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EVALUATION OF THE WINDSOR PROBE TEST FOR ESTIMATING COMPRESSIVE STRENGTH OF CONCRETE

by

V. M. MALHOTRA AND K. PAINTER

MINERAL PROCESSING DIVISION

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V.M. Malhotra* and K. Painter**

SUMMARY OF RESULTS

The hardness of coarse aggregate affects the penetration of the Windsor probe into concrete. On cylinders of the same 28-day compressive strength, the exposed length of probe is 1.56 in. (4.0 cm) for limeston concrete compared to 1.66 in. (4.2 cm) for gravel concrete.

Tests indicate that a 0.1-in. (0.25-cm) increase in the exposed length of probe represents an increase of about 500 psi (35 kg/cm^2) in the 28-day compressive strength of limestone concrete. The corresponding value for gravel concrete is 600 psi (42 kg/cm^2).

The average within-batch coefficient of variation for the exposed length of probe is 4.4 per cent for gravel concrete and 2.1 per cent for limestone concrete, indicating that perhaps concrete made with softer aggregates may give more reproducible results than concrete made with harder aggregates.

Correlations between exposed probe length and 28-day compressive strength of concrete are significant according to measurements made on slabs, cylinders,and drilled cores, For gravel concrete, the correlation coefficients vary from 0.885 to 0.978; for limestone concrete, the value of coefficients vary from 0.927 to 0.969.

The standard error of estimate of 28-day compressive strength of gravel concrete, determined from exposed probe length, is 304 psi (21 kg/cm^2) compared to 488 psi (34 kg/cm^2) determined from drilled cores. For limestone concrete, the corresponding values of the standard error of estimate are 444 psi (31 kg/cm^2) and 386 psi (27 kg/cm^2).

For the same concrete, the exposed length of probes increased with increasing age of concrete, to indicate that probe measurements are useful for determining the relative strength of concrete.

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INTRODUCTION

In December, 1970 the Mines Branch (1) issued an investigation report IR 71-1 entitled: "Preliminary Evaluation of Windsor Probe Equipment for Estimating the Compressive Strength of Concrete". In that report, data were presented on the testing of 6 x 12-in. (15 x 30-cm) cylinders by both the Windsor probe test and conventional compression test.

The main conclusions were:

> "The Windsor probe test is suitable for determining the relative quality of concrete test specimens and concrete in place in much the same way as the Schmidt test hammer. However, its usefulness in quantitatively predicting the 28-day compressive strength of concrete is doubted because of relatively large within-batch variation in the probe test results".

This report presents additional data for evaluating the Windsor probe with respect to its applicability in estimating the compressive strength of large concrete slabs made in the laboratory. It is believed that the Windsor probe testing is more suitable for estimating the compressive strength of large sections of concrete than compression testing of 6 x 12-in. (15 x 30-cm) cylinders.

SCOPE OF INVESTIGATION

Two series of concrete mixes were made in the laboratory. The first series, consisting of eight mixes, was made with river gravel aggregate and natural sand. Slabs 24 x 24 x 8 inches (61 x 61 x 20 cm) were cast and probed, and the results were compared with the compressive strengths of 4 x 8-in. (10 x 20-cm) cores drilled from the slabs and companion 6 x 12-in. (15 x 30-cm) and 4 x 8-in. (10 x 20-cm) cylinders. The casting and testing of specimens in the second series of mixes were identical to the first except that only seven mixes were made and limestone was used as the coarse aggregate.

CONCRETE MIXES

A total of 15 concrete mixes were made in the Mines Branch laboratory between February 1971 and March 1971. A 2.5-cu-ft laboratory counter-current mixer was used for preparing the concrete batches. In order to have sufficient concrete for casting large slabs, each mix, consisting of two 2.25-cu-ft batches, was dumped on a large steel trough and remixed thoroughly by shovel before casting specimens.

Materials

Normal portland cement (ASTM Type I) was used for the concrete mixes. The physical properties and chemical analyses of the cement are given in Table 1.

Minus 1-in. (25-mm) river gravel and limestone were used as coarse aggregate and local sand was used as fine aggregate in Series I and II. To keep the grading uniform for each mix, the sand was separated into different size fractions which were combined to specification.

The grading and physical properties of both the coarse and fine aggregates are given in Tables 2 and 3.

Mix Proportioning

Mix proportioning data for the concrete mixes are given in Table 4. The aggregates were room dry, and the mixing water was adjusted according to the water absorbed by the aggregate.

Darex air-entraining agent was used in all the mixes.

Properties of Fresh Concrete

The properties of the fresh concrete, i.e., temperature, slump, unit weight, and air content, are given in Table 4.

PREPARATION AND TESTING OF SPECIMENS

One concrete slab, 24 x 24 x 8 in. (61 x 61 x 20 cm), four 6 x 12-in. (15 x 30-cm) cylinders and four 4 x 8-in. (10 x 20-cm) cylinders were cast from each mix in Series I and II. The slabs were cast by filling the form progressively from one end and compacting with an internal vibrator. The 6 x 12-in. (15 x 30-cm) cylinders were cast by filling the steel moulds in approximately three equal layers and compacting by rodding each layer in accordance with ASTM Standard C31. The 4 x 8-in. (10 x 20-cm) cylinders were cast by filling steel moulds in approximately two equal layers and compacting by hand rodding as before. After casting, all the moulded specimens were covered with water-saturated burlap, left in the casting room* for 24 hours, and then they were demoulded. The specimens were again covered with saturated burlap and left in the casting room* until required for testing, the burlap being kept wet.

At seven and 28 days, two 6 x 12-in. (15 x 30-cm) and two 4 x 8-in. (10 x 20-cm) cylinders from each mix were capped with a sulphur and flint mixture and tested in compression on a Amsler testing machine. At the same time, two 4 x 8-in. (10 x 20-cm) diamond drill cores were taken from each of the cast slabs. When necessary, the ends of the cores were lapped to smooth, even surfaces; then were capped and immediately compression tested dry to stimulate the field curing condition. This was followed by firing three individual Windsor probes into the top surface of the slab. Before measuring the exposed lengths, the probes were tested for firmness of inbedment.

All cylinders and drilled cores were subjected to the Schmidt hammer test using the procedure outlined in Reference 2.

Figure 1 shows a view of the Windsor probe equipment and Figures 2 and 3 show slabs after drilling and probing.

A random pattern of drilling cores and firing probes was adopted; however it was ensured that drill holes were at least 2 inches (5.0 cm) and the probes were at least 5 inches (10.0-cm) apart and at equal respective distances from the nearest edge of the concrete slab.

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*75 $\pm$ 3.0^{o}F (25 $\pm$ 1.7^{o}C) and 50% relative humidity.

TESTS RESULTS AND THEIR ANALYSIS

Sixty 6 x 12-in. (15 x 30-cm), sixty 4 x 8-in. (10 x 20-cm), sixty 4 x 8-in. (10 x 30-cm) drilled cores, and fifteen 24 x 24 x 8-in. (61 x 61 x 20-cm) slabs were tested in this investigation. The test results are summarized in Tables 5 and 6. The standard deviation and coefficient of variation calculated for the test data are shown in Tables 7 and 8.

The relationships between the exposed lengths of probe, rebound numbers, and compressive strengths of 4 x 8-in. (10 x 20-cm) cylinders and 4 x 8-in. (10 x 20-cm) drilled cores together with other comparisons are shown in Figures 4 to 21; where possible, regression lines have been fitted to the data and 95 per cent confidence limits have been drawn. A summary of the regression analyses is shown in Tables 9 and 10.

Calibration charts obtained in this investigation are compared with those supplied by the manufacturer in Figure 22, and with those published by other investigators in Figure 23.

Within-Test Variation in Results

No comparison can be made of the within-test reproducibilities of various tests because different numbers of specimens were used for different tests. For example, fifteen readings constituted one test for the Schmidt rebound hammer but only three probe values were available for the Windsor probe test; for the compression test, only two cylinders of each size and two drilled cores were tested at each age. Despite this limitation, it appears that within-test reproducibility for probes improves with age and is better for limestone concrete than for river gravel concrete. The average within-batch C.V.* for the 28-day compressive strength of 6 x 12-in. (15 x 30-cm) cylinders and 4 x 8-in. (10 x 20-cm) cores is of the order of 3 per cent while the corresponding value for the 4 x 8-in. (10 x 20-cm) cylinders is of the order of 5.0 per cent. The average C.V. values for the probes fired at 7 days were 6.5 and 4.7 per cent for river gravel and limestone concretes respectively, the corresponding values at 28 days were 4.4 and 2.1 respectively. The average C.V. values for the Schmidt rebound hammer readings at 28 days are of the order of 6 and 7 per cent for both types of concretes.

*Coefficient of Variation

CALIBRATION OF THE WINDSOR PROBE

The manufacturer's calibration curves, relating exposed length of the probe with compressive strength of concrete, are shown in Figure 22 together with the regression lines established in this investigation. The aggregates used in this investigation were crushed limestone and gravel having Mohs'* scale hardness numbers of 5.5 and 6.5 respectively. From Figure 22 it is seen that, up to 5000 psi (350 kg/cm^2), the manufacturer's curves give a lower estimate of the strength of concrete than the values obtained by crushing 6 x 12-in. (15 x 30-cm) cylinders. Beyond 5000 psi (350 kg/cm^2) this trend appears to reverse itself. Somewhat similar results have been reported by Arni (3), and Law and Burt (4). For the types of concretes investigated, manufacturer's calibration charts cannot be used with satisfactory results and it is essential for each user of the probe to calibrate his equipment with the type of concrete being used.

NATURE OF DAMAGE TO SLABS CAUSED BY PROBING

During probing the damage to slabs was relatively small, consisting of a minor disturbance on a very small area with a 5/16-in. (8-mm) hole in the concrete for the depth of penetration of probe. No major cracks or spalls were evident as was the case with 6 x 12-in. (15 x 30-cm) cylinders (1).

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*Named after mineralogist Mohs who devised a scale of hardness in which talc, the softest of all minerals is given No. 1, and diamond, the hardest of all known substances, is numbered 10.

DETECTION OF INCREASE IN STRENGTH WITH INCREASING AGE

The exposed length of the probes increased with increasing age for both gravel and limestone concretes; e.g., in one test Table 6, the exposed length of probe increased from 1.193 in. (3.03 cm) at 7 days to 1.452 in. (3.69 cm) at 28 days. The probe measurements can thus be useful for studying relative strengths of concrete in a structure.

THE WINDSOR PROBE AND OTHER TESTS

Windsor Probe Penetration Test Versus Compressive Strength of Drilled Cores

The Windsor probe test has been suggested as an alternative to drilling cores from structural concrete and testing them in compression, but the suggestion does not appear to be valid. Both tests have their merits. The Windsor probe test measures hardness of concrete from surface to a depth of about 2 in. (5.08 cm) and an estimate of compressive strength of concrete can be made from the depth reached. In the core test, cores of various sizes are drilled from structural members and are broken in compression to determine their strengths. Thus, though the two tests are aimed at estimating the strength of structural concrete, they are basically measuring two different parameters. In places (bridge abutments) where it is difficult to drill cores and if time presses,* the probe penetration versus compressive strength calibration charts could be used with advantage to assist in making decisions regarding strength of concrete in a structural member.

*In ASTM Designation C42-68 for the obtaining and testing of drilled cores, the Cores have to be submerged in lime-saturated water at 73.4 ± 3.0 F (23.0 ± 1.7C) for at least 40 hr immediately prior to making the compression test.

The regression analyses of the test data (Table 10) and plot of the test results, Figures 10, 15, 16 and 21 show that the standard error of estimate (S.E.) of 28-day compressive strength of 4 x 8-in. (10 x 20-cm) cylinders is of the same order regardless of the test method used to obtain this estimate. The S.E. based on the probe test varies from 304 psi (21 kg/cm^2) for gravel concrete to 444 (31 kg/cm^2) for limestone concrete. The corresponding values based on compressive strength of drilled cores are 488 psi (34 kg/cm^2) for gravel concrete and 386 psi (27 kg/cm^2) for limestone concrete.

It was not possible to compare the costs of the two tests. A set of three probes, a minimum for a test, costs approximately $5.25 and requires 3 to 4 minutes of operator time. A set of two 4 x 8-in. (10 x 20-cm) cores, considered minimum for a valid test could cost up to $7.00 per core if allowances are made for operator time, transportation of the cores to a laboratory, smoothening of ends, capping, and testing. In Canada and northern United States, Windsor probe tests cannot be performed in winter months on exposed concrete because of its frozen state, whereas the drilling of cores, though difficult, can still be satisfactorily performed. Under these conditions the cost comparison becomes absolutely meaningless.

Windsor Probe Test Versus Schmidt Rebound Hammer

The probe penetration test is somewhat similar to the Schmidt rebound hammer test in that both are basically hardness testers. The probe measures hardness at depth, up to two inches (5 cm), but the rebound hammer is strictly a surface hardness tester. Probe test data can be more meaningful. Probe test data are influenced to a lesser degree by surface moisture, texture, and carbonation effects because of the greater penetration of the probes in concrete. Against this there are the recurring expenses for the probes and only a limited number of probe tests can be made on a given concrete surface. The rebound hammer does not suffer from these disadvantages because an almost unlimited number of test "shots" can be taken and repeated, if necessary, without added expense.

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*This price assumes that drilling and coring is to be done by a departmental crew.

Both tests suffer from the disadvantage that they cannot be used on exposed concrete surface in winter months because of the frozen state of concrete. Also, both tests damage the concrete surface differently. The test hammer leaves surface blemishes on young concrete (2), whereas the probe leaves 5/16-in. (8-mm)-diameter holes that are damaging if not injurious to concrete (1).

There is some degree of correlation (Table 10) between the Schmidt rebound hammer test results and those obtained with the probe test. No comparison of accuracy of estimation of compressive strength of concrete from the results of the above test methods was possible, because the rebound hammer test data did not lend itself to satisfactory statistical analysis. The plot of the test results in Figures 10, 14, 16 and 20 shows that both tests may equally well predict the compressive strength of structural concrete. The accuracy of estimation may be somewhat better for the Windsor probe than for the Schmidt rebound hammer.

COMPARISON OF RESULTS OF THIS INVESTIGATION WITH THOSE OBTAINED BY OTHERS

The results obtained in this investigation have been compared with those obtained by other investigators. A comparative set of plots is shown in Figure 23. The regression lines based on the results of this investigation and that obtained by Law and Burt (4) indicate that for the same compressive strength the exposed length of probe increases with an increase in hardness of the aggregate. However, the regression line obtained by Arni (3) based on data obtained from concrete made with trap roch (Mohs' hardness number 7) lies closer to the regression line for concrete made with limestone aggregate having a Mohs' hardness of 5.5 (Figure 23).

GENERAL COMMENTS

In this investigation the results of the probe test have been expressed as exposed probe length in inches and this parameter has been correlated with strength properties of concrete and Schmidt rebound number. It would be appropriate, however, to express probe test results as probe penetration in inches (cm).

The manufacturer has tried to establish a theoretical basis for the test in terms of kinetic energy developed by the probe, but Arni (3), in his detailed analysis of this test, has challenged this basis. According to Arni, the penetration of the probe produces not only compressive forces but a complex of tension, shear, and friction forces. Considering the nature of the probe test and the number of variables involved, it is futile to insist on a sound theoretical basis for the test. Instead, like the Schmidt rebound hammer, the test should be looked upon as having only empirical relationships with compressive strength of concrete, and enough field data should be generated using this test to compensate for the variables involved.

CONCLUSIONS

The Windsor probe test gives more satisfactory results on 24 x 24 x 8-in. (61 x 61 x 20-cm) concrete slabs than on 6 x 12-in. (15 x 30-cm) cylinders (1). The probe measurements on slabs show reasonable correlation with the compressive strength of concrete cylinders and drill cores.

Each user of the Windsor probe must prepare his own calibration charts for the type of concrete under investigation.

The Windsor probe, basically a hardness test, will not yield absolute values for the strength of concrete. However, like the Schmidt rebound hammer, the probe test will indicate the relative strengths of concrete in the same structure or the relative strengths of concrete in different structures.

REFERENCES

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2. V.M. Malhotra, "Non-destructure Methods for Testing Concrete", Mines Branch Monograph No. 875, Department of Energy, Mines and Resources, Ottawa, Canada 1968, 68 pp.

3. H.T. Arni, "Impact and Penetration Tests of Concrete", First Draft Report, Federal Highway Administration, Washington, February 1971, 49 pp.

4. S.M. Law and W.T. Burt III, "Concrete Probe-Strength Study", Louisiana Department of Highways Research Report No. 44, Baton Rouge, Louisiana, December 1969, 37 pp.

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TABLE 1

Physical Properties and Chemical Analyses of the Cement*

Description of Test	
Physical Tests, General	
Time of Set (Vicat Needle): Initial	1 hr 15 min
Final	4 hr 50 min
Fineness: No. 200 (Passing)	97.9 per cent
Soundness - Autoclave	0.2 per cent
Physical Tests - Mortar Strength	
Compressive Strength of 2-in. (5-cm) cubes	
3-day	2340 psi (164 kg/cm^2)
7-day	3850 psi (271 kg/cm^2)
28-day	5370 psi (378 kg/cm^2)
Chemical Analysis	
Insoluble Residue	0.12 per cent
Silicon dioxide (SiO_2)	21.1 per cent
Aluminum Oxide (Al_2O_3)	5.8 per cent
Ferric Oxide (Fe_2O_3)	2.6 per cent
Calcium Oxide (CaO) Total	64.1 per cent
Magnesium Oxide (MgO)	2.9 per cent
Sulphur Trioxide (SO_3)	2.2 per cent
Loss on Ignition	0.34 per cent
Others	0.12 per cent

*Test results and chemical analyses supplied by the cement manufacturing company.

TABLE 2

Grading of Aggregates

Coarse Aggregate		Fine Aggregate	
Sieve size	Percentage retained	Sieve size	Percentage retained
3/4 in. (19 mm)	33.3	4-mesh 8-mesh	0 10.0
3/8 in. (9.5 mm)	66.6	16-mesh 30-mesh	32.5 57.5
No. 4	100.0	50-mesh 100-mesh Pan	80.0 94.0 100.0

TABLE 3

Physical Properties of Coarse and Fine Aggregates

	River Gravel	Crushed Limestone	Natural Sand
Specific Gravity	2.72	2.68	2.70
Absorption, %	0.40	0.40	0.50

TABLE 4

Mix Design Data and Properties of Fresh Concrete

Mix Series	Mix No.	Mix Design Data: Water/Cement Ratio*	Mix Design Data: Aggregate/Cement Ratio*	Temp °F	Temp °C	Slump in.	Slump cm	Unit Weight lb/cu ft	Unit Weight kg/cu m	Air Content %
I	1	**	**	72	22	3.0	7.6	140.4	2249	5.5
	2	0.67	7.76	70	21	2.5	6.4	142.2	2278	5.1
	3	0.57	6.52	70	21	2.5	6.4	143.4	2297	5.1
Gravel	4	0.46	5.28	73	23	3.0	7.6	144.8	2320	5.0
Concrete	5	0.44	4.70	70	21	3.0	7.6	145.2	2326	4.3
	6	0.41	4.45	72	22	3.0	7.6	148.0	2371	3.9
	7	0.39	3.95	72	22	3.5	8.9	146.8	2352	4.0
	8	0.33	3.04	70	21	2.5	6.4	148.8	2384	3.1
II	1	0.71	8.43	73	23	3.0	7.6	135.2	2166	5.5
	2	0.69	7.76	73	23	3.0	7.6	142.8	2287	4.2
Limestone	3	0.57	6.51	70	21	3.0	7.6	142.4	2281	5.0
	4	0.46	5.28	74	23	3.0	7.6	145.6	2332	4.0
Concrete	5	0.41	4.45	74	23	2.75	7.0	143.2	2294	5.0
	6	0.39	3.94	74	23	2.75	7.0	147.0	2355	4.0
	7	0.34	3.05	74	23	2.25	5.7	147.0	2355	4.1

*All ratios are by weight.
**Not available.

TABLE 5

Summary of Test Results After 7 Days' Aging

Series No.	Mix No.	Exposed Lengths of Probes		Compressive Strengths of Companion Cylinders				Compressive Strengths of 4 x 8-in. (10 x 20-cm) Drilled Cores	
				6 x 12-in. (15 x 30-cm)		4 x 8-in. (10 x 20-cm)			
		in.	cm	psi	kg/cm^2	psi	kg/cm^2	psi	kg/cm^2
I	1	1.193	3.030	1185	83.3	990	69.6	1400	98.4
	2	1.208	3.068	2135	150.1	2240	157.5	1990	139.9
	3	1.495	3.797	2625	184.5	2980	209.5	2750	193.3
	4	1.649	4.188	3280	230.6	3415	240.1	3740	262.9
Gravel	5	1.823	4.630	3510	246.8	3860	271.4	4040	284.0
	6	1.827	4.641	3595	252.7	4185	294.2	4040	284.0
Concrete	7	1.684	4.277	4390	308.6	4580	322.0	4710	331.1
	8	1.892	4.806	5050	255.0	5255	369.4	5510	387.4
II	1	1.017	2.583	1625	114.2	---	---	1465	103.0
	2	1.452	3.688	1995	140.2	2090	146.9	2020	142.0
Limestone	3	1.609	4.087	2985	209.8	3070	215.8	2580	181.4
	4	1.841	4.676	3670	258.0	4080	286.8	3250	228.5
Concrete	5	1.792	4.552	3875	272.4	4205	295.6	3720	261.5
	6	1.819	4.620	4255	299.1	4010	281.9	3620	254.5
	7	1.817	4.615	4510	317.1	4460	313.5	4380	307.9

Notes:
1. Each probe value is the average of three individual tests.
2. Each compressive strength value is the average of two tests.
3. All probes were fired on the trowelled finished top surface of the slabs.

TABLE 6

Summary of Test Results After 28 Days' Aging

Series No.	Mix No.	Exposed Lengths of Probes on Slabs		Compressive Strengths of Companion Cylinders				Compressive Strengths of 4 x 8-in. (10 x 20-cm) drilled cores from slabs		Rebound Number on Slabs
				6 x 12-in. (15 x 30-cm)		4 x 8-in. (10 x 20-cm)				
		in.	cm	psi	kg/cm^2	psi	kg/cm^2	psi	kg/cm^2	
I	1	1.452	3.688	1510	106.2	1345	94.6	1880	132.2	26
	2	1.755	4.458	3130	220.0	3495	245.7	2705	190.2	29
	3	1.788	4.542	3635	255.5	4090	287.5	3605	253.4	30
Gravel	4	1.895	4.813	4195	294.9	4550	319.9	4675	328.7	35
Concrete	5	1.857	4.717	4370	307.2	4590	322.7	4935	346.9	37
	6	2.056	5.222	4450	312.8	5025	353.3	4695	330.0	36
	7	1.802	4.577	4740	333.2	--	--	5190	364.9	36
	8	2.149	5.458	6115	429.9	5970	419.7	6360	447.1	43
II	1	1.345	3.416	2120	149.0	2375	167.0	1990	139.9	24
	2	1.556	3.952	2540	178.6	2820	198.2	2460	172.9	32
	3	1.730	4.394	3855	271.0	3795	266.8	3155	221.8	30
Limestone	4	1.800	4.572	4630	325.5	4850	341.0	3980	279.8	35
	5	1.891	4.803	4415	310.4	4330	304.4	4065	285.8	34
Concrete	6	1.863	4.732	4980	350.1	5390	378.9	4010	281.9	37
	7	1.979	5.027	5310	373.3	5295	372.2	4920	345.9	40

Notes:
1. Each probe value is the average of three individual tests.
2. Each compressive strength value is the average of two tests.
3. All probes were fired on the top surface of the slabs.
4. All rebound numbers were taken on the top surface of the slabs with the Schmidt rebound hammer (No. N2-6) directed downward; the values obtained were corrected for using the hammer against gravity (2).

TABLE 7

Within-Batch Standard Deviations and Coefficients of Variation in Results of Tests 7 Days After Casting

Series No.	Mix No.	Exposed Lengths of Probes			6 x 12-in. cylinder (15 x 30-cm)			4 x 8-in. cylinder (10 x 20-cm)			4 x 8-in. cores (10 x 20-cm)		
		S.D.*		C.V.**	S.D.*		C.V.**	S.D.*		C.V.**	S.D.*		C.V.**
		in.	cm	%	psi	kg/cm^2	%	psi	kg/cm^2	%	psi	kg/cm^2	%
I	1	0.121	0.307	10.2	60	4.22	2.8	88	6.19	8.9	46	3.23	3.3
	2	0.109	0.277	9.0	106	7.45	4.0	39	2.74	1.7	21	1.48	1.1
	3	0.167	0.424	11.2	88	6.19	2.7	28	1.97	1.0	236	16.59	8.6
Gravel	4	0.195	0.495	11.8	53	3.73	1.5	269	18.91	7.9	18	1.27	0.5
Concrete	5	0.037	0.094	2.1	67	4.71	1.3	88	6.19	2.3	180	12.65	4.5
	6	0.037	0.094	2.1	57	4.01	4.8	67	4.71	1.6	255	17.93	6.3
	7	0.081	0.206	4.8	95	6.68	2.2	282	19.82	6.2	7	0.49	0.2
	8	0.040	0.102	2.1	174	12.23	5.0	134	9.42	2.6	170	11.95	3.1
II	1	0.058	0.147	5.7	46	3.23	2.3	--	--	--	7	0.49	0.5
	2	0.112	0.284	7.7	21	1.48	0.7	85	5.98	4.1	0.0	0.0	0.0
Limestone	3	0.079	0.201	4.9	212	14.91	5.8	67	4.71	2.2	71	4.99	2.7
	4	0.077	0.196	4.2	14	0.98	0.3	311	21.86	7.6	18	1.27	0.5
Concrete	5	0.096	0.244	5.3	78	5.48	1.7	79	5.55	1.9	141	9.91	3.8
	6	0.033	0.084	1.8	35	2.46	2.2	293	20.60	7.3	11	0.77	0.3
	7	0.059	0.150	3.2	78	5.48	2.0	92	6.47	2.1	205	14.41	4.7

*Standard deviation

**Coefficient of variation

Notes: 1. For probes, within-batch S.D. is based on three probes.

2. For cylinders, within-batch S.D. is based on two tests.

3. For cores, within-batch S.D. is based on two tests.

TABLE 8

Within-Batch Standard Deviations and Coefficients of Variation in Results of Tests 28 Days After Casting

Series No.	Mix No.	Exposed Length of Probes in slabs 24 x 24 x 8-in. (61 x 61 x 20-cm) S.D.*		C.V.**	Cylinders 6 x 12-in. (15 x 30-cm) S.D.*		C.V.**	Cylinders 4 x 8-in. (10 x 20-cm) S.D.*		C.V.**	Cores 4 x 8-in. (10 x 20-cm) S.D.*		C.V.**	Rebound Number on Slabs S.D.*	C.V.**
		in.	cm	%	psi	kg/cm^2	%	psi	kg/cm^2	%	psi	kg/cm^2	%		%
I Gravel Concrete	1	0.192	0.488	13.2	35	2.46	1.1	35	2.46	2.6	95	6.68	5.1	1.4	6.7
	2	0.088	0.224	5.0	163	11.46	4.5	212	14.90	6.1	21	1.48	0.8	1.2	5.0
	3	0.043	0.109	2.4	106	7.45	2.5	156	10.97	3.8	11	0.77	0.3	3.3	13.4
	4	0.039	0.099	2.0	166	11.67	3.7	71	4.99	1.6	57	4.01	1.2	1.4	4.7
	5	0.010	0.025	0.5	46	3.23	0.8	11	0.77	2.3	92	6.47	1.9	2.0	6.4
	6	0.087	0.221	4.2	42	2.95	2.8	779	54.76	15.5	134	9.42	2.9	1.0	3.1
	7	0.072	0.183	4.0	262	18.42	5.5	79	5.55	1.3	95	6.68	1.8	2.2	7.2
	8	0.087	0.221	4.1	46	3.23	1.1	297	20.88	5.0	18	1.27	0.3	1.8	4.6
II Limestone Concrete	1	0.030	0.076	2.2	39	2.74	1.5	21	1.48	0.9	32	2.25	1.6	1.9	10.4
	2	0.035	0.089	2.2	99	6.96	2.6	134	9.42	4.8	99	6.96	4.0	2.1	7.8
	3	0.032	0.081	1.8	346	24.33	7.5	219	15.40	5.8	299	21.02	9.2	1.6	6.2
	4	0.017	0.043	1.0	113	7.95	2.3	71	4.99	1.5	28	1.96	0.7	1.4	4.8
	5	0.041	0.104	2.2	110	7.73	2.1	354	24.89	8.2	120	8.44	3.0	1.2	4.0
	6	0.041	0.104	2.2	42	2.95	2.0	399	28.05	7.4	212	14.90	5.3	2.2	6.7
	7	0.057	0.145	2.9	134	9.42	3.0	375	26.36	7.1	184	12.94	3.7	2.9	8.3

*Standard deviation

**Coefficient of variation

Notes:
1. For probes, within-batch S.D. based on three probes.
2. For cylinders, within-batch S.D. based on two test results.
3. For cores, within-batch S.D. based on two test results.
4. For rebound number, within-batch S.D. based on 15 readings.

TABLE 9

Summary of Regression Analysis of Results of Tests 7 Days After Casting

Series No.	Nature of Relationship	Refer to Figure No.	Correlation Coefficient	Regression Equation	Standard Error of Estimate psi	Standard Error of Estimate kg/cm^2
I Gravel Concrete	Exposed probe length versus compressive strength of 4x8-in. (10x20-cm) cylinders	4	0.919	$Y^{**}=4567X^{*}-3852$ psi	535	38
	Exposed probe length versus compressive strength of 4 x 8-in. (10 x 20-cm) cores	5	0.930	$Y^{**}=4693X^{*}-3969$ psi	508	36
II Limestone Concrete	Exposed probe length versus compressive strength of 4 x 8-in. (10 x 20-cm) cylinders	7	0.975	$Y^{**}=5591X^{*}-5974$ psi	199	14
	Exposed probe length versus compressive strength of 4 x 8-in. (10 x 20-cm) cores	8	0.893	$Y^{**}=3041X^{*}-1925$ psi	462	32

*X=Exposed probe length, in.
**Y=Compressive strength, psi

TABLE 10

Summary of Regression Analysis for 28-Day Test Results

Series No.	Nature of Relationship	Refer to Figure No.	Correlation Coefficient	Regression Equation	Standard Error of Estimate			
					psi	kg/cm^2	in.	cm
I Gravel Concrete	Exposed probe length vs compressive strength of 4x8-in. (10x20-cm) cylinders	10	0.978	$Y^{**}=-7536+6317X^{*}$ psi	304	21	----	----
	Exposed probe length vs compressive strength of 4x8-in. (10x20-cm) cores	11	0.865	$Y=-6740+5962X$ psi	725	51	----	----
	Exposed probe length vs compressive strength of 6x12-in. (15x30-cm) cylinders	12	0.918	$Y=-6776+5853X$ psi	529	37	----	----
	Rebound number vs Exposed probe length	13	0.882	$^{++}Y_1=0.681+0.0342X_1^{+}$ in.	---	--	0.1	0.25
	Compressive strength of 4x8-in. (10x20-cm) cores vs compressive strength of 4x8-in. (10x20-cm) cylinders	15	0.942	$Y=395+0.911X$ psi	488	34	---	---
II Limestone Concrete	Exposed probe length vs compressive strength of 4x8-in. (10x20-cm) cylinders	16	0.927	$Y=-4574+5004X$ psi	444	31	----	----
	Exposed probe length vs compressive strength of 4x8-in. (10x20-cm) cores	17	0.969	$Y=-4362+4531X$ psi	252	18	----	----
	Exposed probe length vs compressive strength of 6x12-in. (15x30-cm) cylinders	18	0.963	$Y=-5333+5385X$ psi	327	23	----	----
	Rebound number vs Exposed probe length	19	0.911	$^{++}Y_1=0.459+0.0386\,^{+}X_1$ in.	--	---	0.09	0.23
	Compressive strength of 4x8-in. (10x20-cm) cores vs compressive strength of 4x8-in. (10x20-cm) cylinders	21	0.945	$Y=289+1.09X$ psi	386	27	----	----

*X=Exposed probe Length, in.

**Y=Compressive strength, psi.

$^{+}X_1$=Rebound number

$^{++}Y_1$=Exposed probe length, in.

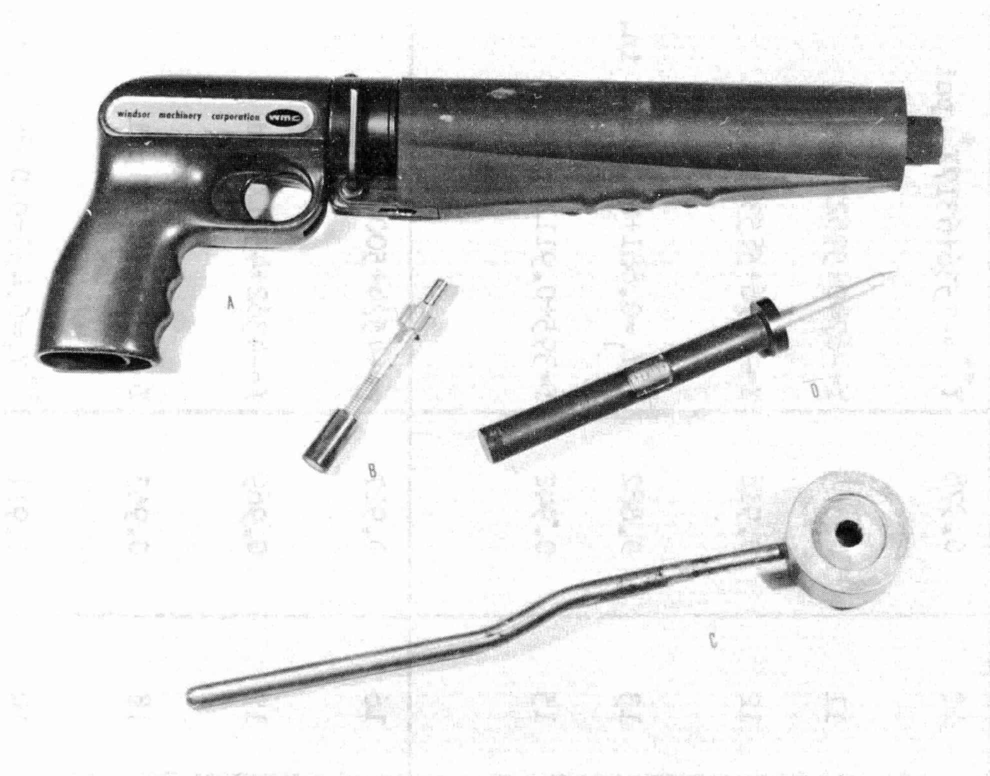

Figure 1 - A view of the Windsor probe equipment.
A: driver unit, B: probe for normal-weight concrete.
C: single-probe templet, D: calibrated depth gauge.

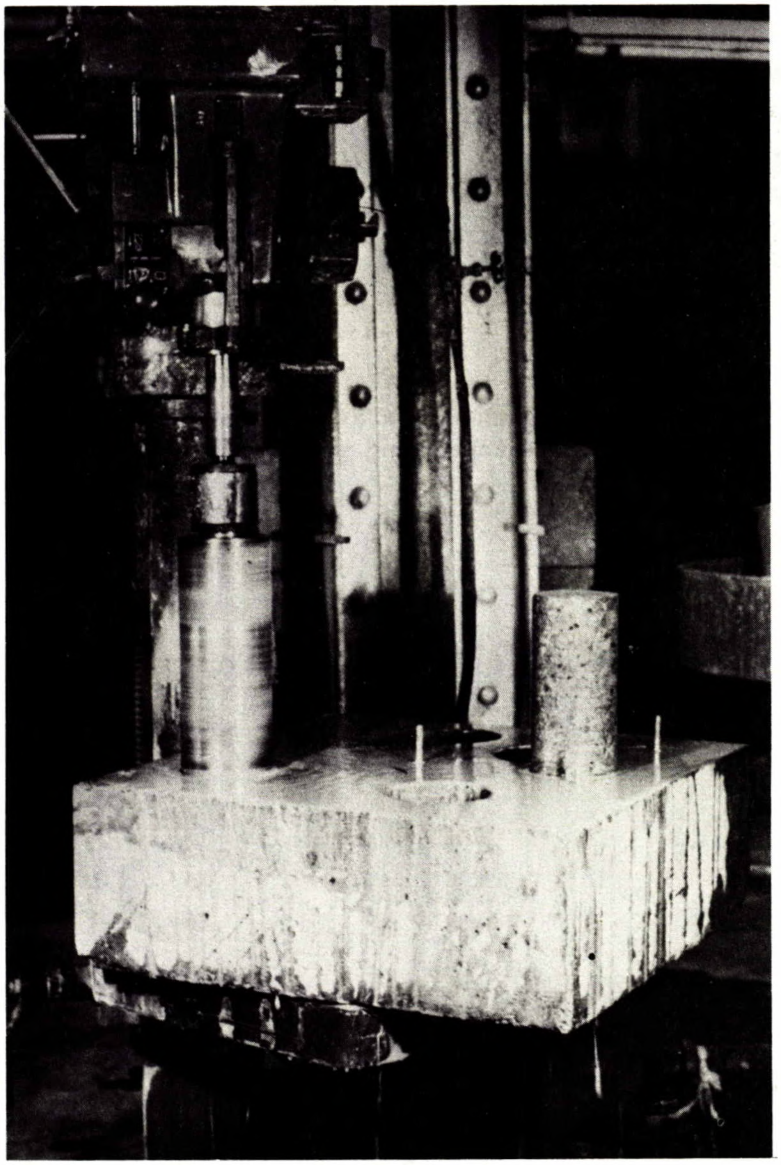

Figure 2 - A view of the 24 x 24 x 8-in. (61 x 61 x 20-cm) slabs being drilled after 28 days to obtain 4 x 8-in. (10 x 20-cm) cores.

Note: Two probes fired into the slab at 7 days can be seen on the right.

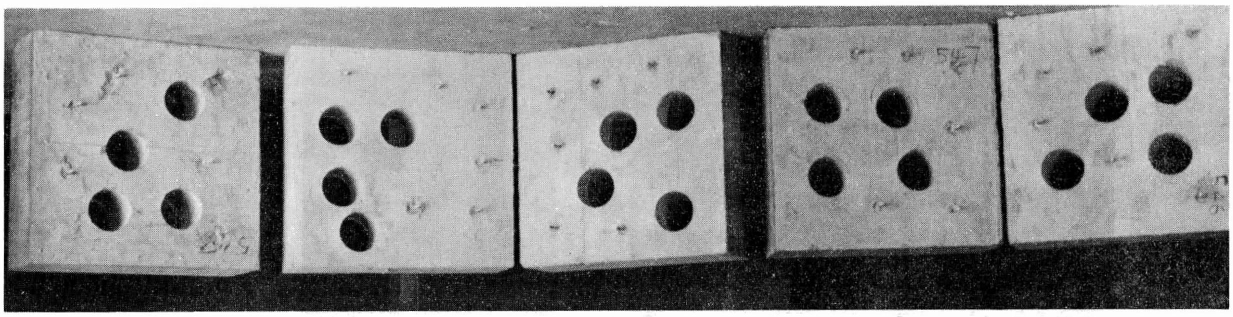

Figure 3(a) - A view of some of the 24 x 24 x 8-in. (61 x 61 x 20-cm) slabs after completion of probing and drilling after 28 days.

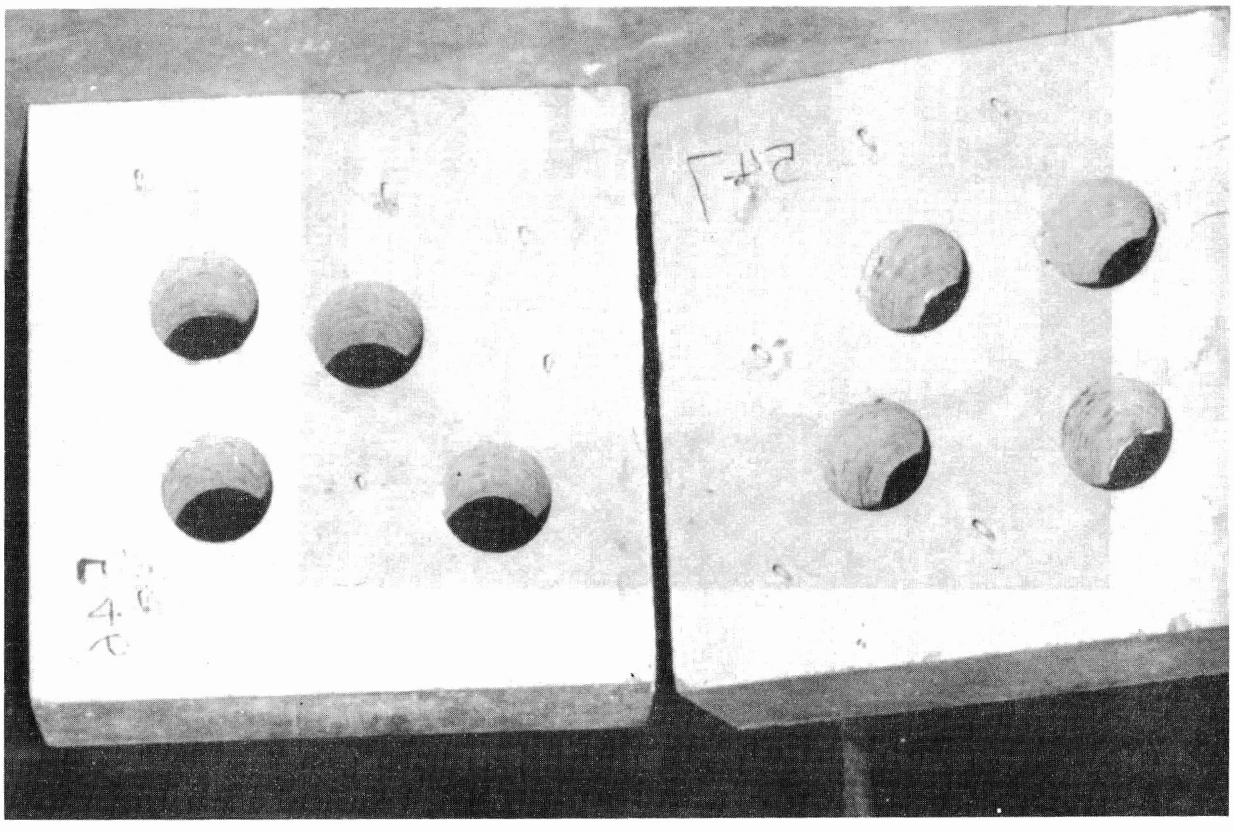

Figure 3(b) - A close-up of the slabs shown in Figure 3(a).

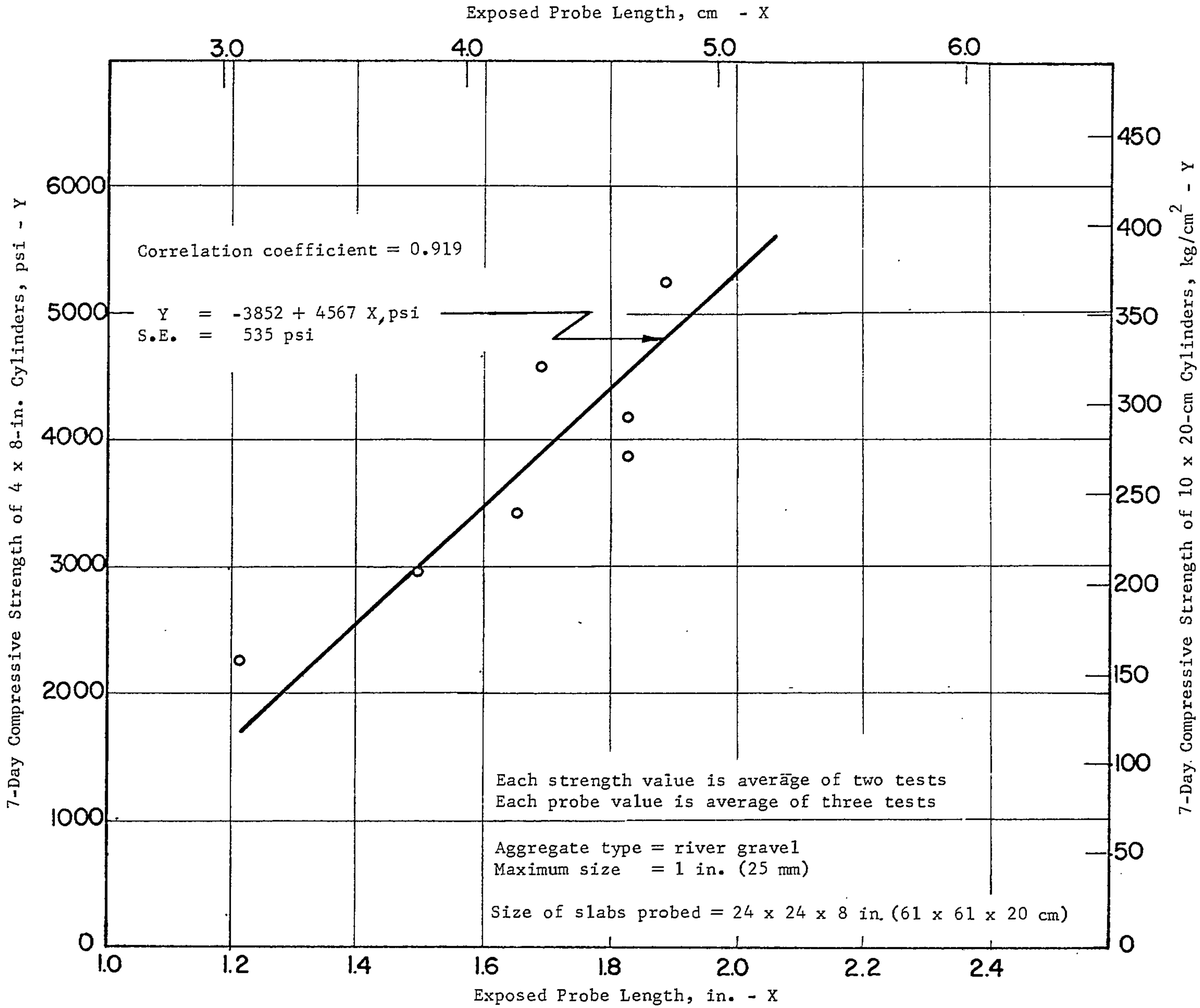

Figure 4 - Relationship between exposed probe lengths and 7-day compressive strengths of 4 x 8-in. (10 x 20-cm) cylinders (river gravel aggregate)

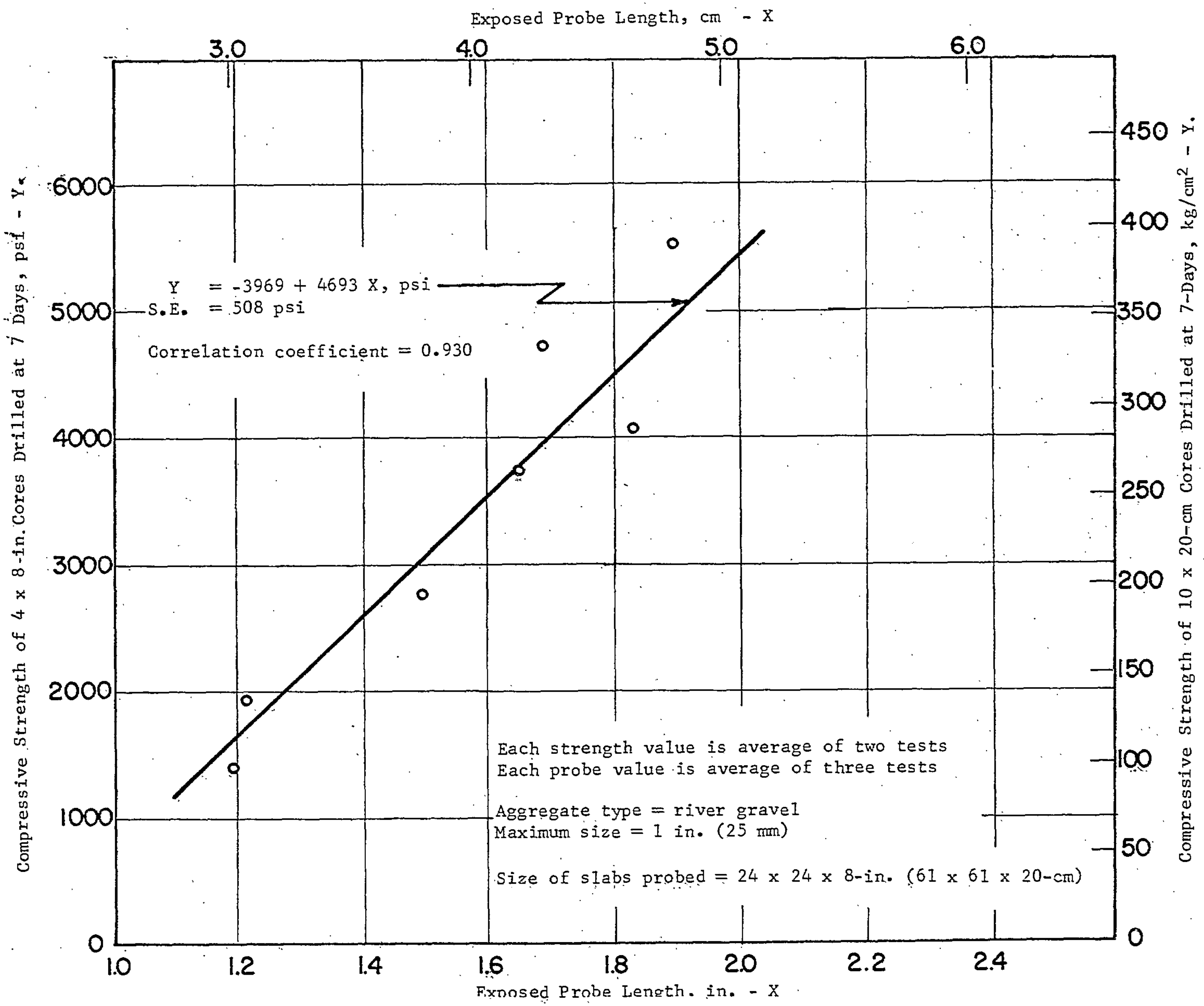

Figure 5 - Relationship between exposed probe lengths and compressive strengths of 4 x 8-in. (10 x 20-cm) cores drilled after 7 days (river gravel aggregate)

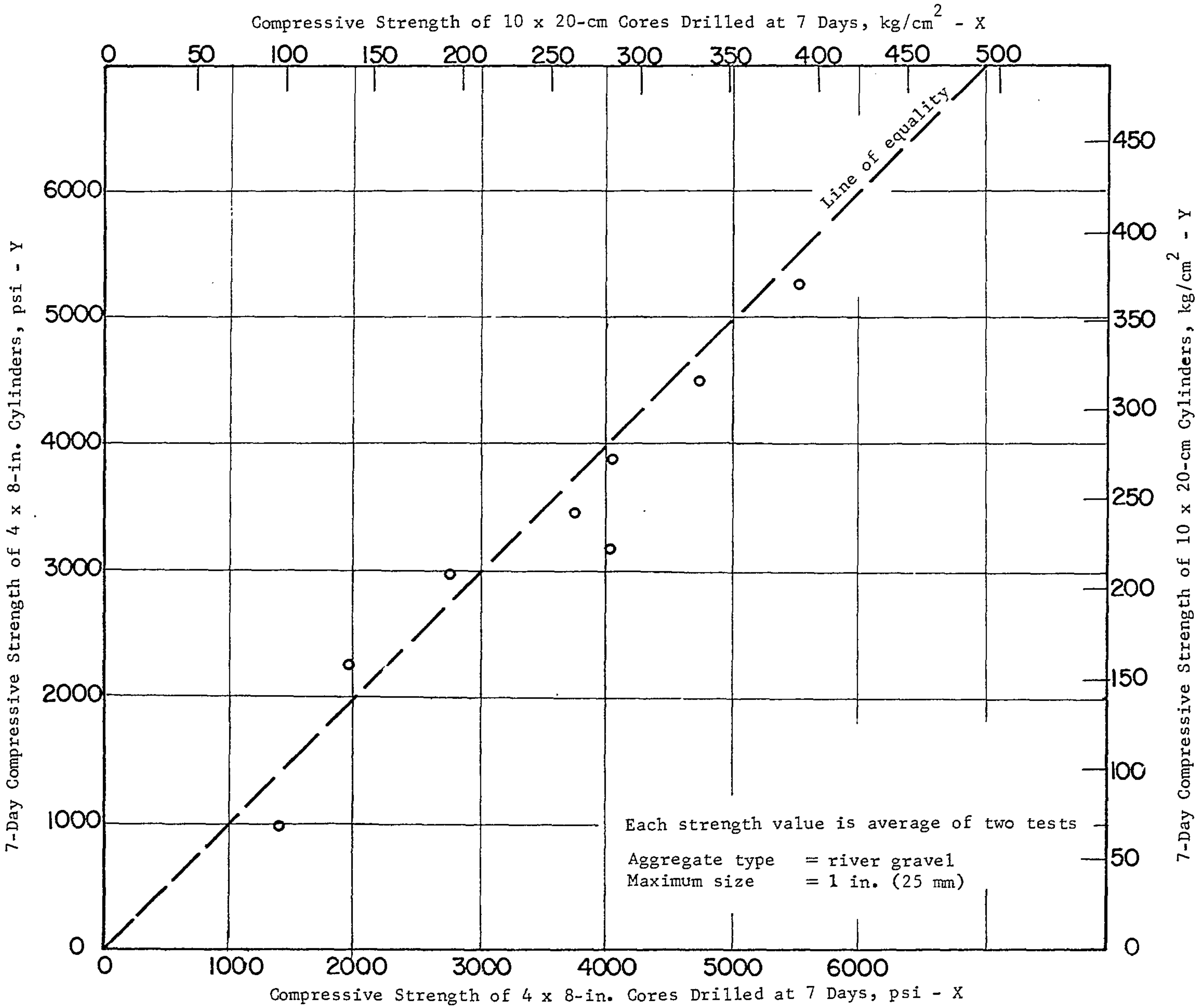

Figure 6 - Relationship between compressive strengths of 4 x 8-in. (10 x 20-cm) cores drilled at 7 days and compressive strengths of 4 x 8-in. (10 x 20-cm) cylinders (river gravel aggregate)

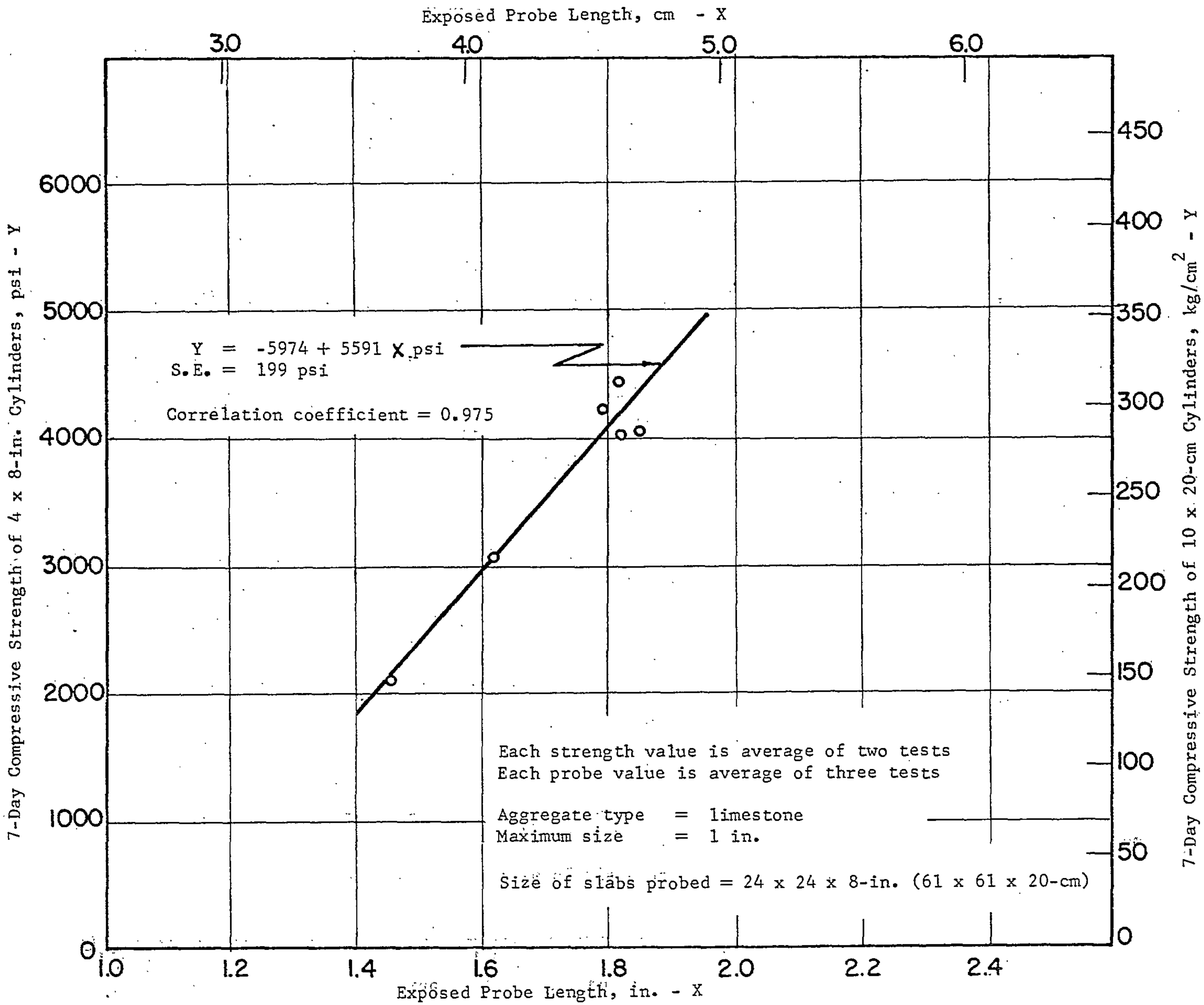

Figure 7 - Relationship between exposed probe lengths and 7-day compressive strengths of 4 x 8-in. (10 x 20-cm) cylinders (limestone aggregate)

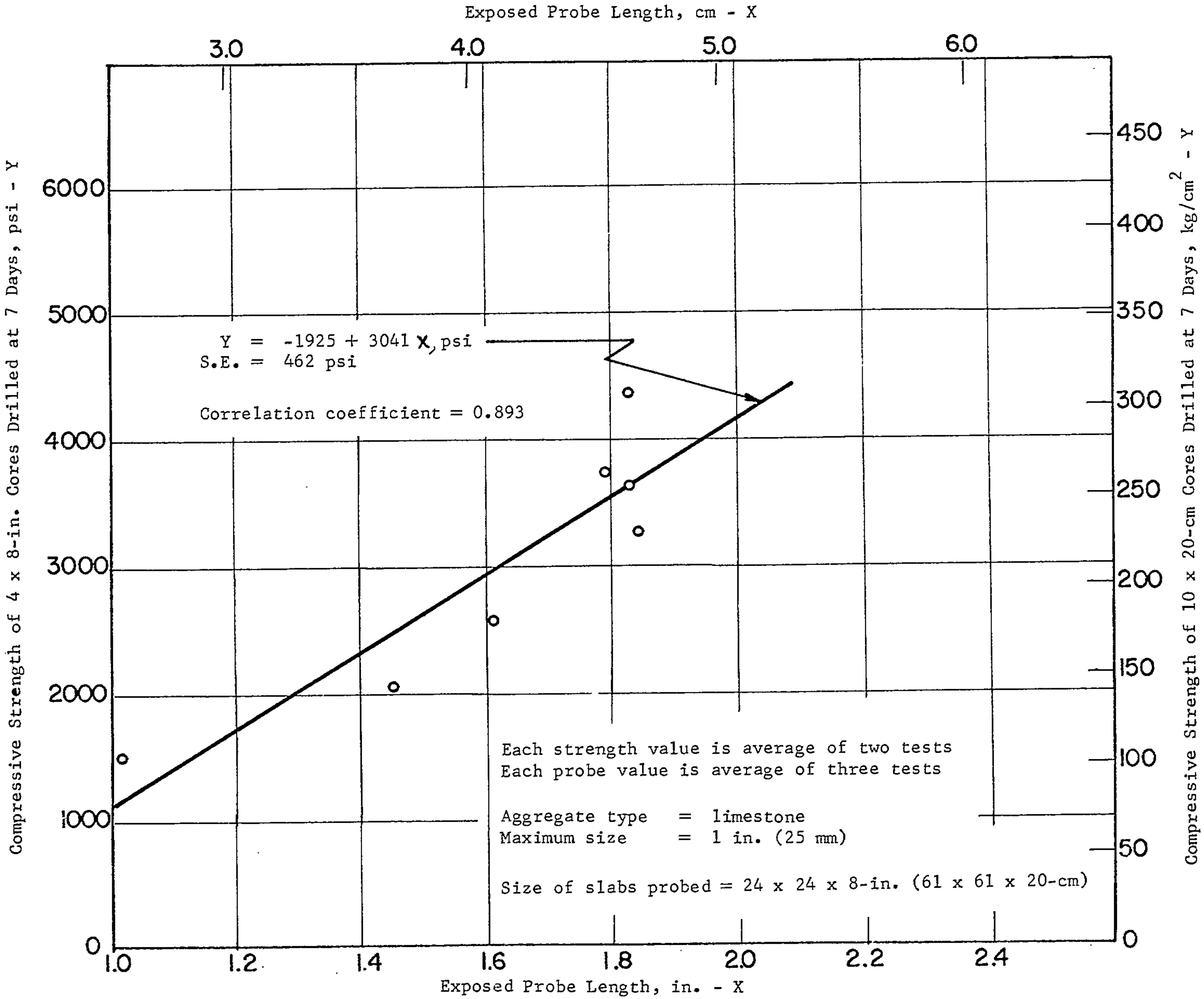

Figure 8 - Relationship between exposed probe lengths and compressive strengths of 4 x 8-in. (10 x 20-cm) cores drilled after 7 days (limestone aggregate)

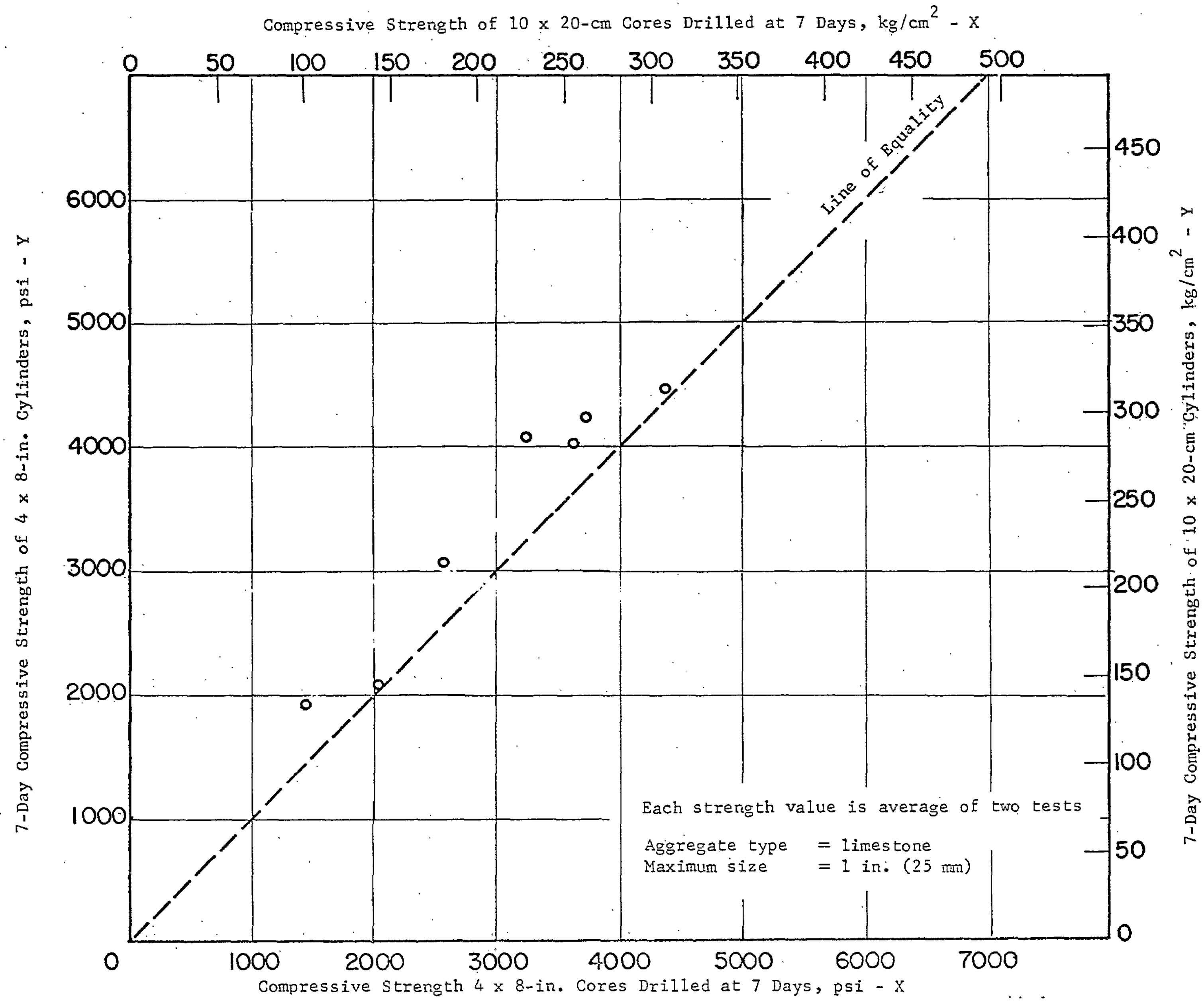

Figure 9 - Relationship between compressive strengths of 4 x 8-in. (10 x 20-cm) cores drilled after 7 days and compressive strengths of 4 x 8-in. (10 x 20-cm) cylinders (limestone aggregate)

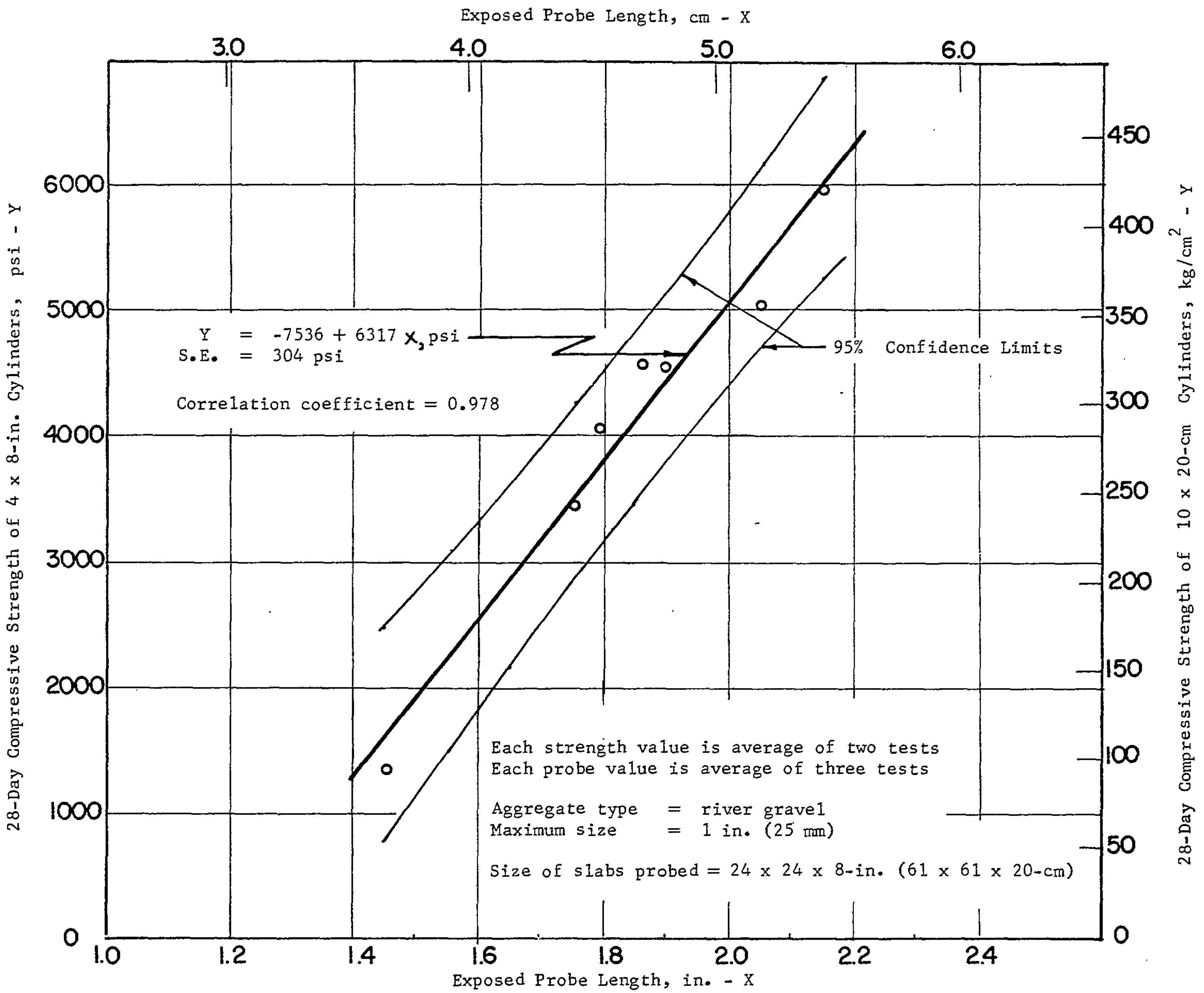

Figure 10 - Relationship between exposed probe lengths and 28-day compressive strengths of 4 x 8-in. (10 x 20-cm) cylinders (river gravel aggregate)

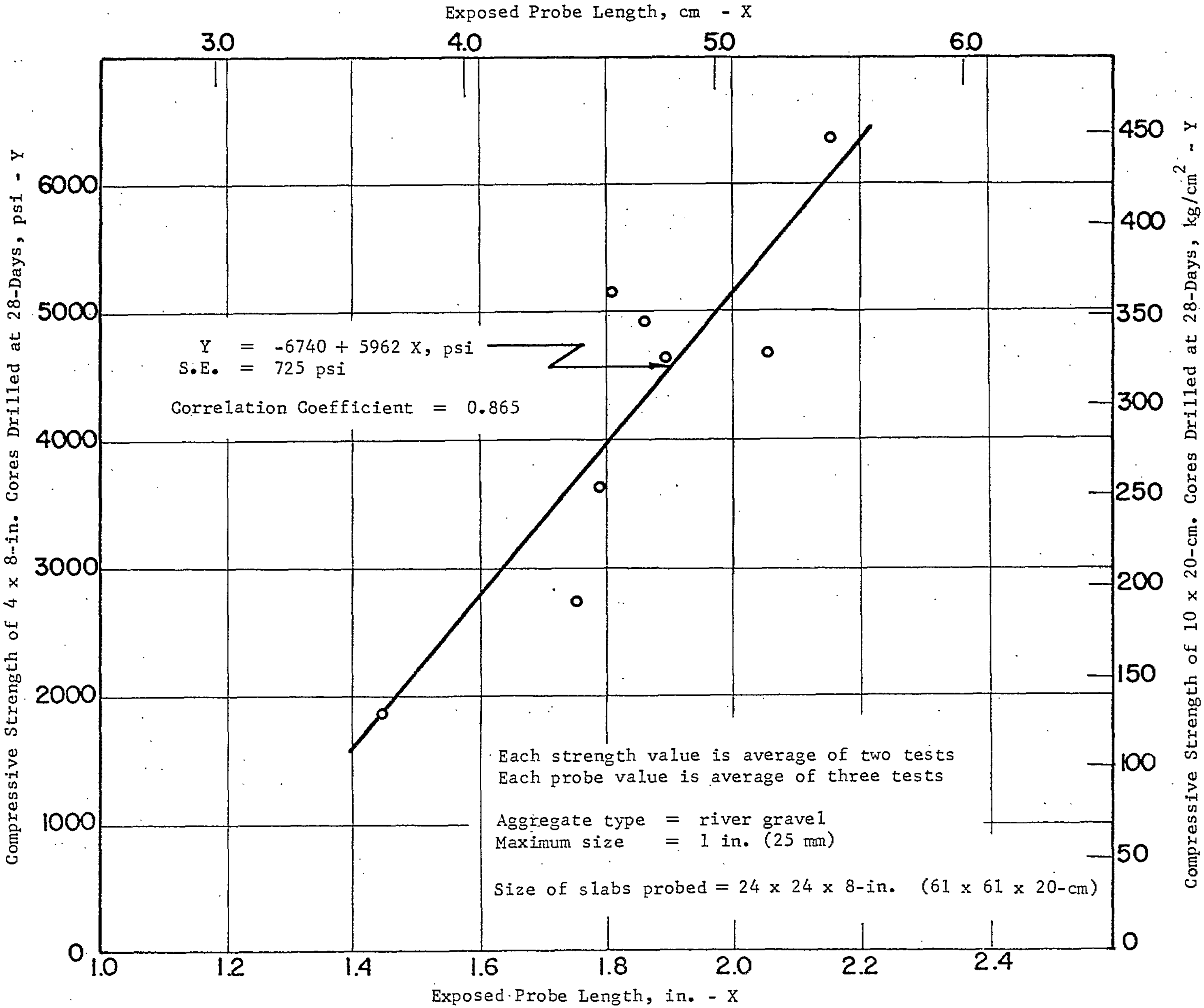

Figure 11 - Relationship between exposed probe lengths and compressive strengths of 4 x 8-in. (10 x 20-cm) drilled cores at 28 days (river gravel aggregate)

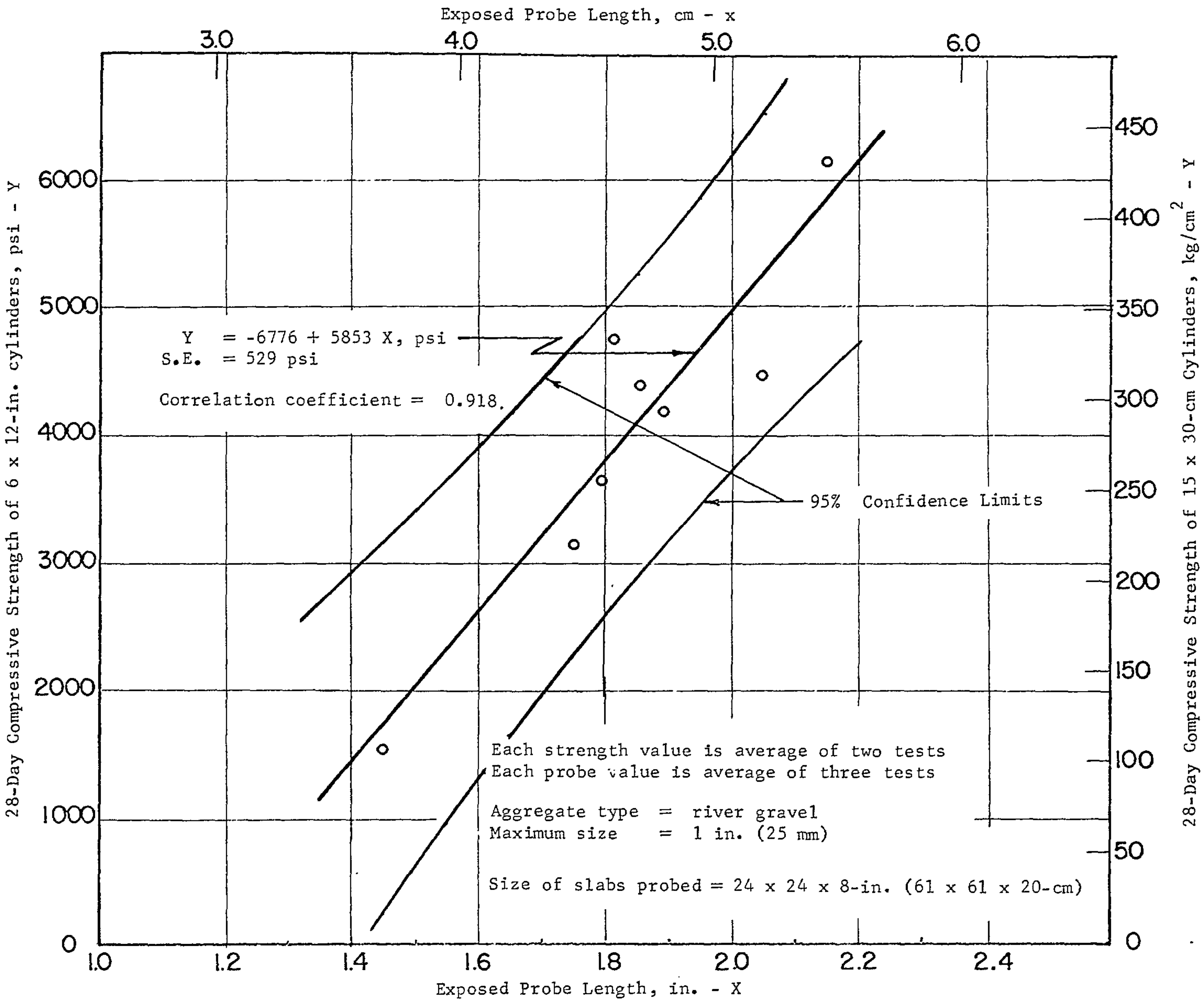

Figure 12 - Relationship between exposed probe lengths and 28-day compressive strengths of 6 x 12-in. (15 x 30-cm) cylinders (river gravel aggregate)

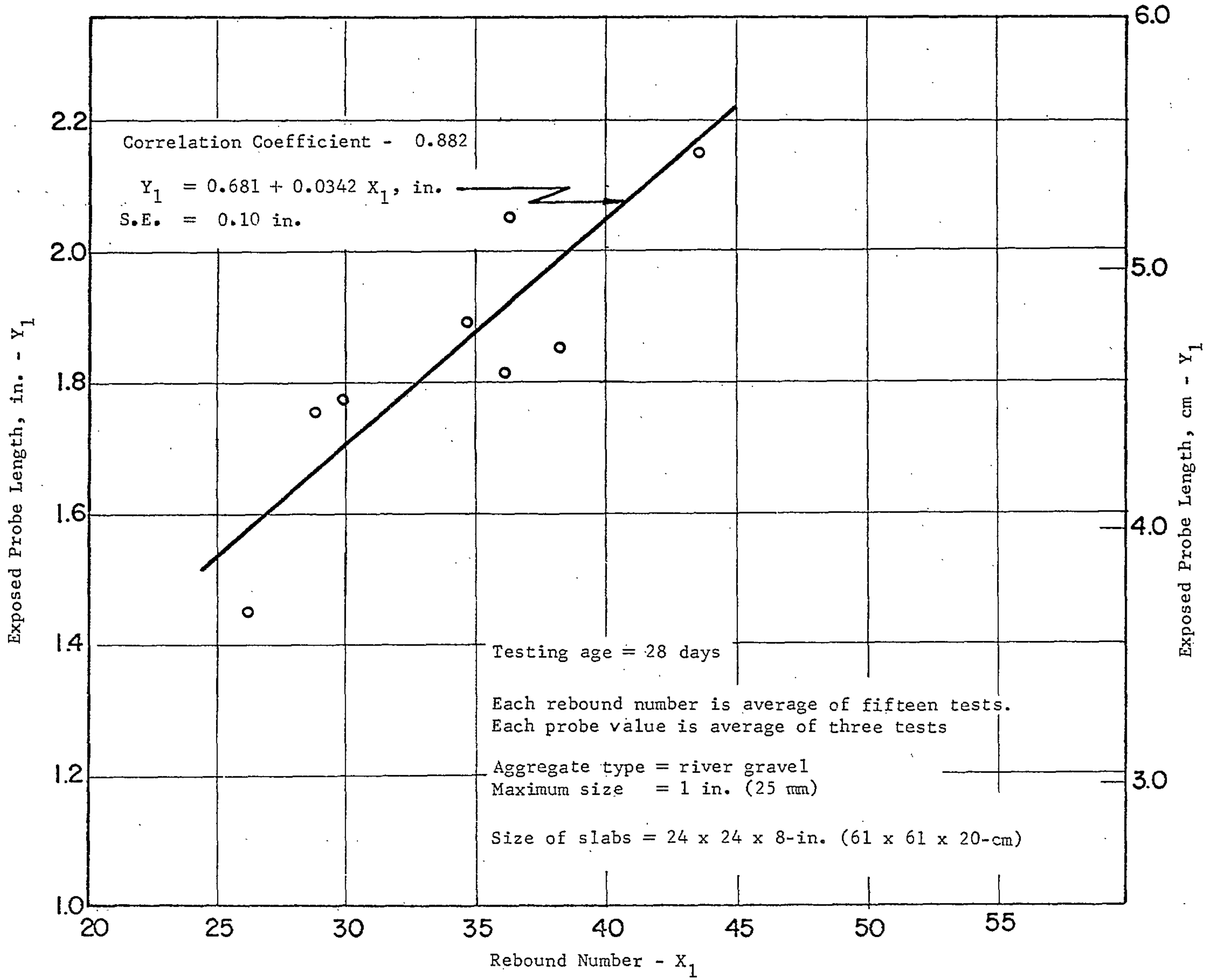

Figure 13 - Relationship between rebound number and exposed probe length (river gravel aggregate)

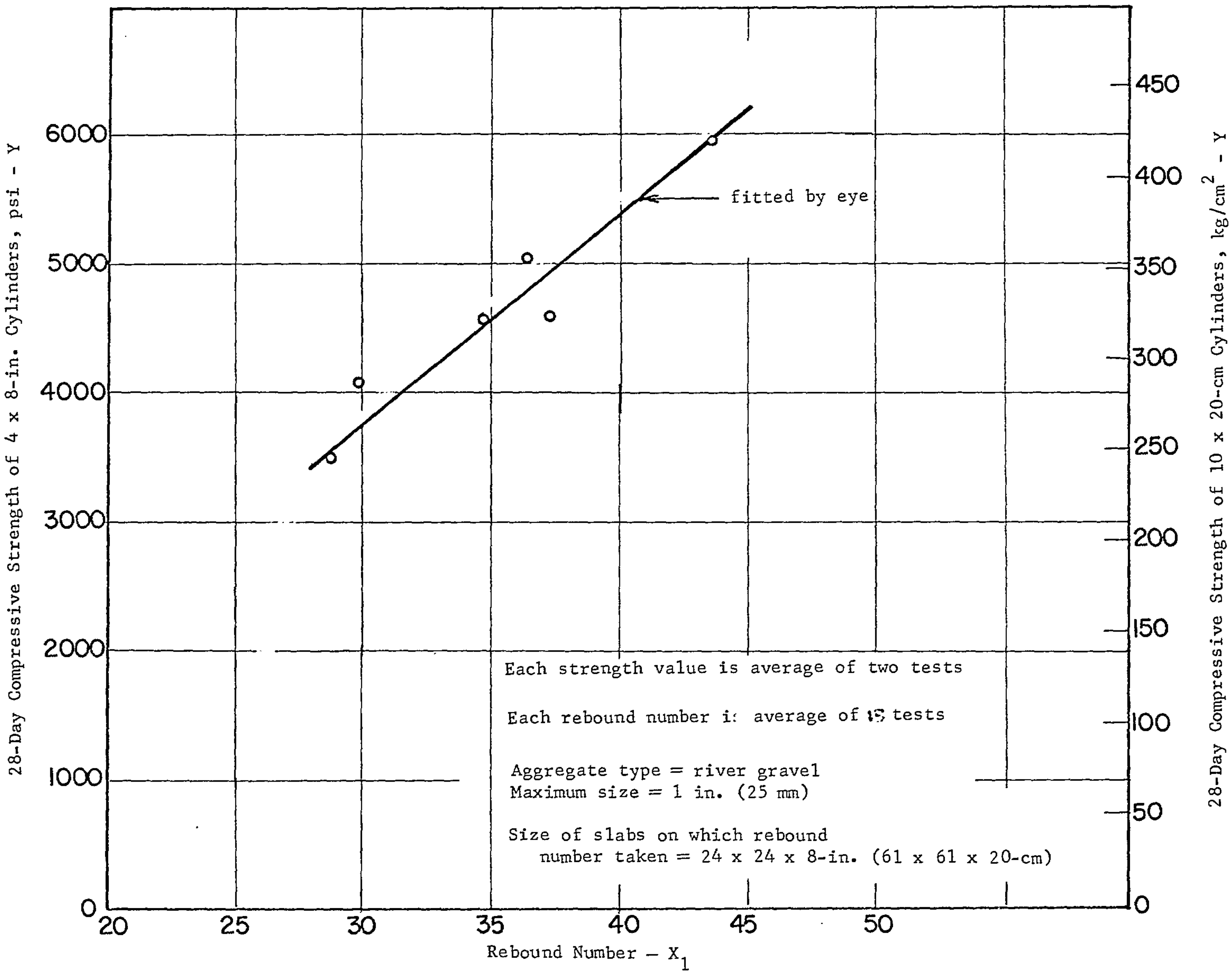

Figure 14 - Relationship between rebound numbers and 28-day compressive strengths of 4 x 8-in. (10 x 20-cm) cylinders (river gravel aggregate)

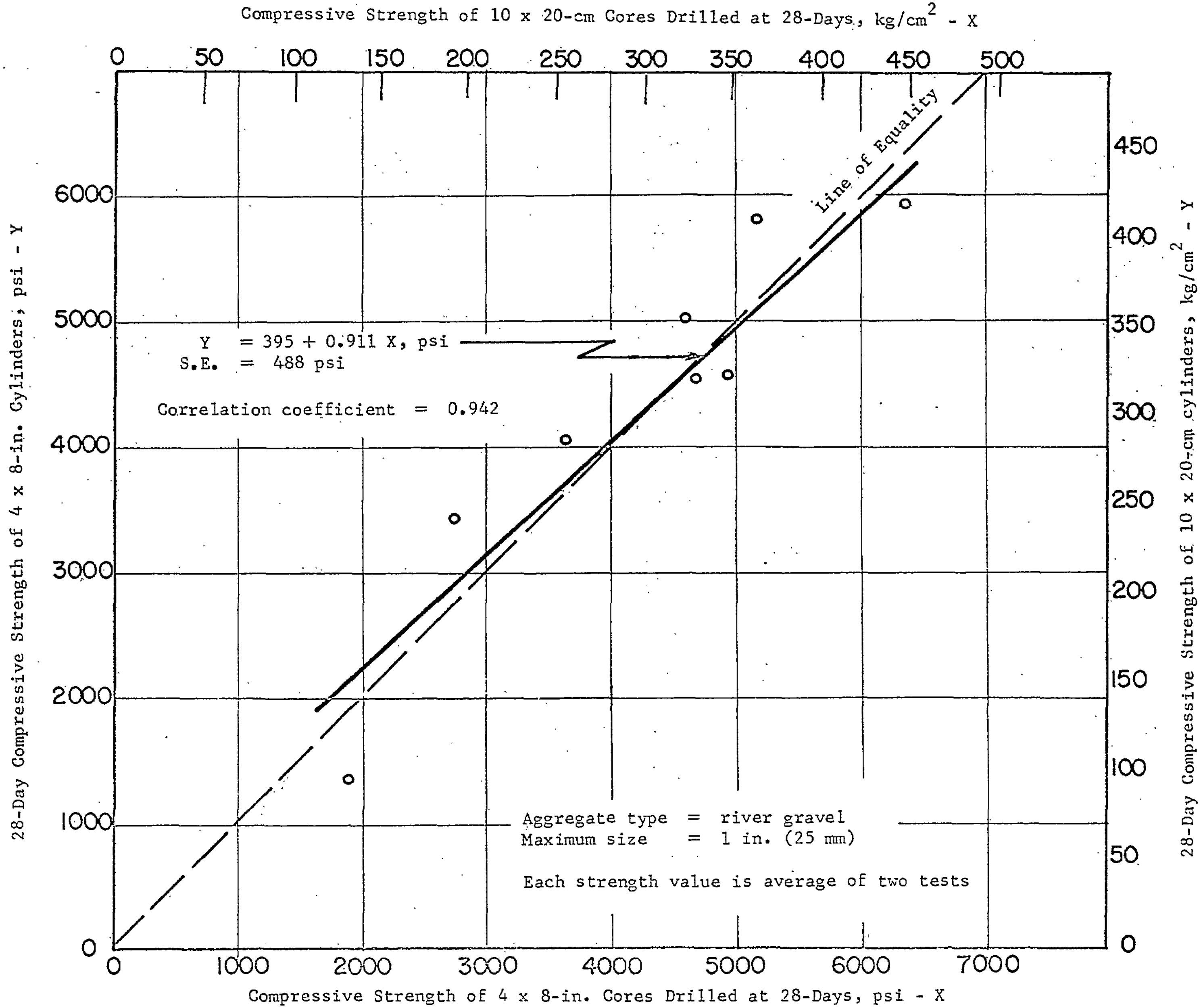

Figure 15 - Relationship between compressive strengths of 4 x 8-in. (10 x 20-cm) cores drilled after 28 days and compressive strengths of 4 x 8-in. (10 x 20-cm) cylinders (river gravel aggregate)

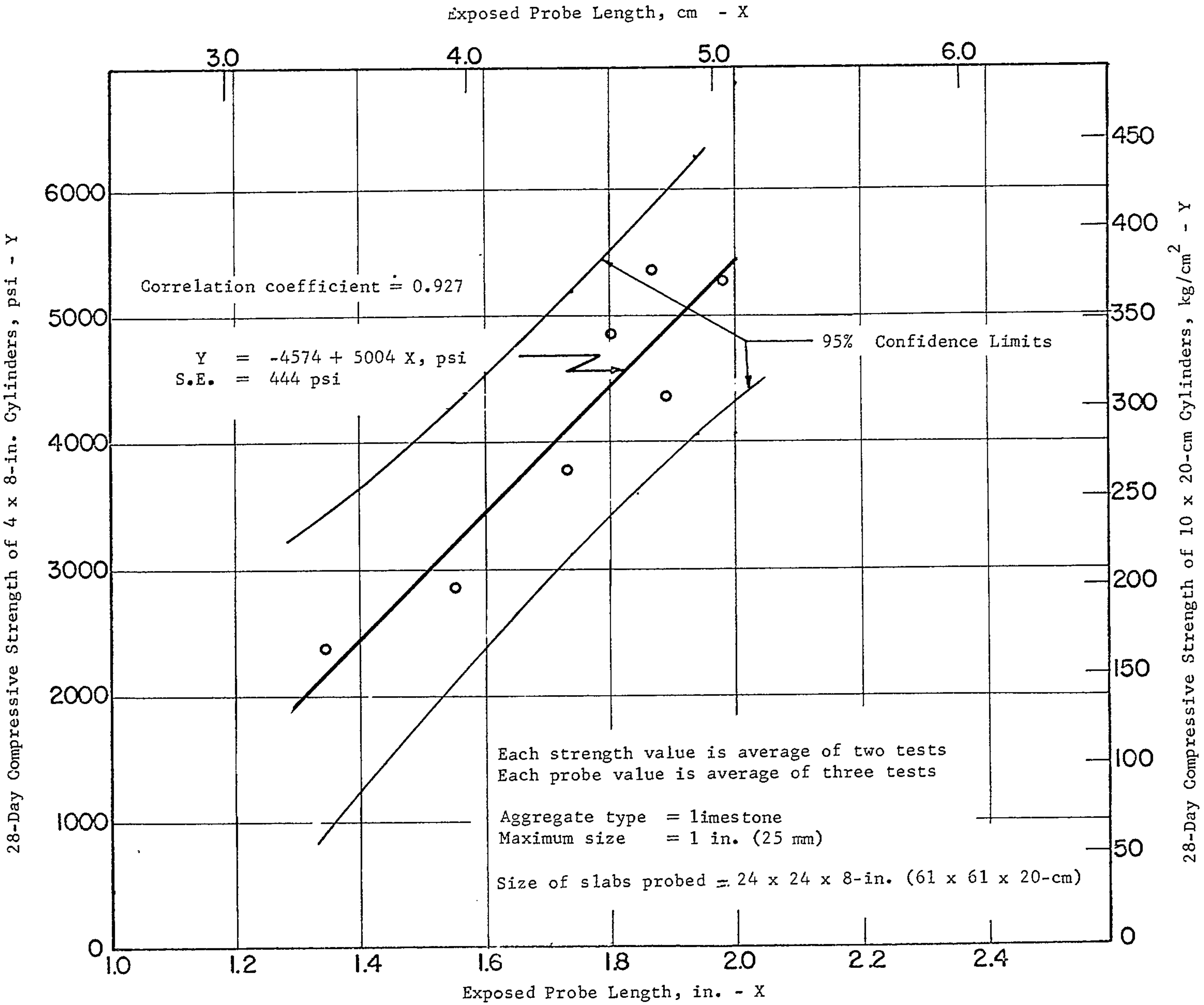

Figure 16 - Relationship between exposed probe lengths and 28-day compressive strengths of 4 x 8-in. (10 x 20-cm) cylinders (limestone aggregate)

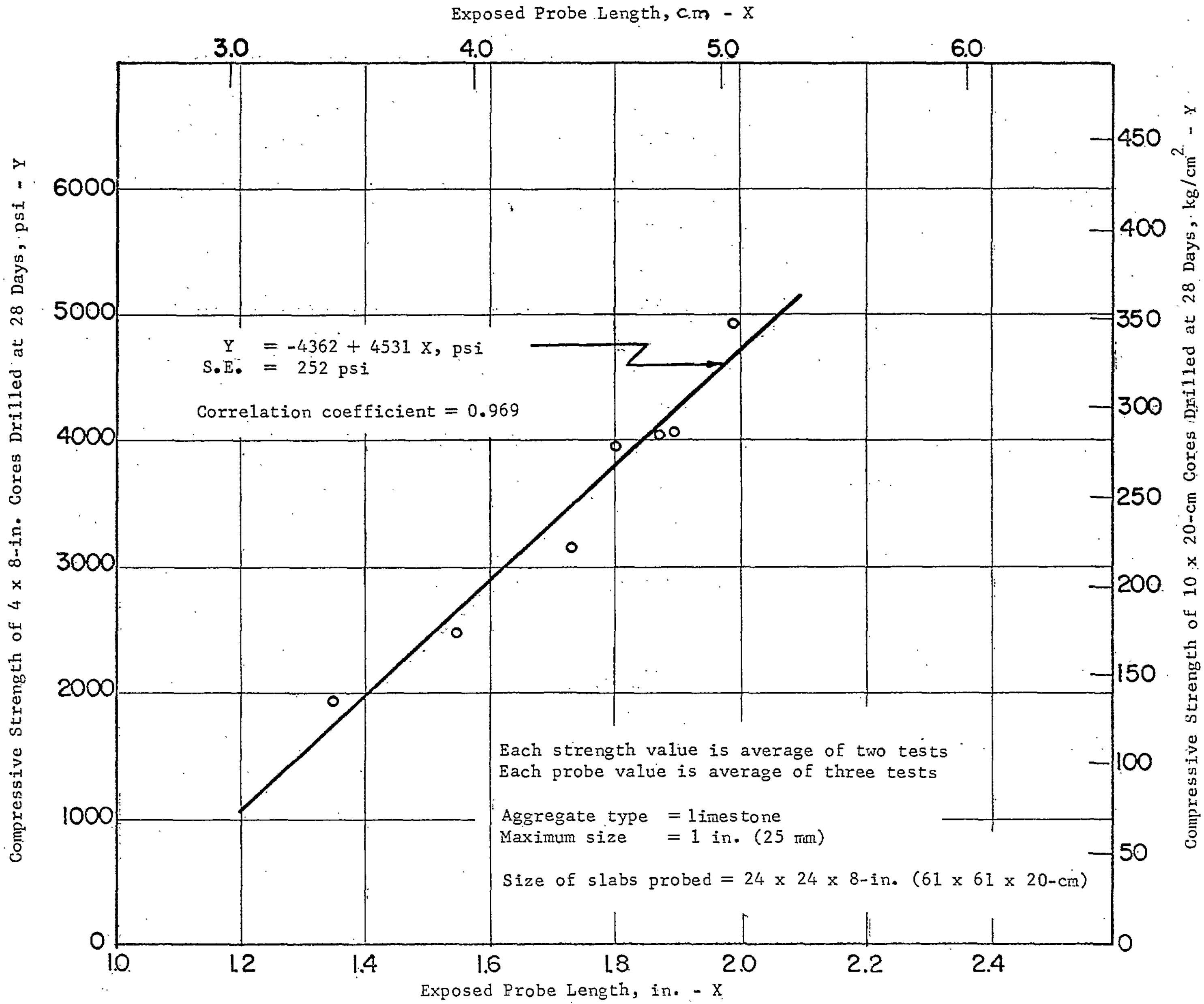

Figure 17 - Relationship between exposed probe lengths and 28-day compressive strengths of 4 x 8-in. (10 x 20-cm) cores drilled after 28 days (limestone aggregate)

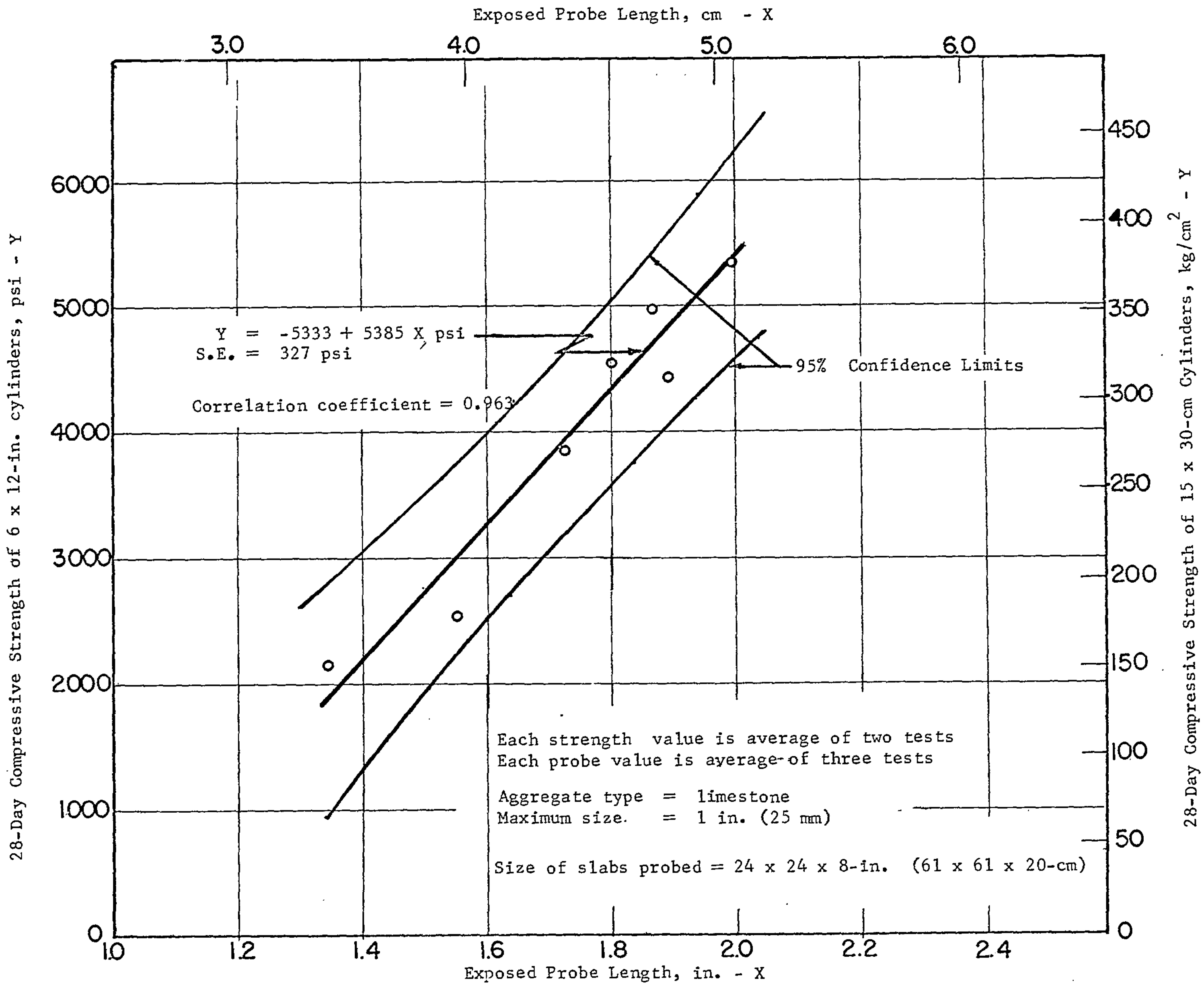

Figure 18 - Relationship between exposed probe lengths and 28-day compressive strengths of 6 x 12-in. (15 x 30-cm) cylinders (limestone aggregate)

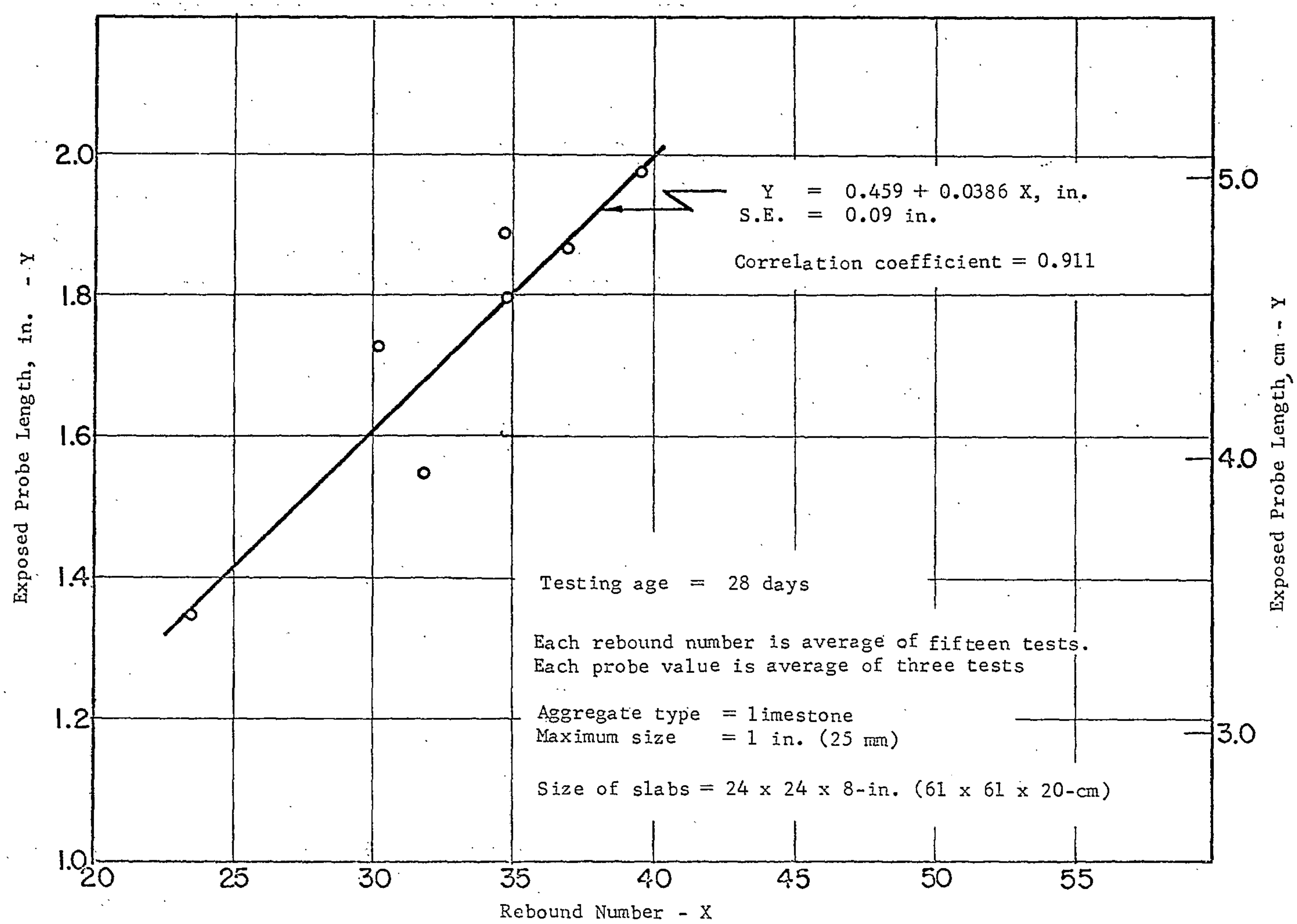

Figure 19 - Relationship between rebound number and exposed probe length (limestone aggregate)

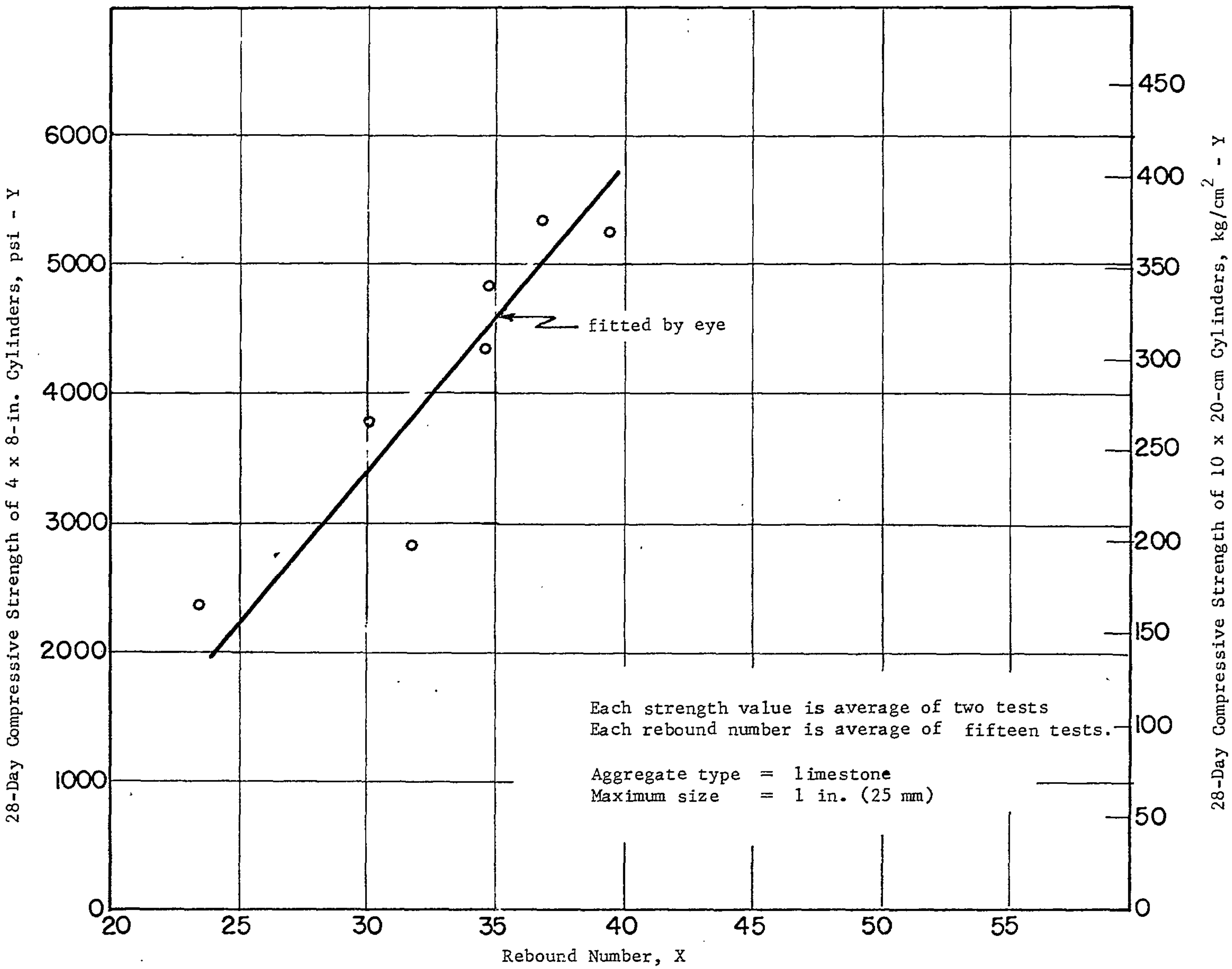

Figure 20 - Relationship between rebound number and 28-day compressive strength of 4 x 8-in. (10 x 20-cm) cylinders (limestone aggregate).

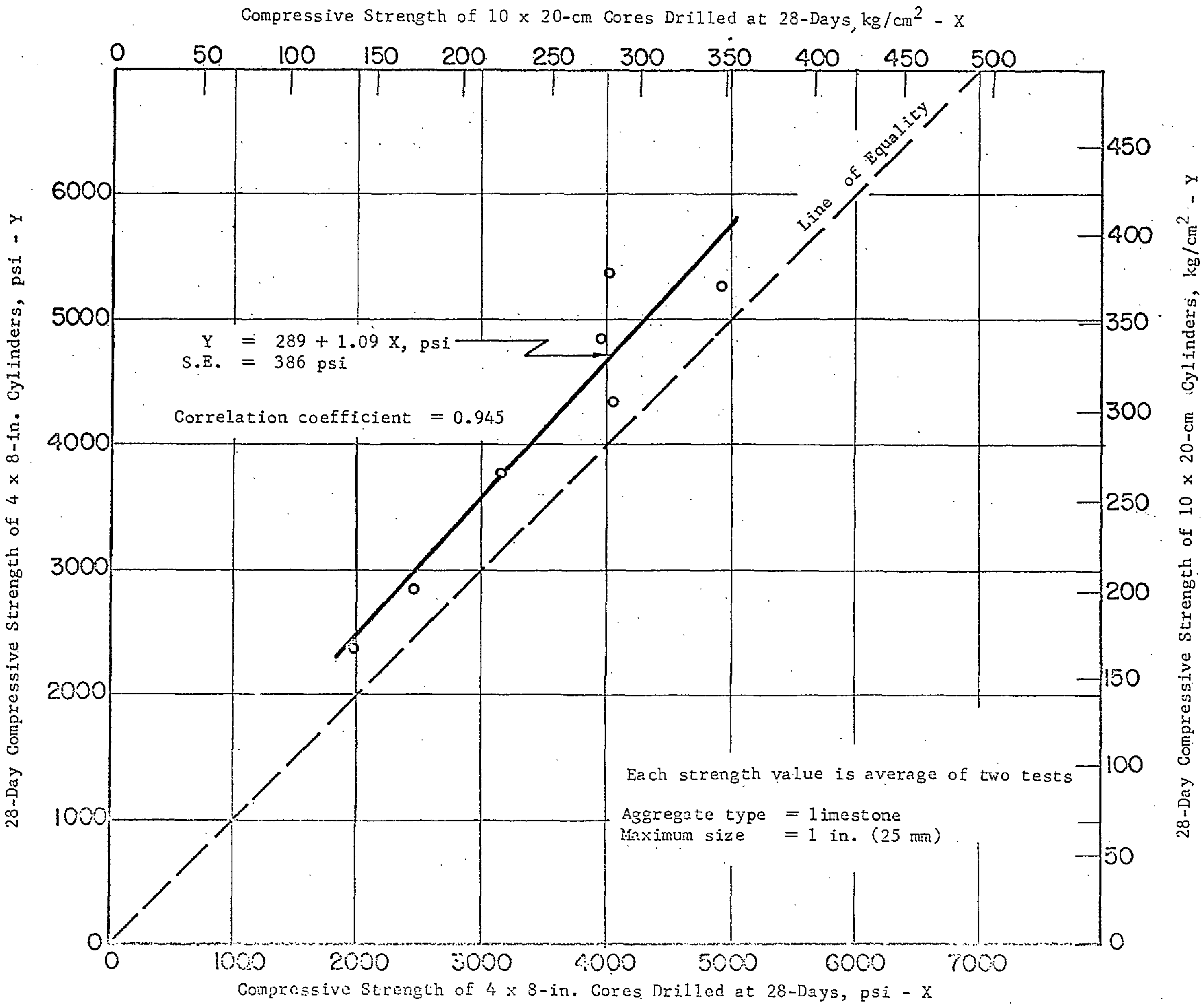

Figure 21 - Relationship between compressive strengths of 4 x 8-in. (10 x 20-cm) cores drilled after 28 days and compressive strengths of 4 x 8-in. (10 x 20-cm) cylinders (limestone aggr   e)

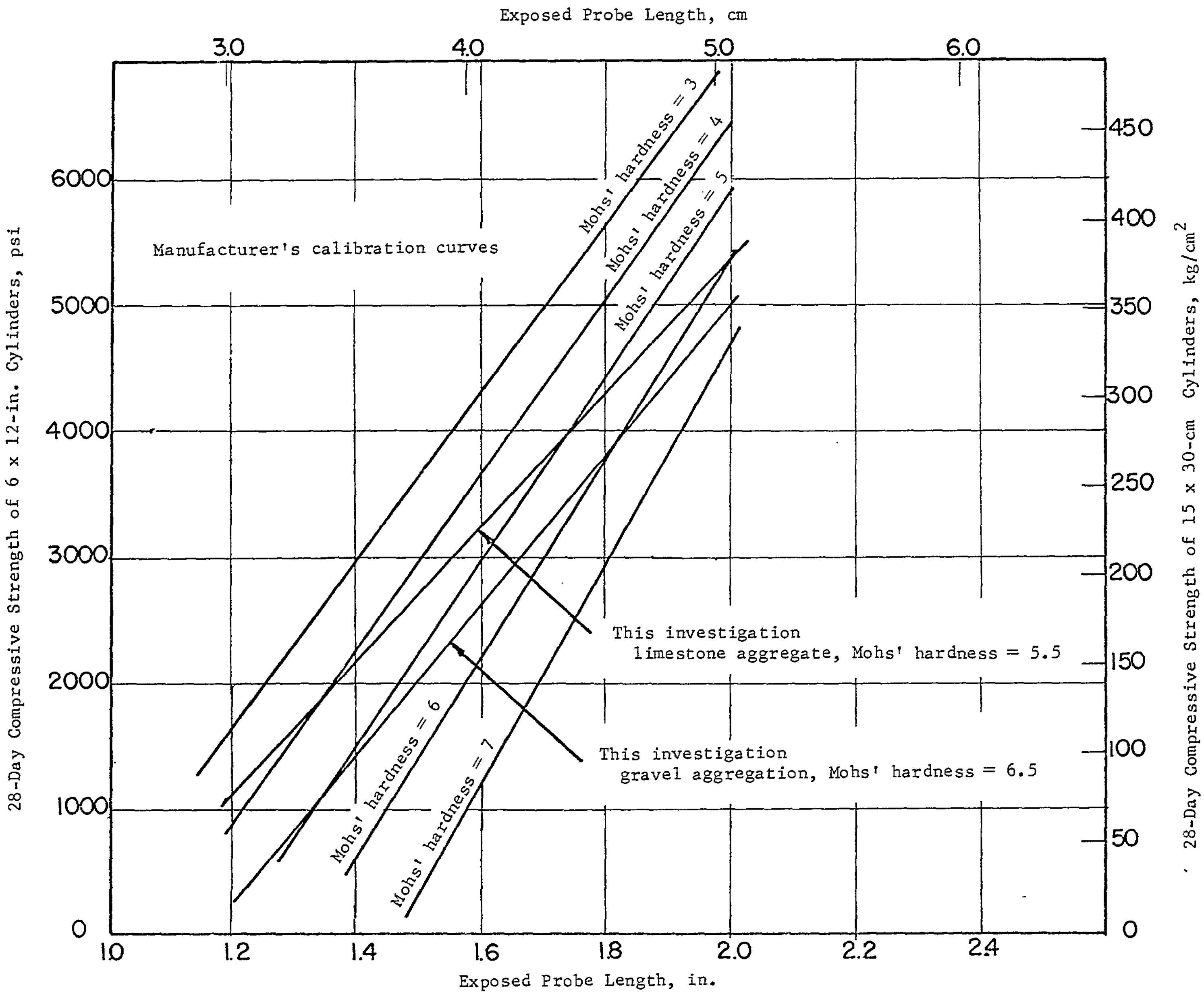

Figure 22 - Comparison of calibration charts supplied by the manufacturer with those obtained in this investigation

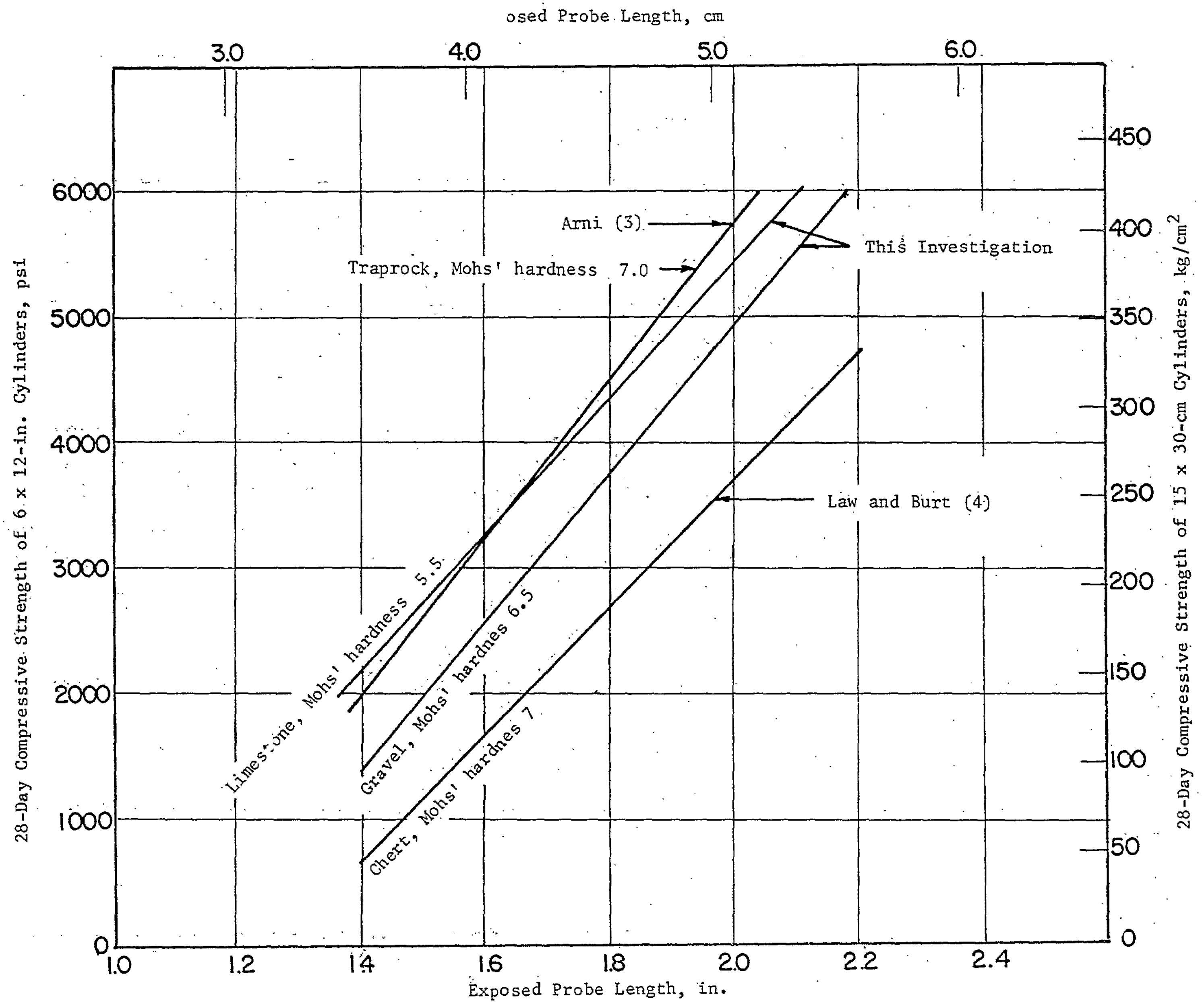

Figure 23 - Comparison of calibration charts obtained in this investigation with those obtained by other investigators.