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accelerated concrete strength study

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16. Abstract

The results of the testing of concrete cylinders using three methods of accelerated curing i.e. boiling, constant temperature, and autogenous, indicate that all three methods can be used to predict the 28 day strength of concrete cylinders. The constant temperature and autogenous cure are the most practical methods for field application. The prediction equations to relate accelerated test specimens to standard must be developed for each materials source and for each class of concrete. Equations that included the concept of degree-hour maturity in their derivation appeared to offer some advantages over the least square regression analysis.

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ACCELERATED CONCRETE STRENGTH STUDY

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INTRODUCTION

The three methods of accelerated curing as outlined by ASTM Committee 9 "Tentative Method of Making and Accelerated Curing of Concrete Test Specimens" Third Draft, September 15, 1970, (See Appendix "A") were to be implemented and trial runs made to determine the practicality of each method for use by the Colorado Division of Highways in the Laboratory and in the Field.

The three procedures were as follows:

A - Autogenous Curing Method
B - Boiling Water Method, and
C - Constant Temperature Method

The concrete used in the evaluation was obtained from active projects being constructed in the Denver Metropolitan Area and from Laboratory Design Mixes. To further extend the evaluation of the three methods, equipment was installed at the Straight Creek Tunnel Project to determine the suitability of accelerated curing at high altitudes and under actual field conditions.

ACCELERATED CURING TESTS

The necessary equipment was assembled, tested, and found to be in reasonably close compliance with the ASTM Standard for accelerated curing by Methods A, B, and C.

Concrete from three projects was used in the initial phase of the research conducted by the Central Laboratory. The proportions and properties of the concrete mixes are shown in Table A.

From the samples of fresh concrete picked up at the job site and delivered to the Central Laboratory, a total of ten cylinders were fabricated - two each for the accelerated cure Methods A, B, and C and two each for seven (7), and twenty-eight (28) day standard cure (100% humidity @ $73.4^{o} \pm 3^{o}F$). Slump, air, and unit weight determinations

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TABLE "A"

Concrete Proportions

Conc. No.	Project No.	Class of Concrete	Cement lbs/cy	Fine Agg. lbs/cy	Coarse Agg. lbs/cy	Water lbs/cy	Water gals/cy	A.E.A. ozs/cy
698	I 225-4(12)	P	564	1090	1960	255	30.6	10
654	I 25-2(88)	D	611	1280	1650	293	35.2	8.5
751	I 80S-1(37)	P	564	1080	2000	222	26.7	10

Concrete Properties (Trial Mix)

Conc. No.	W/C	% F.A.	Slump (in.)	Ball Pen. (in.)	A/C Total	Unit Wt. (lbs/ft^3)	Compressive Str. psi 7 day	(ave. 3 cyl.) 28 day
698	.452	36	2-1/4	1-1/2	5.0	146.12	3385	4990
654	.479	44	2-3/4	1-1/2	6.6	141.80	2905	4735
651	.394	35	2-0	1-3/4	4.7	145.52	3270	4870

Samples of Field Concrete

Conc. No.	No. of Sets	Average Slump	Standard Deviation	Average Air	Standard Deviation
698	16	2.0 in.	0.76 in.	5.23%	1.19%
654	28	2.3 in.	0.89 in.	5.11%	0.90%
751	13	1.56 in.	0.70 in.	4.89%	1.08%

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were made at the time of casting test cylinders. Limitations of equipment and periodic breakdowns did not always permit making all three accelerated cure tests.

The data from the series of tests were analyzed by least square regression and the relationship established between the computed and the actual 28 day strength by statistical analysis. The following symbols are used:

S_M = predicted 28 day strength based on least square regression.

S_{28} = actual 28 day strength - average of two cylinders.

S_m = strength at the end of the accelerated cure.

$\bar{S}$ = average 28 day strengths of any set of tests of one class of concrete from a single project.

D_s = standard deviation of a set of concrete cylinder breaks, usually from one class of concrete from a single project.

D_e = error of the regression equation.

D_t = testing error.

D_p = prediction error.

I_c = index of correlation $\left(\sqrt{\frac{D_s^2 - D_e^2}{D_s^2}}\right)$

The following equations are used in the analysis:

$\underline{S_M = C + KS_m}$ (the general form of the regression equation "C" and "K" are constants)

$$D_s = \sqrt{\frac{(S_{28} - \bar{S})^2}{2n}}$$ (n = number of sets of cylinders tested)

$$D_e = \sqrt{\frac{(S_{28} - S_M)^2}{2n}}$$ (equation error)

$$D_t = \sqrt{\frac{(X_1 - X_2)^2}{2n}}$$ (X_1 and X_2 are paired 28-day test results)

$$D_p = \sqrt{D_e^2 - D_t^2}$$ (prediction error)

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Table "B" shows the results of 94 sets of cylinders; the regression equations for the tests of a single class of concrete from a single source and for all tests regardless of class and source.

The method of analysis suggested by FHWA Notice HO 31, January 21, 1972, "Procedure for Establishing an Equation for Predicting Potential Strength of Early Tests on Concrete Cylinders" was tried on the accumulated data for Autogenous Cure ("A") and Constant Temperature ("C").

At this point in the research, the Boiling Method ("B") of accelerated cure did not appear to have any advantage over Methods A and C and had these several disadvantages: (1) The expense of the equipment necessary for the test, including special cylinder molds, insulated boiling tank and heater, and the electric power consumption necessary to bring to a boil the large amount of water required. (2) The inherent danger to personnel of placing and removing the heavy concrete cylinder molds from the boiling water.

The equation proposed by Hudson and Steele for the predicted strength of concrete cylinders from early tests was as follows. (See Appendix B).

$S_M = S_m + b (\log M - \log m)$

S_M = predicted strength at maturity "M"

S_m = strength at maturity "m"

b = slope of the prediction line

M & m = maturity in degree - hours (F-hr.)

This method offered considerable flexibility in the time of testing which would be highly desirable for both field and laboratory operations.

The data for Concrete No. 654 were analyzed by the method outlined in the Hudson and Steele paper for Autogenous and Constant Temperature Cure. Figures IV and V show the comparison between the two methods of analysis. These equations were then applied to the results of the remainder of the available data and the results tabulated in Table "C" and shown in Figures VI and VII.

TABLE "B"

Conc. No.	No. of Sets	Acc. Cure Method	Regression Equation	D_s psi	D_e psi	D_t psi	D_p psi	I_c
654	7	A(24 hr.)	$S_M = 1790 + 1.86S_m$	383	159	144	66	.91
654	21	A(48 hr.)	$S_M = 2000 + 1.18S_m$	296	134	144	52	.89
698	6	A	$S_M = 3180 + .49S_m$	211	152	144	48	.69
751	8	A	$S_M = 1090 + 1.37S_m$	245	188	144	120	.64
654	28	B	$S_M = 2885 + .88S_m$	324	225	144	172	.72
698	12	B	$S_M = 2055 + S_m$	299	145	144	17	.87
751	12	B	$S_M = 2760 + .7\ S_m$	272	223	144	170	.57
654	20	C(48 hr.)	$S_M = 2345 + 1.02S_m$	250	138	144	41	.83
698	4	C(48 hr.)	$S_M = 2820 + .59S_m$	173	53	144	133	.95
751	7	C(48 hr.)	$S_M = 1660 + 1.53S_m$	236	137	144	55	.81
All	49	A	$S_M = 3520 + .42S_m$	340	307	144	271	.42
All	56	B	$S_M = 3120 + .68S_m$	383	275	144	234	.69
All	43	C(48 hr.)	$S_M = 3255 + .58S_m$	361	266	144	223	.68
All	12	C(24 hr.)	$S_M = 2960 + .89S_m$	499	391	144	363	.62

See Appendix C Pages 36 through 46

Figures I through III show the data for Concrete No. 654 and for "All" Concretes tested. With the exception of Method "B" the equations for "All" Concretes would not be suitable for predicting 28-day strength of concrete from an individual source.

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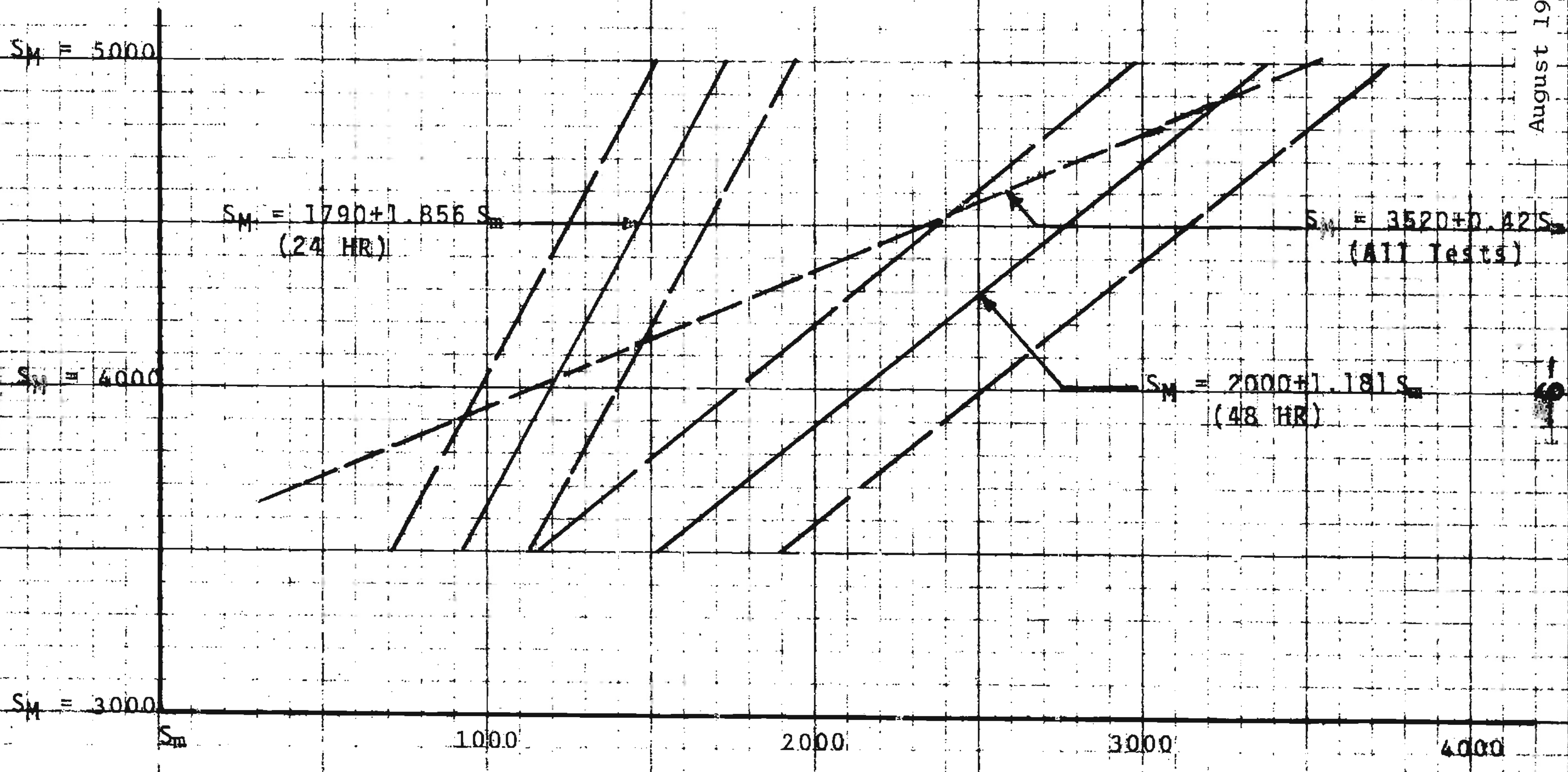
FIGURE I



AUTOGENOUS CURE

CONC. 654

(SEE APPENDIX C)

STANDARD DEVIATION

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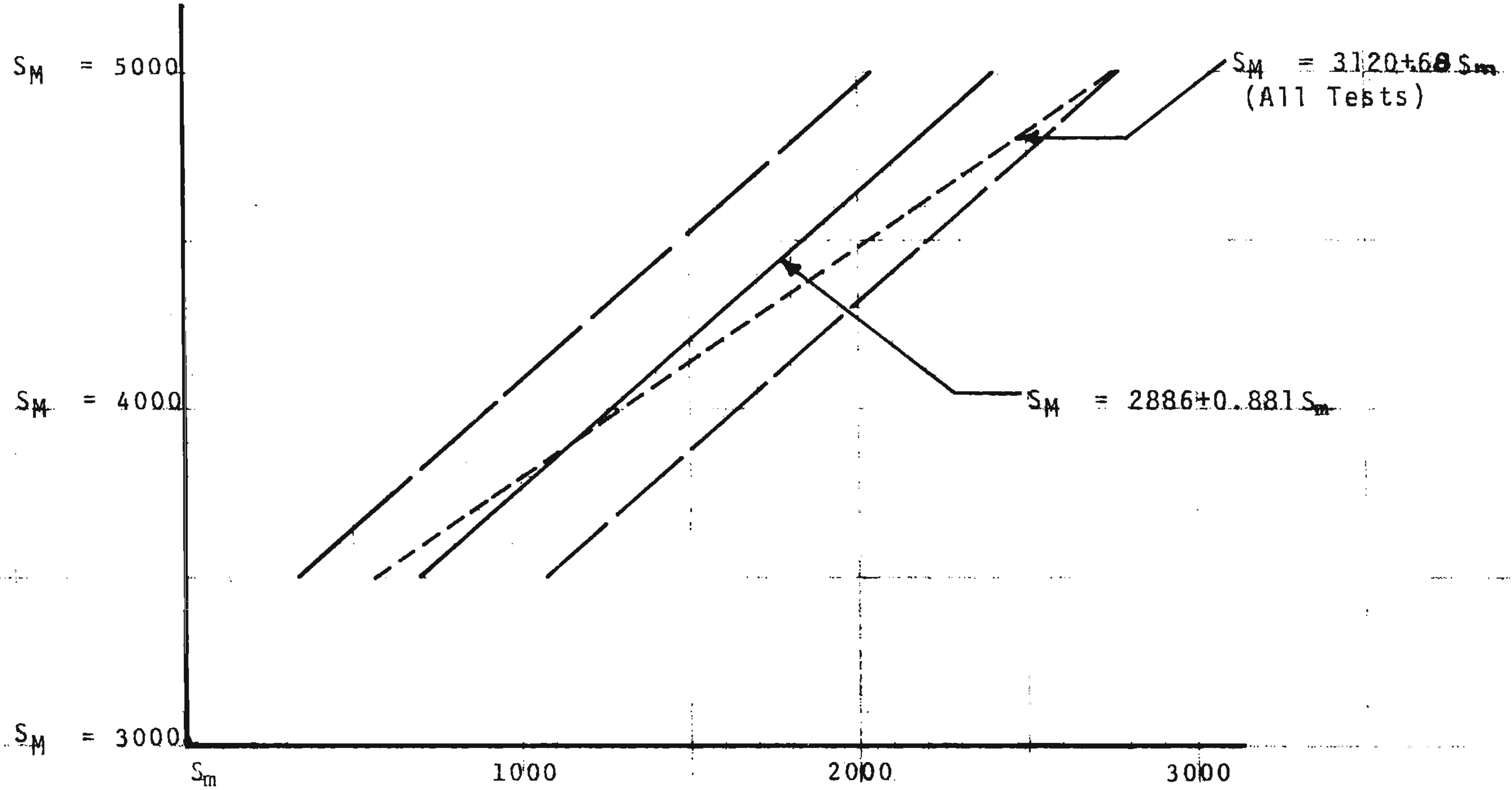
FIGURE II



BOILING WATER CURE

CONC. 654 STANDARD DEVIATION

(SEE APPENDIX "C")

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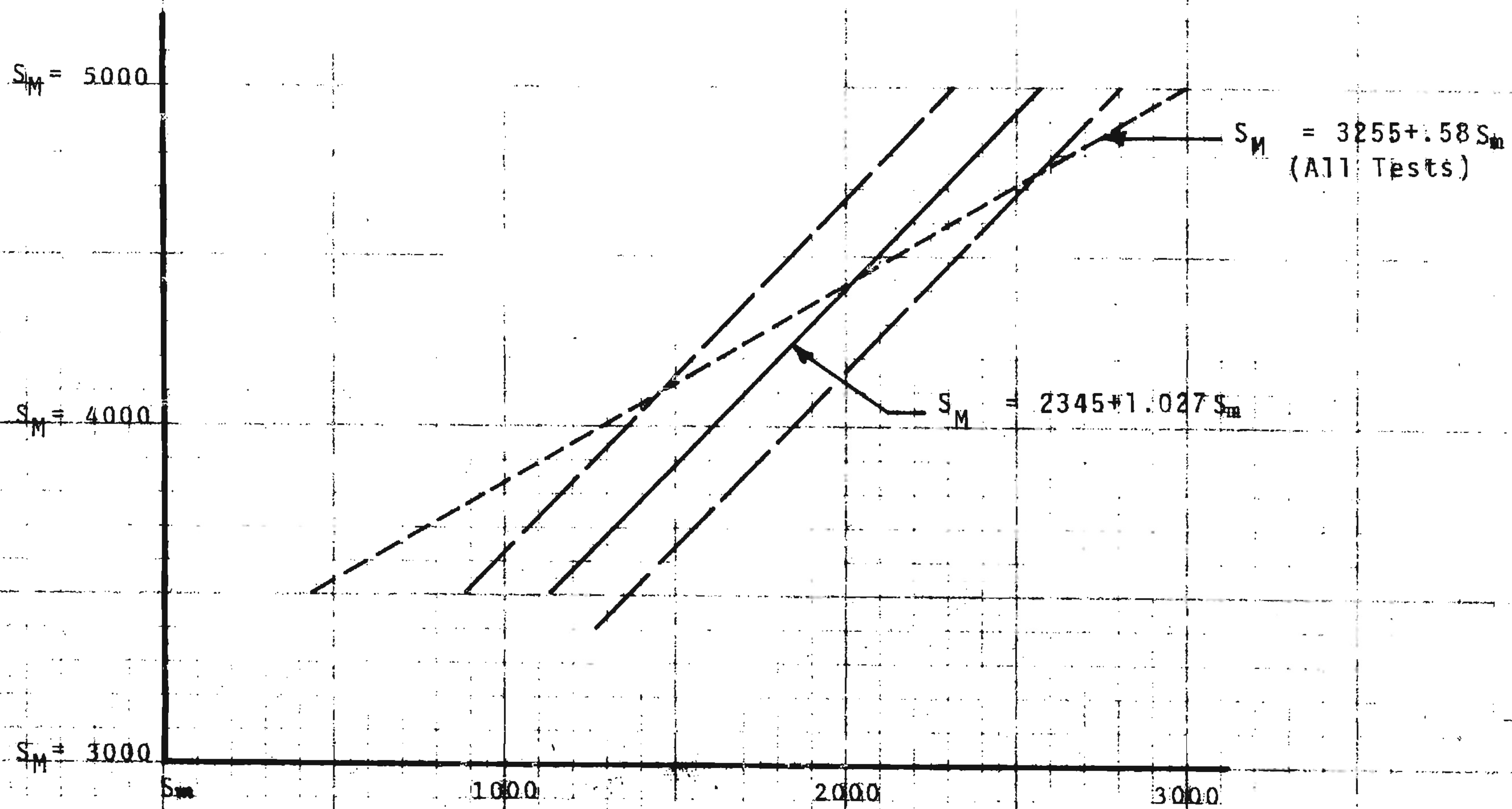
FIGURE III



CONSTANT TEMPERATURE CURVE (48 HRS)

CONC. 654 STANDARD DEVIATION

(SEE APPENDIX "C")

TABLE "C"

Set Nos.	Acc. Cure Method	Equation	D_s psi	D_e psi	D_t psi	D_p psi	I_c
R-17 to R-44	A	$S_M = S_m + 2060(\text{Log } M - \text{Log } m)$	323	165	144	80	.86
R-5 to R-64	A	$S_M = S_m + 2060(\text{Log } M - \text{Log } m)$	409	371	144	342	.42
RL-1 to RL-28	A	$S_M = S_m + 2060(\text{Log } M - \text{Log } m)$	537	299	144	262	.85
R-17 to R-44	C	$S_M = S_m + 2020(\text{Log } M - \text{Log } m)$	323	169	144	88	.85
R-2 to R-65	C	$S_M = S_m + 2020(\text{Log } M - \text{Log } m)$	465	344	144	312	.67
RL-3 to RL-29	C	$S_M = S_m + 2020(\text{Log } M - \text{Log } m)$	440	316	144	281	.70

See Appendix D Pages 47 through 54

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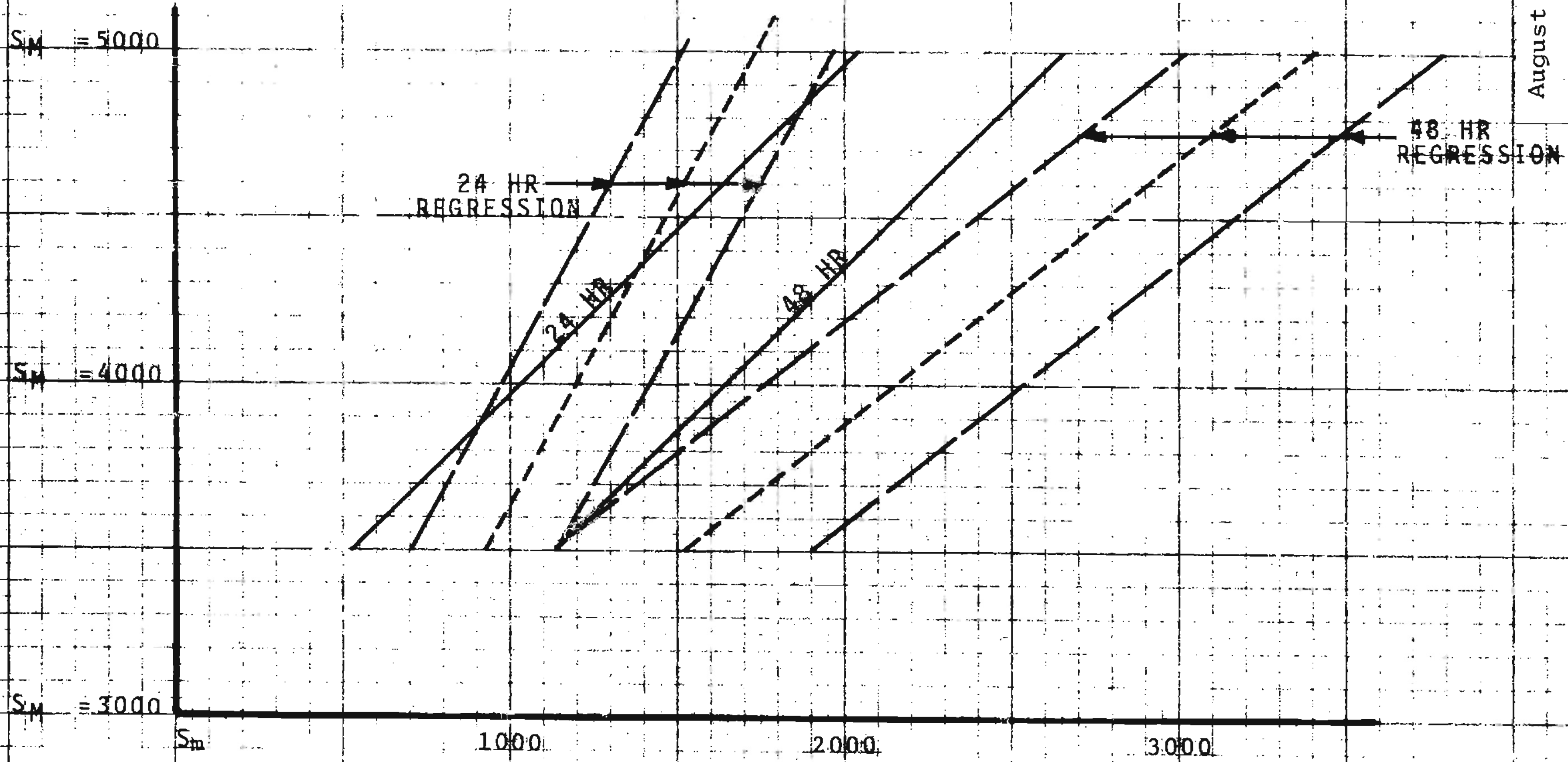
FIGURE IV



AUTOGENOUS CURE
(CONCRETE 654)
(S_M = S_m + 2060 (Log M - Log m)

STANDARD DEVIATION

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FIGURE V

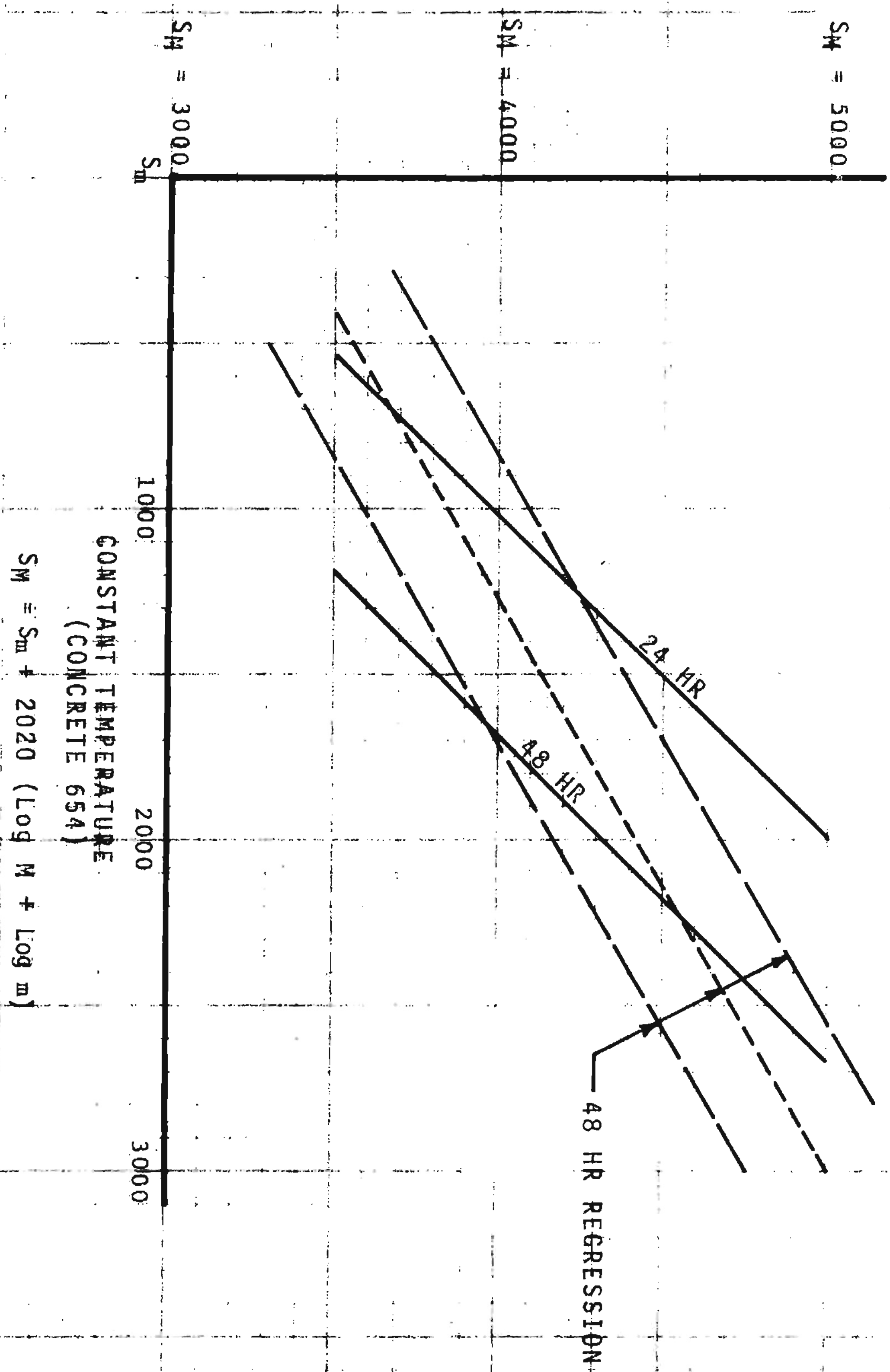

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FIGURE VI

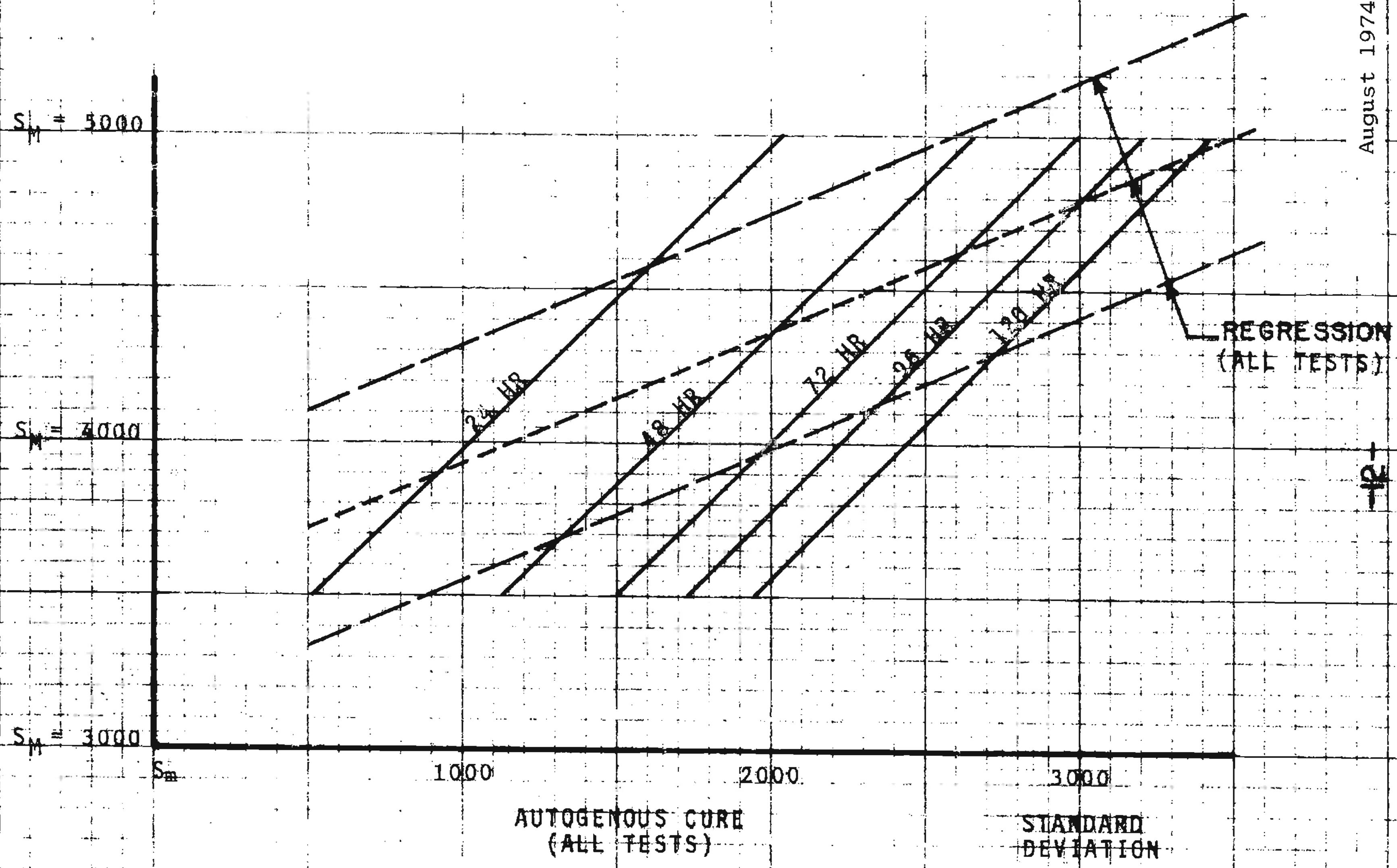

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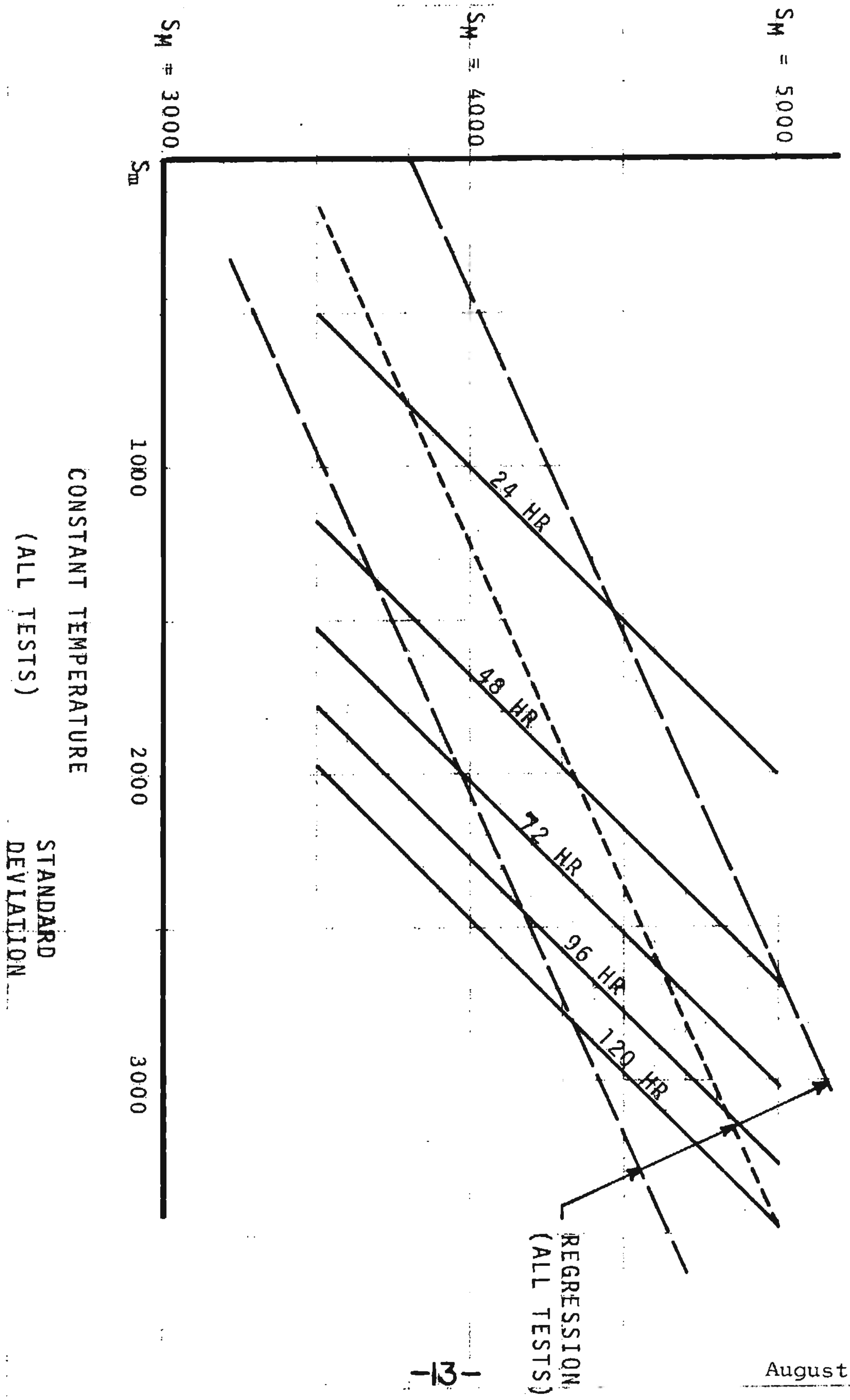
FIGURE VII



SM = 3000
SM = 4000
SM = 5000
Sm
1000
2000
3000
24 HR
48 HR
72 HR
96 HR
120 HR
CONSTANT TEMPERATURE (ALL TESTS)
STANDARD DEVIATION
REGRESSION (ALL TESTS)

The method produced results that were comparable to the regression analysis and provided flexibility for the time of test, enabling all sets to be included in any one curing method.

The initial twenty-three (23) sets of data received from the Straight Creek Tunnel project (see Table "D", page 18) were analyzed by least square regression as shown in Figure VIII, pages 16 and 17.

The most practical method of accelerated cure of the Straight Creek Tunnel project appeared to be constant temperature for the following reasons:

1. A large number of cylinders would be necessary for each placement of tunnel lining.
2. The constant temperature tanks had the required holding capacity for the 24 hour test.
3. The best results for Autogenous Cure is 48 hour and the number of boxes available would not have been adequate for the number of cylinders required.
4. Boiling was ruled out for reasons previously stated.

A total of ten cylinders were cast from Concrete Mix No. SC-10H numbered Set AW 498. Six cylinders were placed in the constant temperature bath and two each were broken at ages 24 hours, 48 hours, and 72 hours, with four receiving standard moist curing (28 days @ 73.4°F - 100% humidity).

Results were plotted and values of C + m' & "b" determined on the semilog plot. (Appendix E, page 55). The equation for the Constant Temperature cure gave values of S_M which were too high.

The graph was re-plotted with the value of S_{28} = 5500 psi and the new constants determined. This new equation gave values for S_M which were too low. A further adjustment of the formula was made by using a value of "b" equal to 4500 and "C" equal to 4240. This revised equation was used on the balance of the Straight Creek Tunnel tests, and the results are shown in Figure IX, Page 17. The least square regression was computed for all the data and is shown in Appendix E. The equation error (D_e) for the Hudson-Steele method compares favorably with the regression (293 psi vs. 256 psi) and it should be noted that the "over age" tests (curing time in excess of 36 hours) were not included in the regression.

CONCLUSIONS

The accelerated curing methods give useable predictions for the 28 day strength of concrete provided the concrete specimens are from a single source. The Boiling Method ("B") has serious disadvantages as previously noted. The Autogenous Method ("A") would be useful for the field in providing early answers (48 hours). The best application for Method "A" would be for projects with average quantities of concrete and where the specimens could be transported to a laboratory for breaking in 48 to 72 hours. For projects that involve large quantities of concrete and where the cylinders could be broken on the project, Method "C" offers the best application.

The Hudson and Steele formulas allow the greatest flexibility in predicting 28 day strengths because of the maturity concept which would allow the development of a reasonably accurate equation based on tests made at different ages on concrete from a single source.

The adoption and use of rapid cure methods will materially speed up information to the field, and permit early detection of low strength concrete so that adjustments in the mix design can be made before work has progressed too far for corrective action.

IMPLEMENTATION

To be able to take full advantage of any of the accelerated cure test methods, the basic concept of early strength determination must be recognized. There is no valid reason for not using accelerated cure strength test as a means of concrete quality control once the initial relationship between the accelerated cure and twenty eight day strengths has been established. By using A. C. strengths directly, the equation error relating the A. C. strengths to 28 day strength is thus eliminated. When a maximum coefficient of variation is specified for concrete quality control, the use of A. C. strength tests will establish the degree of quality control and the concrete supplier's conformance to specification requirements. The early determination of the coefficient of variation will enable the concrete supplier to make any necessary adjustments in his operation before a substantial yardage of concrete has been placed.

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A. C. strength tests determined at the time of the concrete mix design formulation for a specific project would allow the engineer a choice of the quality control methods best suited for his particular operational requirements.

The application of the A. C. strength concept lends itself to those projects that have a substantial yardage of concrete involved and where concrete placement is continuing rather than sporadic. One exception would be where a number of smaller projects are being constructed using the same concrete mix design. It is conceivable that A. C. concrete strength would replace the 28 day strength concept in its entirety.

Figure VIII

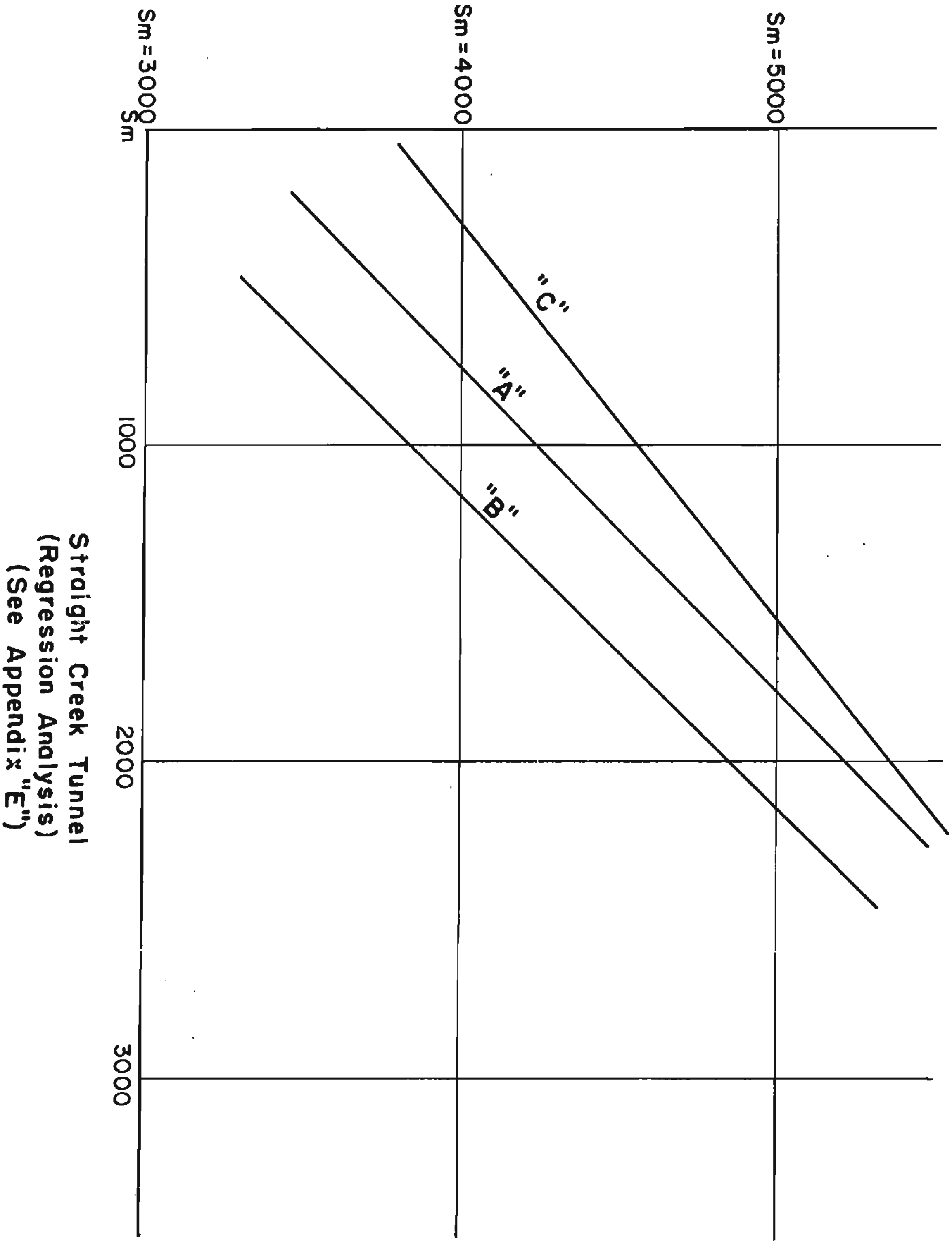

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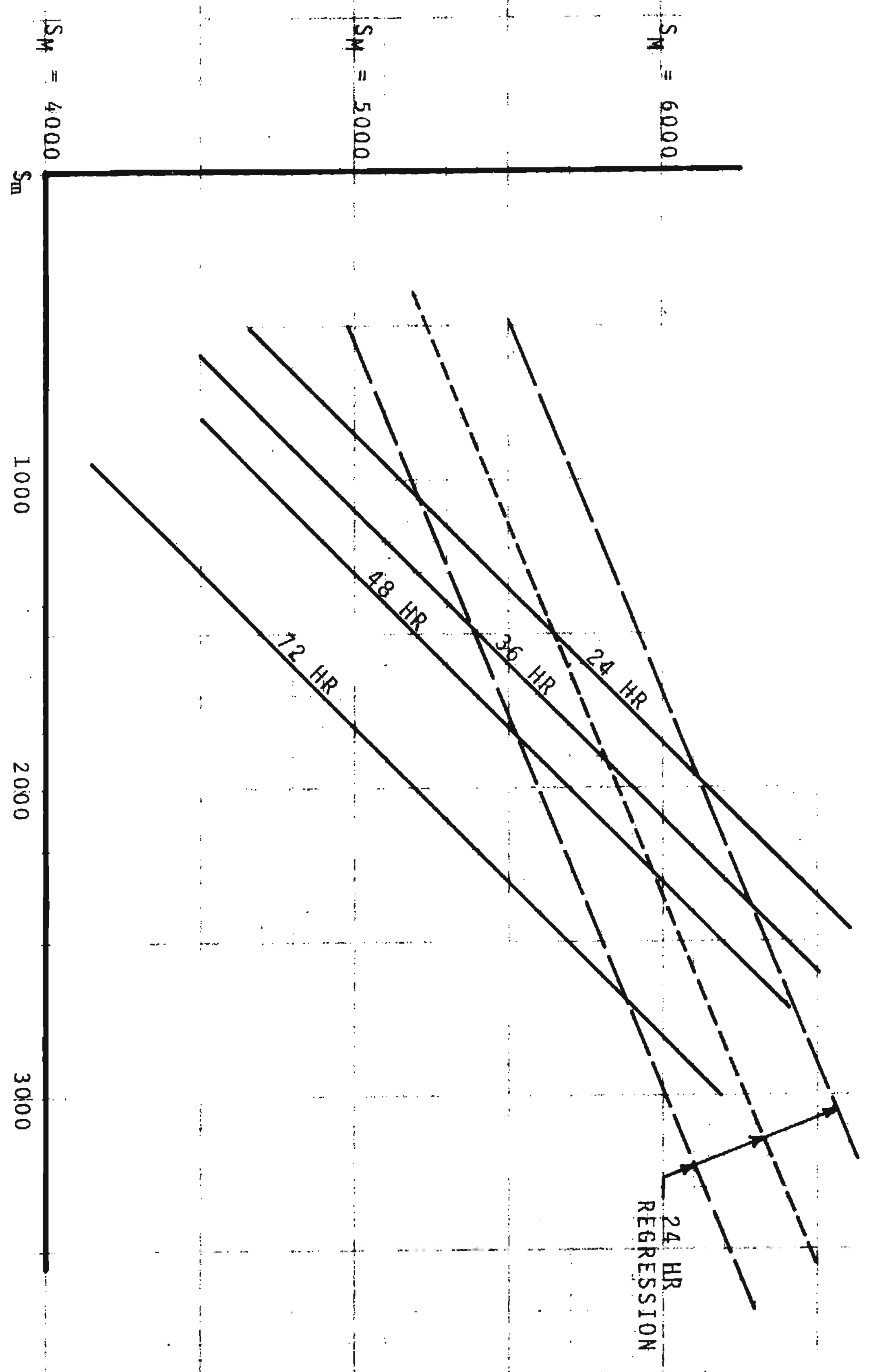
FIGURE IX



CONSTANT TEMPERATURE
STRAIGHT CREEK TUNNEL
$S_M = S_m + 4500 (\text{Log } M + \text{Log } m)$

TABLE "D"

RECAP SHEET OF ACCELERATED CURING

OF CONCRETE TEST SPECIMEN BREAKS

STRAIGHT CREEK TUNNEL

CYLINDER NO.	A AUTOGENOUS	B BOILING	C CONSTANT TEMP.	D CONTROL
1X	NONE	1980 2015	1415 1445	4570 4720
2X	1415 1540	1990 2005	1455 1505	5130 4505
3X	1615 1625	1810 1790	1190 1185	4665 4455
4X	1545 1505	1785 1705	1125 1120	4685 4705
5X	1415 1450	1685 1775	---	4615 4795
6X	1660 1720	2150 2195	1640 1660	5240 5530
7X	1845 1820	2205 2285	1605 1640	5545 5485
8X	1790 1930	2285 2225	1505 1480	5565 5470
9X	1805 1860	2265 2225	1450 1495	5240 5535
10X	1980 2015	2085 2155	1485 1465	4760 4760
11X	1820 1825	2120 2075	1505 1485	4670 4730
12X	1645 1650	1890 1930	1220 1345	4540 4540
13X	1580 1615	1855 1870	1360 1370	4545 4635
14X	1760 1735	1990 1955	1555 1505	4165 4545
15X	1890 1805	2195 2230	1470 1625	4140 5035
16X	1770 1885	2370 2350	1805 1785	5325 5145
17X	1945 1855	2300 2315	1535 1570	5120 4910
18X	1750 1770	2245 2230	1520 1550	5325 5360
19X	1770 1590	2205 2120	1520 1515	5350 5335
20X	1800 1820	1910 1955	1305 1340	5190 5165
21X	1660 1600	2300 2365	1715 1730	5035 4790
22X	1600 1770	2095 2090	1680 1720	4330 4350
23X	1310 1290	1470 1475	1260 1475	4590 4610

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TABLE"E"

STRAIGHT CREEK TUNNEL CYLINDER STRENGTHS
(Autogenous Cure)

SCT SA VS S28

COEFFICIENTS A(K)

$S_M = 3270.14 + .975276\ S_m$

I	S_m	S_{28}	S_M	$(S_{28} - S_M)^2$	$(S_{28} - \bar{S})^2$
1	1480.00	4820.00	4713.55	11331.3	13068.6
2	1620.00	4560.00	4850.09	84152.1	140114
3	1530.00	4700.00	4762.32	3883.16	54905.0
4	1430.00	4710.00	4664.79	2044.18	50318.6
5	1690.00	5390.00	4918.36	222445	207646
6	1830.00	5520.00	5054.90	216320	343023
7	1860.00	5520.00	5084.16	189960	343023
8	1830.00	5390.00	5054.90	112294	207646
9	2000.00	4760.00	5220.69	212240	30386.8
10	1820.00	4700.00	5045.14	119125	54905.0
11	1650.00	4540.00	4879.35	115157	155487
12	1600.00	4590.00	4830.58	57880.8	118555
13	1750.00	4355.00	4976.88	386729	335610
14	1850.00	5035.00	5074.40	1552.62	10136.8
15	1830.00	5240.00	5054.90	34262.9	93441.4
16	1900.00	5015.00	5123.17	11700.1	6509.56
17	1760.00	5340.00	4986.63	124871	164578
18	1680.00	5340.00	4908.61	186100	164578
19	1810.00	5180.00	5035.39	20911.4	60359.6
20	1630.00	4910.00	4859.84	2515.77	591.374
21	1690.00	4340.00	4918.36	334499	353214
22	1300.00	4600.00	4538.00	3843.80	111769

INDEX OF CORRELATION 4.3294423618E-01

EQUATION ERROR(R(I)) = 236.15

STANDARD DEVIATION (YA(I)) = 262

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TABLE"F"
STRAIGHT CREEK TUNNEL CYLINDER STRENGTHS
(Boiled)

SCT SB VS S28

COEFFICIENTS A(K)

$S_M = 2798.16 + 1.03337\ S_m$

I	S_m	S_{28}	S_M	$(S_{28} - S_M)^2$	$(S_{28} - \bar{S})^2$
1	2000.00	4650.00	4864.90	46180.6	73960.3
2	2000.00	4820.00	4864.90	2015.71	10395.1
3	1800.00	4560.00	4658.22	9647.79	131013
4	1750.00	4700.00	4606.55	8732.01	49264.7
5	1730.00	4710.00	4585.89	15403.9	44925.6
6	2170.00	5390.00	5040.57	122102	219065
7	2250.00	5520.00	5123.24	157420	357656
8	2260.00	5520.00	5133.57	149326	357656
9	2250.00	5390.00	5123.24	71161.7	219065
10	2120.00	4760.00	4988.90	52395.6	26229.9
11	2100.00	4700.00	4968.23	71949.2	49264.7
12	1910.00	4540.00	4771.89	53774.6	145891
13	1860.00	4590.00	4720.23	16958.6	110195
14	1970.00	4355.00	4833.90	229341	321440
15	2210.00	5035.00	5081.90	2199.97	12778.8
16	2360.00	5240.00	5236.91	9.55443	101152
17	2310.00	5015.00	5185.24	28981.9	8657.09
18	2240.00	5340.00	5112.90	51572.2	174760
19	2160.00	5340.00	5030.24	95954.1	174760
20	1930.00	5180.00	4792.56	150109	66586.4
21	2330.00	4910.00	5205.91	87561.5	142.958
22	2090.00	4340.00	4957.90	381800	338673
23	1470.00	4600.00	4317.21	79969.1	103656

INDEX OF CORRELATION 6.2571822817E-01

EQUATION ERROR(R(I)) = 202.41

STANDARD DEVIATION (YA(I) = 259

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TABLE"G"
STRAIGHT CREEK TUNNEL CYLINDER STRENGTHS
(Constant Temperature)

SCT SC VS S28

COEFFICIENTS A(K)

$S_M = 3745.83 + .798247\ S_m$

I	S_m	S_{28}	S_M	$(S_{28} - S_M)^2$	$(S_{28} - \bar{S})^2$
1	1430.00	4650.00	4887.32	56322.9	79293.4
2	1480.00	4820.00	4927.24	11499.7	12452.5
3	1190.00	4560.00	4695.75	18426.8	138080
4	1120.00	4700.00	4639.87	3615.87	53634.3
5	1650.00	5390.00	5062.94	106969	210139
6	1620.00	5520.00	5038.99	231369	346225
7	1490.00	5520.00	4935.22	341968	346225
8	1470.00	5390.00	4919.25	221601	210139
9	1480.00	4760.00	4927.24	27968.2	29443.4
10	1500.00	4700.00	4943.20	59147.1	53634.3
11	1280.00	4540.00	4767.59	51796.0	153343
12	1370.00	4590.00	4839.43	62215.2	116684
13	1530.00	4355.00	4967.15	374727	332457
14	1550.00	5035.00	4983.11	2692.14	10693.4
15	1800.00	5240.00	5182.68	3286.05	95116.2
16	1550.00	5015.00	4983.11	1016.71	6957.08
17	1540.00	5340.00	4975.13	133129	166798
18	1520.00	5340.00	4959.17	145034	166798
19	1320.00	5180.00	4799.52	144767	61707.1
20	1720.00	4910.00	5118.82	43604.2	466.167
21	1700.00	4340.00	5102.85	581942	349980
22	1370.00	4600.00	4839.43	57326.6	109953

INDEX OF CORRELATION 3.4818906138E-01

$\bar{S} = 4931$

EQUATION ERROR (R(I)) = 246.82

STANDARD DEVIATION (YA(I)) = 263

August 1974

APPENDIX A

Third Draft
September 15, 1970

Tentative Method of Making and Accelerated Curing of Concrete Test Specimens

1. Scope

1.1 This method covers three procedures for making, curing, and testing specimens of concrete stored under conditions intended to accelerate the development of strength. The choice of which procedure to use should be made by the user on the basis of his experience and local condition. The three procedures are: Procedure A - Warm Water Method, Procedure B - Boiling Water Method, and Procedure C - Autogenous Curing Method.

> Note 1 - All material in this method not designated as belonging specifically to one of the three procedures applies to all procedures.

2. Applicable Documents

ASTM C 470, C 31, C 172, C 33, C 39, C 617

3. Summary of Method

3.1 Concrete specimens are exposed to elevated temperatures and to moisture conditions adequate to develop a significant portion of their ultimate strength within 24 to 48 hours depending upon the procedure selected. Procedures A and B utilize storage of specimens in heated water at elevated curing temperatures without moisture loss. The primary function of the moderately heated water used in Procedure A is to serve as insulation while the temperature level employed in Procedure B provides thermal acceleration. Procedure C involves storage of specimens in insulated curing containers in which the elevated curing temperature is obtained from heat of hydration of the cement. The sealed containers also prevent moisture loss. Sampling and testing procedures are the same as for normally cured specimens (Methods C 172 and C 39 respectively).

3.2 Important characteristics of the procedures are given in Table 1.

TABLE 1

Brief Description of Accelerated Curing Procedures

Procedure	Molds	Accelerated Curing Medium	Accelerated Curing Temperature	Age Accelerated Curing Begins	Duration of Accelerated Curing	Age* At Testing
A Autogenous	single-use	Heat of hydration	Initial Concrete Temperature	Immediately after casting	48 hrs. ± 15 min.	49 hrs. ± 15 min.
B Boiling Water	Reusable or single-use	Water	$212^{\circ}F$ ($100^{\circ}C$)	23 hrs. after casting	3½ hrs. ± 5 min.	28½ hrs. ± 15 min.
C Warm Water**	Reusable or single-use	Water	$95^{\circ}F$ ($35^{\circ}C$)	Immediately after casting of cylinder	23½ hrs. ± 30 min.	24 hrs. ± 15 min.

*May be reduced if cylinders are tested without capping as outlined in 5.1.2.3
**ASTM Method (Similar to Constant Temperature Method)

4. Significance

4.1 The accelerated curing procedures provide, for a particular combination of materials at the earliest practical time, an indication of the ultimate strength to be expected. They also provide information on the variability of the production process for use in process control.

4.2 The correlation between the accelerated and later strengths depends upon the materials comprising the concrete and the specific procedure employed. Prediction should be limited only to concretes using the same materials as those used for establishing the correlations.

4.3 The ratio of accelerated to ultimate strength increased with the cement content and initial mixture temperature.

5. Procedure A - Warm Water

5.1 Apparatus

5.1.1 General - Equipment and small tools for fabricating specimens, measuring slump and determining air content shall conform, if necessary to the applicable requirements of Method C 31 "Making and Curing Concrete Compressive and Flexural Test Specimens in the Field."

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5.1.2 Molds

5.1.2.1 - Molds for specimens shall conform to the requirements for cylinder molds in Method C 31, except that cardboard molds shall not be used.

5.1.2.2 - Single-use light gage molds with lids shall conform to the requirements of Specification C 470 "Single Use Molds for Forming 6 by 12-in. Concrete Compression Test Cylinders."

5.1.2.3 - When test specimens are to be tested without capping, machined plates shall be provided for both top and bottom which can be securely connected to the mold and which will provide bearing surfaces plane within 0.002 in. (0.050 mm). The mold assembly shall be sufficiently tight to permit the filled mold to be turned from the vertical filling position to a horizontal curing position without loss of concrete or damage to the test specimen.

5.1.3 Accelerated Curing Tank

5.1.3.1 - The tank may be of any configuration suitable for the number of cylinders to be tested and the cylinders may be arranged in a line or in rectangular configuration provided a clearance of 2 in. (50 mm) between the side of the cylinder and the surface of the tank and 4 in. (100 mm) between adjacent cylinders is maintained.

Note 2 - A number of different tanks have been used successfully. Two are shown in Appendix Figures 1 and 2.

5.1.3.2 - The tank shall be capable of providing the specified water temperature. The temperature, at any point in the water shall be maintained within $\pm$ 5°F (2.8°C) of that specified. Insulation is not normally required for tanks used in Procedure A, but depending upon the design features of the tank insulation, mechanical agitation, or both might be necessary to meet the temperature requirements. Thermometers or other recording devices shall be used, independent of the thermostat, to check the temperature of the water.

5.1.3.3 - The plate supporting the cylinders shall have sufficient open perforations so as not to interfere with the circulation of the water.

5.1.3.4 - A close fitting lid shall be provided. The water level shall be checked periodically and maintained at the specified level.

5.2 Procedure

5.2.1 Preparation of Test Specimens

5.2.1.1 - Samples of concrete for test specimens shall be taken in accordance with ASTM Method C 172 "Sampling Fresh Concrete." The place of depositing in the structure of the sampled batch shall be noted in the job records.

5.2.1.2 - The slump and air content shall be measured and the specimens molded as required in ASTM Method C 31.

5.2.1.3 - The test specimens shall conform to the requirements for 6 by 12 in. (15 by 30 cm) cylinders contained in ASTM Method C 31.

5.2.2 Curing

5.2.2.1 - Cover the top of the specimen with a rigid plate to prevent loss of mortar to the water bath. (Note 3)

5.2.2.2 - Place the specimen into the curing tank. (Note 3) The water at the time of immersion and throughout the curing period shall be 95°F $\pm$ 5°F (35° $\pm$ 3°C). The temperature of the curing water after immersion of the cylinders shall not drop more than 5°F (2.8°C) and shall return to 95°F $\pm$ 5°F (35° $\pm$ 3°C) within 15 minutes.

5.2.2.3 - The temperature of the curing water should be continuously recorded or periodically measured throughout the curing period.

5.2.2.4 - After curing for 23½ hours $\pm$ 30 minutes, remove the cylinder from the tank and demold the cylinder.

Note 3 - When the cylinders are cast in molds with plates on both ends to conform with the provisions of 5.1.2.3, the plates shall prevent the loss of mortar. If the cylinders are cast in molds meeting the requirements of 5.1.2.3 they may be stored horizontally, otherwise they are to be stored in the curing tank with the long axis vertical.

5.2.3 Capping and Testing

5.2.3.1 - The ends of specimens that are not plane within 0.002 in. (0.050 mm) shall be capped as specified in ASTM Method C 617.

5.2.3.2 - When tested in accordance with provisions of ASTM Method C 617, the capping material shall develop at an age of 30 minutes a strength equal to or greater than the strength of cylinders to be tested.

5.2.3.3 - The cylinder shall be tested for strength in accordance with the requirements of ASTM Method C 39 at an age of 24 hours $\pm$ 15 minutes. If cylinders are capped, the age at time of test shall be 26 hours $\pm$ 15 minutes.

6. Procedure B - Boiling Water

6.1 Apparatus

6.1.1 The requirements for small tools and molds are the same as those stated in 5.1.

6.1.2 The tank shall conform to the requirements specified in 5.1.3.

Caution 1 - The use of boiling water imposes the need for safety measures to prevent scalding or eye burns resulting from sudden immersion or dropping the cylinders into the boiling water. Lifting tongs are suggested.

6.2 Procedure

6.2.1 Preparation of Test Specimens - Specimens shall be prepared in accordance with 5.2.1.

6.2.2 Initial Curing - Cover the cylinder to prevent loss of moisture and store in an upright position in a safe storage area such that they will not be disturbed or subjected to vibration or jarring. In the storage area the temperature adjacent to the cylinders shall be maintained at 70°F $\pm$ 10°F (21° C). Protection and storage shall conform to the requirements of ASTM Method C 31.

Note 4 - Strict attention to the protection and storage of the cylinder during this initial period is necessary for meaningful results because of the short total curing period.

6.2.3 Accelerated Curing

6.2.3.1 - Place the covered cylinder molds in the water tank at 23 hours $\pm$ 15 minutes after molding. The temperature of the water at the time of immersion and throughout the curing period shall be at boiling (212°F)(100°C) at sea level. (Notes 3 and 5) The temperature of the water shall not drop more than 5°F (2.8°C) after the cylinders are placed and shall return to boiling within 15 minutes.

Note 5 - In confined places the temperature of the water may be kept just below the boiling point to avoid excessive evaporation. The temperature at which water boils varies because of differences in elevation above sea level. Differences in strengths caused by the differences in temperatures are not believed to be significant, but comparison of results among areas so affected should be supported by appropriate correlations and interpreted with the knowledge of the temperature variations.

6.2.3.2 - The temperature of the curing water should be continuously recorded or measured at regular intervals throughout the curing period.

6.2.3.3 - After curing for 3½ hours ± 5 minutes remove the check cylinder to cool for 1 hour at room temperature.

6.2.4 Capping and Testing

6.2.4.1 - The cylinders shall be capped and tested in accordance with 5.2.3 except that the age at time of test shall be 28½ hours ± 15 minutes.

7. Procedure C - Autogenous Curing

7.1 Apparatus

7.1.1 General

7.1.1.1 The container shall consist of thermal insulating material, of specified properties and thickness, closely surrounding the concrete test cylinder.

7.1.1.2 The container shall be capable of being opened to permit insertion and/or withdrawal of the cylinder and where required shall have an outer casing and inner liner to protect the insulation from mechanical damage.

7.1.1.3 The container may be provided with a maximum and minimum recording thermometer which shall not be insulated from the test cylinder (See Note 8).

7.1.1.4 Provision shall be made to keep the container securely closed during the specified curing period.

7.1.1.5 The container shall be capable of holding either one or two cylinders. A satisfactory container is shown in Appendix Figure 4 (Note 6).

Note 6 - Drawings and guidelines for construction of suitable containers are included in the Appendix. Any configuration is acceptable so long as it meets the performance requirements of 7.1.2.

7.1.2 Proving Tests Requirements

7.1.2.1 Heat Retention - A watertight container with internal dimensions of 12 in. by 6 in. diameter (30 by 15 cm) shall be placed in the curing container and then filled to within 1/4 in. (0.6 cm) of the brim with water at a temperature of 180°F (82°C). A thermocouple shall be inserted in the water and the initial temperature of the water measured with an electrical potentiometer. The water container shall then be sealed with a cap or plastic bag. The autogenous container shall then be closed. When the autogenous curing container is stored in still air at 70°F (21°C), $\pm$ 2°F (1°C), the water temperature shall be:

After 12 hrs.	152° $\pm$ 5°F	(66 $\pm$ 3C)
24 hrs.	136° $\mp$ 6°F	(57 $\mp$ 3C)
48 hrs.	114° $\mp$ 7°F	(45 $\mp$ 4C)
72 hrs.	100° $\pm$ 8°F	(37 $\pm$ 4C)

7.1.2.2 Rightness Test for Gasket Heat Seal - When the autogenous curing container is immersed in water to a depth of 6 in. above the joint between the separable parts, no air shall escape through the heat seal within a period of 5 minutes.

7.1.2.3 Stability of the Container - The container or any part thereof shall not display embrittlement, fracturing or distortion when maintained in an ambient temperature of -20°F (-29°C) for 72 hours, nor softening or distortion when maintained at an ambient temperature of 140°F (60°C) for 72 hours. The gasket type heat seal shall immediately fully recover its original thickness after 50 percent compression under the temperature conditions specified above.

7.2 Procedure

7.2.1 Preparation of Test Specimens - Specimens shall be prepared in accordance with 5.2.1.

7.2.2 Curing

7.2.2.1 Immediately after molding, cover the mold with a metal plate or a tightly fitted cap and place in a heavy duty plastic bag from which as much of the entrapped air as possible is expelled prior to tying the neck. (Alternatively, a moisture-tight plastic cap may be used.) The plastic bag should be of sufficient weight and strength to resist punctures and serve as a lifting grip for removal of the cylinder from the autogenous container.

Note 7 - The container, either during the first 2 hours of curing or after 12 hours of curing, may be transported from the place of molding the cylinders to the place of testing without crating or other protection.

7.2.2.2 Reset the maximum-minimum thermometer (if used) and secure the container lid.

7.2.2.3 Record the time of molding to the nearest 15 minutes and the temperature of the fresh concrete clearly on the outside of the container.

7.2.2.4 During the curing period, the container shall not be moved, disturbed or jarred between the 2nd and 12th hour of storage and shall be stored out of the sun, preferably at a temperature between 60 and 80°F. (Note 7)

7.2.2.5 At an age of 48 hours ± 15 minutes after the time at which the cylinder was molded, remove the cylinder from the container and demold. Allow to stand for 30 minutes at room temperature.

7.2.2.6 Record the maximum and minimum temperatures in the container indicated on the thermometer. (Note 8)

Note 8 - Comparison of the maximum and minimum with the recorded temperature of the fresh concrete will provide an indication of abnormal or interrupted curing which may cause high or low strength results.

7.2.3 Capping and Testing - The cylinders shall be capped and tested in accordance with 5.2.3 except that the age at the time of test shall be 49 hours ± 15 minutes. (Note 9)

Note 9 - Capping and Testing may be performed at ages different from that specified in 7.2.3. Agencies using the procedure have for convenience established relationships between test results at 24, 72, and 96 hours with those obtained by standard moist curing. However, at 24 hours, the relationship is less satisfactory than those obtained by accelerated autogenous curing for 48, 72, or 96 hours. Where the curing period is other than that specified in 7.2.3, the age at testing shall be the curing period plus 1 hour. The tolerance of ± 15 minutes shall still apply.

8. Interpretation of Test Results

8.1 Because strength requirements in existing specifications and codes are not based upon accelerated curing, use of results from this method in the prediction of specification compliance of strengths at later ages must be applied with great caution. As stated in Section 10, Precision, the variability of the method is the same or less than that from traditional methods. Thus, results can be useful in rapid assessment of variability for process control and signalling the need for indicated adjustments. On the other hand, the magnitude of the strength values obtained is influenced by the specific combination of materials so that the use of the results from either conventional tests at any arbitrary age or those from this method must be supported by experience or correlations developed by the specific agency for the existing local conditions and materials. Factors influencing relationships between measured strengths and those of concrete in place are no different from those affecting conventional strength tests.

9. Report

9.1 The report shall include the following:

9.1.1 Identification number

9.1.2 Diameter (and length, if not standard), in inches

9.1.3 Cross-sectional area, in square inches

9.1.4 Maximum load, in pounds

9.1.5 Compressive strength calculated to the nearest 10 psi (0.7 $Kgf./cm^2$)

9.1.6 Type of fracture, if other than the usual cone

9.1.7 Defects in either specimen or caps

9.1.8 Age of specimens

9.1.9 Accelerated curing method used

9.1.10 Initial mix temperature to the nearest °F (°C)

9.1.11 Maximum and minimum temperature to the nearest °F (°C) if Method C was used

9.1.12 Method of transportation used for shipping specimens to the Laboratory

9.1.13 Ambient temperature of specimen or container during storage for Methods B and C.

10. Precision

10.1 The single-laboratory coefficient of variation has been determined as 3.6 percent for a pair of cylinders cast from the same batch. Therefore, results of two properly conducted strength tests by the same laboratory on the same materials should not differ more than 10 percent of their average.

10.2 The single-laboratory, multi-day coefficient of variation has been determined as 8.7 percent for the average of pairs of cylinders cast from single batches mixed on two days. Therefore, results of two properly conducted strength tests by the same laboratory on the same materials should not differ by more than 25 percent of their average.

APPENDIX B

(From Part II of the Report, "Determination of Statistical Parameters for Highway Construction - Continuation II, "West Virginia Department of Highways Research Project No. 18.)

Procedure for Establishing an Equation for Predicting Potential Strength from Early Tests on Concrete Cylinders

1. Prepare laboratory batches of a design mix to which equation will apply. The size of the laboratory batches should be large enough to make six test cylinders. Repeat on five different days.

   To minimize variation, make cylinders in place where they can remain undisturbed for 24 hours at 73 degrees Fahrenheit $\pm$ 3 degrees Fahrenheit.

2. At the end of 24 hours, test one cylinder from each batch with or without conditioning such as 3-hour immersion in 200 degrees Fahrenheit bath or 200 degrees Fahrenheit oven. Place remaining cylinders under standard moist cure at 73.4 degrees Fahrenheit $\pm$ 3 degrees Fahrenheit.

3. Test one cylinder from each batch at end of 48, 72, and 96 hours with or without conditioning, same as (2) above. Test two cylinders at 28 days without conditioning.

4. Average test results ($\bar{X}5$) for each age.

5. Prepare sheet of semilog graph paper, 2 cycle by 70 divisions (K&E 46-4970, or similar) by numbering 1 inch division in thousands of pounds per square inch. The log scale will represent maturity (m) in thousands of degree-hours (F hr.) at time of test.

6. Draw horizontal lines across graph from pounds per square inch scale for each average strength. Plot point for 28-day pounds per square inch at 50,000 degree-hours (F hr.) of maturity.

7. Points for each strength should lie on their respective lines in such positions that a straight line from the 28-day strength point will pass through, or near all the early strength points. Since both the slope of the line and the maturity values of the points are unknown, the equation must be found graphically, by trial and error.

   It is known that the maturity values of the points will be 1760 degree-hours (F hr.) (24 x 73.4 degrees) apart. Then each point will have a maturity value of some multiple of 1760, plus some value C determined by conditioning, (if any) autogenous heating, and unknown factors.

   The iterative method of finding the line of prediction is shown in the following table and attached graph, using fictitious data.

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Sc (psi)		m'	(O) C = 240	(X) C = 2240	(Δ) C = 1240
			m = m' + C		
24-hour	2000	1760	2000	4000	3000
48-hour	2600	3520	3760	5760	4760
72-hour	3000	5280	5520	7520	6520
96-hour	3300	7040	7280	9280	8280
28-day	5500	50000	50000	50000	50000

As seen from Figure A-1, the first series of points (O) have too flat a slope to intersect the 28-day point. The second trial (X) points have too steep a slope. Third trial (Δ) provides points falling very closely on the line projected to the 28-day point, so the best value of C is 1240.

8. The slope of (b) of this line is the vertical scale distance between the intercept on the 10,000 m line and the intercept on the 100,000 m line or about 2850 in the case of the example.

9. The general form of the prediction equation is

$$S_M = S_m + b\ (\log M - \log m) \qquad \text{Equation (A-1)}$$

Where:

S_M is the predicted potential strength at maturity M;

S_m is the measured compressive strength at maturity m;

b is the slope of the line of prediction;

Log M and log m are the common Briggs logarithms of the respective values of maturity in degree-hours (F hr.).

10. In the case of the example, the potential 28-day strengths projected from the 24-hour test would be

$$\begin{aligned} S_{28} &= 2000 + 2850\ (4.699 - 3.477) \\ &= 2000 + 2850\ (1.222) \\ &= 2000 + 3480 \\ &= 5480 \text{ psi} \end{aligned}$$

11. The graphical method described above provides and approximate prediction equation for averages of groups of compressive test results. A better estimate of the value of slope (b) can be obtained by the method of zero sum using the equation.

$$b = \frac{\sum (SM - Sm)}{\sum (\log M - \log m)} \qquad \text{Equation (A-2)}$$

When using this method, the difference between each early test result and the corresponding 28-day test results on cylinders from the same batch are noted along with the matching difference in the logarithms of the maturities. The total of the differences in compressive strengths is then divided by the total of the difference in the logarithms of the maturities.

12. The prediction equation is tested by computing an exposure table. Using the slope (b) obtained by the method of zero sum (item 11 above), the 28-day strength is predicted from each individual early test result. The algebraic difference between each predicted result and the corresponding measured 28-day test results are listed and totaled. The total should be zero or nearly so.

13. The equation error is computed by the use of the formula

$$Q_e = \frac{\sum (S_M - S_{28})^2}{2\eta} \qquad \text{Equation (A-3)}$$

The best values of b and C are indicated the lowest value of Q_e.

A one-sided confidence limit can be established by

$$S_M - 1.645 \quad Q_e > L \qquad \text{Equation (A-4)}$$

which indicates that 95 times out of 100, the true average strength is greater than L.

14. The testing error is computed by use of the Equation

$$Q_t = \frac{\sum (X_1 - X_2)^2}{2\eta} \qquad \text{Equation (A-5)}$$

where X_1 and X_2 are the paired 28-day test results on cylinders from the same batch.

15. The actual prediction error is

$$Q_p = \sqrt{Q_e^2 - Q_t^2} \qquad \text{Equation (A-6)}$$

16. Equation (A-1) may be used to predict potential strength at any age from a test result of a cylinder of any age, providing the temperature history of the cylinder prior to test can be estimated.

For example, the potential 14-day strength of concrete can be estimated from a cylinder 41 hours old at time of test when the average temperature of the cylinder was 90 degrees Fahrenheit.

b = 2850 C - 1240

$M = 14 \times 24 \times 73.4 = 24640$ $\qquad$ $\log = 4.39164$

$m = (41 \times 90) + 1240 = 4930$ $\qquad$ $\log = \underline{3.69285}$

$S_m = 2210$ psi $\qquad$ diff. $= 0.69879$

$$
\begin{aligned}
S_{14} &= 2210 + 2850\ (0.699) \\
&= 2210 + 1990 \\
&= 4200 \text{ psi}
\end{aligned}
$$

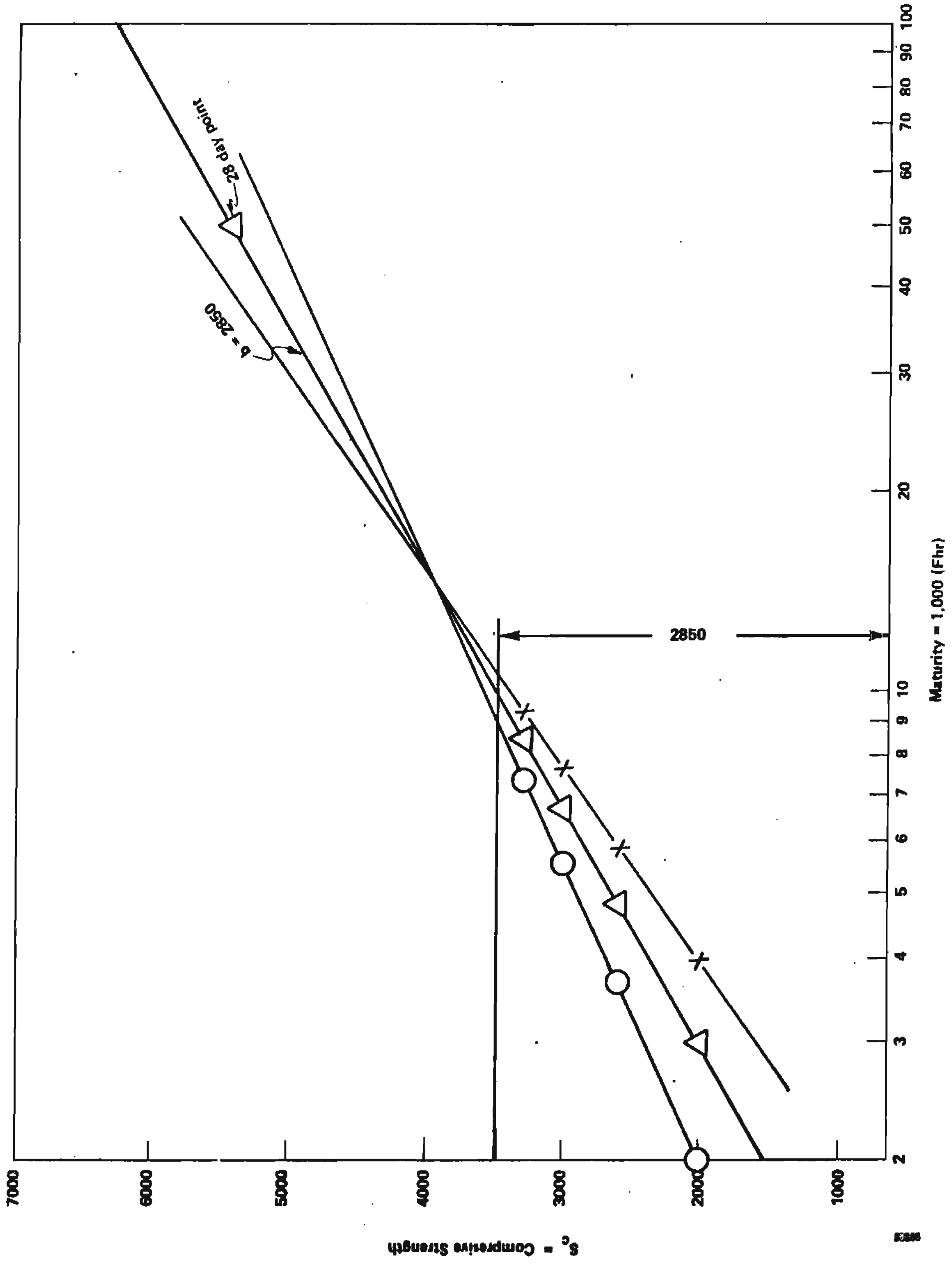

Figure A-1. Determine Line of Prediction

APPENDIX C

DATA AND CALCULATIONS FOR CORRELATION BETWEEN ACCELERATED CURE STRENGTH AND 28 DAY STRENGTH

CONC 654 SA VS S28 24 Hr.

COEFFICIENTS A(K)

$S_M = 1792.55 + 1.85622\ S_m$

I	S_m	S_{28}	S_M	$(S_{28} - S_M)^2$	$(S_{28} - \bar{S})^2$
1 R-19	1940.00	5260.00	5393.63	17855.7	620719
2 R-23	1430.00	4215.00	4446.95	53801.4	66122.4
3 R-27	1160.00	3745.00	3945.77	40309.0	528737
4 R-33	1485.00	5035.00	4549.04	236154	316808
5 R-37	1050.00	3785.00	3741.59	1884.74	472165
6 R-39	1515.00	4585.00	4604.73	389.282	12736.7
7 R-43	1525.00	4680.00	4623.29	3215.75	43204.6

INDEX OF CORRELATION 9.1015711001E-01

$\bar{S} = 4472$

EQUATION ERROR(R(I)) = 158.93

STANDARD DEVIATION (YA(I)) = 383

CONC 654 SA VS S28 48 Hr.

COEFFICIENTS A(K)

$S_M = 2000.98 + 1.18134\ S_m$

I	S_m	S_{28}	S_M	$(S_{28} - S_M)^2$	$(S_{28} - \bar{S})^2$
1 R-17	2190.00	4390.00	4588.13	39253.8	3402.78
2 R-18	2200.00	4615.00	4599.94	226.832	27777.8
3 R-20	1950.00	4240.00	4304.60	4173.58	43402.8
4 R-21	2025.00	4420.00	4393.20	718.027	802.778
5 R-22	2290.00	4900.00	4706.26	37535.2	204003
6 R-24	1915.00	4080.00	4236.26	33582.8	135669
7 R-25	1585.00	3885.00	3873.41	134.261	317344
8 R-26	2215.00	4515.00	4617.66	10538.9	4444.44
9 R-28	1590.00	3775.00	3879.32	10882.6	453378
10 R-29	1355.00	3465.00	3601.70	18688.0	966944
11 R-30	1965.00	4470.00	4322.32	21808.4	469.444
12 R-31	2265.00	4890.00	4676.73	45485.6	195069
13 R-32	1740.00	4200.00	4056.52	20586.2	61669.4
14 R-34	2110.00	4695.00	4493.62	40554.6	60844.4
15 R-35	1980.00	4775.00	4340.04	189187	106711
16 R-36	2110.00	4585.00	4493.62	8350.64	18677.8
17 R-38	2575.00	5270.00	5042.94	51555.0	675136
18 R-40	2555.00	4870.00	5019.32	22295.3	177803
19 R-41	2410.00	4605.00	4848.02	59059.3	24544.4
20 R-42	1970.00	4075.00	4328.23	64125.5	139378
21 R-44	2510.00	4695.00	4966.16	73525.3	60844.4

INDEX OF CORRELATION 8.9190027533E-01

EQUATION ERROR (R(I)) = 133.83

STANDARD DEVIATION (YA(I)) = 296

August 1974

APPENDIX C

CONC 698 SA VS S28

COEFFICIENTS A(K)

S_M = 3182.07 + .485582 S_m

I	S_m	S_{28}	S_M	$(S_{28} - S_M)^2$	$(S_{28} - \bar{S})^2$
1 R-8	2685.00	4890.00	4485.86	163328	151451
2 R-9	2845.00	4720.00	4563.55	24475.2	48034.0
3 R-11	2190.00	4130.00	4245.50	13339.8	137517
4 R-12	2355.00	4240.00	4325.62	7330.64	68034.0
5 R-15	2695.00	4260.00	4490.72	53230.4	58000.7
6 R-16	3525.00	4765.00	4893.75	16576.6	69784.0

INDEX OF CORRELATION 6.9117409382E-01

EQUATION ERROR (R(I)) = 152.28

STANDARD DEVIATION (YA(I)) = 211

CONC 751 SA VS S28 <u>48 Hr.</u>

COEFFICIENTS A(K)

S_M = 1088.49 + 1.36568 S_m

I	S_m	S_{28}	S_M	$(S_{28} - S_M)^2$	$(S_{28} - \bar{S})^2$
1 R-45	2325.00	4530.00	4263.71	70909.3	41259.8
2 R-47	2250.00	4275.00	4161.29	12930.9	2691.02
3 R-48	2215.00	3995.00	4113.49	14039.1	110141
4 R-49	2565.00	4545.00	4591.48	2160.06	47578.5
5 R-51	2350.00	3725.00	4297.85	328162	362254
6 R-55	2260.00	4105.00	4174.94	4891.96	49228.5
7 R-56	2710.00	4860.00	4789.50	4970.15	284222
8 R-58	2295.00	4580.00	4222.74	127634	64072.3

INDEX OF CORRELATION 6.4157545023E-01

EQUATION ERROR (R(I)) = 188.03

STANDARD DEVIATION (YA(I)) = 245

APPENDIX C

CONC 654 SB VS S28

COEFFICIENTS A(K)

S_M 2886.38 + .881485 S_m

I	S_m	S_{28}	S_M	$(S_{28} - S_M)^2$	$(S_{28} - \overline{S})^2$
1 R-17	1700.00	4390.00	4384.91	25.9366	2500.00
2 R-18	2030.00	4615.00	4675.80	3696.30	30625.0
3 R-19	2300.00	5260.00	4913.80	119586	672400
4 R-20	1690.00	4240.00	4376.09	18521.1	40000.0
5 R-21	1790.00	4420.00	4464.24	1957.25	400.000
6 R-22	2000.00	4900.00	4649.35	62824.1	211600
7 R-23	1675.00	4215.00	4362.87	21865.6	50625.0
8 R-24	1440.00	4080.00	4155.72	5733.69	129600
9 R-25	1430.00	3885.00	4146.91	68594.9	308025
10 R-26	1070.00	4515.00	3829.57	469812	5625.00
11 R-27	1070.00	3745.00	3829.57	7152.39	483025
12 R-28	1515.00	3775.00	4221.83	199659	442225
13 R-29	1205.00	3465.00	3948.57	233842	950625
14 R-30	1855.00	4070.00	4521.54	203886	136900
15 R-31	1745.00	4890.00	4424.57	216621	202500
16 R-32	1520.00	4200.00	4226.24	688.534	57600.0
17 R-33	1990.00	5035.00	4640.54	155600	354025
18 R-34	1660.00	4695.00	4349.65	119268	65025.0
19 R-35	1630.00	4775.00	4323.20	204120	112225
20 R-36	1580.00	4585.00	4279.13	93557.1	21025.0
21 R-37	1260.00	3785.00	3997.05	44966.9	429025
22 R-38	2330.00	5270.00	4940.24	108740	688900
23 R-39	2070.00	4585.00	4711.06	15890.3	21025.0
24 R-40	2595.00	4870.00	5173.84	92316.4	184900
25 R-41	2200.00	4605.00	4825.65	48686.2	27225.0
26 R-42	1970.00	4075.00	4622.91	300203	133225
27 R-43	1890.00	4680.00	4552.39	16284.5	57600.0
28 R-44	2140.00	4695.00	4772.76	6046.70	65025.0

INDEX OF CORRELATION 7.1918244780E-01

EQUATION ERROR (R(I)) = 225.21

STANDARD DEVIATION (YA(I)) = 324

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APPENDIX C

CONC 698 SB VS S28

COEFFICIENTS A(K)

$S_M = 2054.21 \quad + \quad .995150\ S_m$

I		S_m	S_{28}	S_M	$(S_{28} - S_M)^2$	$(S_{28} - \bar{S})^2$
1	R-2	2750.00	4835.00	4790.87	1947.30	1314.06
2	R-3	3415.00	5525.00	5452.65	5235.04	527439
3	R-4	3130.00	5095.00	5169.03	5480.25	87764.1
4	R-5	2780.00	5125.00	4820.73	92582.5	106439
5	R-6	2950.00	5380.00	4989.90	152177	337852
6	R-8	2780.00	4890.00	4820.73	4798.86	8326.56
7	R-9	3075.00	4720.00	5114.30	155469	6201.56
8	R-10	2660.00	4620.00	4701.31	6611.03	31951.6
9	R-11	2085.00	4130.00	4129.10	.815324	447227
10	R-12	2135.00	4240.00	4178.85	3738.77	312202
11	R-15	2455.00	4260.00	4497.30	56312.5	290252
12	R-16	2880.00	4765.00	4920.24	24099.8	1139.06

INDEX OF CORRELATION 8.7429901770E-01

EQUATION ERROR(R(I)) = 145.55

STANDARD DEVIATION (YA(I)) = 299

CONC 751 SB VS S28

COEFFICIENTS A(K)

$S_M = 2762.56 \quad + \quad .699299\ S_m$

I		S_m	S_{28}	S_M	$(S_{28} - S_M)^2$	$(S_{28} - \bar{S})^2$
1	R-45	2125.00	4530.00	4248.57	79201.6	85556.2
2	R-46	1600.00	3680.00	3881.44	40578.1	310806
3	R-47	1930.00	4275.00	4112.21	26501.0	1406.25
4	R-48	1880.00	3995.00	4077.24	6764.06	58806.2
5	R-49	2060.00	4545.00	4203.12	116883	94556.2
6	R-51	2145.00	3725.00	4262.56	288969	262656
7	R-52	2945.00	4700.00	4822.00	14883.5	213906
8	R-54	2110.00	3800.00	4238.08	191916	191406
9	R-55	2120.00	4105.00	4245.08	19621.2	17556.2
10	R-56	2430.00	4860.00	4461.86	158517	387506
11	R-57	2050.00	4055.00	4196.12	19916.2	33306.2
12	R-58	1915.00	4580.00	4101.72	228752	117306

INDEX OF CORRELATION 5.7278439577E-01

EQUATION ERROR(R(I)) = 222.91

STANDARD DEVIATION (YA(I)) = 272

APPENDIX C

CONC 654 SC VS S28 48 Hr.

COEFFICIENTS A(K)

$S_M = 2345.33 + 1.02690\ S_m$

I	S_m	S_{28}	S_M	$(S_{28} - S_M)^2$	$(S_{28} - \bar{S})^2$
1 R-17	2085.00	4390.00	4486.42	9296.30	18975.1
2 R-18	2270.00	4615.00	4676.39	3769.17	7612.56
3 R-20	1890.00	4240.00	4286.17	2131.86	82800.1
4 R-21	1960.00	4420.00	4358.06	3837.18	11610.1
5 R-22	2290.00	4900.00	4696.93	41236.8	138570
6 R-24	1960.00	4080.00	4358.06	77314.6	200480
7 R-25	1585.00	3885.00	3972.97	7738.38	413128
8 R-26	2050.00	4515.00	4450.48	4163.36	162.562
9 R-28	1740.00	3775.00	4132.14	127547	566633
10 R-30	2140.00	4470.00	4542.90	5313.94	3335.06
11 R-31	2425.00	4890.00	4835.56	2963.40	131225
12 R-32	1790.00	4200.00	4183.48	272.836	107420
13 R-34	2020.00	4695.00	4419.67	75807.2	27972.6
14 R-35	1980.00	4775.00	4378.59	157139	61132.6
15 R-36	2140.00	4585.00	4542.90	1772.68	3277.56
16 R-38	2690.00	5270.00	5107.69	26344.2	550935
17 R-40	2595.00	4870.00	5010.14	19638.0	117135
18 R-41	2385.00	4605.00	4794.49	35905.3	5967.56
19 R-42	1970.00	4680.00	4368.32	97141.9	23180.1
20 R-44	2540.00	4695.00	4953.66	66903.0	27972.6

INDEX OF CORRELATION 8.3273483367E-01

EQUATION ERROR(R(I)) = 138.40

STANDARD DEVIATION (YA(I)) = 250

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APPENDIX C

CONC 751 SC VS S28

COEFFICIENTS A(K)

$S_M = 1659.05 \quad + \quad 1.53091\ S_m$

I	S_m	S_{28}	S_M	$(S_{28} - S_M)^2$	$(S_{28} - \bar{S})^2$
1 R-46	1295.00	3680.00	3641.58	1476.05	201858
2 R-47	1840.00	4275.00	4475.93	40372.1	21232.7
3 R-48	1465.00	3995.00	3901.84	8679.57	18032.7
4 R-49	1705.00	4545.00	4269.25	76035.4	172818
5 R-51	1565.00	3725.00	4054.93	108852	163447
6 R-55	1625.00	4105.00	4146.78	1745.72	589.796
7 R-58	1800.00	4580.00	4414.69	27326.9	203143

INDEX OF CORRELATION 8.1326514259E-01

EQUATION ERROR(R(I)) = 137.45

STANDARD DEVIATION (YA(I)) = 236

CONC 698 SC VS S28

COEFFICIENTS A(K)

$S_M = 2818.25 \quad + \quad .585836\ S_m$

I	S_m	S_{28}	S_M	$(S_{28} - S_M)^2$	$(S_{28} - \bar{S})^2$
1 R-11	2300.00	4130.00	4165.68	1272.80	47861.6
2 R-12	2260.00	4240.00	4142.24	9556.45	11826.6
3 R-15	2635.00	4260.00	4361.93	10390.0	7876.56
4 R-16	3255.00	4765.00	4725.15	1588.07	173264

INDEX OF CORRELATION 9.514867764E-01

EQUATION ERROR(R(I)) = 53.39

STANDARD DEVIATION (YA(I)) = 173

APPENDIX C

R SA VS S28

COEFFICIENTS A(K)

S_M = 3518.23 + .422869 S_m

I	S_m	S_{28}	S_M	$(S_M - S_{28})^2$	$(S_{28} - \bar{S})^2$
1 R-5	2615.00	4620.00	4624.03	16.2322	39511.7
2 R-7	3285.00	4710.00	4907.35	38947.4	83391.3
3 R-8	2685.00	4625.00	4653.63	819.662	41524.5
4 R-9	2845.00	4720.00	4721.29	1.66087	89266.8
5 R-11	2190.00	4130.00	4444.31	98790.6	84811.7
6 R-12	2355.00	4240.00	4514.08	75121.5	32842.3
7 R-13	2275.00	6105.00	4480.25	2.639801E+06	2.835100E+06
8 R-15	2695.00	4260.00	4657.86	158291	25993.3
9 R-16	352[illegible].00	4765.00	5008.84	59457.7	118182
10 R-17	2190.00	4390.00	4444.31	2949.54	974.969
11 R-18	2200.00	4550.00	4448.54	10294.5	16583.1
12 R-19	1940.00	5260.00	4338.59	84 992	703544
13 R-20	1950.00	4240.00	4342.82	10572.2	32842.3
14 R-21	2025.00	4420.00	4374.54	2066.95	1.49938
15 R-22	2340.00	4900.00	4507.74	153868	229226
16 R-23	1430.00	4215.00	4122.93	8477.00	42528.5
17 R-24	1915.00	4080.00	4328.02	61514.3	116434
18 R-25	1585.00	3985.00	4188.47	41401.7	190292
19 R-26	2215.00	4515.00	4454.88	3614.25	8793.85
20 R-27	1160.00	3745.00	4008.75	69566.6	457280
21 R-28	1590.00	3775.00	4190.59	172714	417606
22 R-29	1355.00	3465.00	4091.21	392144	914365
23 R-30	1965.00	4470.00	4349.16	14601.3	2379.05
24 R-31	2265.00	4890.00	4476.02	171375	219750
25 R-32	1740.00	4200.00	4254.02	2918.02	48940.3
26 R-33	1485.00	5035.00	4146.19	789988	376720
27 R-34	2110.00	4695.00	4410.48	80951.5	74953.0
28 R-35	1980.00	4775.00	4355.51	175974	125157
29 R-36	2110.00	4585.00	4410.48	30457.2	26822.4
30 R-37	1050.00	3785.00	3962.24	31413.7	404782
31 R-38	2575.00	5270.00	4607.11	439418	720420
32 R-39	1575.00	4585.00	4184.25	160604	26822.4
33 R-40	2555.00	4870.00	4598.66	73627	201399
34 R-41	2410.00	4605.00	4537.34	4577.77	33773.4
35 R-42	1970.00	4070.00	4351.28	79117.6	123359
36 R-43	1525.00	4680.00	4163.10	267184	66964.8
37 R-44	2510.00	4695.00	4579.63	13310.8	74953.0
38 R-45	2325.00	4530.00	4501.40	818.134	11832.1
39 R-46	2180.00	3680.00	4440.08	577723	549414
40 R-47	2250.00	4275.00	4469.68	37901.0	21381.6
41 R-48	2215.00	3995.00	4454.88	211491	181667
42 R-49	2005.00	3995.00	4366.08	137700	181667
43 R-50	2565.00	4545.00	4602.89	3350.73	15320.4
44 R-51	2350.00	3725.00	4511.97	619320	484729
45 R-55	2260.00	4105.00	4473.91	136095	99997.9
46 R-56	2710.00	4860.00	4664.20	38337.1	192524
47 R-59	1970.00	4070.00	4351.28	79117.6	123359
48 R-60	1830.00	4160.00	4292.08	17444.3	68238.2
49 R-61	1785.00	3775.00	4273.05	248052	417606

INDEX OF CORRELATION 4.2629871504E-01

EQUATION ERROR(R(I)) = 307.93 STANDARD DEVIATION (YA(I)) = 340

APPENDIX C

R SB VS S28

COEFFICIENTS A(K)

$S_M = 3120.26 + .679384\ S_m$

I	S_m	S_{28}	S_M	$(S_M - S_{28})^2$	$(S_{28} - \overline{S})^2$
R-1	2240.00	4640.00	4642.09	4.34914	12656.3
R-2	2750.00	4835.00	4988.57	23584.2	94556.2
R-3	3415.00	5525.00	5440.36	7163.57	995006
R-4	3130.00	5095.00	5246.74	23024.3	322056
R-5	2780.00	5125.00	5008.95	13466.9	357006
R-6	2950.00	5380.00	5124.45	65306.6	726756
7 R-8	2780.00	4890.00	5008.95	14149.8	131406
8 R-9	3075.00	4720.00	5209.37	239484	37056.2
9 R-10	2660.00	4620.00	4927.43	94511.3	8556.25
10 R-11	2085.00	4130.00	4536.78	165471	158006
11 R-12	2130.00	4240.00	4567.35	107160	82656.3
12 R-13	3175.00	6105.00	5277.31	685071	2.488506E+06
13 R-14	2650.00	5960.00	4920.63	1.080284E+06	2.052056E+06
14 R-15	2450.00	4260.00	4784.76	275369	71556.2
15 R-16	2880.00	4765.00	5076.89	97276.3	56406.3
16 R-17	1700.00	4390.00	4275.22	13174.9	18906.3
17 R-18	2030.00	4550.00	4499.41	2558.87	506.250
18 R-19	2300.00	5260.00	4682.85	333104	536556
19 R-20	1690.00	4240.00	4268.42	807.926	82656.3
20 R-21	1790.00	4420.00	4336.36	6995.24	11556.2
21 R-22	2000.00	4900.00	4479.03	177213	138756
22 R-23	1675.00	4215.00	4258.23	1869.12	97656.3
23 R-24	1440.00	4080.00	4098.58	345.140	200256
24 R-25	1430.00	3985.00	4091.78	11402.8	294306
25 R-26	1070.00	4515.00	3847.21	445949	156.250
26 R-27	1070.00	3745.00	3847.21	10446.0	612306
27 R-28	1510.00	3775.00	4146.13	137741	566256
28 R-29	1205.00	3465.00	3938.92	224603	1.128906E+06
29 R-30	1850.00	4470.00	4377.13	8625.66	3306.25
30 R-31	1740.00	4890.00	4302.39	345282	131406
31 R-32	1520.00	4200.00	4152.93	2215.71	107256
32 R-33	1990.00	5035.00	4472.24	316700	257556
33 R-34	1660.00	4695.00	4248.04	199771	28056.2
34 R-35	1630.00	4775.00	4227.66	299580	61256.2
35 R-36	1580.00	4585.00	4193.69	153122	3306.25
36 R-37	1260.00	3785.00	3976.29	36591.4	551306
37 R-38	2330.00	5270.00	4703.23	321228	551306
38 R-39	2070.00	4585.00	4526.59	3411.72	3306.25
39 R-40	2175.00	4870.00	4597.93	74024.5	117306
40 R-41	2200.00	4605.00	4614.91	98.2097	6006.25
41 R-42	1510.00	4070.00	4146.13	5796.51	209306
42 R-43	1890.00	4680.00	4404.30	76010.0	23256.2

APPENDIX C

R SB VS S28

COEFFICIENTS A(K)

$S_M = 3120.26 + .679384\ S_m$

I	S_m	S_{28}	S_M	$(S_M - S_{28})^2$	$(S_{28} - \bar{S})^2$
43-R 44	2140.00	4695.00	4574.15	14605.4	28056.2
44 R-45	2125.00	4530.00	4563.96	1153.03	6.25000
45 R-46	1600.00	3680.00	4207.28	278024	718256
46 R-47	1930.00	4275.00	4431.48	24484.8	63756.2
47 R-48	1880.00	3995.00	4397.51	162012	283556
48 R-49	2060.00	4545.00	4519.80	635.228	306.250
49 R-51	2140.00	3725.00	4574.15	721051	644006
50 R-52	2940.00	4700.00	5117.65	174435	29756.2
51 R-54	2110.00	3800.00	4553.77	568162	529256
52 R-55	2120.00	4105.00	4560.56	207534	178506
53 R-56	2430.00	4860.00	4771.17	7891.04	110556
54 R-57	2050.00	4055.00	4513.00	209766	223256
55 R-60	1520.00	4070.00	4152.93	6877.17	209306
56 R-60	1485.00	4160.00	4129.15	951.708	135056

INDEX OF CORRELATION 6.9707581360E-01

EQUATION ERROR(R(I)) = 275.12

STANDARD DEVIATION (YA(I)) = 383

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APPENDIX C

R SC VS S28 48 Hr.

COEFFICIENTS A(K)

$S_M = 3253.44 + .582455\ S_m$

I		S_m	S_{28}	S_M	$(S_{28} - S_M)^2$	$(S_{28} - \bar{S})^2$
1	R-2	3450.00	4835.00	5262.91	183106	144665
2	R-3	4025.00	5525.00	5597. 2	5302.92	1.145647F+06
3	R-10	2120.00	4620.00	4488.24	17359.7	27340.2
4	R-11	2300.00	4130.00	4593.09	214449	105398
5	R-12	2260.00	4240.00	4569.79	108760	46075.1
6	R-13	2240.00	6105.00	4558.14	2.392780E+06	2.723651E+06
7	R-15	2635.00	4260.00	4788.21	279004	37889.1
8	R-16	3255.00	4765.00	5149.33	147710	96316.4
9	R-17	2085.00	4390.00	4467.86	6061.87	4179.77
10	R-18	2270.00	4550.00	4575.61	655.985	9091.40
11	R-19	1975.00	5260.00	4403.79	733099	648587
12	R-20	1890.00	4240.00	4354.28	13059.7	46075.1
13	R-21	1960.00	4420.00	4395.05	622.448	1200.70
14	R-22	2290.00	4900.00	4587.26	97805.5	198336
15	R-24	1960.00	4080.00	4395.05	99257.2	140363
16	R-25	1585.00	3985.00	4176.63	36722.2	220572
17	R-26	2050.00	4515.00	4447.47	4560.02	3641.98
18	R-27	1150.00	3745.00	3923.26	31777.5	503605
19	R-28	1740.00	3775.00	4266.91	241976	461926
20	R-29	1010.00	3465.00	3841.72	141917	979409
21	R-30	2140.00	4470.00	4499.89	893.593	235.587
22	R-31	2430.00	4890.00	4668.81	48927.2	189529
23	R-32	1790.00	4200.00	4296.03	9222.47	64847.2
24	R-34	2020.00	4695.00	4430.00	70225.8	57767.6
25	R-35	1980.00	4775.00	4406.70	135645	102623
26	R-36	2140.00	4585.00	4499.89	7243.20	16990.8
27	R-38	2690.00	5270.00	4820.24	202281	664794
28	R-40	2595.00	4870.00	4764.91	11043.9	172515
29	R-41	2385.00	4605.00	4642.59	1413.35	22604.8
30	R-42	1970.00	4070.00	4400.88	109479	147957
31	R-43	1760.00	4680.00	4278.56	161154	50782.1
32	R-44	2540.00	4695.00	4732.88	1434.52	57767.6
33	R-45	2195.00	4530.00	4531.93	3.71746	5677.45
34	R-46	1295.00	3680.00	4007.72	107399	600084
35	R-47	1870.00	4275.00	4342.63	4573.83	32274.5
36	R-48-O	1560.00	3995.00	4162.07	27912.1	211279
37	R-48-W	1465.00	3995.00	4106.74	12484.9	211279
38	R-49	1705.00	4545.00	4246.53	89087.3	8162.91
39	R-51	1565.00	3725.00	4164.98	193584	532391
40	R-55	1625.00	4105.00	4199.93	9011.44	122256
41	R-56	2445.00	4860.00	4677.54	33291.0	164308
42	R-59	1180.00	4070.00	3940.74	16709.2	147957
43	R-60	1085.00	4160.00	3885.40	75403.6	86819.3

INDEX OF CORRELATION 6.7636490275E-01

EQUATION ERROR(R(I)) = 265.99

STANDARD DEVIATION (YA(I)) = 361

August 1974

APPENDIX C

R SC VS S28 24 Hr.

COEFFICIENTS A(K)

S_M = 2959.50 + .896981 S_m

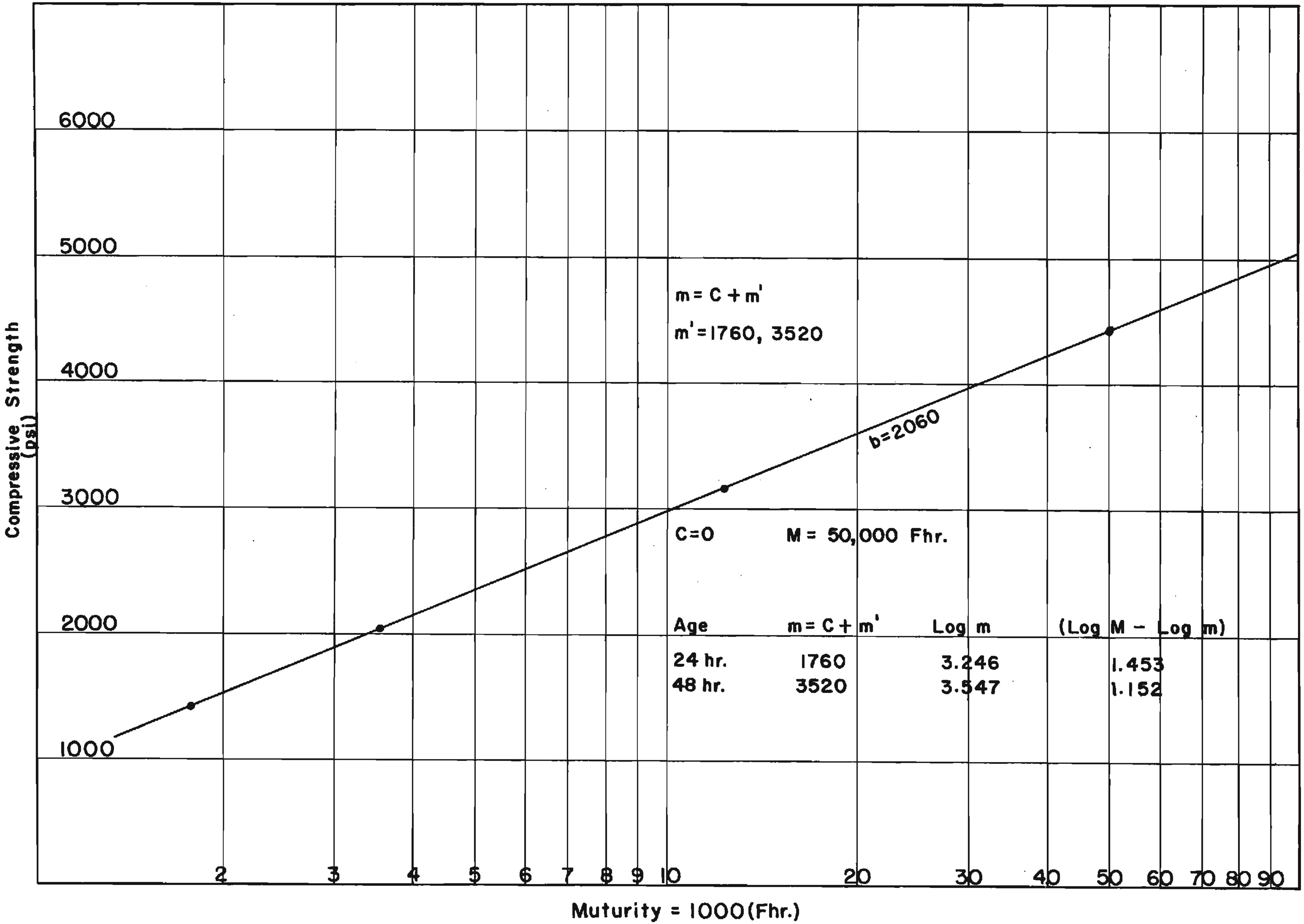
I	S_m	S_{28}	S_M	$(S_{28} - S_M)^2$	$(S_{28} - \bar{S})^2$
1 R-14	2200.00	5960.00	4932.85	1.055032E+06	2.414139E+06
2 R-19	1975.00	5260.00	4731.03	279807	728889
3 R-23	1480.00	4215.00	4287.03	5187.79	36576.6
4 R-33	1665.00	5035.00	4452.97	338762	395327
5 R-37	1200.00	3785.00	4035.87	62936.6	385952
6 R-39	1690.00	4585.00	4475.39	12013.9	31951.6
7	2730.00	4280.00	5408.25	1.272953E+06	15939.1
8	1180.00	4070.00	4017.93	2711.06	113064
9	1085.00	4160.00	3932.72	51656.7	60639.1
10 R-60	980.00	3345.00	3838.54	243578	1.126252E+06
11 R-59	1370.00	3600.00	4188.36	346166	650039
12 R-58	1800.00	4580.00	4574.06	52.2821	30189.1

INDEX OF CORRELATION 6.2214576363E-01

EQUATION ERROR(R(I)) = 391.09

STANDARD DEVIATION (YA(I)) = 499

Autogenous Cure — Conc. 654 — Class D — Proj. I25-2(88)



August 1974

APPENDIX D

CALCULATIONS FOR DERIVATION OF CONSTANTS FOR CORRELATION WITH VARIOUS TYPES OF ACCELERATED CURING

Autogenous Cure

Concrete 654 - Class D - Project I 25-2(88) $S_M = S_{mt}$ 2060 (Log M - Log m)

Sample Number	Age at Test 48 hr.	24 hr.	S_M	S_{28}	b(Log M - Log m)
R 17	2190		4560	4390	
R 18	2200		4570	4615	24 hrs. = 2990
R 19		1940	4930	5260	
R 20	1950		4320	4240	48 hrs. = 2370
R 21	2025		4395	4420	
R 22	2290		4660	4900	
R 23		1430	4220	4215	
R 24	1915		4285	4080	
R 25	1585		3955	3885	
R 26	2215		4585	4515	
R 27		1160	4150	3745	
R 28	1590		3960	3775	
R 29	1355		3725	3465	
R 30	1965		4335	4470	
R 31	2265		4635	4890	
R 32	1740		4110	4200	
R 33		1485	4475	5035	
R 34	2110		4480	4695	
R 35	1980		4350	4775	
R 36	2110		4480	4585	
R 37		1050	4040	3785	
R 38	2575		4945	5270	
R 39		1515	4505	4585	
R 40	2555		4925	4870	
R 41	2410		4780	4605	
R 42	1970		4340	4075	
R 43		1525	4515	4680	
R 44	2510		4880	4695	

$\bar{X}_{48} = 2070$ $\bar{X}_{24} = 1445$ $\bar{S} = 4454$

$D_s = 323$ psi

$I_c = .86$

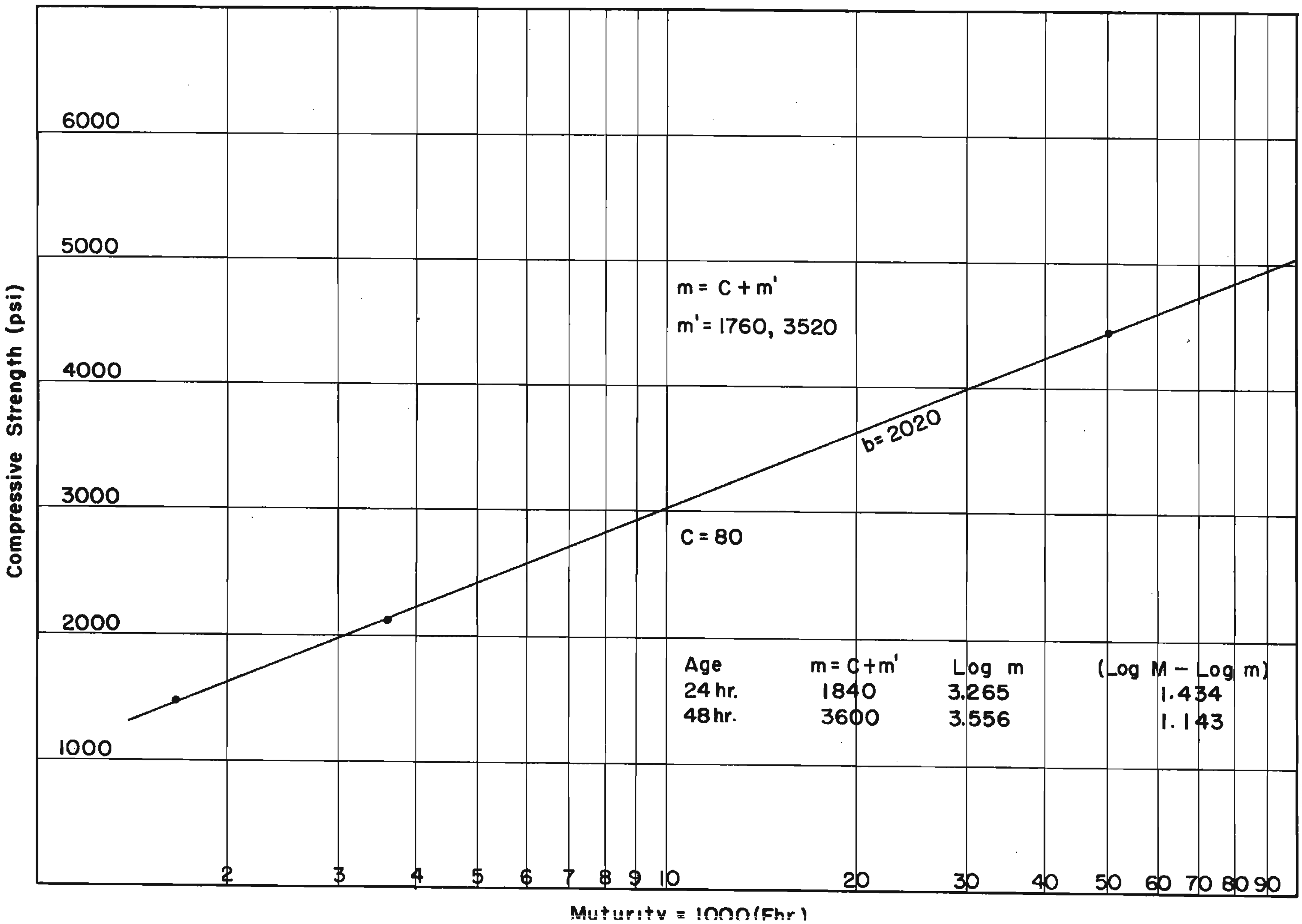
$D_p = 80$ psi

$$D_e = \sqrt{\frac{\Sigma (S_{28} - S_m)^2}{2n}}$$

$$D_e = \sqrt{\frac{1663075}{56}} = 165 \text{ psi}$$

August 1974

Constant Temp.—Conc. 654—Class D Proj I25-2(88)



APPENDIX D

Constant Temperature

$S_M = S_m + 2020\ (\text{Log } M - \text{Log } m)$ Concrete 654 - Class D - Project I 25-2(88)

Sample Number	Age at Test 48 hrs	24 hrs	28 days	S_M	
R-17	2085		4390	4395	b(Log M - Log m)
R-18	2270		4615	4580	
R-19		1975	5260	4870	24 hrs. = 2895
R-20	1890		4240	4200	48 hrs. = 2310
R-21	1960		4420	4270	
R-22	2290		4900	4600	
R-23		1480	4215	4375	
R-24	1960		4080	4270	
R-25	1585		3885	3895	
R-26	2050		4515	4360	
R-27		1150	3745	4045	
R-28	1740		3775	4050	
R-29		1010	3465	3905	
R-30	2140		4470	4450	
R-31	2425		4890	4735	
R-32	1790		4200	4100	
R-33		1665	5035	4560	
R-34	2020		4695	4330	
R-35	1980		4775	4290	
R-36	2140		4585	4450	
R-37		1200	3785	4095	
R-38	2690		5270	5000	
R-39		1690	4585	4585	
R-40	2595		4870	4905	
R-41	2385		4605	4695	
R-42	1970		4075	4280	
R-43		1760	4680	4655	
R-44	2540		4695	4850	
28	42505	11930	124720	$1{,}604{,}225 = \Sigma(S_{28} - S_M)^2$	

$(\div 2n) \div 56 = 28647$

$D_e = 169$ psi

$\overline{X}_{48} = 2125$ $\quad \overline{X}_{24} = 1490$ $\quad \overline{S} = 4454$

$I_c = .85$

$D_p = 88$ psi

$\Sigma(S_{28} - \overline{S})^2 = 5{,}741{,}788$

$\div 56 = 104{,}396$

$D_s = 323$ psi

$V = 7.3\%$

August 1974

APPENDIX D

Autogenous Cure
R 5 to R 16 & R 45 to R 64

Sample Number	Age at Test 24 hr	48 hr	72 hr	96 hr	120 hr		S_M	S_{28}
R 5		2615					4990	5125
R 7			3285				5295	4710
R 8		2685					5060	4890
R 11		2190					4565	4130
R 12		2355					4730	4240
R 13	2275						5270	6105
R 15		2695					5070	4260
R 16		3525					5900	4765
R 45		2325					4700	4530
R 46-1 & 2	1240(1)			2180(2)		4235(1)	3935(2)	3680
R 47		2250					4625	4275
R 48		2215					4590	3995
R 49		2565					4940	4545
R 50-1 & 2			2450(1)	2600(2)		4460(1)	4355(2)	4600
R 51		2350					4725	3725
R 52					3360		4915	4700
R 53				3300			5055	4750
R 54				2675			4430	3800
R 55		2260					4635	4105
R 56		2710					5085	4860
R 57				2435			4190	4055
R 58		2295					4670	4580
R 59-1 & 2	1450(1)				2450(2)	4085(2)	4445(1)	3600
R 60		1310					3685	3345
R 62		1430					3805	3950
R 63		1770					4145	3870
R 64		1825					4200	3565

$$S_M = S_m + 2060(\text{Log } M - \text{Log } m)$$

24 hr = 2995
48 hr = 2375
72 hr = 2010
96 hr = 1755
120 hr = 1555

$$I_c = \sqrt{\frac{409^2 - 371^2}{409^2}}$$

$$I_c = .42$$

$$D_p = \sqrt{371^2 - 144^2}$$

$$D_p = 342 \text{ psi}$$

$$\Sigma(S_M - S_{28})^2 \doteq 7{,}429{,}800$$

$$\div 54 = 137{,}589$$

$$D_e = 371 \text{ psi}$$

$$\bar{S} = \frac{116755}{27} = 4324 \text{ psi}$$

$$\Sigma(S_{28} - \bar{S})^2 = 9053.087$$

$$\div 54$$

$$D_s = 409 \text{ psi}$$

August 1974

APPENDIX D

Autogenous Cure
(RL 2 to RL 28)

mple mber	Age at Test 24 hr	48 hr	72 hr	96 hr	120 hr	168 hr	S_m	S_{28}
-2-1						2905	4160	4790
-2-2						4520	5775	6310
-2-3						5140	6395	6900
-3		1990					4365	4615
-5		1705					4080	3940
-6		1970					4345	4160
-7		1680					4055	3875
-8-1		2340					4715	4970
-8-2		1855					4230	4550
-9-1		1425					3800	3395
-9-2		2110					4485	4245
-10-1		2070					4445	4315
-11-1		2095					4470	4385
-12-1		1940					4315	4605
-12-2		1835					4210	4175
-13		2900					5275	5960
-14		1505					3880	3510
-15		1770					4145	3270
-16-1		1795					4170	3590
-16-2			2795				4805	5075
-17		1625					4000	4010
-19		2290					4665	5020
-20				2620			4375	3945
-21		1910					4285	3915
-22		2190					4565	4020
-23					2900		4455	3930
-24-1		3465					5840	5065
-24-2			3610				5620	5065
-25		2145					4520	4260
-26		3010					5385	5010
-28		2460					4835	5005

$S_M = S_m + 2060(\text{Log } M - \text{Log } m)$

24 hrs = 2995
48 hrs = 2375
72 hrs = 2010
96 hrs = 1755
20 hrs = 1555

$D_p = \sqrt{299^2 - 744^2}$

$D_p = 262$ psi

$D_s = 573$ psi

$I_c = \sqrt{\dfrac{573^2 - 299^2}{573^2}}$

$I_c = .85$

$\Sigma(S_M - S_{28})^2 = 5{,}532{,}775$

$\div\ 62 = 89238$

$D_e = 299$ psi

$\bar{S} = \dfrac{139880}{31} = 4512$ psi

$\Sigma(S_{28} - \bar{S})^2 = 20{,}332{,}694$

$\div\ 62 = 327{,}947$

August 1974

APPENDIX D

Constant Temperature
(R-2 to R-16 & R-45 to R-65)

Sample Number	Age at Test 24 hrs	48 hrs	72 hrs	96 hrs	120 hrs	12 days	S_M	S_{28}
R-2					3450		4970	4835
R-3					4025		5545	5525
R-10	2120						5015	4620
R-11		2300					4610	4130
R-12		2260					4570	4240
R-13	2240						5135	6105
R-14	2200						5095	5960
R-15		2635					4945	4260
R-16		3255					5565	4765
R-45		2195					4505	4530
R-46	1295						4190	3680
R-47	1840						4735	4275
R-48	1465						4360	3995
R-49	1705						4600	4545
R-50 1 & 2			2445(1)	2520(2)			4405(1) 4230(2)	4600
R-51	1565						4460	3725
R-52						4020	5540	4700
R-53 1 & 2				3430(1)		3635(2)	5140(1) 5155(2)	4750
R-54				2705			4415	3800
R-55	1625						4520	4105
R-56		2445					4755	4860
R-57				2440			4150	4055
R-58	1800						4695	4580
R-59	1370						4265	3600
R-60	980						3875	3345
R-62	1230						4125	3950
R-63	1340						4235	3870
R-64	1255						4150	3565
R-65	1350						4245	4185

$S_M = S_m + 2020(\text{Log } M - \text{Log } m)$

24 hrs = 2895
48 hrs = 2310
72 hrs = 1960
96 hrs = 1710
120 hrs = 1520

$I_c = \sqrt{\dfrac{465^2 - 344^2}{465^2}}$

$I_c = .67$

$D_p = \sqrt{344^2 - 144^2}$

$D_p = 312$ psi

$\Sigma(S_M - S_{28})^2 = 7{,}117{,}625$

$\div 60 = 118{,}627$

$D_e = 344$ psi

$\bar{S} = \dfrac{127451}{30} = 4238$ psi

$\Sigma(S_{28} - \bar{S})^2 = 12{,}946{,}121$

$\div 60 = 215{,}769$

$D_s = 465$ psi

August 1974

APPENDIX D

Constant Temperature
(RL-3 to RL-28)

Sample Number	Age at Test 24 hrs	48 hrs	72 hrs	S_M	S_{28}
RL-3		2195		4505	4530
RL-4		2575		4885	4590
RL-6		1970		4280	4160
RL-7		1895		4205	3875
RL-8-1	1580			4475	4970
RL-8-2	1305			4200	4550
RL-9-1	870			3765	3395
RL-9-2	1280			4175	4245
RL-10-1	1325			4220	4315
RL-10-2	1450			4345	4595
RL-11-1	1350			4245	4385
RL-12-1	1185			4080	4605
RL-12-2	1185			4080	4175
RL-13	1520			4415	5960
RL-14	875			3770	3510
RL-15	1055			3950	3270
RL-16	1320			4215	3590
RL-17	1050			3945	4010
RL-19	1440			4335	5020
RL-21	1225			4120	3915
RL-22	1730			4625	4020
RL-24	2160			5055	5065
RL-25	1410			4305	4260
RL-26-1	1395			4290	4205
RL-26-2	1720			4615	5010
RL-28	1680			4575	5005
RL-29-1			1305	3265	3270
RL-29-2			1965	3925	3700
RL-29-3			2005	3965	3615

$S_M - S_m + 2020(\text{Log } M - \text{Log } m)$

24 hrs = 2895
48 hrs = 2310
72 hrs = 1960

$$I_c = \sqrt{\frac{440^2 - 316^2}{440^2}}$$

$$I_c = .70$$

$$D_p = \sqrt{316^2 - 144^2}$$

$$D_p = 281 \text{ psi}$$

$$\Sigma (S_M - S_{28})^2 = 5,799,625$$

$$\div 58 = 99994$$

$$D_e = 316 \text{ psi}$$

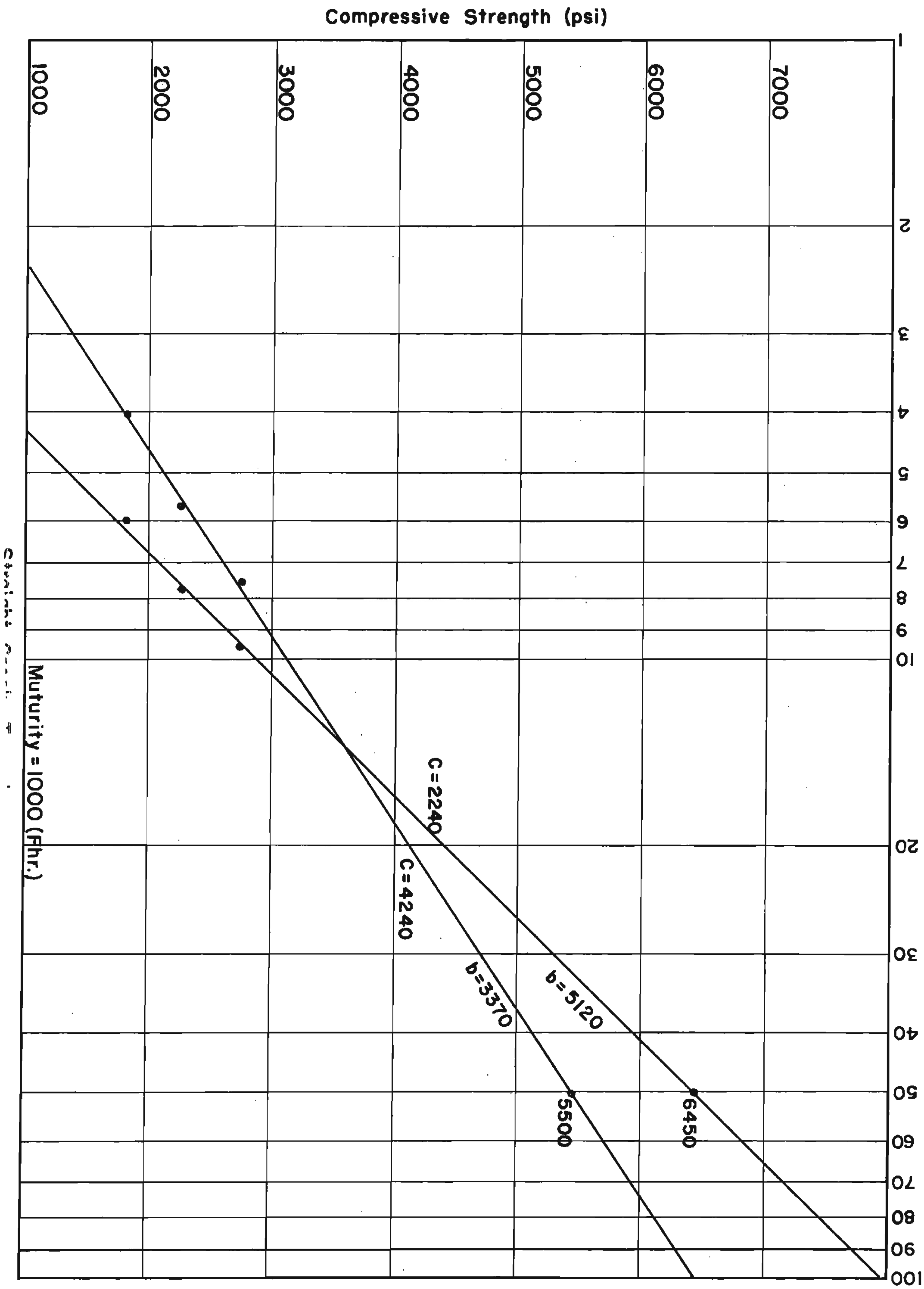
$$\bar{S} = \frac{123815}{29} = 4269$$

$$\Sigma (S_{28} - \bar{S})^2 = 11,216,542$$

$$\div 58 = 193,388$$

$$D_s = 440 \text{ psi}$$

August 1974


Compressive Strength (psi)
1000
2000
3000
4000
5000
6000
7000
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100
Muturity = 1000 (Fhr.)
C = 2240
C = 4240
b = 3370
b = 5120
5500
6450

APPENDIX E

APPENDIX E

MIX AND STRENGTH DATA FROM STRAIGHT CREEK TUNNEL
Project I 70-3(34)

Concrete Proportions

Conc. No.	Class Conc.	Cement lbs/cy	Sand lbs/cy	3/4 Rock lbs/cy	1-1/2 Rock lbs/cy	Water lbs/cy	Water gals/cy	Admix. Quan/cy	W/C
SC-8S	2	639	1270	809	1006	262	31.5	--	.41
SC-26	2	646	1363	1537	--	290	34.9	(1) 80 lbs	.45
SC-13M	1 & 2	658	1143	1754	--	276	33.2	--	.42
SC-10H		(Agr.)	1189	1064	760	269	32.3	(1) 80	.48

(1) Fly Ash

Concrete Properties

Slump Average	Standard Deviation	Air Entrainment	Standard Deviation	Mix Temperature	Standard Deviation
5.21 in	0.73 in.	2.66%	1.02%	54.65°F	1.19°F

Concrete AW 498

Cylinder Number	Age at Test	Strength (psi)	Average
1	24 hr.	1840	1810
2	24 hr.	1730	
3	48 hr.	2300	2260
4	48 hr.	2220	
5	72 hr.	2700	2750
6	72 hr.	2800	
7	28 days	6310	6450
8	28 days	6410	
9	28 days	6600	
10	28 days	6480	

August 1974

APPENDIX E

STRAIGHT CREEK TUNNEL

Constant Temperature Accelerated Cure

$S_M = S_m + 4500(\text{Log } M - \text{Log } m)$; $m = 4240 + m'$; $\text{Log } M = 4.699$

Set No.	Age at Test (hrs.)	S_m	m	Log m	(Log M-Log m)b	S_M	S_{28}
AW 501	36	2050	6955	3.842	3855	5905	5440
AW 501	30	1650	6660	3.823	3940	5590	5555
AW 502	30	1680	6440	3.809	4005	5610	5660
AW 502	30	1605	6440	3.809	4005	5685	5280
AW 503	30	1630	6220	3.794	4070	5700	5715
AW 504	24	1620	6000	3.778	4145	5765	5890
AW 504	24	1580	6000	3.778	4145	5725	5715
AW 505	24	1495	6000	3.778	4145	5640	5700
AW 505	24	1600	6000	3.778	4145	5745	5695
AW 506	30	1675	6220	3.794	4070	5745	5980
AW 506	30	1955	6660	3.823	3940	5935	6125
AW 507	30	1660	6440	3.809	4005	5665	5485
AW 507	30	1870	6440	3.809	4005	5875	6005
AW 508	30	1770	6440	3.809	4005	5775	5730
AW 508	30	1735	6440	3.809	4005	5740	5730
AW 509	24	1540	6000	3.778	4145	5685	6520
AW 509	24	2360	--	--	--	5505	6905
AW 510	36	2520	6735	3.828	3920	6440	6045
AW 510	30	2275	6660	3.823	3940	6215	5905
AW 511	30	2480	6440	3.809	4005	6485	6200
AW 511	36	2675	6810	3.833	3900	6570	6255
AW 512	30	1850	6220	3.794	4070	5920	6175
AW 512	24	1805	6150	3.784	4095	5900	6555
AW 513	24	1255	--	--	4145	5400	5980
AW 513	24	1515	--	--	--	5660	6405
AW 514	24	1590	--	--	--	5735	5845
AW 514	24	1615	--	--	--	5760	6010
AW 515	24	1425	--	--	--	5570	5550
AW 515	24	1270	--	--	--	5415	5355
AW 516	24	1390	--	--	--	5535	5280
AW 520	24	1820	--	--	--	5965	5600
AW 520	24	1895	--	--	--	6040	5420
AW 521	24	1745	--	--	--	5890	5955
AW 521	24	1730	--	--	--	5875	5730
AW 522	24	1680	--	--	--	5825	5345
AW 523	30	2120	6440	3.809	4005	6125	5475
AW 523	25	1935	6075	3.781	4115	6050	5380
AW 524	30	1975	6295	3.799	4050	6025	5620
AW 524	24	1760	5930	3.773	4165	5925	5740
AW 525	24	1830	5780	3.762	4215	6040	5340
AW 526	24	1470	6150	3.789	4095	5565	6015
AW 526	24	1350	--	--	4145	5485	5940
AW 527	24	1470	--	--	4145	5615	5700

August 1974

APPENDIX E

STRAIGHT CREEK TUNNEL

Constant Temperature Accelerated Cure

$S_M = S_m + 4500(\text{Log } M - \text{Log } m)$; $m = 4240 + m'$; $\text{Log } M = 4.699$

Set No.	Age at Test (hrs.)	S_m	m	Log m	(Log M-Log m)b	S_M	S_{28}
AW 527	24	1320	--	--	4145	5465	5660
AW 528	30	1690	--	--	4050	5740	6305
AW 528	24	1450	--	--	4095	5545	6110
AW 529	30	1555	6370	3.804	4030	5585	5640
AW 529	22	1305	--	--	4115	5420	5550
AW 530	24	1285	--	--	4145	5430	5295
AW 530	24	1540	--	--	4165	5705	5880
AW 532	24	1275	--	--	4145	5420	5490
AW 532	24	1575	--	--	4145	5720	5575
AW 533	24	1330	--	--	4145	5475	5465
AW 533	24	1295	--	--	4145	5440	5815
AW 534	24	1190	--	--	4145	5335	5700
AW 535	36	1435	--	--	3900	5335	4475
AW 535	30	1550	--	--	3940	5490	5310
AW 536	30	1590	6515	3.813	3990	5580	5625
AW 536	30	1625	--	--	4030	5655	5765
AW 537	24	1540	--	--	4095	5635	5370
AW 538	24	1350	--	--	4145	5495	5385
AW 538	24	1310	--	--	4145	5455	5055
AW 539	24	1310	--	--	4165	5475	5330
AW 539	24	1335	--	--	4145	5480	5515
AW 540	24	1220	--	--	4145	5365	5605
AW 541	24	1270	--	--	4165	5435	5655
AW 541	24	1285	--	--	4145	5430	5560
AW 542	48	2115	7545	3.877	3700	5815	5560
AW 543	48	2100	7765	3.890	3640	5740	5780
AW 545	24	1465	--	--	4165	5630	5860
AW 545	24	1505	--	--	4215	5720	6085
AW 546	24	1625	--	--	4145	5770	5805
AW 547	24	1725	--	--	4115	5840	5595
AW 547	24	1480	--	--	4145	5625	5540
AW 548	24	1480	--	--	4215	5495	5430
AW 549	30	1480	--	--	4030	5510	5460
AW 549	30	1530	--	--	4070	5600	5570
AW 550	24	1395	--	--	4115	5510	5370
AW 550	24	1360	--	--	4145	5505	5435
AW 551	24	1305	--	--	4145	5450	5480
AW 552	30	1470	6295	3.799	4050	5520	5285
AW 552	24	1255	--	--	4115	5370	5230
AW 553	24	1235	--	--	4145	5380	5165
AW 553	24	1175	--	--	4145	5320	5130
AW 554	24	1365	--	--	4145	5510	5315
AW 554	24	1220	--	--	4145	5365	5145
AW 556	30	1440	--	--	4070	5510	5540
AW 556	72	2675	9670	3.985	3215	5890	5420
AW 557	72	2830	9525	3.979	3240	6070	5610

August 1974

APPENDIX E

STRAIGHT CREEK TUNNEL

Constant Temperature Accelerated Cure

$S_M = S_m + 4500(\text{Log } M - \text{Log } m)$; $m = 4240 + m'$; $\text{Log } M = 4.699$

Set No.	Age at Test (hrs.)	S_m	m	Log m	(Log M-Log m)b	S_M	S_{28}
AW 558	54	2390	8130	3.910	3550	5940	5640
AW 558	54	2390	--	--	3550	5940	5675
AW 559	24	1210	--	--	4145	5355	5095
AW 561	24	1445	--	--	4145	5590	5390
AW 561	24	1475	--	--	4145	5620	6045
AW 562	24	1470	--	--	4145	5615	6285
AW 562	24	1475	--	--	4145	5620	6290
AW 563	24	1370	5854	3.767	4195	5565	6380
AW 563	24	1165	--	--	4215	5380	6050
AW 564	24	1205	5487	3.739	4320	5525	6635
AW 565	24	1455	--	--	4095	5550	--
AW 565	24	1680	--	--	4145	5825	--
AW 566	24	1710	5710	3.757	4240	5950	--
AW 567	54	2470	8425	3.926	3480	5950	--
AW 567	54	2540	8205	3.914	3530	6070	--
AW 568	54	2830	7910	3.898	3605	6435	--
AW 569	24	1530	--	--	4145	5675	5830
AW 569	24	1505	--	--	4145	5650	5860
AW 572	30	1805	--	--	3940	5745	5195
AW 572	30	1785	--	--	3990	5775	5730
AW 573	24	1720	--	--	4115	5835	5830
AW 573	30	1715	--	--	4030	5745	5625
AW 574	24	1625	--	--	4115	5740	5275
AW 578	30	2000	--	--	4030	6030	5375
AW 579	30	2055	--	--	4050	6105	5710
AW 580	36	2545	--	--	3900	6445	5235
AW 581	36	2540	6880	3.838	3875	6415	5570
AW 581	30	2165	6590	3.819	3960	6125	5675
AW 582	30	2380	--	--	4030	6410	6285

636575 ÷ 112

INDEX OF CORRELATION

$I_c = .45$

$$D_e^2 = \frac{(S_M - S_{28})^2}{2n} = 86082$$

$$D_e = 293$$

$\bar{S} = 5684$

$D_s = 267$

$V = 4.7$

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APPENDIX E

SCT SC VS S28 24 Hr.

COEFFICIENTS A(K)

$S_M = 5027.94 + .416870\ S_m$

I	S_m	S_{28}	S_M	$(S_{28} - S_M)^2$	$(S_{28} - \bar{S})^2$
1	2050.00	5440.00	5382.52	195824	64072.3
2	1650.00	5555.00	5715.77	25847.1	19078.5
3	1680.00	5660.00	5728.28	4661.93	1097.27
4	1605.00	5280.00	5697.01	173900	170672
5	1630.00	5715.00	5707.43	57.2314	478.516
6	1620.00	5890.00	5703.27	34869.5	38759.8
7	1580.00	5715.00	5686.59	807.050	478.516
8	1495.00	5700.00	5651.16	2385.60	47.2656
9	1600.00	5695.00	5694.93	5.074600E-03	3.51563
10	1675.00	5980.00	5726.19	64417.5	82297.3
11	1955.00	6125.00	5842.92	79570.5	186516
12	1660.00	5485.00	5719.94	55197.3	43316.0
13	1870.00	6005.00	5807.48	39012.7	97266.0
14	1770.00	5730.00	5765.80	1281.40	1359.77
15	1735.00	5730.00	5751.21	449.703	1359.77
16	1540.00	6520.00	5669.92	722642	683772
17	2360.00	6905.00	6011.75	797896	1.468641E+06
18	2520.00	6045.00	6078.45	1118.84	123816
19	2275.00	5905.00	5976.32	5085.96	44891.0
20	2480.00	6200.00	6061.77	19106.4	256922
21	2675.00	6255.00	6143.06	12529.7	315704
22	1850.00	6175.00	5799.15	141266	232204
23	1805.00	6555.00	5780.39	600025	742829
24	1255.00	5980.00	5551.11	183948	82297.3
25	1515.00	6405.00	5659.49	555778	506766
26	1590.00	5845.00	5690.76	23790.0	23066.0
27	1615.00	6010.00	5701.18	95368.7	100410
28	1425.00	5550.00	5621.98	5180.62	20484.8
29	1270.00	5355.00	5557.36	40950.3	114329
30	1390.00	5280.00	5607.39	107182	170672
31	1820.00	5600.00	5786.64	34834.5	8672.27
32	1895.00	5420.00	5817.91	158329	74597.3
33	1745.00	5955.00	5755.37	39850.2	68578.5
34	1730.00	5730.00	5749.12	365.645	1359.77
35	1680.00	5345.00	5728.28	146902	121191
36	2120.00	5475.00	5911.70	190708	47578.5
37	1935.00	5380.00	5834.58	206643	98047.3
38	1975.00	5620.00	5851.25	53478.9	5347.27
39	1760.00	5740.00	5761.63	467.768	2197.27
40	1830.00	5340.00	5790.81	203229	124697
41	1470.00	6015.00	5640.74	140074	103604
42	1340.00	5940.00	5586.54	124932	60947.3
43	1470.00	5700.00	5640.74	3512.26	47.2656
44	1320.00	5660.00	5578.21	6690.39	1097.27
45	1690.00	6305.00	5732.45	327817	374391
46	1450.00	6110.00	5632.40	228103	173785
47	1555.00	5640.00	5676.17	1308.24	2822.27
48	1305.00	5550.00	5571.95	481.897	20484.8
49	1285.00	5295.00	5563.61	72153.9	158504
50	1540.00	5880.00	5669.92	44135.0	34922.3
51	1275.00	5490.00	5559.45	4822.76	41259.8
52	1575.00	5575.00	5684.51	11991.8	13953.5

APPENDIX E

SCT SC VS S28 24 Hr.

COEFFICIENTS A(K)

$S_M = 5027.94 + .416870\ S_m$

I	S_m	S_{28}	S_M	$(S_{28} - S_M)^2$	$(S_{28} - \bar{S})^2$
53	1330.00	5465.00	5582.37	13776.6	52041.0
54	1295.00	5815.00	5567.78	61116.0	14853.5
55	1190.00	5700.00	5524.01	30971.7	47.2656
56	1435.00	4475.00	5626.15	1.325135E+06	1.483829E+06
57	1550.00	5310.00	5674.09	132558	146785
58	1590.00	5625.00	5690.76	4324.39	4641.02
59	1625.00	5765.00	5705.35	3558.06	5166.02
60	1540.00	5370.00	5669.92	89950.0	104410
61	1350.00	5385.00	5590.71	42317.1	94941.0
62	1310.00	5055.00	5574.04	269399	407204
63	1310.00	5330.00	5574.04	59553.8	131860
64	1335.00	5515.00	5584.46	4824.45	31728.5
65	1220.00	5605.00	5536.52	4689.75	7766.02
66	1270.00	5655.00	5557.36	9533.24	1453.52
67	1285.00	5560.00	5563.61	13.0665	17722.3
68	1465.00	5860.00	5638.65	48995.2	27847.3
69	1505.00	6085.00	5655.33	184620	153566
70	1625.00	5805.00	5705.35	9930.02	12516.0
71	1725.00	5595.00	5747.04	23115.4	9628.52
72	1480.00	5540.00	5644.90	11004.9	23447.3
73	1280.00	5430.00	5561.53	17300.2	69234.8
74	1480.00	5460.00	5644.90	34189.6	54347.3
75	1530.00	5570.00	5665.75	9167.66	15159.8
76	1395.00	5370.00	5609.47	57346.1	104410
77	1360.00	5435.00	5594.88	25561.6	66628.5
78	1305.00	5480.00	5571.95	8455.20	45422.3
79	1470.00	5285.00	5640.74	126548	166566
80	1255.00	5230.00	5551.11	103111	214485
81	1235.00	5165.00	5542.77	142711	278916
82	1175.00	5130.00	5517.76	150357	317110
83	1365.00	5315.00	5596.96	79503.9	142979
84	1220.00	5145.00	5536.52	153287	300441
85	1440.00	5540.00	5628.23	7784.46	23447.3
86	1210.00	5095.00	5532.35	191275	357754
87	1445.00	5390.00	5630.31	57750.8	91884.8
88	1475.00	6045.00	5642.82	161749	123816
89	1470.00	6285.00	5640.74	415077	350316
90	1475.00	6290.00	5642.82	418842	356260
91	1370.00	6380.00	5599.05	609885	471797
92	1165.00	6050.00	5513.59	287735	127360
93	1205.00	6635.00	5530.27	1.220439E+06	887129
94	1530.00	5830.00	5665.75	26978.8	18734.8
95	1505.00	5860.00	5655.33	41891.4	27847.3

APPENDIX E

SCT SC VS S28 24 Hr.

COEFFICIENTS A(K)

$S_M = 5027.94 \quad + \quad .416870\ S_m$

1	S_m	S_{28}	S_M	$(S_{28} - S_M)^2$	$(S_{28} - \bar{S})^2$
96	1805.00	5195.00	5780.39	342678	248129
97	1785.00	5730.00	5772.05	1768.18	1359.77
98	1720.00	5830.00	5744.95	7232.97	18734.8
99	1715.00	5625.00	5742.87	13893.1	4641.02
100	1625.00	5275.00	5705.35	185202	174829
101	2000.00	5375.00	5861.68	236854	101204
102	2055.00	5710.00	5884.60	30486.7	284.766
103	2165.00	5675.00	5930.46	65259.9	328.516
104	2380.00	6285.00	6020.09	70178.8	350316

INDEX OF CORRELATION 3.3776903380E-01

$\bar{S} = 5694$

EQUATION ERROR(R(I)) = 255.90

STANDARD DEVIATION (YA(I)) = 271.88

August 1974