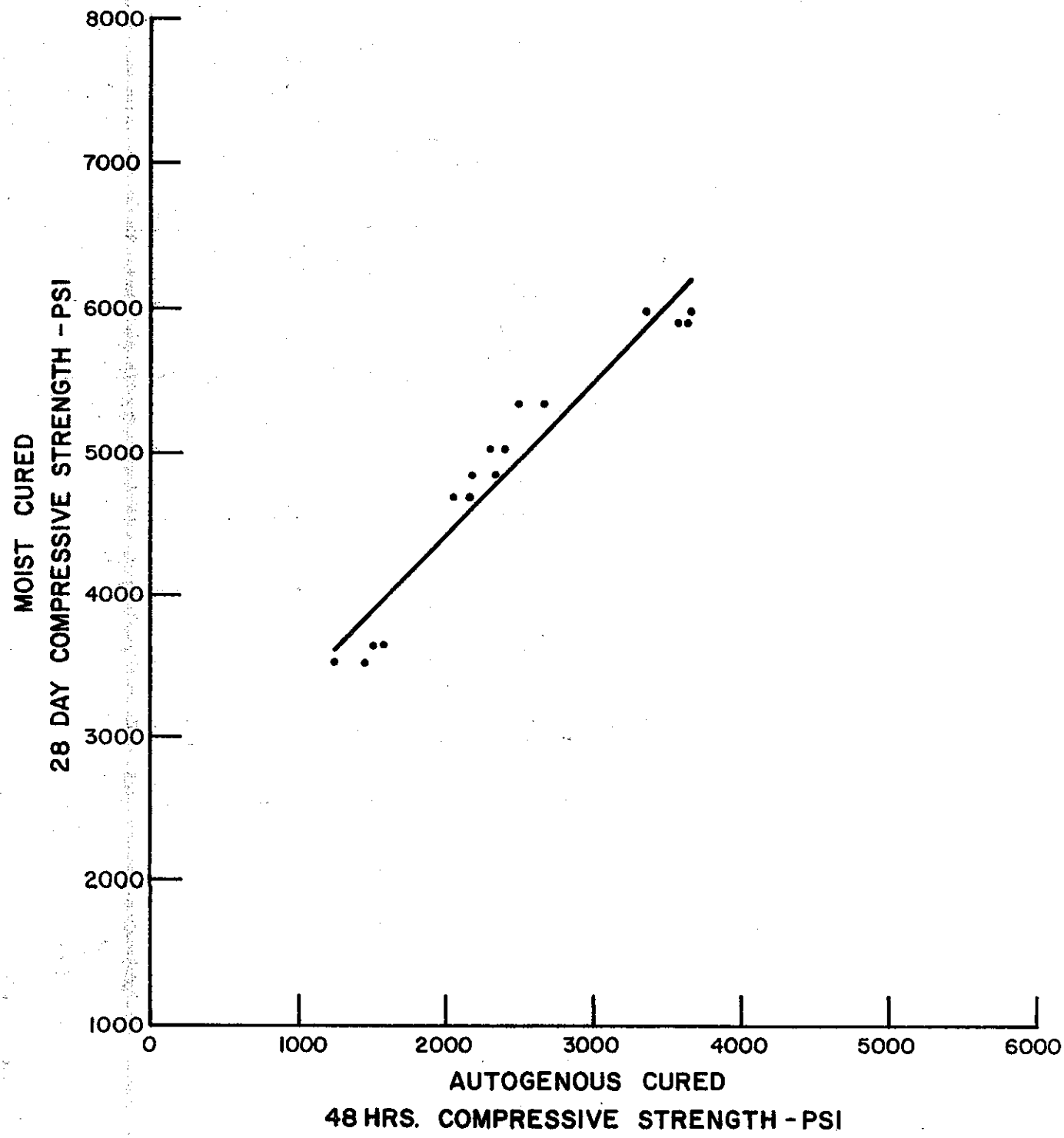


Fig. 6



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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)

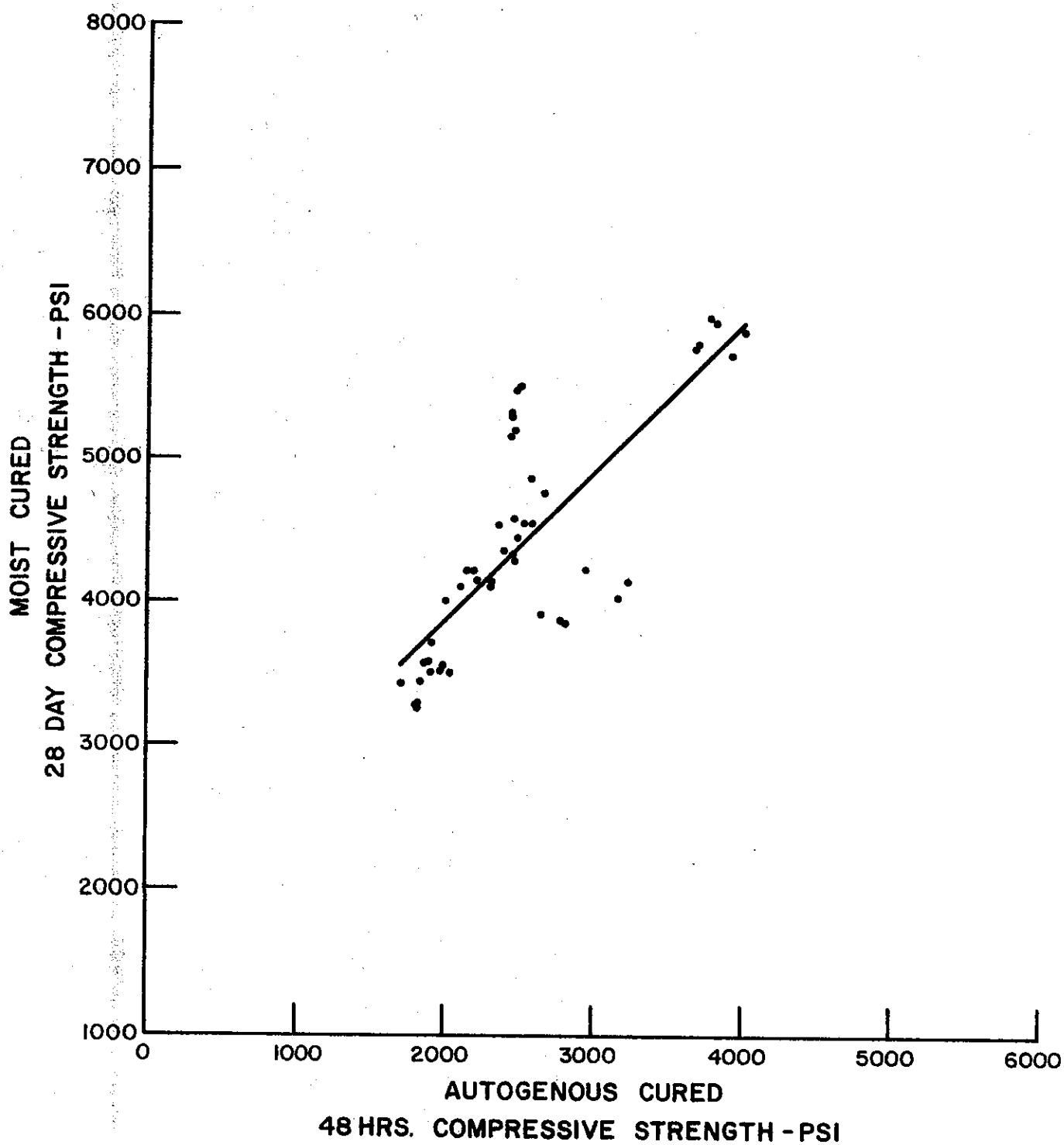


Fig. 7



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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 ($\varepsilon$) 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 | | | | |
|---|---|---|---|---|---|
| | $X_{48H}$ | $Y_{28D}$ | $\hat{Y}$ | $\varepsilon = Y_{28D} - \hat{Y}$ | $\varepsilon^2$ |
| 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 ($\varepsilon$) 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.

| | $X_{48H}$ | $\hat{Y}_{28D}$ | $\hat{Y}$* | $\varepsilon = Y_{28D} - \hat{Y}$ | $\varepsilon^2$ |
|---|---|---|---|---|---|
| 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 | $\sigma$ | 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 ($\varepsilon$) 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).

| | $X_{48H}$ | $Y_{28D}$ | $\hat{Y}$ | $\varepsilon = Y_{28D}-\hat{Y}$ | $\varepsilon^2$ |
|---|---|---|---|---|---|
| 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 $\varepsilon$ = 0 | $\Sigma\varepsilon^2$ = 2,163,340 |
| $\sigma$ | 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

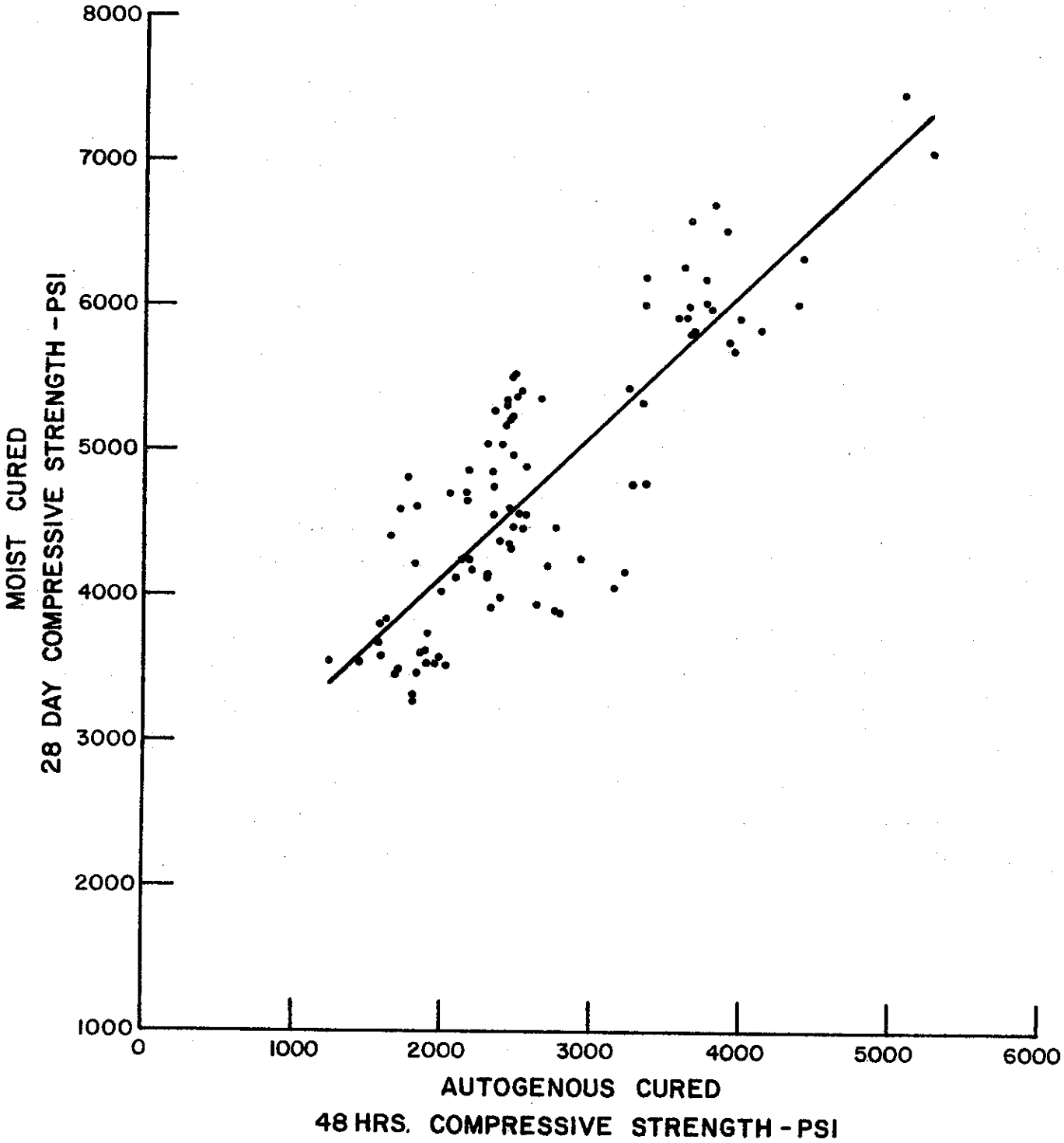


Fig. 8



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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<br>3580<br>3540<br>3780<br>4180<br>3580 | | | | |
| Avg. = | 3650 | 1860 | 2740 | 2530 | 3450 |
| σ = | 318 | | | | |
| 2 | 3380<br>3110<br>3220<br>3180<br>3300<br>3420 | | | | |
| Avg. = | 3270 | 1860 | 2720 | 2670 | 3500 |
| σ = | 120 | | | | |
| 3 | 3380<br>3420<br>3420<br>3300<br>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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## REFERENCES


1. Smith, Peter, "Quick Quality Testing of Concrete", ASCE Vol 40, No. 3, August 1970.

2. Hudson, S. B. and Steel, G. W., "Prediction of Potential Strength of Concrete From Results of Early Tests", West Virginia Highway Department, presented at the 50th Meeting of Transportation Research Board, Washington, D. C., January 1971.

3. "Cooperative Testing Program", ASTM C-9, Subcommittee II-i, November, 1966.

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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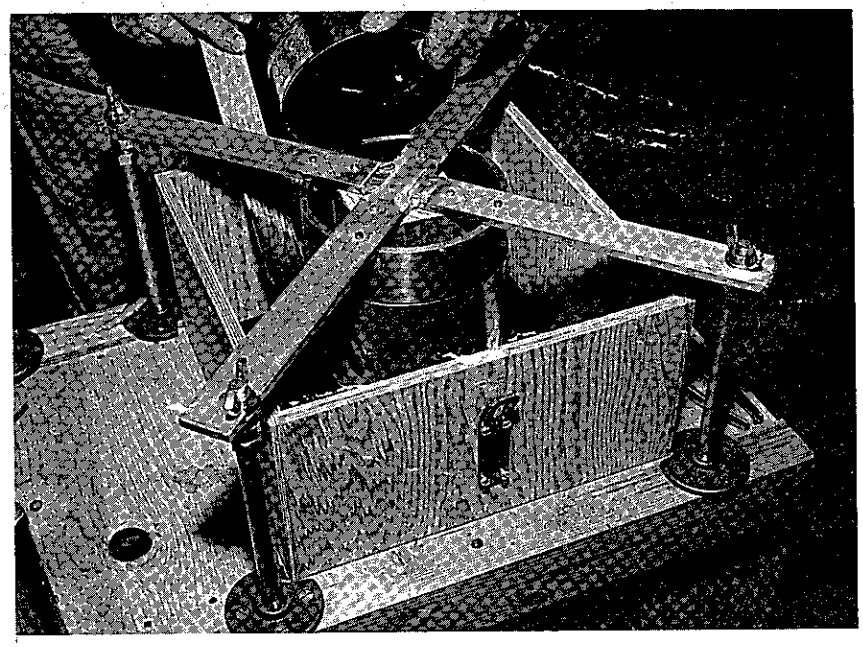

Figure 1

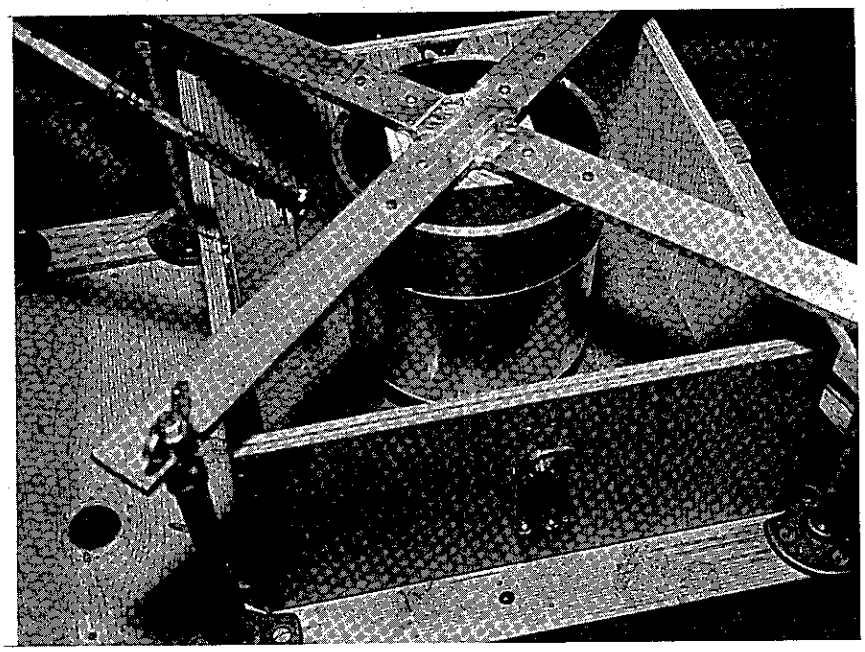

Figure 2
Pouring polyurethane into shell



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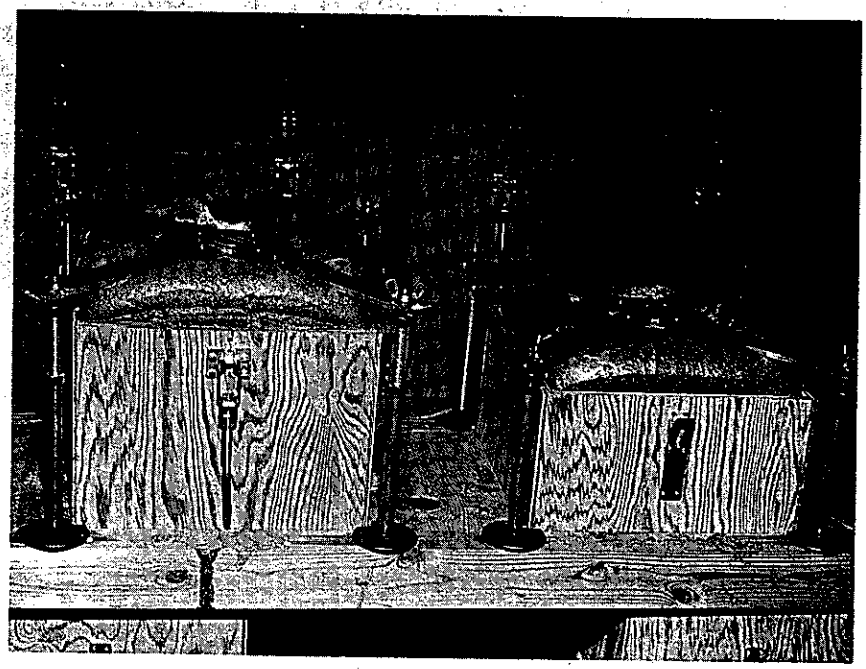

Figure 3

Polyurethane poured and cured

Figure 4

Removing excess polyurethane



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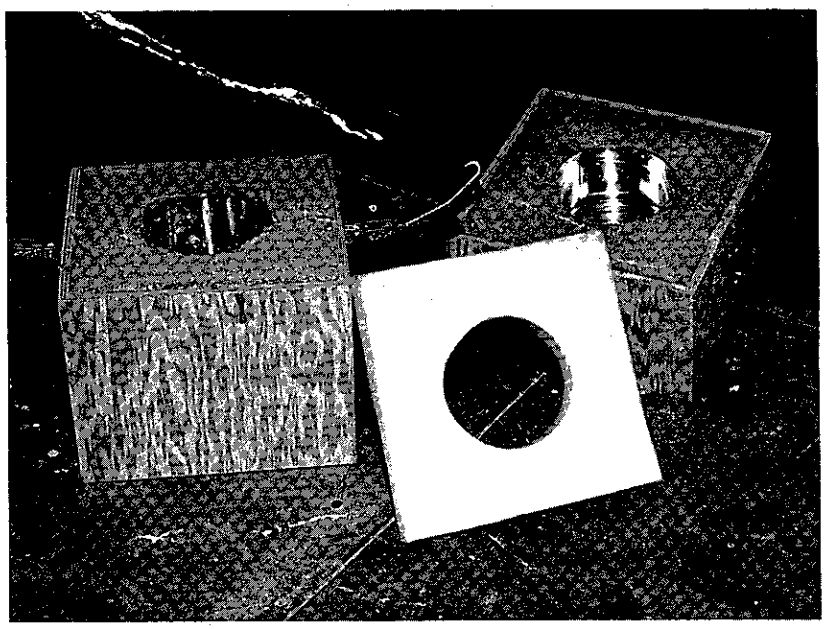

Figure 5 - Finished Container Parts

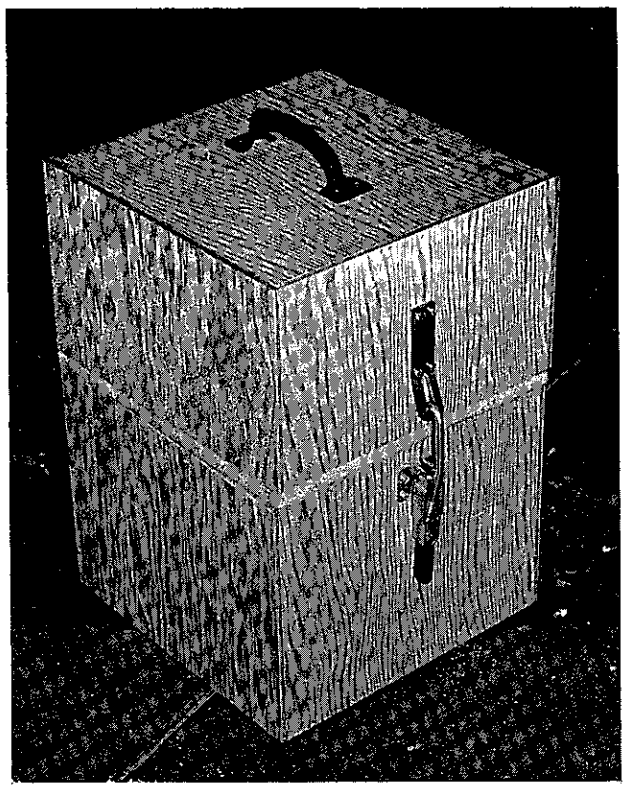

Figure 6

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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