RAPID CURING AND STRENGTH RELATIONSHIPS OF CONCRETE

Final Report

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ABSTRACT

The rapid rate of concrete construction has created a need to have information on the strength of concrete at the earliest possible time. Having to wait 28 days before the design strength can be determined may cause serious problems if inferior concrete had been used in a member or a section which is already in place. The use of an accelerated strength test would give the engineer valuable information for quality control. In this study the ASTM procedure C-684, Making, Accelerated Curing, and Testing of Concrete Compression Test Specimens, procedure A, warm water method, and procedure B, boiling water method, were evaluated using two types of coarse aggregate, locally available chert gravel and Kentucky limestone. Thirty mixes were prepared for both groups. Compressive strength cylinders were tested after being cured by each accelerated curing method and by standard moist curing. The data from each accelerated method was plotted against the normally cured 28-day strength and the best fit curve was determined using a least square linear regression. The equation of this curve for the gravel group is $y = 1.16x + 2519$ for procedure A and $y = 1.05x + 2140$ for procedure B. For the limestone group the equation is $y = 1.7x + 1558$ for procedure A and $y = 1.7x + 1124$ for procedure B. In these equations y is the 28-day strength and x is the accelerated curing strength. By determining the accelerated curing strength the equation can be solved for y, which is the estimated 28-day strength. Also, the predicted 28-day strength could be directly determined from the graphs.

Based on the information obtained in this report and a literature search, it seems that the accelerated curing method can be used reliably to estimate the actual 28-day strength.

IMPLEMENTATION STATEMENT

Accelerated curing methods can be a valuable tool for concrete mix designers in both the construction industry and for the Department. Improved quality control and the security of having early production data are important advantages of accelerated strength testing.

The findings of this study will be reviewed by the Department's Structures and Hydraulics Project Advisory Committee. Based on their favorable recommendation, it is anticipated that the correlations developed in this report will be implemented on large-scale concrete construction projects, where, due to the schedule of the construction, there is an urgent need for early determination of concrete strength. On such a project deficiencies could be checked and modified, eliminating the need to wait 28 days to verify design strength.

METRIC CONVERSION FACTORS*

To Convert from	To	Multiply by
	Length	
foot	meter (m)	0.3048
inch	millimeter (mm)	25.4
yard	meter (m)	0.9144
mile (statute)	kilometer (km)	1.609
	Area	
square foot	square meter (m^2)	0.0929
square inch	square centimeter (cm^2)	6.451
square yard	square meter (m^2)	0.8361
	Volume (Capacity)	
cubic foot	cubic meter (m^3)	0.02832
gallon (U.S. liquid)**	cubic meter (m^3)	0.003785
gallon (Can. liquid)**	cubic meter (m^3)	0.004546
ounce (U.S. liquid)	cubic centimeter (cm^3)	29.57
	Mass	
ounce-mass (avdp)	gram (g)	28.35
pound-mass (avdp)	kilogram (kg)	0.4536
ton (metric)	kilogram (kg)	1000
ton (short, 2000 lbs)	kilogram (kg)	907.2
	Mass per Volume	
pound-mass/cubic foot	kilogram/cubic meter (kg/m^3)	16.02
pound-mass/cubic yard	kilogram/cubic meter (kg/m^3)	0.5933
pound-mass/gallon (U.S.)**	kilogram/cubic meter (kg/m^3)	119.8
pound-mass/gallon (Can.)**	kilogram/cubic meter (kg/m^3)	99.78
	Temperature	
deg Celsius (C)	kelvin (K)	$t_K=(t_C+273.15)$
deg Fahrenheit (F)	kelvin (K)	$t_K=(t_F+459.67)/1.8$
deg Fahrenheit (F)	deg Celsius (C)	$t_C=(t_F-32)/1.8$

*The reference source for information on SI units and more exact conversion factors is "Metric Practice Guide" ASTM E 380.

**One U.S. gallon equals 0.8327 Canadian gallon.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

INTRODUCTION

Developments in the rapid placement of concrete have caused a need for improvement in quality assurance procedures such as knowing the potential strength of concrete at the earliest possible time after the concrete has been placed. High capacity concrete plants, transit mixer trucks, prefabricated forms, slip-form construction, power vibrators, finishing equipment and concrete pumps have enabled the contractors to place and finish large quantities of concrete (as much as 120 to 400 cubic yards per hour). By the time 28-day compressive strength tests are obtained from the initial pours, many additional days of production have been placed. Problems stemming from the initial mix design could remain undetected and might be repeated in successive pours, which could lead to serious consequences. Therefore, the use of reliable accelerated strength test data would give the engineers valuable information to control the quality of concrete and make the desired changes sooner.

ASTM has standardized three methods for predicting the 28-day compressive strength of concrete. These methods are the (a) warm water method, (b) boiling water method, and (c) autogenous method. The 28-day compressive strength can be predicted with accelerated curing cylinders in less than two days by the (a) and (b) methods. This research was initiated to evaluate the warm water and boiling water methods and to establish relationships for estimating the 28-day concrete strength soon after pouring. The autogenous method was not evaluated in this study.

PURPOSE AND SCOPE

The specific aims of this research study were:

1. To determine the feasibility of using accelerated testing for the prediction of concrete strength (28 days and earlier).

2. To evaluate several test methods available.

3. To establish correlation curves for each material evaluated and also each test method evaluated.

The scope of this project was limited to laboratory evaluation of accelerated curing techniques indicated in ASTM procedure C-684, "Making, Accelerated Curing, and Testing of Concrete Compression Test Specimens," procedures A and B. Two types of course aggregates, river gravel and limestone, were used in this study.

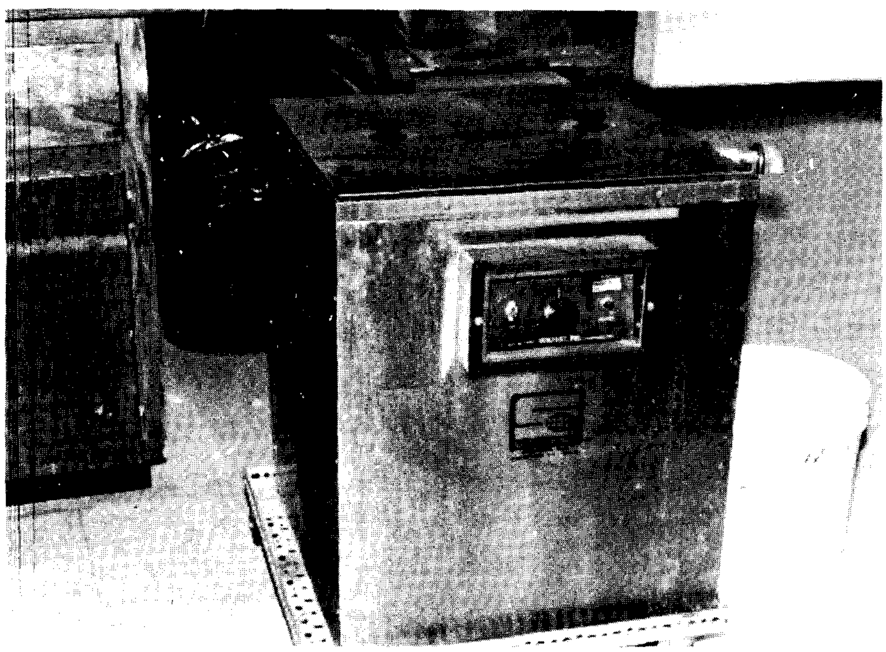
METHODOLOGY

There were two types of coarse aggregate evaluated in this study, chert gravel and limestone. The chert gravel was obtained locally and limestone was imported from Kentucky. The same type of fine aggregate was used for all mixes. Mix designs were set up to exhibit a wide range of strengths in order to establish a strength curve for each material. Variables affecting the strength, such as cement content, water-cement ratio (w/c) and air content, were used to obtain a range of strengths. Also, air entraining agents, water and super water reducers were used to adjust the strength and workability of the mixes. There were thirty mixes for the gravel group and thirty mixes for the limestone group. The cement content varied from 4 to 7.5 bags per cubic yard of concrete (376 lbs to 705 lbs) and water-cement ratios of 0.75 to 0.35, respectively. Mix design for the gravel and limestone mixes along with the slump, air content and unit weight which were determined during the mixing operation are indicated in Table 1 and Table 3 (Appendix A). For each mix four 6-inch by 12-inch cylinders were made to be cured and tested in accordance with ASTM C-684, procedure A. Four more 6-inch by 12-inch cylinders were made for procedure B. Additionally, cylinders were cast and cured conventionally in the moist room and tested at 3 days, 7 days, 14 days, 21 days and 28 days.

The specimens were cast in steel molds for procedure A and were immediately placed in the curing tank for a period of 23-1/2 hours ± 30 minutes. The curing tank water temperature was 95 ± 5°F. The tops of the molds were covered to prevent loss of the mortar to the water bath. Figure 1 shows a laboratory technician placing a concrete cylinder in the curing tank. A long handle was used to avoid injury to the hand by the hot water. For procedure B, the cylinders were cast in steel molds and were cured initially for 23 hours in the laboratory environment (approximate temperature 72°F). The cylinders were then placed in boiling water and remained there for a period of 3-1/2 hours before testing. Figure 2 shows the tank used in this study.

Placement of a Concrete Cylinder in the Curing Tank

FIGURE 1



Curing Tank Used in This Study

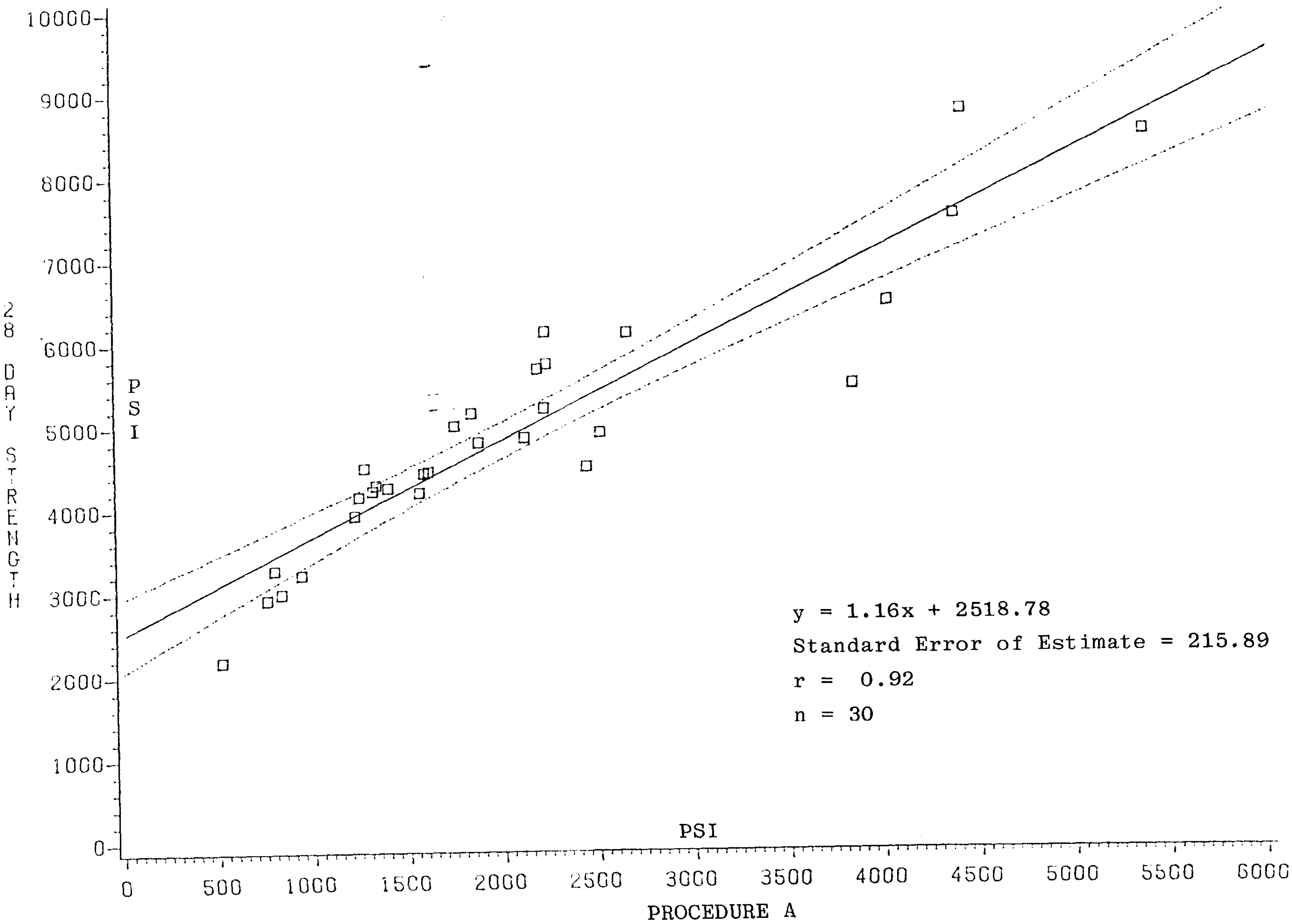
FIGURE 2

DISCUSSION OF RESULTS

The compressive strength of each accelerated method was examined with respect to the corresponding 3, 7, 14, 21 and 28-day strength of moist cured cylinders. A least square linear regression with 95% confidence level was used to determine the best fit. The Department's Statistical Analysis System (SAS computer program) general linear model procedures was used for this purpose. The equation of the best fit curve in the form of $y = a_o x + a$ was established for each age by procedure A and procedure B. In this format the dependent variable y was the compressive strength of normally cured cylinders and independent variable x was the strength of the accelerated curing cylinders; a_o and a_1 were the constants determined for each equation.

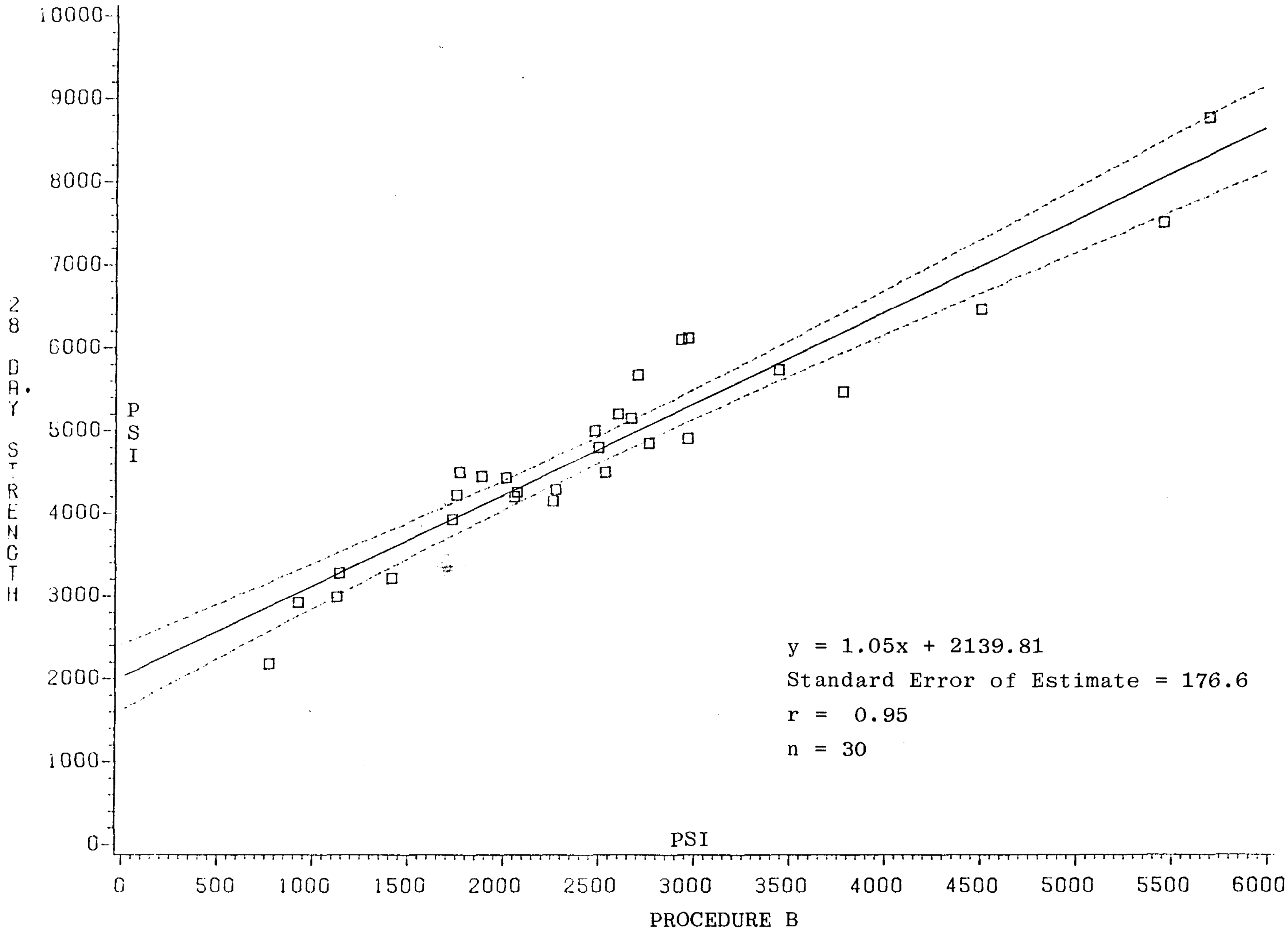
The correlation curve for the 28-day strength data for procedures A and B, gravel group, are depicted in Figures 3 and 4, respectively. The same information is depicted in Figures 5 and 6 for the limestone group. The curves for 3, 7, 14 and 21 are shown in Figures 7 through 14 for the gravel group and in Figures 15 through 20 for the limestone in Appendix A. No 3-day correlation was established for the limestone group. These curves could be used as a check point during concrete construction and initial phases of using accelerated curing methods. For example, if the predicted strength of 14 or 21-day-old concrete matches the actual strength at the same age, more reliability can be placed on the 28-day strength curve.

For each curve a correlation coefficient is calculated. This coefficient indicates the fit of the curve to the plotted points. A correlation coefficient of 1.00 would indicate a perfect fit. Also, for each curve the upper and the lower limit of the 95% confidence levels, standard error of estimate and the number of data points used are presented.



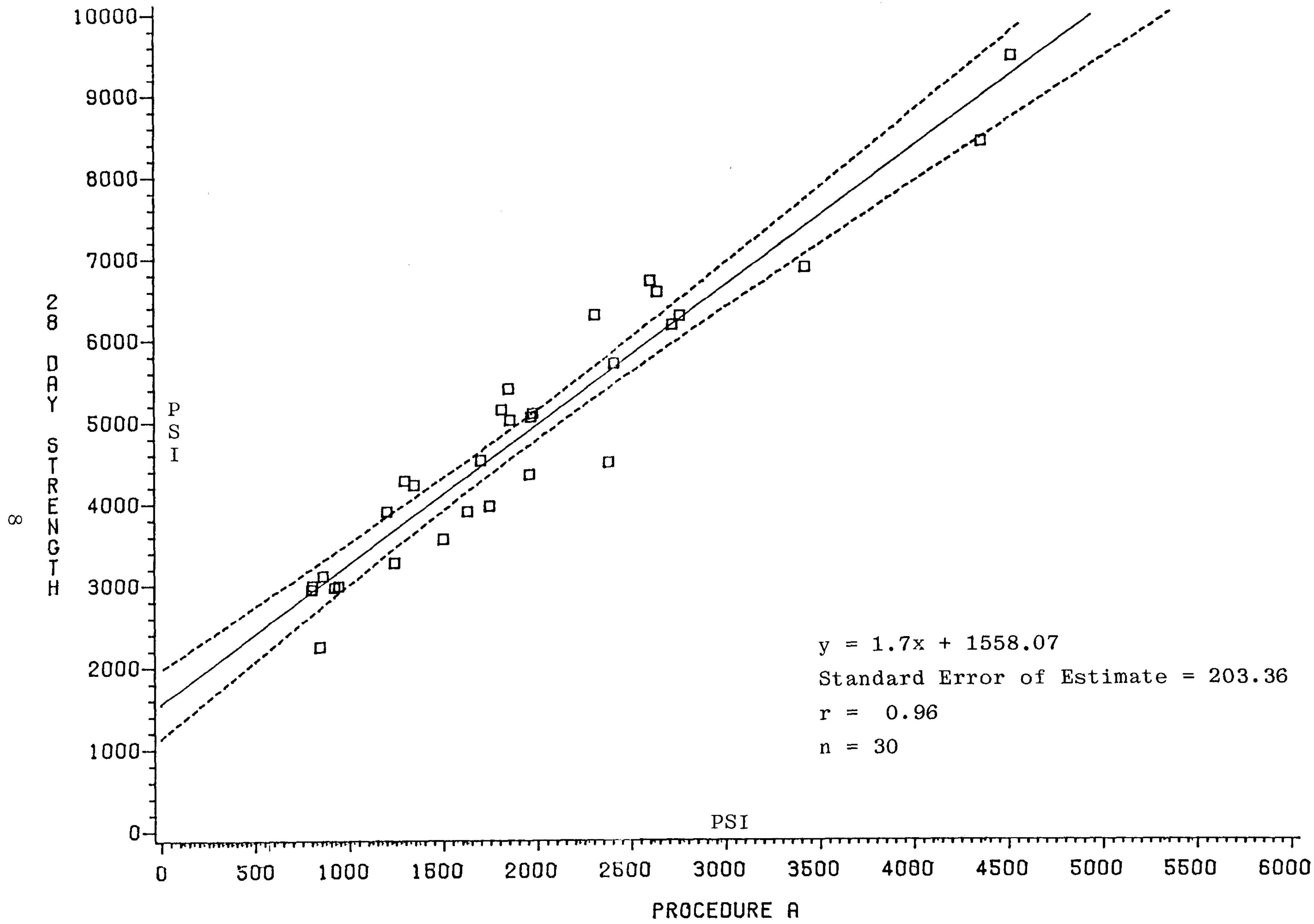
PLOT OF PROCEDURE VERSUS STRENGTH (GRAVEL GROUP)

FIGURE 3



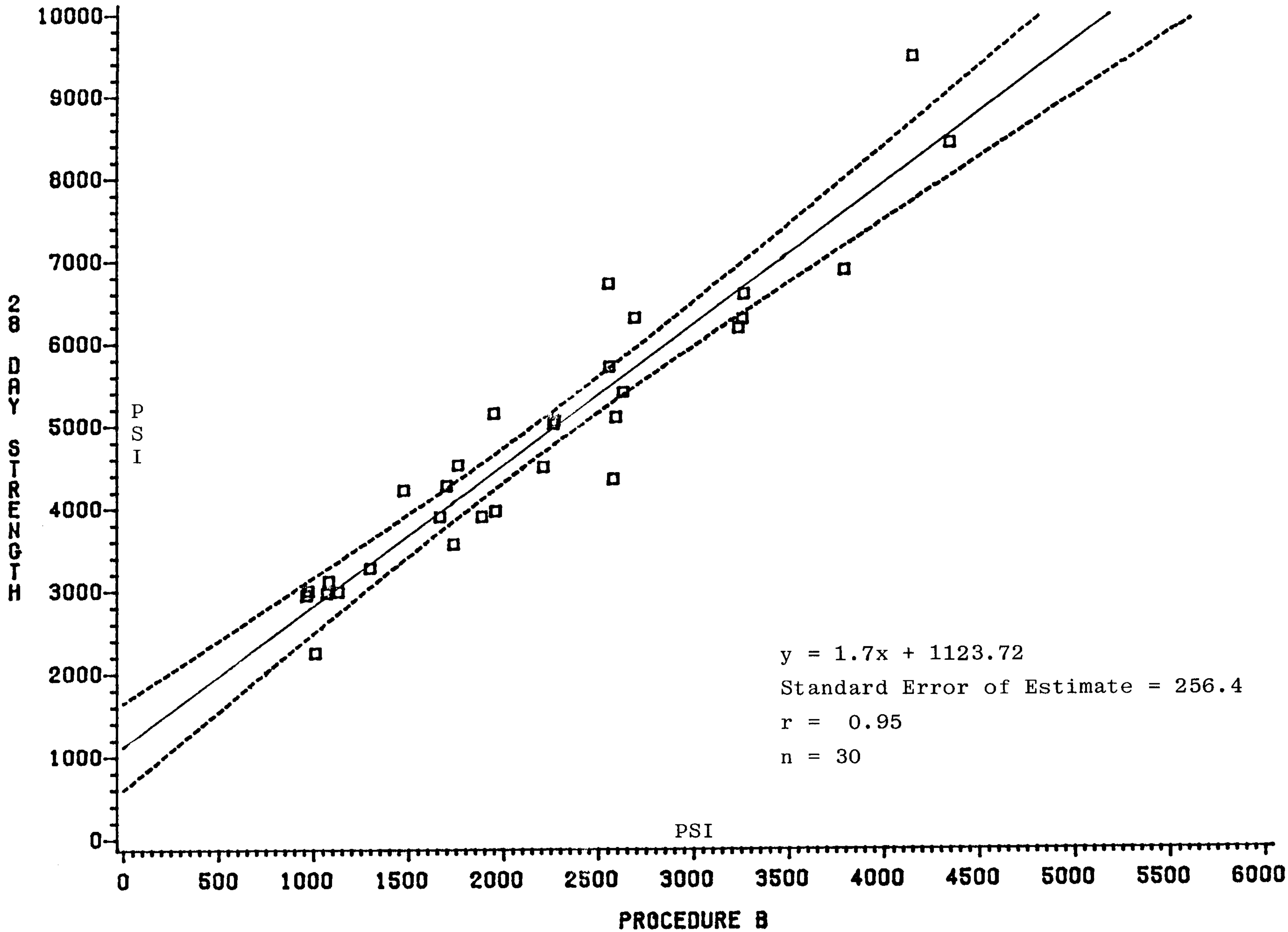
PLOT OF PROCEDURE VERSUS STRENGTH (GRAVEL GROUP)

FIGURE 4



PLOT OF PROCEDURE VERSES STRENGTH (LIMESTONE GROUP)

FIGURE 5



PLOT OF PROCEDURE VERSES STRENGTH (LIMESTONE GROUP)

FIGURE 6

Both procedures evaluated can be used to predict the strength of concrete. There is no conclusion in this study that could indicate one is more accurate over the other one; however, the procedures in using each technique differ and are dependent on the job situation. Procedure A requires immediate placement in the warm water (95 ± 5°F) and curing for 23-1/2 ± 30 minutes prior to testing. This would require that the curing tank be available at the job site. If this cannot be done, procedure B can be used. The specimens are allowed to be air cured initially for 23 hours before the start of curing; this way the cylinders could be brought to the laboratory, cured and tested. In procedure B the samples were placed in boiling water and remained there for a period of 3-1/2 hours. All of the concrete cylinders placed in the curing tank were cast in reusable steel molds.

An attempt was also made to establish a direct correlation between the cement content, the amount of water used and the 28-day strength of concrete using the data from the mixes that were produced in this study and also similar mixes from other research projects. The intent of this correlation was to predict the strength of concrete based on water cement ratio and cement content. For more information see the Addendum, page . Also, ACI Committee 214 report "Use of Accelerated Strength Testing" is included in Appendix B. Guidelines indicated in the ACI-214 report were used to develop the information contained in this report and can be used to develop such relationships with different types of cement (or even different shipments of cement), pozzolans or aggregates.

The equipment used in this study is commercially available and it is relatively inexpensive or it can be built locally. Using simple precautions and appropriate tools, no safety hazard such as burns due to steam or boiling water can occur.

Although it is not expected that the accelerated strength be a replacement for the actual strength, it is felt that the efforts involved in predicting the 28-day strength are well worth the knowledge that is obtained. This knowledge is particularly important to the contractors to check the strength of concrete to avoid penalties or possible rebuilding.

<u>How To Use Accelerated Strength Curves</u>

The following steps are needed to use the graphs avilable in this report to predict the strength of concrete in the construction projects at the desired age.

1. Determine which accelerated method will be used. Procedure A requires the specimen to be immediately submerged in the curing tank after casting. This requires that the curing tank be available at the job site. If this cannot be done, use procedure B, which allows the specimens to be cured initially for 23 hours before the start of curing. This way the cylinder could be brought to the laboratory, cured and tested.

2. Cast the four 6-inch by 12-inch cylinders in watertight steel molds according to the standard procedures and record the type of coarse aggregate used.

3. Cure and test concrete cylinders according to the ASTM C-684 procedure. Record the compressive strength and the procedures used (procedure A or procedure B).

4. Go to the appropriate graph for the type of coarse aggregate used and the selected age. Locate the accelerated strength in the horizontal axis and read the compressive strength using the solid line curve. The value obtained is

the approximate value for the compressive strength at the selected age. A range could also be established using the upper and the lower 95 percent confidence levels. The actual strength should be in this range.

If the value indicated in the predicted strength is lower than the minimum strength specified in the design, adjustments should be made to correct the problem.

The curves indicated in this report are not thoroughly field tested and were developed using laboratory-made mixes. However, in order to validate the data obtained the equation $y = 1.05(x) + 2139.8$, where y is the predicted 28-day compressive strength and x is the accelerated curing strength, was used in checking the compressive strength of the concrete in two different paving projects. The results indicated the actual 28-day strengths were within 1 percent to 16 percent of the predicted values.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions have been reached in this study:

1. The equipment used in determining the accelerated curing method is relatively inexpensive or can be built locally. No safety hazards such as burns due to the steam or boling water should occur using simple precautions.

2. Both procedures evaluated in this study can be used for estimating the strength of concrete at the design age. However, conditions at the job site dictate the type of procedure to be used.

3. Although it is not expected that accelerated strength be a replacement for the actual strength, it is felt that the efforts involved in predicting the 28-day strength should provide valuable information for the quality control of concrete placement.

It is recommended that the Department use the accelerated curing method developed in this study in one of its construction projects to check the actual 28-day strength using the accelerated curing strength. Based on the level of confidence obtained, the contractor could use the curves in this study as a quality control tool or develop his own curve using the concrete used in that construction project.

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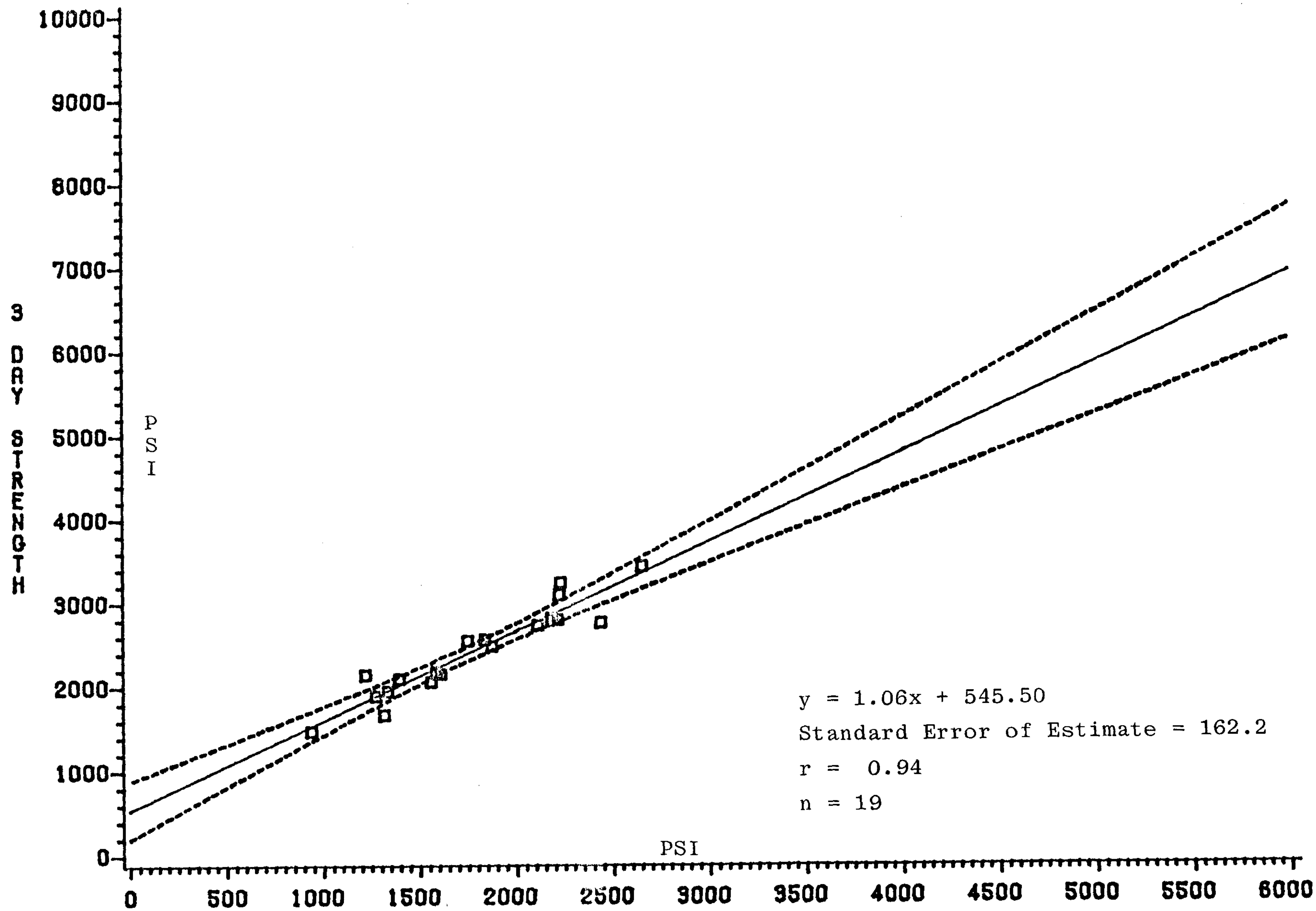
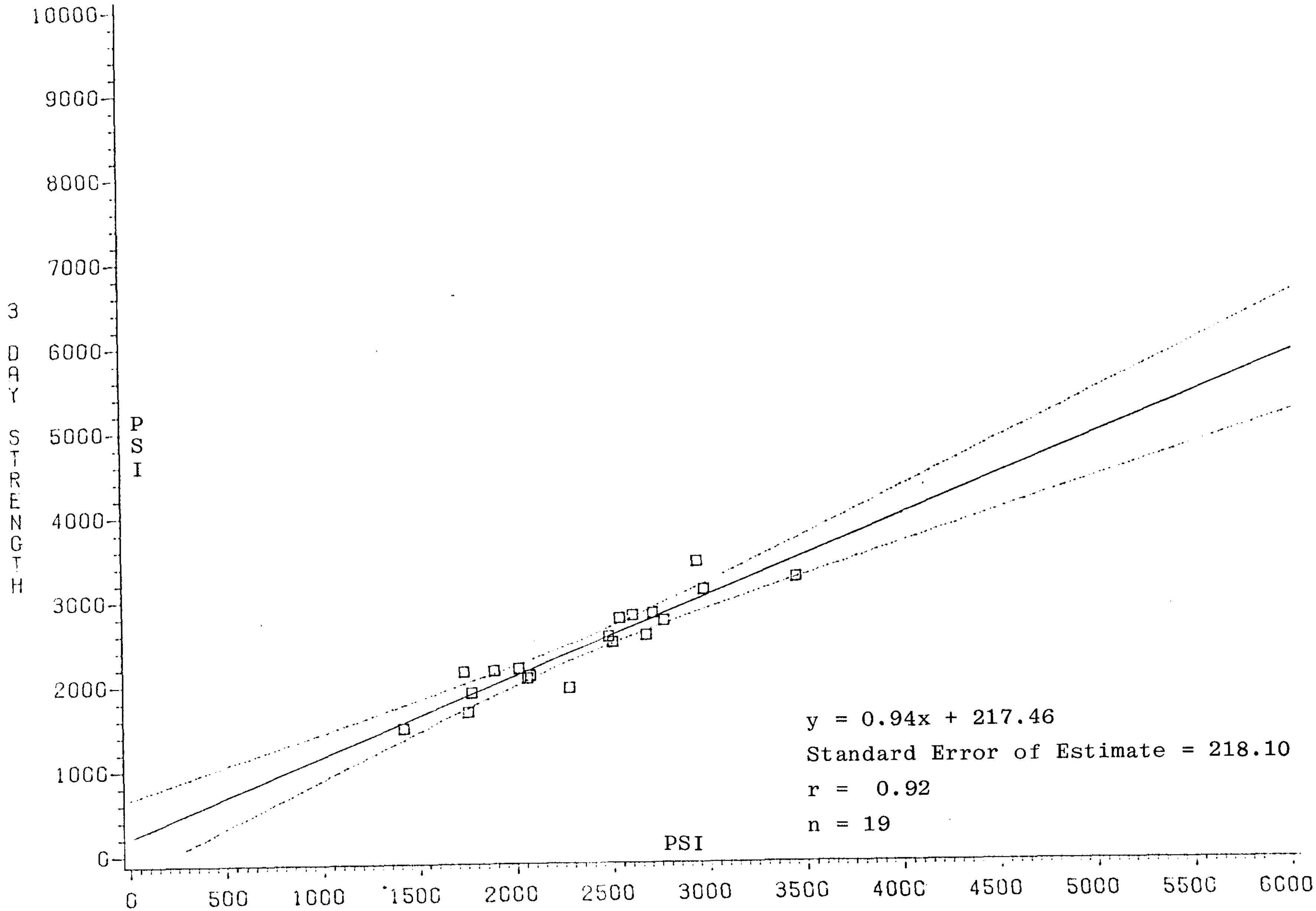
APPENDIX A



PROCEDURE A

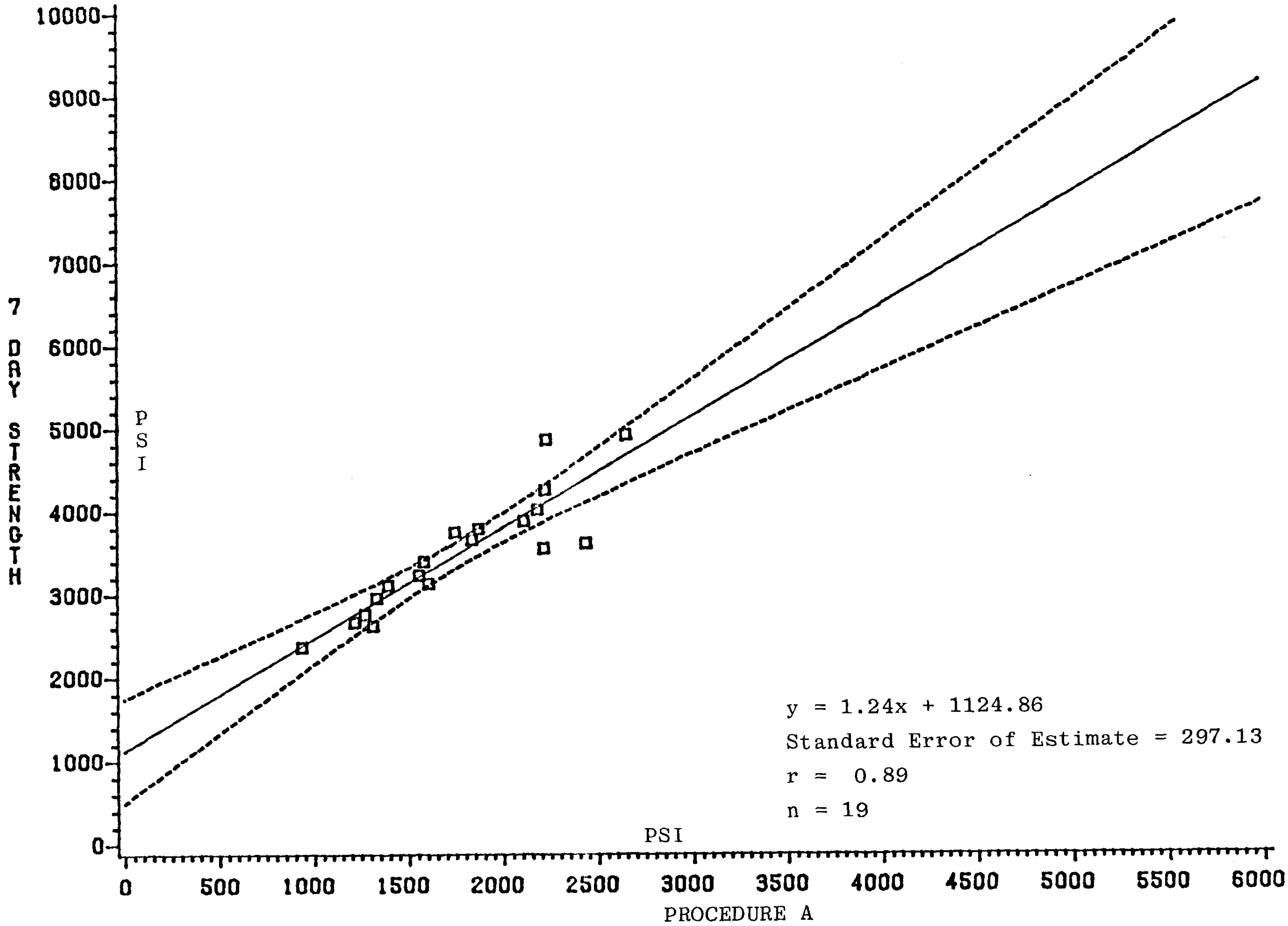
PLOT OF PROCEDURE VERSUS STRENGTH (GRAVEL GROUP)

FIGURE 7



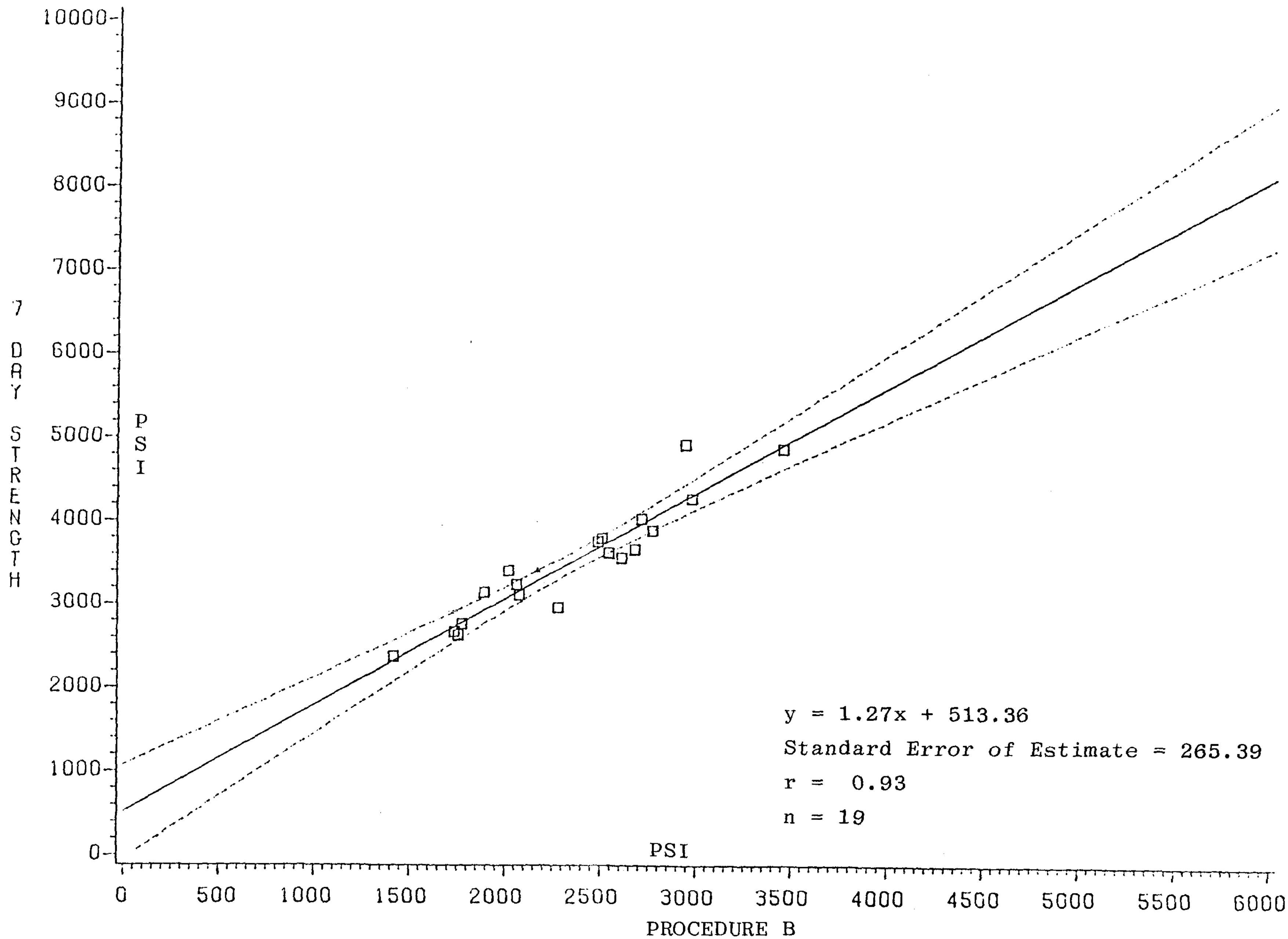
PLOT OF PROCEDURE VERSUS STRENGTH (GRAVEL GROUP)

FIGURE 8



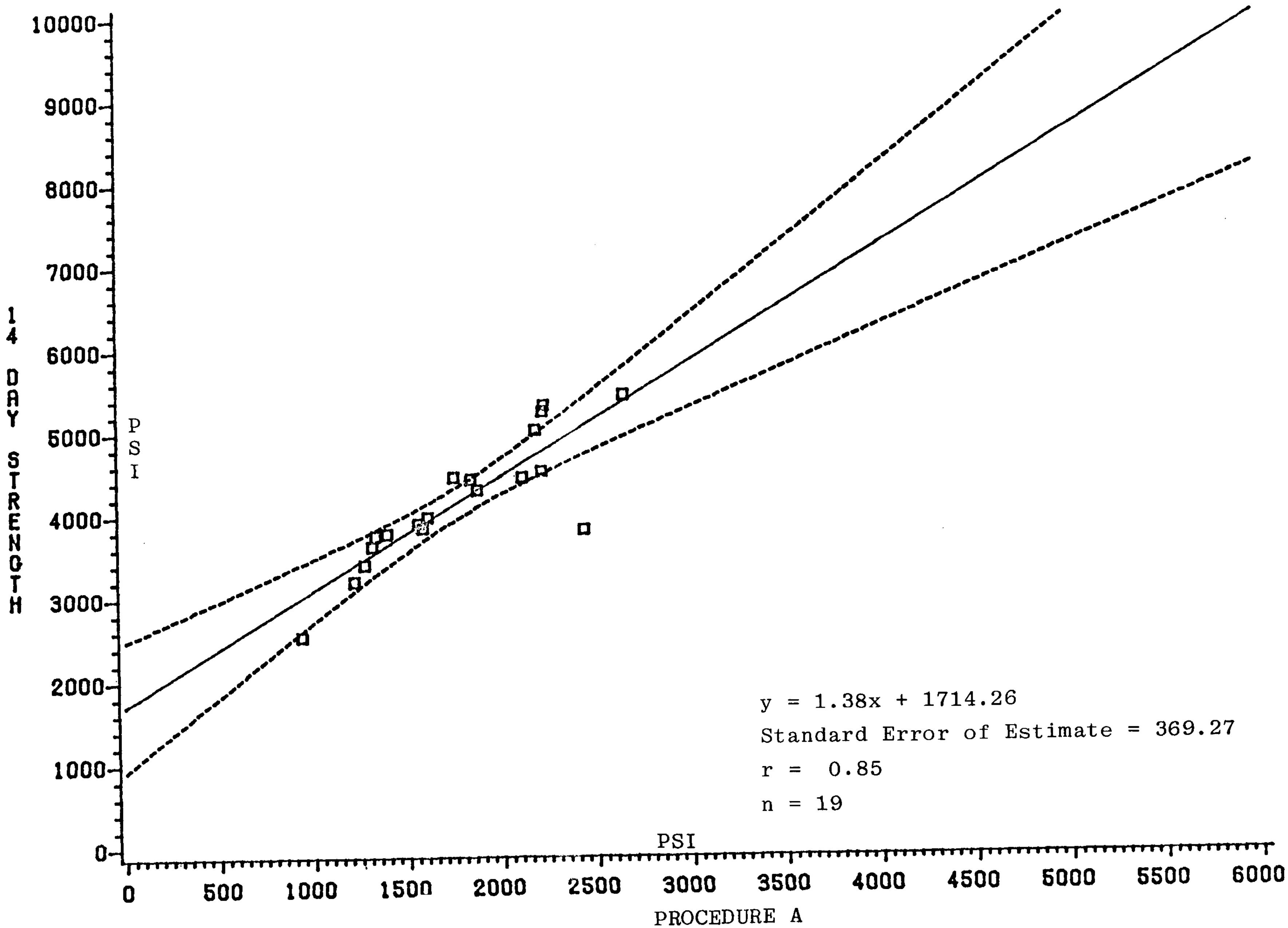
PLOT OF PROCEDURE VERSUS STRENGTH (GRAVEL GROUP)

FIGURE 9



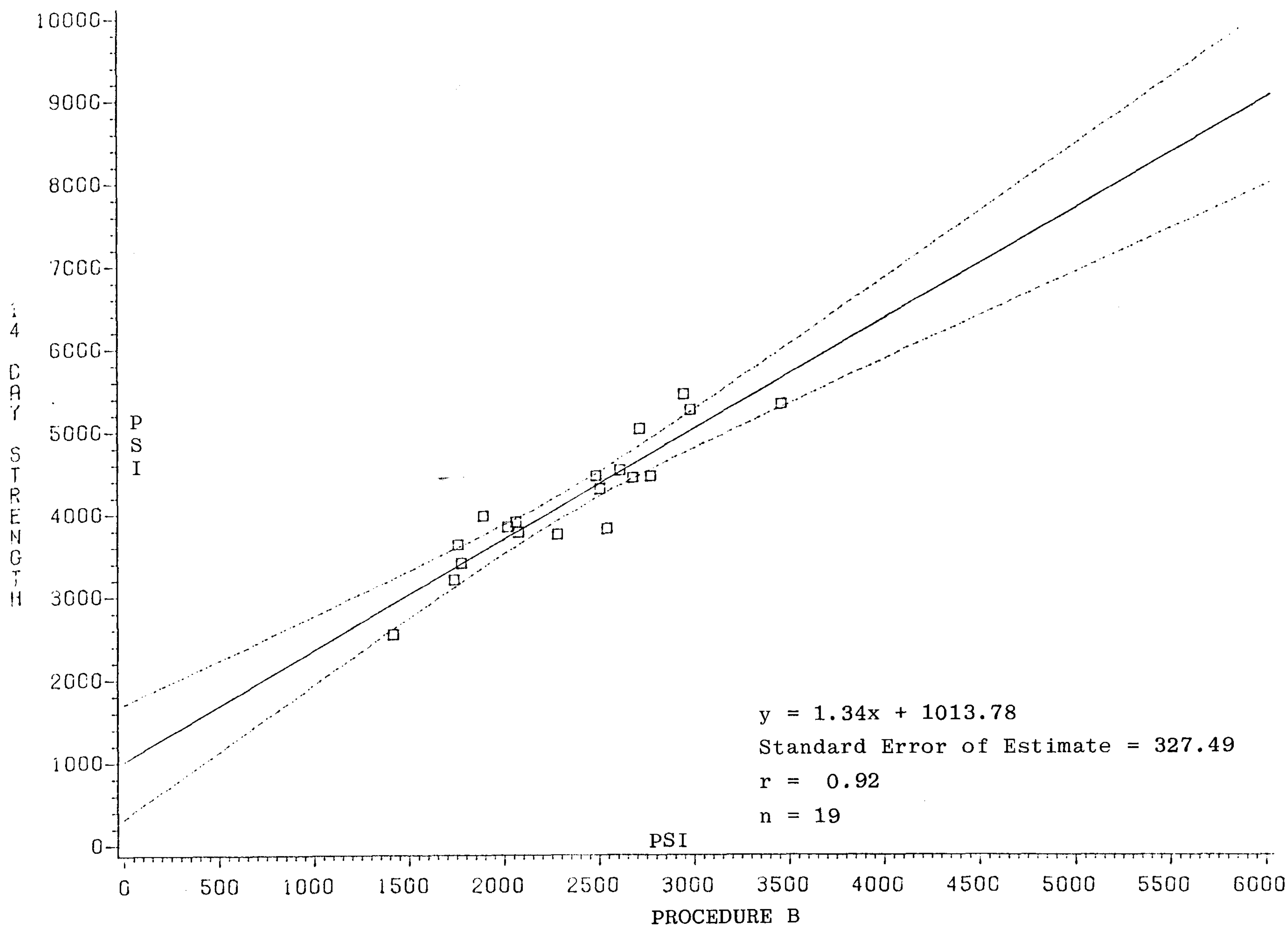
PLOT OF PROCEDURE VERSUS STRENGTH (GRAVEL GROUP)

FIGURE 10



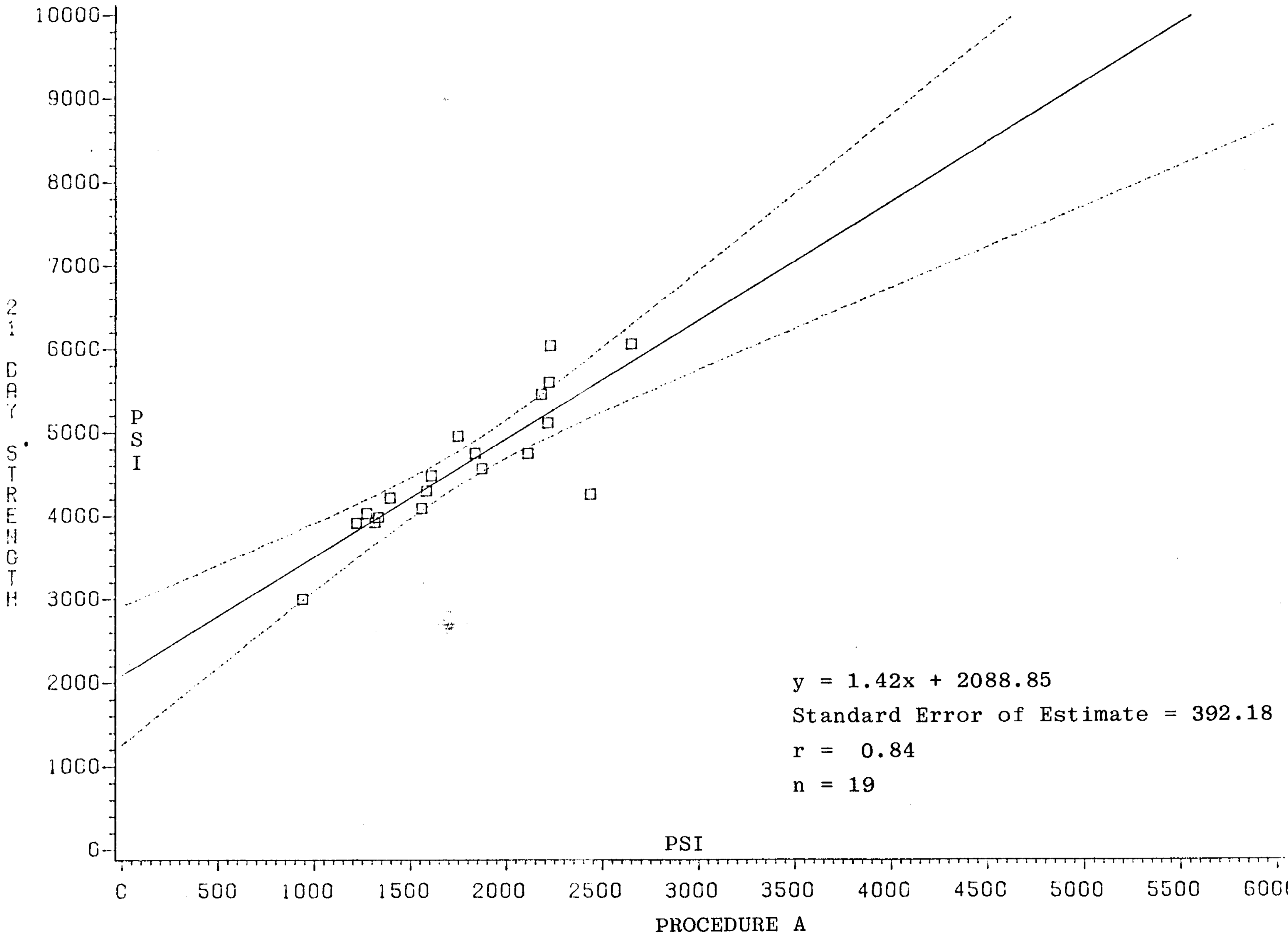
PLOT OF PROCEDURE VERSUS STRENGTH (GRAVEL GROUP)

FIGURE 11



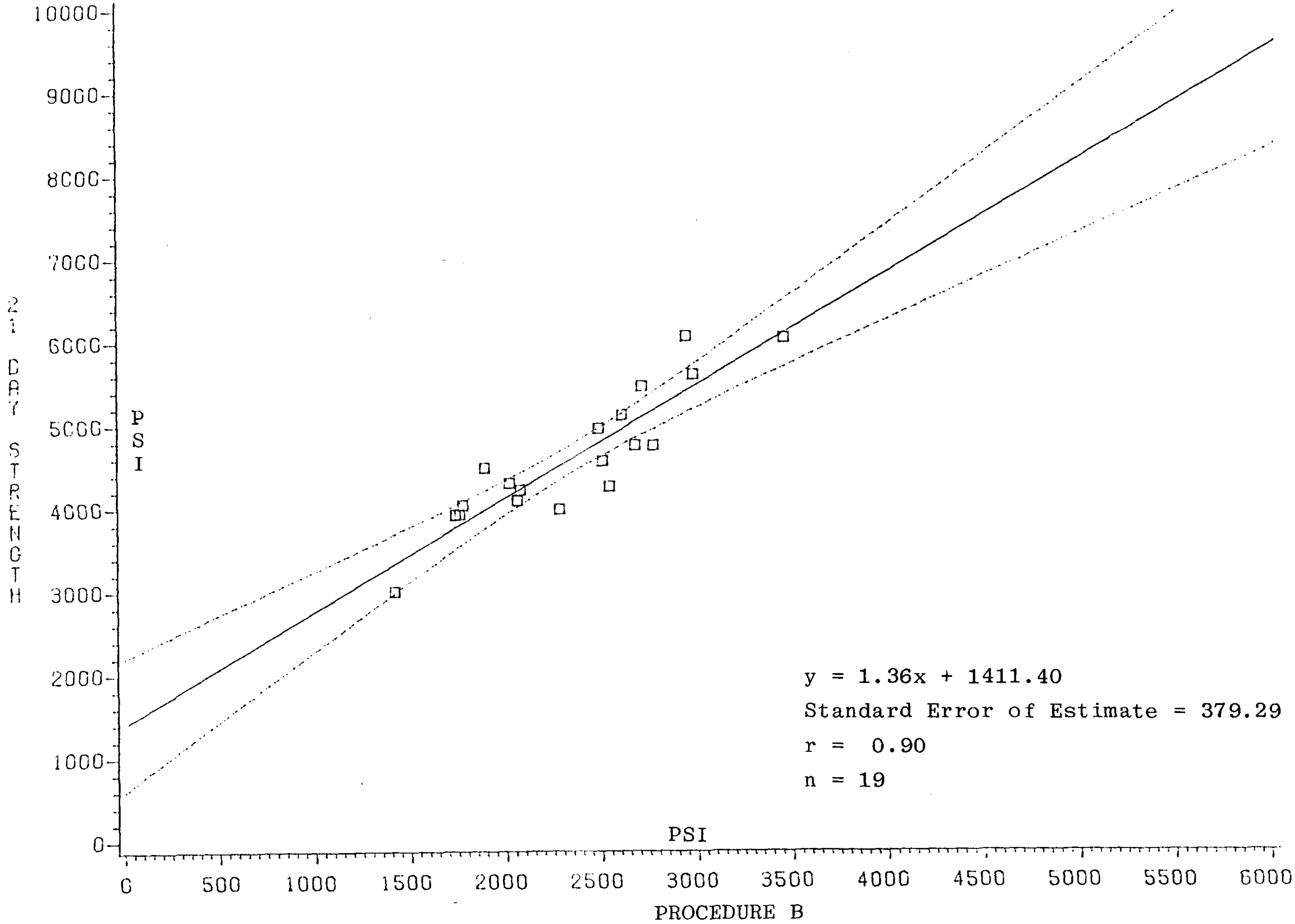
PLOT OF PROCEDURE VERSUS STRENGTH (GRAVEL GROUP)

FIGURE 12



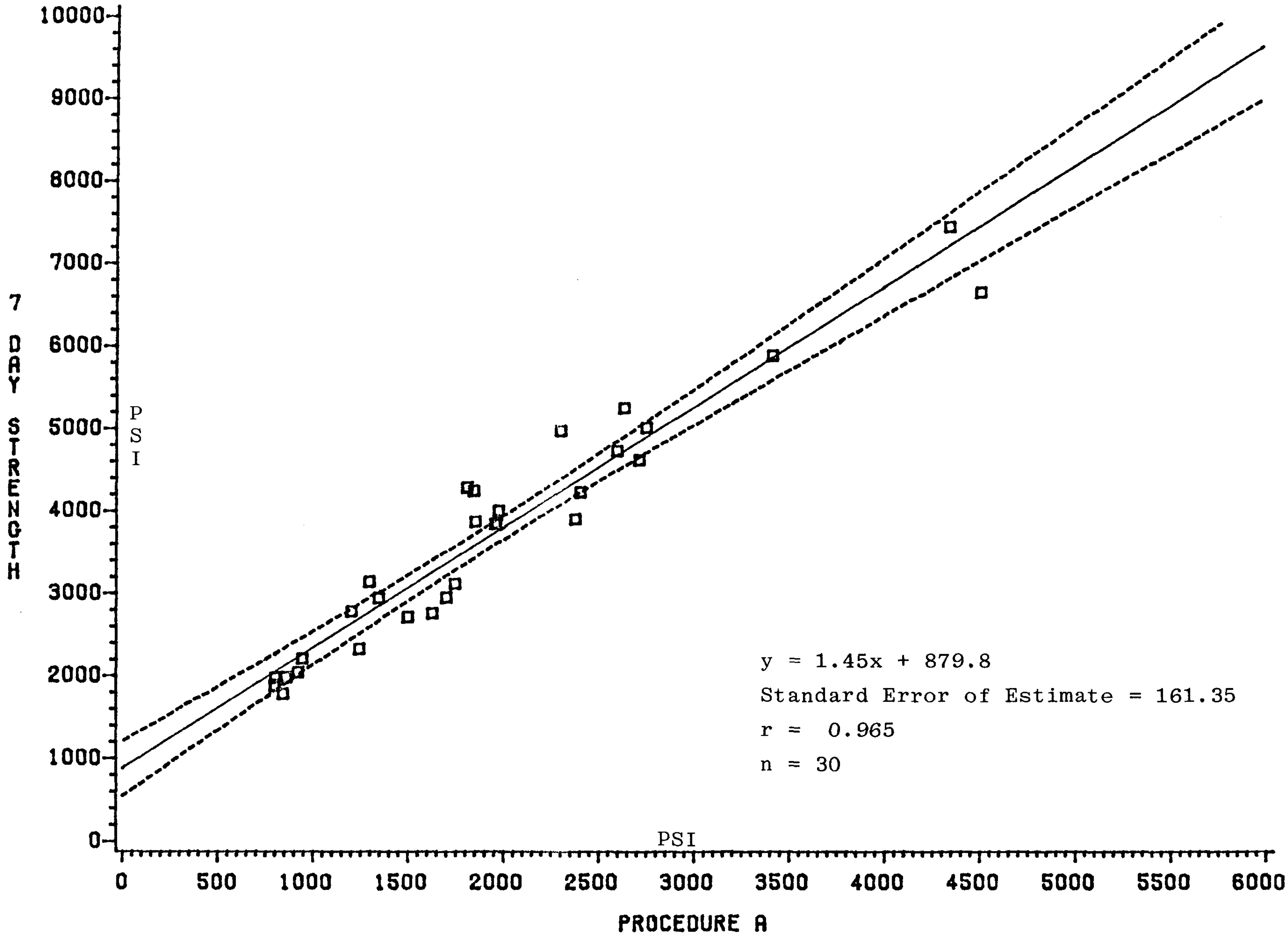
PLOT OF PROCEDURE VERSUS STRENGTH (GRAVEL GROUP)

FIGURE 13



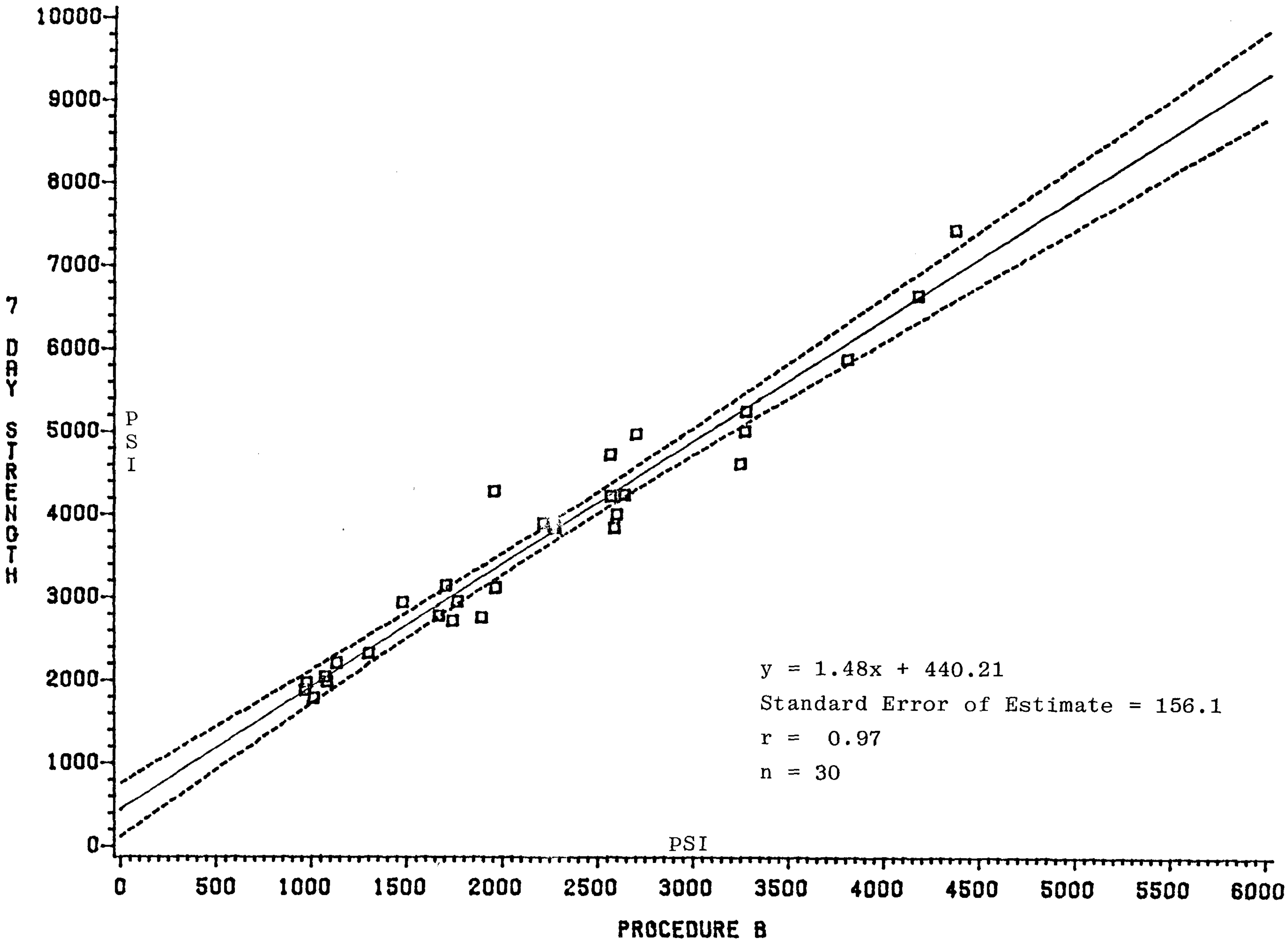
PLOT OF PROCEDURE VERSUS STRENGTH (GRAVEL GROUP)

FIGURE 14



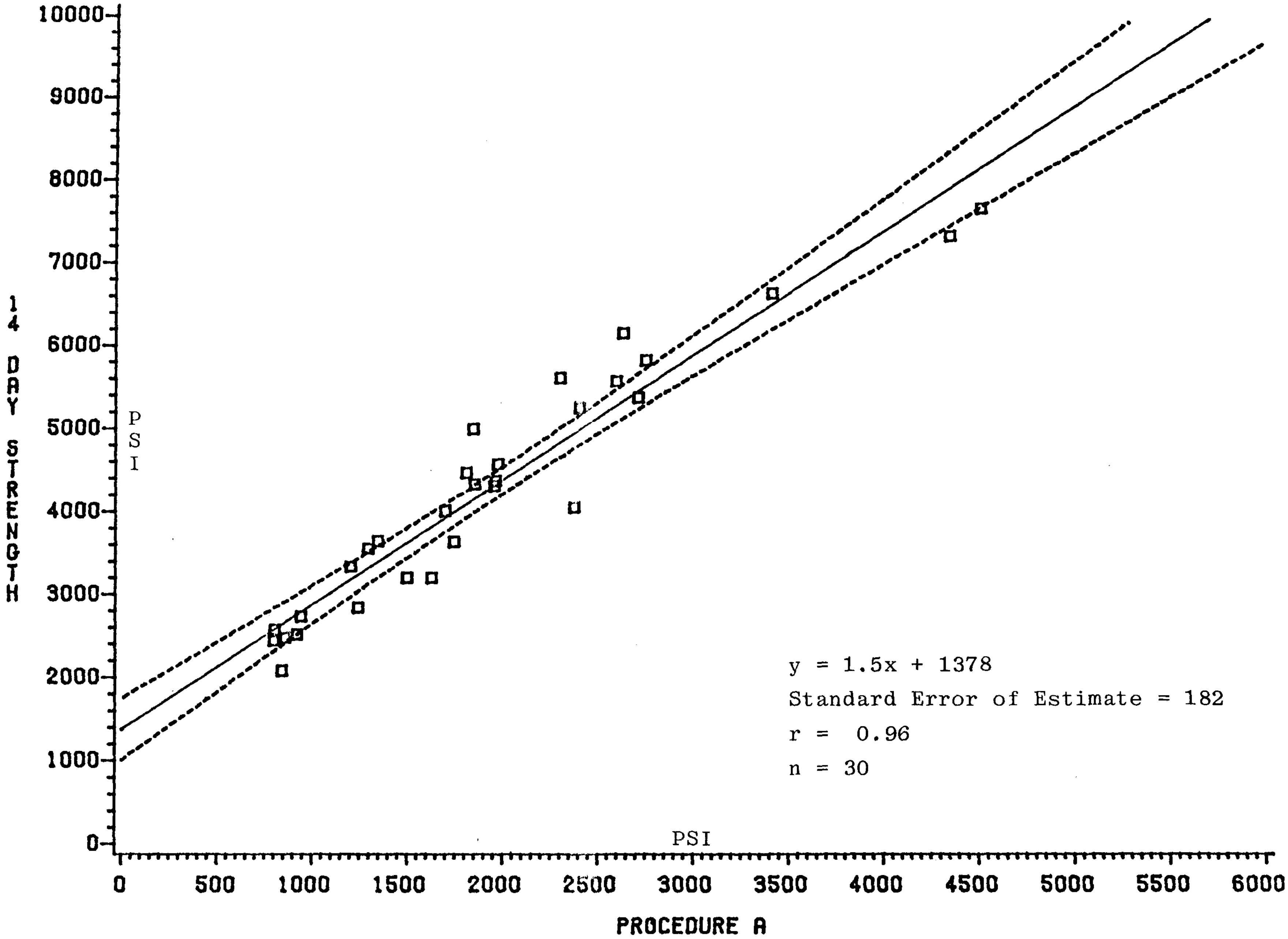
PLOT OF PROCEDURE VERSES STRENGTH (LIMESTONE GROUP)

FIGURE 15



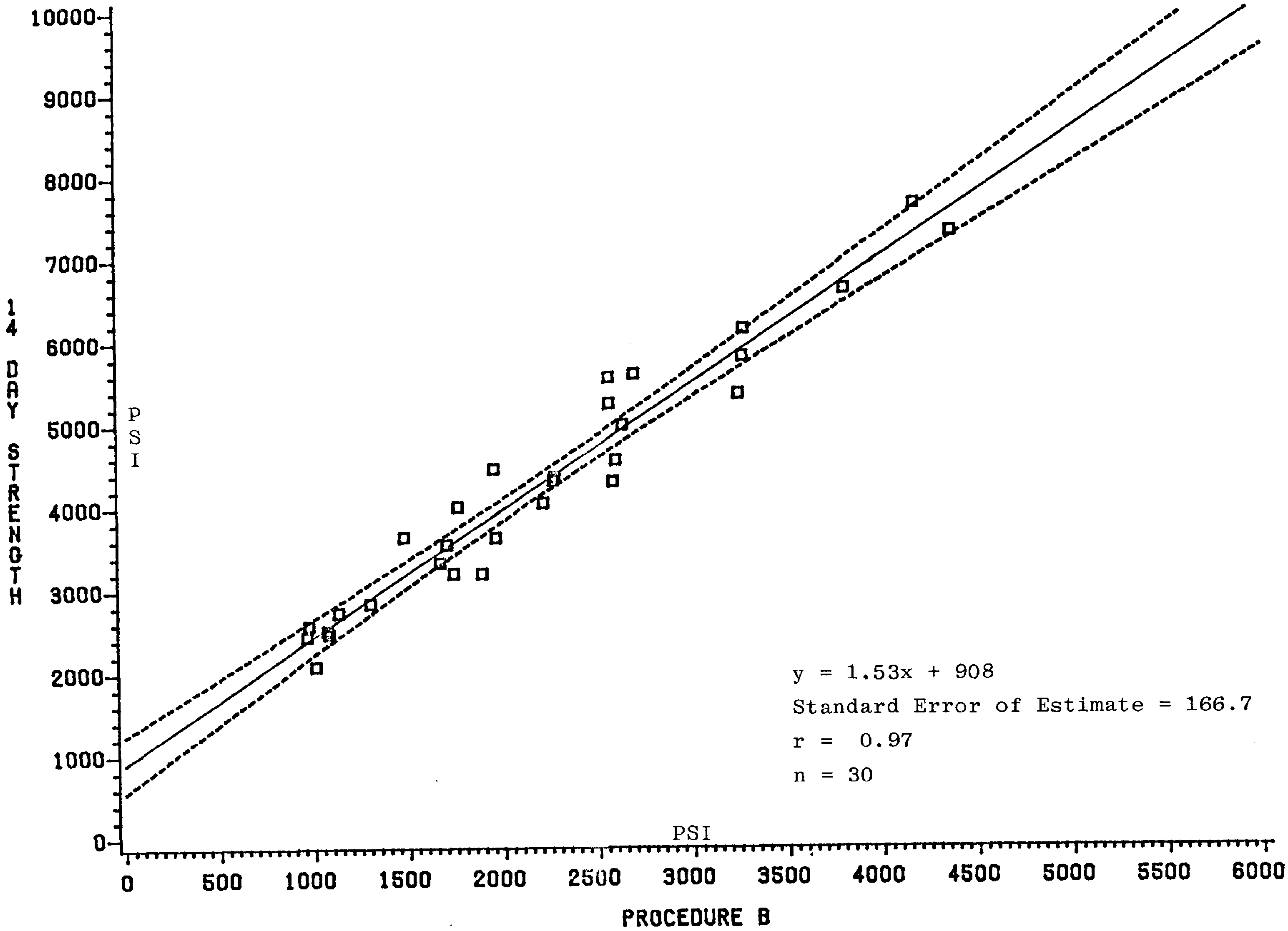
PLOT OF PROCEDURE VERSES STRENGTH (LIMESTONE GROUP)

FIGURE 16



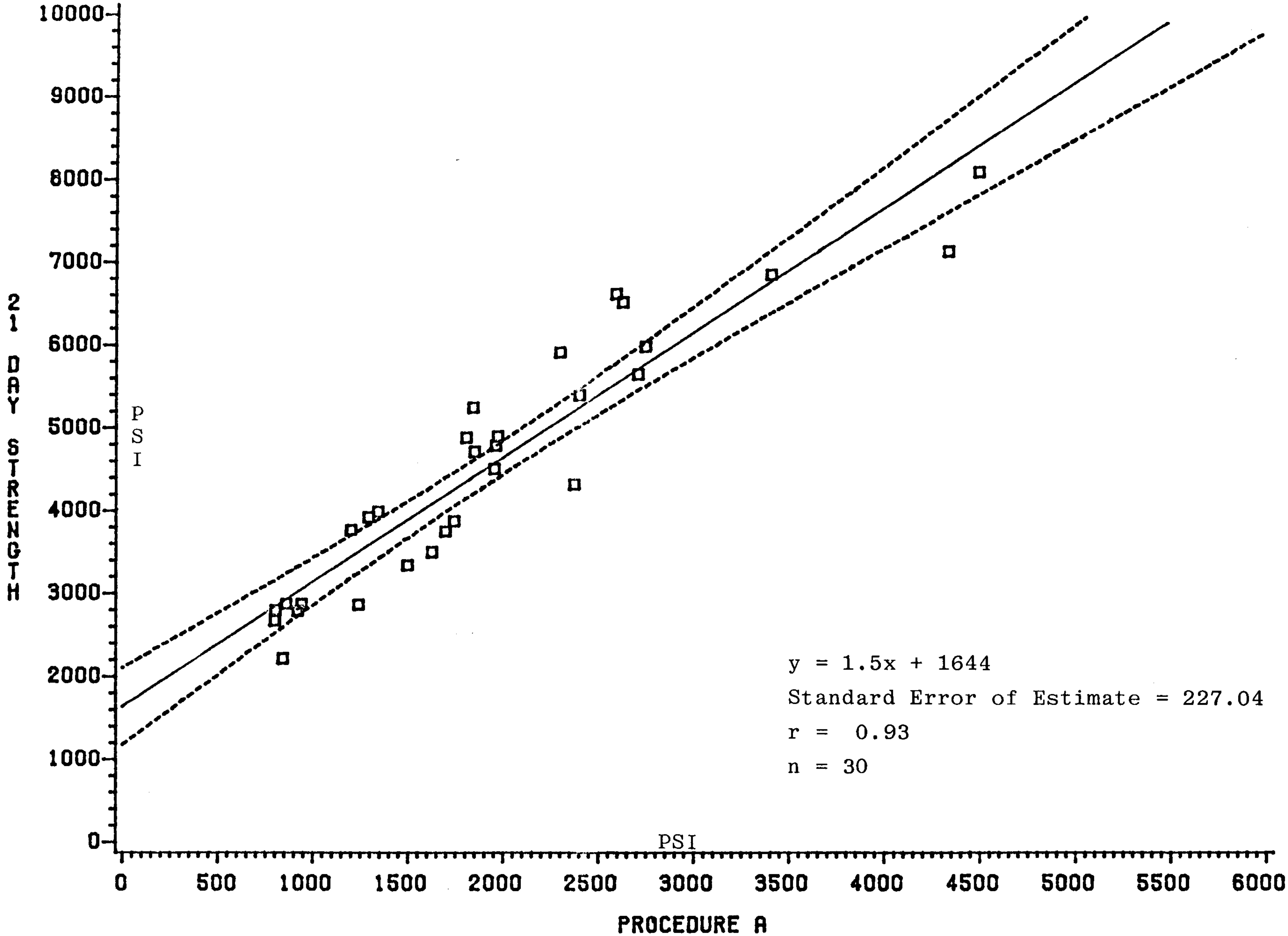
PLOT OF PROCEDURE VERSES STRENGTH (LIMESTONE GROUP)

FIGURE 17



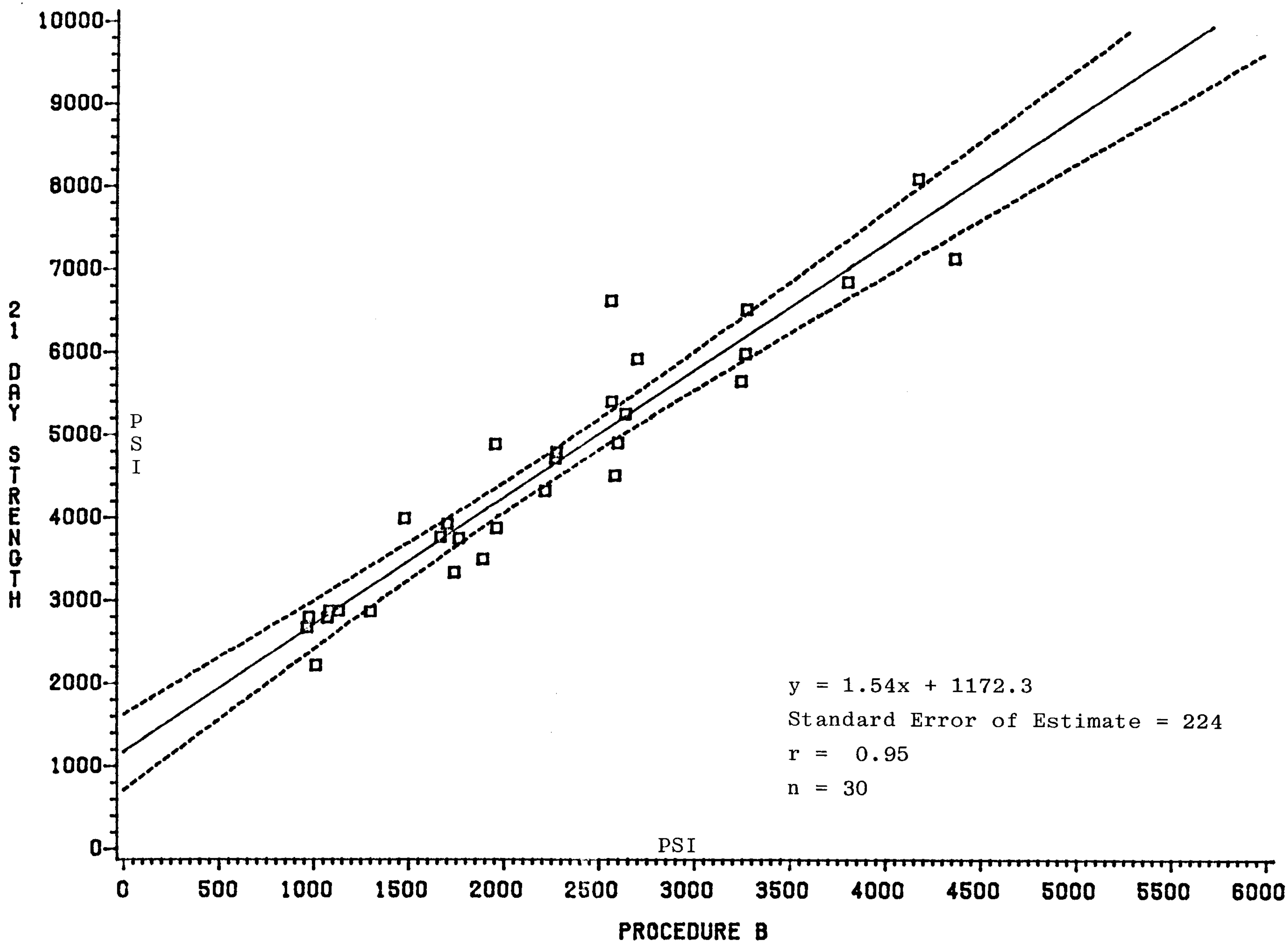
PLOT OF PROCEDURE VERSES STRENGTH (LIMESTONE GROUP)

FIGURE 18



PLOT OF PROCEDURE VERSES STRENGTH (LIMESTONE GROUP)

FIGURE 19



PLOT OF PROCEDURE VERSES STRENGTH (LIMESTONE GROUP)

FIGURE 20

TABLE 1

MIX DESIGN AND PLASTIC CONCRETE DATA
GRAVEL GROUP

Lab No.	Cement Content	W/C Ratio	Admixture	Slump (In.)	Air Content (%)	Unit Weight (Lbs/ft^3)
C-1041	5.0	0.40	Water reducer	1	2.7	146.8
C-1045	5.0	0.40	Air, water reducer	3	6.4	139.2
C-1050	5.0	0.50	None	1-3/4	2.0	144.8
C-1068	5.0	0.60	None	6-1/2	1.0	144.8
C-1069	5.0	0.54	Air	6-3/4	5.1	139.6
C-1070	6.0	0.40	Water reducer	3	3.0	145.2
C-1071	6.0	0.40	Air	2	4.0	143.2
C-1072	6.0	0.50	None	7	1.0	145.2
C-1073	6.0	0.50	Air	7-1/2	4.0	140.0
C-1074	6.0	0.60	None	9-3/4	0.5	143.2
C-1075	6.0	0.60	Air	-	2.8	140.0
C-1076	6.0	0.44	None	2-3/4	1.7	146.4
C-1079	6.0	0.44	Air	5	5.4	139.2
C-1080	7.0	0.44	None	5-3/4	1.0	145.2
C-1081	7.0	0.42	None	2-1/2	1.0	146.4
C-1083	7.0	0.42	Air	6-1/2	5.0	140.0
C-1083(A)	7.0	0.38	Air	2-1/4	4.8	143.2
C-1116	7.0	0.45	None	5	1.2	145.2
C-1144	7.5	0.40	None	4-1/4	1.2	146.0
C-1146	7.5	0.35	None	1/4	1.2	148.0
C-1147	7.5	0.30	Super water reducer	7	1.0	150.8
C-1148	7.5	0.36	Air	1/2	3.0	146.0
C-1152	7.5	0.31	Air & sup. wat. red.	2	2.6	148.0
C-1155	7.5	0.27	Air & sup. wat. red.	2	3.0	148.0
C-1156	4.0	0.11				
C-1157	Void					
C-1159	4.0	0.50	Super water reducer	3/4	N.R.	145.6
C-1160	4.0	0.65	None	3	N.R.	144.8
C-1163	4.0	0.58	Air	4-1/4	5.4	139.6
C-1165	4.0	0.70	None	4-1/2	1.3	144.8
C-1169	4.0	0.75	None	9	1.3	144.4

TABLE 2

LISTING OF COMPRESSIVE STRENGTHS IN PSI

(GRAVEL GROUP)

LABORATORY NUMBER	CEMENT WATER RATIO	BAGS OF CEMENT	3 DAY STRENGTH	7 DAY STRENGTH	14 DAY STRENGTH	21 DAY STRENGTH	28 DAY STRENGTH	PROCEDURE A	PROCEDURE B
C-1041	0.40	5.0	2569	3656	4435	4751	5150	1840	2673
C-1045	0.40	5.0	1951	2960	3750	3980	4295	1335	2275
C-1050	0.50	5.0	2161	3134	3975	4481	4449	1609	1886
C-1055	0.50	5.0	2067	3230	3898	4095	4200	1561	2057
C-1068	0.60	5.0	1900	2758	3396	4030	4497	1275	1770
C-1069	0.54	5.0	2151	2666	3199	3916	3928	1221	1732
C-1070	0.40	6.0	3239	4865	5328	6040	5730	2231	3446
C-1071	0.40	6.0	2730	3885	4453	4746	4851	2114	2763
C-1072	0.50	6.0	2553	3746	4462	4956	4996	1749	2480
C-1073	0.50	6.0	2102	3108	3776	4213	4257	1396	2071
C-1116	0.45	7.0	2797	3557	4525	5119	5203	2217	2605
C-1083	0.38	7.0	2768	3619	3820	4259	4496	2441	2535
C-1083	0.42	7.0	2484	3794	4302	4567	4804	1874	2499
C-1081	0.42	7.0	3430	4913	5439	6060	6096	2652	2937
C-1080	0.44	7.0	3099	4263	5254	5597	6115	2224	2970
C-1079	0.44	6.0	2181	3403	3844	4301	4435	1585	2016
C-1076	0.44	6.0	2827	4021	5026	5455	5677	2187	2706
C-1075	0.60	6.0	1482	2364	2540	3000	3218	940	1413
C-1074	0.60	6.0	1678	2628	3629	3921	4227	1317	1753
C-1169							2181	518	773
C-1165							2921	757	925
C-1163	0.58	4.0					2992	833	1127
C-1159	0.50	7.5					4152	1247	2262
C-1160	0.65	4.0					3273	797	1140
C-1155	0.27	7.5					8492	5358	6567
C-1152	0.31	7.5					7500	4364	5463
C-1148	0.36	7.5					5464	3832	3782
C-1147	0.30	7.5					8761	4404	5711
C-1146	0.35	7.5					6455	4016	4506
C-1144	0.40	7.5					4908	2509	2969

TABLE 3

MIX DESIGN AND PLASTIC CONCRETE DATA
LIMESTONE GROUP

Lab No.	Cement Content	W/C Ratio	Admixture	Slump (In.)	Air Content (%)	Unit Weight (Lbs/ft^3)
C-1175	5.0	0.58	None	4-1/2	0.5	148.8
C-1179	5.0	0.53	Air agent	4	5.0	144.4
C-1180	5.0	0.50	None	3/4	0.6	149.2
C-1181	5.0	0.45	Air agent	1	4.0	146.0
C-1184	4.0	0.71	Air agent	2-1/2	1.5	148.8
C-1187	4.0	0.64	Air agent	5	7.6	138.8
C-1193	4.0	0.60	Air agent	1/4	0.8	150.4
C-1197	4.0	0.54	Air & sup. wat. red.	1-3/4	5.7	146.4
C-1207	6.0	0.53	None	6	0.5	148.4
C-1218	6.0	0.46	Air agent	4-1/2	7.4	139.6
C-1219	6.0	0.45	None	2	1.4	150.4
C-1223	6.0	0.41	Air agent	2	4.8	145.2
C-1231	7.0	0.53	Air agent	10	0.4	147.6
C-1232	7.0	0.48	Air agent	10	4.6	142.4
C-1233	7.0	0.44	None	3-3/4	1.4	150.8
C-1235	7.0	0.40	Air agent	3-1/4	4.0	146.0
C-1236	6.0	0.35	Super water reducer	1-1/2	2.3	154.0
C-1237	7.0	0.39	Super water reducer	3-1/4	1.6	150.4
C-1244	4.0	0.80	None	6	1.0	147.2
C-1245	4.0	0.72	Air agent	8	4.0	143.6
C-1246	4.0	0.71	Air agent	6	3.5	145.2
C-1248	4.0	0.60	Air agent	1-3/4	3.8	146.8
C-1255	4.0	0.65	Air agent	4	6.8	140.0
C-1257	4.0	0.75	None	4	1.1	147.2
C-1258	5.0	0.55	None	1-3/4	0.8	150.0
C-1262	6.0	0.49	None	4	1.0	150.4
C-1267	6.0	0.40	None	1	0.9	151.2
C-1269	7.0	0.50	None	8-1/2	0.8	149.6
C-1270	7.0	0.35	Air agent	4	7.0	140.8
C-1273	6.0	0.35	Air & sup. wat. red.	1-1/2	4.0	149.2

TABLE 4

LISTING OF COMPRESSIVE STRENGTHS IN PSI

(LIMESTONE GROUP)

LABORATORY NUMBER	CEMENT WATER RATIO	BAGS OF CEMENT	7 DAY STRENGTH	14 DAY STRENGTH	21 DAY STRENGTH	28 DAY STRENGTH	PROCEDURE A	PROCEDURE B
1175	0.58	5	3142	3552	3926	4274	1297	1704
1179	0.53	5	2780	3331	3763	3901	1202	1667
1180	0.50	5	4243	4991	5250	5401	1845	2637
1181	0.45	5	3844	4310	4508	4348	1958	2581
1184	0.71	4	2327	2845	2870	3277	1244	1300
1187	0.64	4	1784	2083	2216	2247	842	1009
1193	0.60	4	2759	3198	3503	3900	1627	1889
1197	0.54	4	3120	3637	3872	3968	1747	1961
1207	0.53	6	2947	4010	3754	4525	1701	1764
1218	0.46	6	2719	3197	3339	3569	1499	1739
1219	0.45	6	4225	5253	5396	5711	2406	2564
1223	0.41	6	3896	4048	4323	4503	2377	2213
1231	0.53	7	3841	4364	4794	5056	1966	2276
1232	0.48	7	3866	4323	4717	5014	1855	2269
1233	0.44	7	5008	5817	5983	6280	2754	3266
1235	0.40	7	4620	5365	5651	6178	2714	3242
1236	0.35	6	6646	7649	8092	9458	4510	4167
1237	0.39	7	5883	6627	6853	6879	3414	3799
1244	0.80	4	1977	2577	2803	2996	802	975
1245	0.72	4	1881	2445	2678	2946	801	964
1246	0.71	4	1985	2477	2877	3118	859	1081
1248	0.60	4	2939	3638	3993	4224	1346	1477
1255	0.65	4	2207	2733	2877	2993	943	1133
1257	0.75	4	2043	2520	2792	2974	922	1071
1258	0.55	5	4280	4468	4880	5150	1809	1952
1262	0.49	6	4721	5568	6614	6720	2599	2560
1267	0.40	6	5247	6153	6516	6586	2635	3273
1269	0.50	7	4979	5607	5919	6302	2302	2697
1270	0.35	7	4002	4567	4897	5097	1975	2595
1273	0.35	6	7444	7320	7132	8410	4346	4360

APPENDIX B

Use of Accelerated Strength Testing

Reported by ACI Committee 214

This report describes the three accelerated test methods given in ASTM C684 and gives guidance for the interpretation of the test results with the help of examples.

Keywords: coefficient of variation; **compression tests;** compressive strength; concrete construction; **concretes;** cylinders; **evaluation; quality control;** sampling; standard deviation; **statistical analysis;** variations.

Introduction

In concrete construction, the 28-day compressive test is usually used to evaluate the strength of concrete, although ACI 318 permits ages other than 28-days for acceptance purposes. Results of the 28-day tests determine if adjustments are required in the batching and mixing process to satisfy concrete quality parameters. With present methods of rapid construction it is imperative that methods be developed to estimate the 28-day strength of concrete cylinders at an earlier age.

ASTM Standard C684 specifies the following procedures to provide an early indication of the potential strength of concrete and the variability of the production process.[2]

Procedure A — Warm Water Method
Procedure B — Boiling Water Method
Procedure C — Autogenous Method

Procedures A and B permit testing of the cylinders at 24 and 28½ hr respectively, while Procedure C requires 49 hr (± 15 minutes) of curing before testing. Variations of these tests are used to conform with normal working hours. For example, one testing laboratory uses a 72 hr test for cylinders made at jobsites on Friday. This permits boiling, cooling, capping, and testing on Mondays.[7]

All three test procedures listed require equipment to control the temperature of the cylinders during the accelerated curing cycle. Fig. 1 and 2 show schematic drawings for two of the methods. After curing, the cylinders should be tested in accordance with ASTM procedures. When Procedure A is used, the cylinders are cured in a warm water bath at 95 ± 5 F (35 ± 3 C) for 23½ hr; ± 30 min. The warm water acts as an insulator and most of the acceleration in strength is provided by the heat of hydration. Procedure B requires an initial cure of 23 hr at 70 ± 10 F (21 ± 5 C) followed by immersion in boiling water for 3½ hr. A thermally insulated container is used with Procedure C. Cylinders are stored in this container for 48 hr, and the heat generated by hydration of the cement accelerates the strength gain. The most important use of accelerated test data is for quality control to permit rapid adjustment of batching and mixing. To estimate the 28-day strength from the accelerated strength test data, an equation must be established for the specific concrete mix using the same materials. This correlation is presently necessary because of the traditional use of the 28-day strength for design procedures. However, in the future as acceptance criteria change, it may be possible to work directly with accelerated strength tests.

Adequate lead time must be provided to establish basic correlation equations. Among factors that need to be considered are: project size, climatic conditions, properties of concrete mix and material, and physical facilities at a batching plant or jobsite. A minimum of 30 sets of test data covering a wide strength range are needed to establish an adequate correlation equation; for a single strength require-

For discussion, see the October 1981 issue of *Concrete International: Design & Construction*.

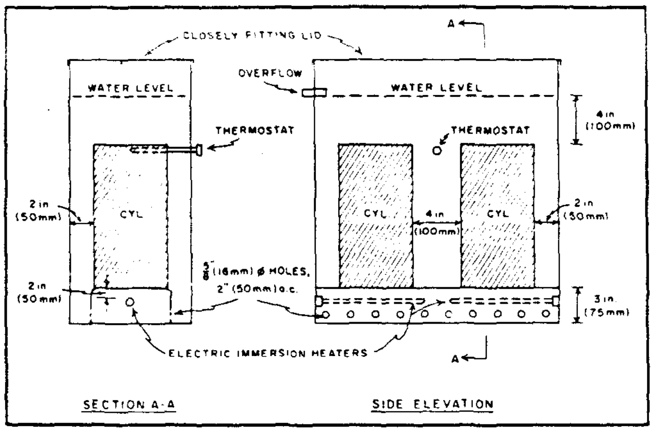


Fig. 1 — Accelerated curing water tank (Procedure A).

ment, the strength range should include the specified strength and should equal at least 75 percent of the specified strength. It should be achieved by the use of not fewer than three water-cement ratios. A correlation coefficient of less than 0.80 should be regarded with suspicion. Fig. 3 shows a typical correlation curve for cylinders tested by the boiling method.[5] Similar curves can be developed for other methods.

Interpretation of test results

ACI 214, "Recommended Practice for Evaluation of Strength Test Results of Concrete,"[1] can be used in interpreting both standard and accelerated test results. The following formula and table of t values can be used for the application of statistical procedures to quality control of concrete:

$$f_{cr} = f_c' + t\sigma \quad (1)$$

where

f_{cr} = required average strength,
f_c' = design strength specified
t = a constant depending on the proportion of tests that may fall below f_c' (Table 1)
σ = forecast value of the standard deviation.

The value of f_c obtained from this equation can be either the usual 28-day strength or the actual accelerated strength, depending upon the corresponding value of f_c'.

The probability value, t, (Table 1) estimates the percentage of cylinders that do not achieve the mix proportion strength f_c'. For example, a value of t equal to 1.28 indicates that 10 percent of the cylinders will test lower than f_c'.

The standard deviation, σ, is based on the variability of test results. For concrete batch plants that have a capability of supplying a consistent strength in their product, the value of σ will be low. References 1, 3, and 4 present methods for computing the standard deviation.

Other statistical methods for comparing test data for different projects and the variation within tests are also presented in ACI 214.[1] However, the above formula is all that is needed to establish the target

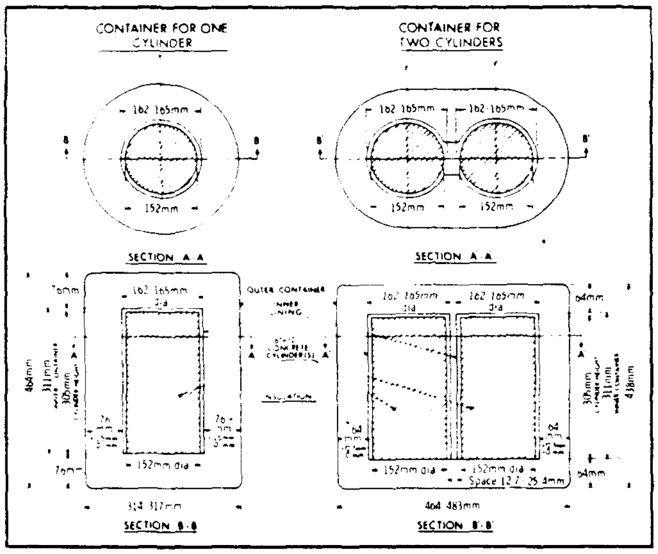


Fig. 2 — Autogenous curing container (Procedure C).

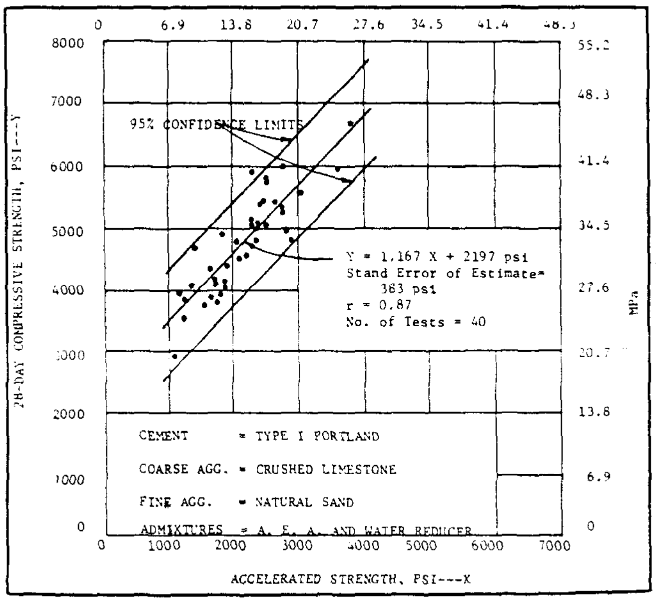


Fig. 3 — Relationship between accelerated and 28-day compressive strength of concrete. Data obtained by the boiling method (Procedure B).

TABLE 1 — Values of t for the equation: $f_{cr} = f_c' + t\sigma$

Likelihood of low test results: Number	Likelihood of low test results: Percentage	t
1 in 1000	0.1	3.09
1 in 500	0.2	2.88
1 in 100	1.0	2.33
1 in 50	2.0	2.06
1 in 25	4.0	1.75
1 in 20	5.0	1.65
1 in 10	10.0	1.28
1 in 5	20.0	0.84
1 in 2	50.0	0.00

TABLE 2 — Values of t for use in Eq. (2)

n	t
10	0.59
11	0.55
12	0.52
13	0.50
14	0.48
15	0.46
16	0.44
17	0.43
18	0.41
19	0.40
20	0.39
21	0.39
22	0.37
23	0.36
24	0.35
25	0.34
26	0.34
27	0.33
28	0.32
29	0.32
30	0.31

n = Number of pairs of test data used in establishing the correlation equation.
Note: Table 2 is based on a one-sided confidence limit of 95 percent for points on the line.

average strength for a given project. The following two examples illustrate the use of the formula:

Example 1: Obtain the value for f_{cr} if contract specifications require the accelerated strength to be 1800 psi and that the t value is 1.28 (1 in 10, the acceptable number of low tests.) Past history of this producer shows that the accelerated strength test standard deviation is 500 psi.

f_{cr} = 1800 + 1.28(500) = 1800 + 640 = 2440 psi.

The concrete mix must be designed so that the average value of the accelerated compressive strength test is at least 2440 psi.

Example 2: If contract specifications require the 28-day strength tp be 4000 psi, what must be the target average value of all cylinders for accelerated strength. Assume the following:

(1) that the t value is 1.28 (1 in 10, the acceptable number of low tests).

(2) the standard deviation for concrete of this producer for the particular accelerated strength test to be used is 525 psi, and

(3) that the following relationship between the accelerated and the 28-day cylinder strength has been established for this producer.

Y = 1.167X + 2197 psi

where Y = 28-day strength, and

X = accelerated strength.

4000 = 1.167 (X) + 2197

Thus X = 1545 psi

And, $f_{cr} = f_c' + t\sigma$

= 1545 + 1.28(525)

f_{cr} = 2217 psi.

The concrete mix proportion must result in an average value of the accelerated compressive strength of at least 2217 psi.

If fewer than 30 tests were used in establishing the correlation used in Example 2, then a more sophisticated statistical treatment is needed. An example is presented in the appendix assuming that the correlation curve was developed with 15 sets of test results.

Concluding remarks

Accelerated strength testing can provide a reliable tool for quality control and for estimating the later age strength of a given concrete mix.[5,6,7] Elaborate equipment is not required for the tests discussed above. The test methods have sufficient flexibility so that testing can be accomplished during normal working hours.[7]

APPENDIX

Correlations based on fewer than 30 tests

One area of uncertainty which has been overlooked in the method given in the main report is the lack of knowledge of the exact position of the regression line. To follow normal statistical procedure the required average accelerated strength should be increased so that it is based on a position of the line that is so unfavorable that larger indicated increases would be required less than 5 percent of the time. When 30 sets of data are used, however, the position of the line is so well determined that for correlations typically encountered the computed increase is less than 70 psi (0.5 MPa). The impact of a correction of this small magnitude does not justify the work involved in its computation.

When the number of tests is reduced below 30, the effect of ignoring this correction becomes progressively more important. It is recommended that correlations never be based on fewer than 10 pairs of tests and that when fewer than 30 are available the results be corrected to the upper 95 percent confidence interval for the regression of accelerated strength on 28-day strength. The method is as follows:

First Step: f_{cr} for 28-day strengths is obtained from Eq. (1) as above where the symbols have the same meaning as given in the previous text.

Second Step: Convert f_{cr} to a corresponding accelerated strength, f_{c_a}' by use of the linear relationship developed according to the method described in Reference 8, pp. 5-31 to 5-34. In developing this relationship, 28-day strength is used as the independent variable and accelerated strength as the dependent variable.

Third Step: The average accelerated strength is obtained by adding a second increment to f_{c_a}', according to the relationship

$$f_{cr_a} = f_{c_a}' + t'\sigma_{y \cdot x} \qquad (2)$$

f_{cr_a} is the required average accelerated strength due to the statistical variation in the relationship between accelerated and 28-day strengths,

$\sigma_{y \cdot x}$ is the standard deviation of y values for a given x value, also called the standard error of estimate

t' is a constant multiplier for $\sigma_{y \cdot x}$ that depends on the number of pairs of data, n, used in calculating the linear regression line. t' is obtained from Table 2.

Eq. (2) is based on the assumption that the average of the accelerated strengths used in the relationship is close to f_{cr_a}. This assumption is met well enough if the data from which the relationship is calculated are obtained from concretes made with the same materials and mix proportions and under the same conditions that will exist in the project. The following example is similar to Example 2, but the correlation curve used in Example 3 was developed from 15 sets of data and uses the 28-day strength as the independent variable.

Example 3: If the contract specifications require the 28-day strength to be 4000 psi, what must be the target average value of all cylinders for accelerated strength? Assume the following:

1. The t value is 1.28 (1 low test in 10) for 28-day strengths.
2. The standard deviation for the concrete of this producer for 28-day cylinders is 525 psi.
3. The following relationship between accelerated cylinder strength and 28-day cylinders has been established for this producer:

$Y = 0.7610\ X - 1332$ psi

where Y = accelerated strength, and

X = 28-day strength.

This relationship was obtained from 15 pairs of results, and $\sigma_{y \cdot x}$ for this relationship is 225 psi.

Using Eq. (1) $f_{cr} = f_c' + t\sigma$

$f_{cr} = 4000 + 1.28\ (525)$

$= 4672$ psi

The corresponding accelerated strength is found from the correlation equation,

$Y = 0.7610X - 1332$ psi

$= 0.7610\ (4672) - 1332$

$= 2223$ psi

Finally the average accelerated strength is found from Eq. (2)

$f_{cr_a} = f_{c_a}' + t' \times \sigma_{y \cdot x}$

$f_{cr_a} = 2223 + 0.46\ (225)$ (where $t' = 0.46$ from Table 2)

$= 2327$ psi.

The concrete mix must be designed so that the average accelerated strength is at least 2327 psi.

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This report was submitted to letter ballot of the committee which consists of 24 members; 17 were affirmative, 2 abstained, and 5 ballots were not returned. It has been processed in accordance with the Institute procedure and is approved for publication and discussion.

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Use of Accelerated Strength Testing

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ADDENDUM

An attempt was made to establish a direct correlation between the cement content, the amount of water used and the 28-day strength of concrete using the data from the mixes that were produced in this study and also similar mixes from other research projects. All of the mixes that were used to plot this graph were chosen from the mixes that had the same aggregate and cement type. No admixtures were used in these mixes.

In order to relate the 28-day strength to cement and water content, an arbitrary factor, which is referred to here as mix factor, was chosen. Mix factor is the cement factor (number of bags only such as 6.5, 7.0, etc.) divided by the water cement ratio (such as 0.4, 0.45, etc.). There is no unit for mix factor due to simplicity of plotting the curve. A mix containing 6.5 bags of concrete per cubic yard and a water cement ratio of 0.4 has a mix factor of $\frac{6.5}{0.4} = 16.25$.

Using the linear regression method, the equation of the best fit curve for the points (28-day strength versus mix factor) was calculated and the curve was plotted. According to this curve, as the water cement ratio increases or decreases the mix factor accordingly decreases or increases and so does the strength.

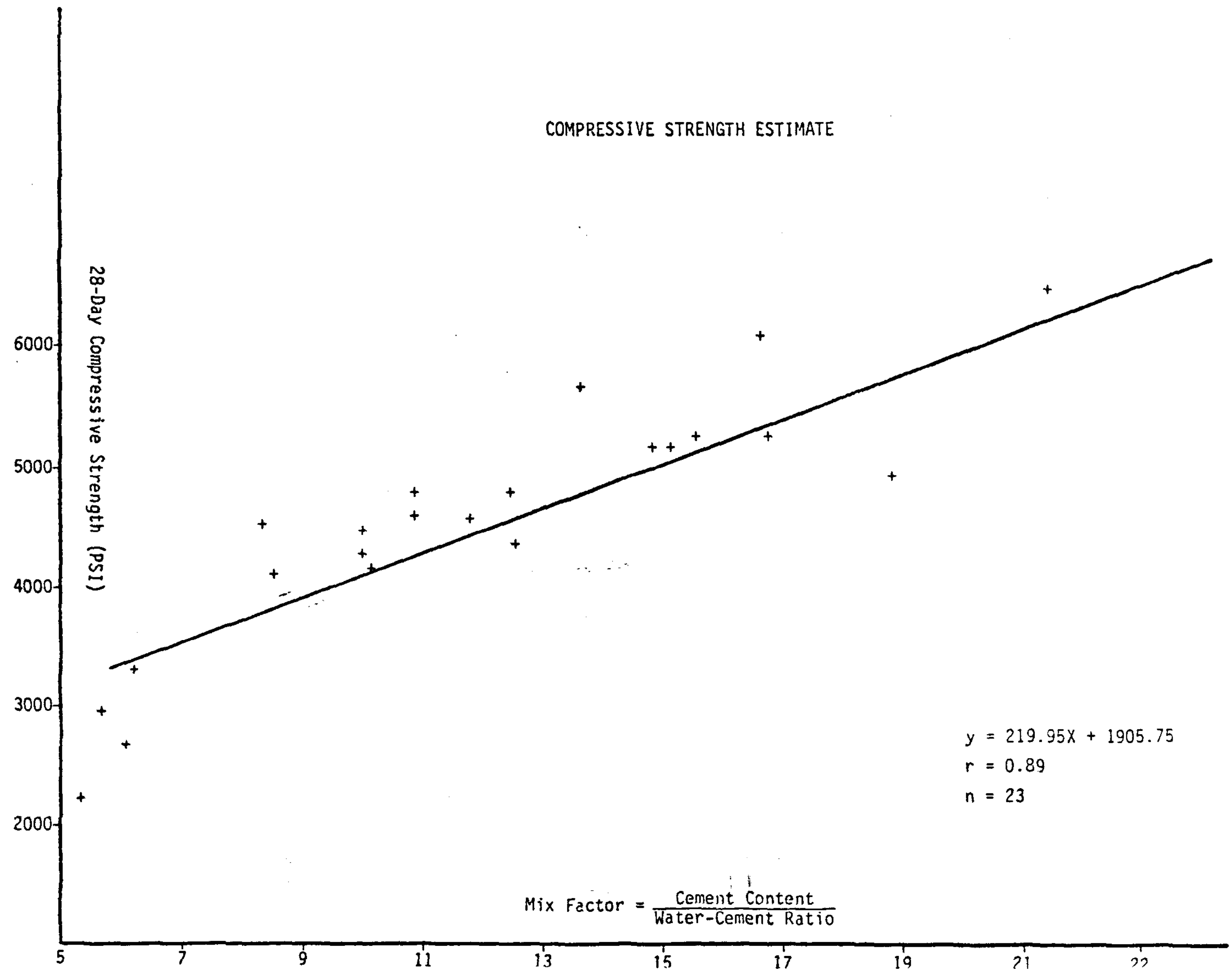
This was done to indicate that such a relationship could be established if there are statistically valid points, so a confidence level could be gained in using such a graph for directly estimating the 28-day strength for the same mixes under similar casting and curing procedures.

TABLE 5

MIX FACTOR DATA

28-DAY COMPRESSIVE STRENGTH FROM MIX FACTOR
(NO AIR, GRAVEL)

C.F.	W/C	Mix Factor $\frac{C.F.}{W/C}$	PSI
4.0	0.70	5.7	2921
4.0	0.75	5.3	2181
4.0	0.65	6.2	3273
4.0	0.67	6.0	2661
5.0	0.59	8.5	4081
5.0	0.50	10.0	4449
5.0	0.60	8.3	4497
5.5	0.51	10.8	4761
5.8	0.49	11.8	4551
6.0	0.48	12.5	4770
6.0	0.60	10.0	4227
6.0	0.44	13.6	5677
6.0	0.48	12.5	4329
6.5	0.43	15.1	5159
6.5	0.44	14.8	5171
7.0	0.44	15.9	5200
7.0	0.42	16.7	5259
7.0	0.42	16.7	6096
7.0	0.45	15.5	5203
7.5	0.40	18.75	4908
7.5	0.35	21.4	6455
6.0	0.50	12.0	4257
7.0	0.44	15.9	6115



28-Day Strength Versus Mix Factor

FIGURE 21