INVESTIGATION OF THE RELATIONSHIP BETWEEN BOND STRENGTH OR TENSILE STRENGTH AND CYLINDER STRENGTH OF CONCRETE

by

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SYNOPSIS

This report describes an experimental investigation of the relationship between bond strength, tensile strength and cylinder strength of concrete made of Type I cement and Type 3 cement moist cured at 72°F for 1, 3 and 7 days and then cured under extended low temperatures of 55°F and 35°F. Compression strength, tensile strength and bond strength are all related, and an increase or decrease in one is reflected similarly in the others.

The commonly assumed relationship that the tensile and bond strengths of concrete are proportional to $(\text{cylinder strength})^{0.5}$ was found to be inaccurate: the tensile strength and bond strength were found to be proportional to $(\text{cylinder strength})^{0.7}$.

The longer the concrete is cured at 72°F the higher the initial rate of gain of strength (up to 28 days). However, the longer the concrete is cured at 72°F the lower the ultimate (3 months) strength of the concrete.

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1.0 Introduction

It is well established that the rate of gain of strength of plain concrete is a function of age, means of curing and temperature of curing. Knowledge of how the various concrete strengths (compressive, tensile, bond and shear) vary with time is essential in construction as many construction sequences impose significant loads on the concrete structure even though it may not have attained its full design strength (ref. 1). An additional complication in northern latitudes like Canada is that much of the construction is carried out in cold weather, i.e. below 72°F. The hydration of the cement power in concrete is a chemical reaction which is retarded at low temperatures hence the rate of gain of strength of the fresh concrete at low temperature is slower. The collapse of many reinforced concrete buildings during construction in cold weather (ref. 2) can be traced directly to this cause.

Consequently in construction, knowledge of the variation of tensile strength, bond strength and shear strength is as essential as a knowledge of the variation of compressive strength. Unfortunately no references are available on the variation of the bond or shear strength of concrete at an early age and only one on the gain of tensile (flexural) strength with time (ref. 3).

Many individuals and organizations have investigated the changes in the rate of gain of concrete strength with various methods of curing and curing temperature. Probably the most authorative work is due to Klieger (ref. 3).

Klieger's study found that the compressive and flexural strengths produced by different types of portland cement and concrete initially increase with an increase in initial and curing temperature; but the higher the early-age curing temperature, the lower the final strengths of the concrete. The variation of compressive strength and flexural strength with temperature for concrete made with different cements were similar in behavior and varied in degree only. The optimum temperature of early-age curing for final strength (not strength at 28 days) is 55^{o}F for Type 1 and Type 2 cements and 40^{o}F for Type 3 cement. The initial temperature of the cement powder exerted no influence on strength of concrete except as it affected the concrete temperature after mixing.

Strength of concrete increased due to an accelerator (2% of $CaCl_2$) added at early ages with lower temperatures but resulted in later-age flexural and compressive strengths lower than for concrete without the accelerator.

The present investigation had as its objective to determine the variation in compressive strength, tensile strength and bond strength of various standard concretes with age when cured at steady below normal temperatures. Shear strength was not included in this study as pure shear failures are rare; failure of concrete under a shearing force is normally due to diagonal tension.

2.0 Experimental Investigation

As stated in the introduction the object of this study was to determine the interrelationship between the various concrete strengths with respect to age. The purpose is to determine whether or not the variation of tensile and bond strengths is proportional to the square root of the cylinder strength at every age and for every curing condition.

Four series of tests were carried out; each series being cast from a single batch of ready mix concrete. Two types of concrete were considered, two casts being made with Type 1 Ordinary Portland cement and two casts with Type 3 High Early Strength Cement. One cast from each cement was subjected to extended curing at 55°F and the other to extended curing at 35°F.

All specimens were cast at 72°F but some specimens were allowed to moist cure at 72°F for one day only, others were moist cured at 72°F for 3 days and the rest were moist cured for 7 days at 72°F before being transferred to the lower curing temperature.

Each cast involved the casting of 160 6" diam. x 12" cylinders and 80 bond specimens. Five specimens were tested for compressive strength, tensile strength and bond strength at ages of 1 day, 3 days, 7 days, 14 days, 28 days and 3 months for each of the 12 curing sequences.

2.1 Casting Procedure

The water cement ratio for each concrete was such as to produce a slump of approximately 2 to 3 in. with the maximum size of gravel of 3/4". Each batch contained sufficient concrete to cast 160 cylinder specimens for compressive and splitting tensile tests and 80 specimens for bond tests. If necessary the concrete in the mixing pan was remixed to prevent segregation. The moulds were filled in approximately two equal layers and vibrated. A complete cast took approximately one hour and 15 minutes.

2.2 Curing Procedure

Wet burlap was used to cover the moulds and specimens until the specimens were removed from the moulds. A polyethylene sheet was placed over the burlap to minimize evaporation. At ages of 1, 3 or 7 days respectively the appropriate number of specimens were stripped and were transferred to the cold rooms for extended curing at either 55^{o}F or 35^{o}F depending upon the series of tests. During the extended curing the specimens were also covered with wet burlap kept moist until the day of test.

2.3.1 Compression Test

The compressive strength was determined using the standard compressive strength test as described in ASTM C192 and C39 using the standard 6" dia. x 12" cylinders.

The standard test involves making a 6" dia. x 12" long concrete cylinder which is cured under not less than 90% humidity at a temperature of 73.4^{o} ± 3^{o}F for 28 days.

The ends are then surface ground or capped to make them plane and parallel and the cylinder is tested to failure in a standard compression testing machine.

In this study single-use waxed paper moulds were used to eliminate the time consuming cleaning of metal moulds. Tests have shown that the differences in strength between cylinders cast in single-use moulds and those cast in steel moulds is between 3 to 9 per cent (refs. 4 and 5).

The moulds were filled in two layers compacted by sufficient internal vibration to compact each layer without segregration of the concrete occurring.

Thin sulfur compound caps were used at each end of the cylinders to ensure that the cylinder ends were plane and perpendicular. Testing was carried out in Forney Concrete Testing Machine and the maximum load recorded.

2.3.2 Tensile Test

There are three types of standard tests for measuring the tensile strength of concrete, namely (a) direct pull tests on briquettes (ref. 6), (b) modulus of rupture tests on beams (ref. 7) and (c) splitting test on cylinders (ref. 8).

The flexural tension is more common in practice than direct tension but inconvenient when large numbers of specimens are needed. The splitting test is an indirect method of determining the tensile strength of concrete. It was first introduced by Carneiro (ref. 9) in Brazil and Akazawa (ref. 10) in Japan.

If a concrete cylinder is loaded in compression across a diameter it splits across the diameter due to internal tensile forces which are set up normal to the applied compressive force.

If concrete can be assumed to be elastic the splitting load can be calculated from the theory of elasticity as postulated by Timoshenko (ref. 11). The splitting tensile strength of the specimen can be computed as follows:

$$T = \frac{2P}{\pi l d}$$

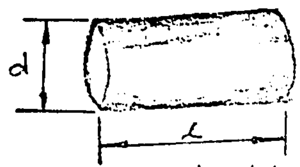

Fig. 1A

Where P = load causing splitting failure

d = equivalent diameter of concrete specimen as shown in Fig. 1A

l = length of concrete specimen as shown in Fig. 1A

T = standard splitting stress for cylinders

The test procedure is to simply load the cylinders across a diametric axis to failure. To distribute the load from the platens of the testing machine thin sacrificial plywood strips are used between the platens and the cylinder.

2.3.3 Bond Strength Test

The standard bond strength test procedure described in ASTM C234 uses #6 reinforced bar cast either into a 6" concrete cube or 6" x 6" x 12" block of concrete. The test consists of placing the block in a testing machine so that the reinforcing bar can be drawn out of the concrete.

However, in view of the large number of specimens envisaged it was not possible to purchase enough cube moulds to use the standard procedure. As the object of the investigation was to study the variation in strength with age and temperature it was decided to devise a comparative test specimen. Specimens were made by casting a #6 reinforcing bar into a 6" dia. 6" long cylindrical block of concrete to approximate as closely as possible the standard specimen.

Moulds were made by simply sawing off the bottom 6" of single-use moulds, the upper 6" being discarded. A 7/8" dia. hole was drilled through the centre of the metal base of the mould to allow the #6 reinforcing bar to be placed through. The moulds were set up on a casting platform with the reinforcing bar projecting through and resting on the floor as shown in Fig. 1. Concrete was placed in two layers, each layer being vibrated as for a compression test cylinder. Thirty-six (36") inch lengths of #6 (6L60) deformed bar as shown in Fig. 2 with 100,000 psi. ultimate tensile strength were used; each length being used twice during the course of the investigation once with one end in the concrete and finally with the other end in the concrete. The specimens were mounted in the testing machine as shown in Fig. 3. A piece of plywood was used as a cushion between the bearing concrete surface and the bearing plate of the testing machine.

All specimens behaved in essentially a similar manner with failure occurring by longitudinal splitting of the concrete.

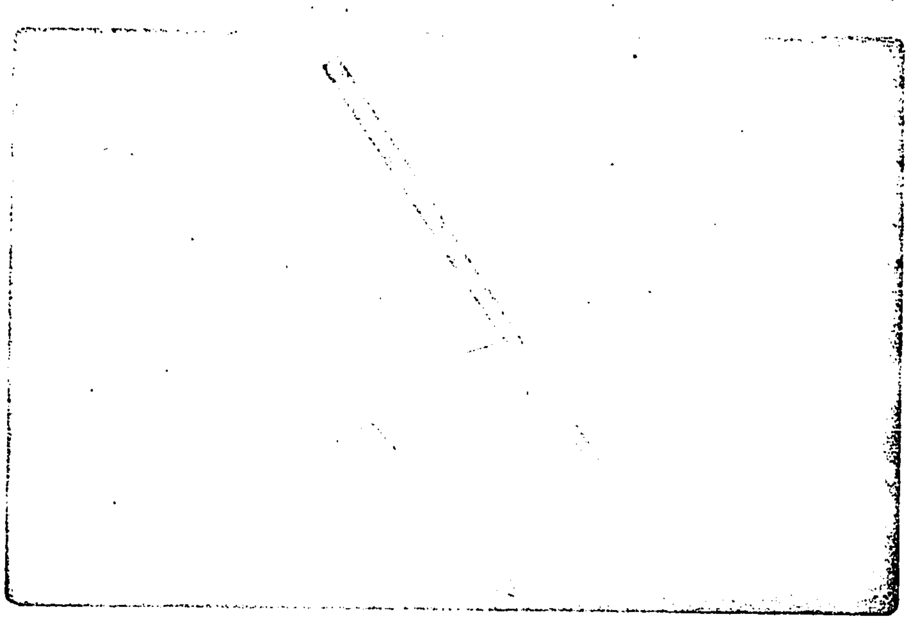

Fig. 1. The photograph of the deformed bar

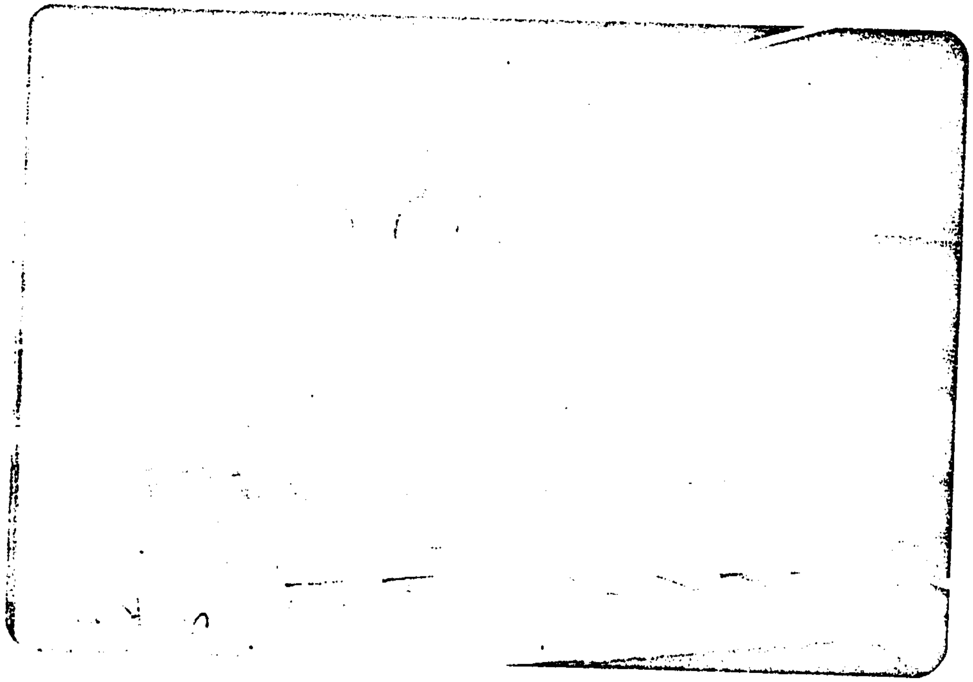

Fig. 2. The casting platform

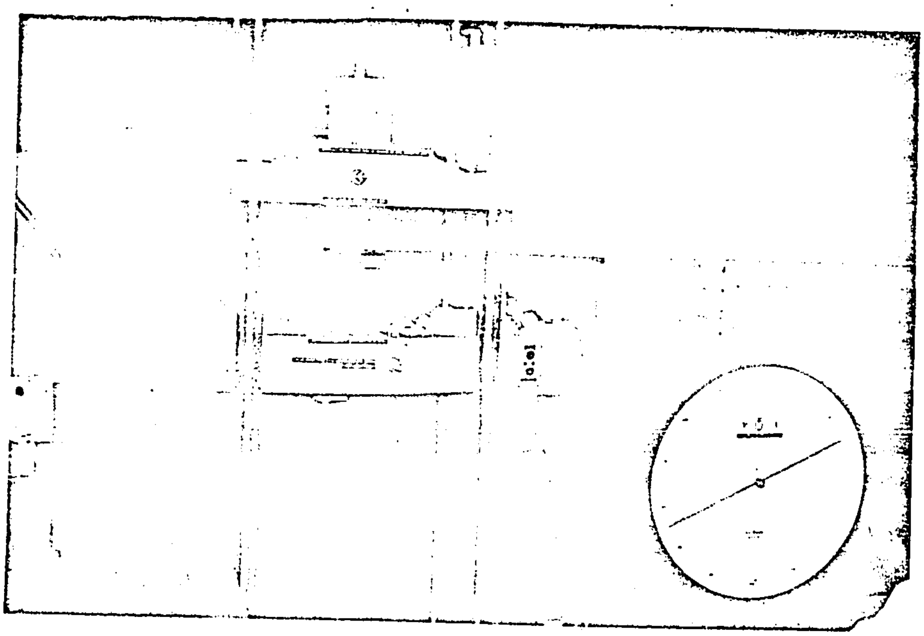

Fig. 3. The specimen with the testing machine

3.0 Discussion of Results

The results as measured are given in detail in Tables 1 through 4. To facilitate comparison between bond strength or tensile strength and cylinder strength, the average results of the five test results for each strength component are also given in Table 1 through 4.

For visualization the average concrete strength, are plotted against log time in Fig. 4 to Fig. 7. In every case, it can be observed that all types of concrete strength increase with age for every curing schedule.

It is interesting to note and consistent with other researchers, that the earlier the curing at the low temperature is commenced the higher the ultimate strength i.e. curing for one day at 72°F and then at 55°F (or 35°F) gives an ultimate strength higher than curing 3 or 7 days at 72°F and then curing at 55°F (or 35°F). However, in the context of construction practice it is the rate of gain of strength from casting to 28 days which is important and for this criterion the longer the specimens are cured at 72°F the higher the strength between 7 days and 28 days.

Tables 5 to 8 give the variation of cylinder strength with curing schedule. Also all the cylinder strengths of a given mix are normalized with respect to the 7 days moist cured at 72°F cylinder strength. For consistency with other researchers the standard rate of gain of strength curves taken from Smith (ref. 9) are also given. From these results it seems that the present results are consistent with previous work, but the standard rate of gain of strength curves are somewhat conservative.

Figures 8a and 8b show on a log-log plot the variation of tensile strength and bond strength with cylinder strength for the specimens cured at 72°F for the 4 mixes. In every case the experimental points lie on a straight line indicating a power law relationship of the form:

$$\left.\begin{matrix}\text{tensile}\\ \text{bond}\end{matrix}\right\} \text{ strength} = b(f_c')^a$$

Table 9 gives the values of a and b calculated for the 4 mixes for concrete moist cured at 72°F. It can be seen that the power 'a' is sensibly contstant for all 4 mixes at 0.90 for bond strength and 0.74 for tensile strength. It should be noted that these results were based on experimental results of 1, 3 and 7 days only and may not hold for older concrete.

Figure 9 to Fig. 12 show graphically the variation of tensile strength and bond strength against cylinder strength on a log-log plot for the various curing schedules. All specimens cast from the same mix are grouped together. Hence Fig. 9 shows all the results for Type 1 cement cured at a temperature of 55°F. All the curves of log tensile strength (bond strength) against log cylinder strength approximate straight lines.

The best straight line was filled through the experimental points and a and b were calculated for each of 12 curing schedules. These calculated values are given in Table 10 but no consistent pattern can be deduced.

Bar plots of range of experimental results are also indicated in Fig. 9 to Fig. 12. It can easily be seen that one straight line could approximate all the results for a given concrete mix. Consequently, the power law constants for the ensemblage results were calculated giving bias to the results between 7 days and 28 days and are given in Table 11.

The results of 'a' and 'b' for the relationship between bond strength or tensile strength and cylinder strength of concrete made of Type 3 cement appear to be invariant with respect to curing temperature. The calculated values for 'a' and 'b' for the concretes made with Type 1 cement are variable and no trend can be predicted. However for practical purposes, it would be unrealistic to use other than a single relationship between tensile strength or bond strength and cylinder strength and a power 'a' of 0.70 seems approximate.

This conclusion is important as it shows that the rate of gain of tensile and bond (and by induction shear) strength is slower than the commonly assumed $\sqrt{f'_c}$. Hence when estimating tensile, bond and shear strength of concrete at early ages for construction scheduling purposes a power law relationship of at least 0.70 should be used. The commonly assured proportionality to $\sqrt{f'_c}$ was derived from standard tests carried out at 28 days for different concrete mixes whereas this result refers to a concrete mix at different ages.

4.0 Conclusion

(1) Compressive strength, tensile strength and bond strength of concrete at early ages increase with increased curing temperature. The lower the initial curing temperature the greater the eventual ultimate strength of the concrete.

(2) Temperature influences tensile and bond strength development of concrete in much the same manner as it does compressive strength development. Compressive strength, tensile strength and bond strength are all related, and an increase or decrease in one is reflected similarly in the others.

(3) Bond strength and tensile strength are proportional to the 0.7 power of the cylinder strength at the appropriate age.

(4) Neither extended curing at temperatures of 35° and 55° or type of cement appear to have any significant effect on the interrelationship of bond strength or tensile strength and cylinder strength.

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Age of Test	Kind of Test	Strength of Specimens No.1	No.2	No.3	No.4	No.5	Ave.	Actual f'_c 28
1 day	Comp.	1100	1210	1150	1120	1120	1140	0.3
	Tensile	179	181	167	172	179	176	
	Bond	313	295	310	320	330	314	
3 days	Comp.	1830	1790	1810	1770	1940	1828	0.49
	Tensile	248	234	219	238	240	236	
	Bond	456	470	475	490	510	480	
7 days	Comp.	2630	2650	2590	2520	2460	2570	0.68
	Tensile	286	315	310	288	326	305	
	Bond	605	655	625	635	640	650	
14 days	Comp.	3480	3440	3275	3340	3500	3407	0.90
	Tensile	386	344	330	360	370	358	
	Bond	770	766	785	805	826	790	
28 days	Comp.	3680	3600	3880	3980	3665	3761	1.00
	Tensile	484	384	392	515	398	435	
	Bond	807	857	840	905	915	865	
3 mon.	Comp.	4300	4255	4470	4340	4600	4393	1.17
	Tensile	668	680	527	488	512	575	
	Bond	985	970	915	947	960	915	

Table 1a. Strength of concrete made with Type I cement cured one day @ 72°F then 55°F.

Age of Test	Kind of Test	Strength of Specimens No.1	No.2	No.3	No.4	No.5	Ave.	Actual f'_c 28
1 day	Comp.							
	Tensile							
	Bond							
3 days	Comp.	2020	1890	1790	1830	1820	1870	0.51
	Tensile	244	248	240	243	256	246	
	Bond	472	522	510	531	490	505	
7 days	Comp.	2620	2570	2610	2700	2750	2650	0.72
	Tensile	310	320	332	310	305	315	
	Bond	692	710	670	647	682	680	
14 days	Comp.	3480	3520	3470	3660	3670	3560	0.97
	Tensile	392	380	360	350	388	374	
	Bond	830	893	863	882	807	855	
28 days	Comp.	3620	3600	3720	3900	3560	3680	1.0
	Tensile	370	417	430	384	450	410	
	Bond	920	837	890	875	887	882	
3 mon.	Comp.	4060	3980	4100	4210	4350	4140	1.12
	Tensile	507	635	537	630	528	567	
	Bond	970	978	905	930	968	950	

Table 1b. Strength of concrete made with Type I cement cured 3 days @ 72°F then 55°F.

Age of Test	Kind of Test	Strength of Specimens						Actual
		No.1	No.2	No.3	No.4	No.5	Ave.	$f'_{c\ 28}$
1 day	Comp.							
	Tensile							
	Bond							
3 days	Comp.							
	Tensile							
	Bond							
7 days	Comp.	2750	2560	2740	2780	2770	2720	0.73
	Tensile	340	337	325	320	330	332	
	Bond	702	696	716	752	683	710	
14 days	Comp.	3460	3750	3625	3680	3340	3573	0.96
	Tensile	405	420	380	413	430	410	
	Bond	855	865	848	917	890	875	
28 days	Comp.	3790	3810	3770	3540	3780	3738	1.00
	Tensile	497	405	390	480	377	430	
	Bond	895	890	878	922	940	905	
3 mon.	Comp.	4110	4150	4070	3950	3885	4033	1.08
	Tensile	570	497	558	462	480	513	
	Bond	920	896	905	942	962	925	

Table 1c. Strength of concrete made with Type I cement cured 7 days @ 72°F then 55°F.

Age of Test	Kind of Test	Strength of Specimens						Actual
		No.1	No.2	No.3	No.4	No.5	Ave.	f'_c 28
1 day	Comp.	1950	2140	2110	2180	2020	2080	0.41
	Tensile	250	271	260	263	256	260	
	Bond	624	587	550	597	605	593	
3 days	Comp.	3110	3140	3080	2980	2940	3050	0.60
	Tensile	318	329	332	344	355	336	
	Bond	880	845	788	795	806	823	
7 days	Comp.	3980	4300	4150	4220	3900	4110	0.81
	Tensile	410	397	402	417	425	410	
	Bond	1050	1040	1010	985	1065	1030	
14 days	Comp.	4900	4500	4750	4830	4820	4750	0.94
	Tensile	456	462	452	473	483	465	
	Bond	1140	1130	1150	1170	1210	1160	
28 days	Comp.	4820	5220	5130	5320	4920	5082	1.00
	Tensile	480	490	500	525	478	495	
	Bond	1250	1220	1170	1150	1185	1195	
3 mon.	Comp.	5570	6110	5800	5650	5620	5750	1.13
	Tensile	550	561	512	528	550	540	
	Bond	1225	1210	1235	1270	1310	1250	

Table 2a. Strength of concrete made with Type III cement cured one day @ 72°F then @ 55°F.

Age of Test	Kind of Test	Strength of Specimens No.1	No.2	No.3	No.4	No.5	Ave.	Actual $f'_{c\ 28}$
1 day	Comp.							
	Tensile							
	Bond							
3 days	Comp.	2970	3230	3200	3040	3260	3140	0.68
	Tensile	370	345	360	367	330	356	
	Bond	870	908	842	820	808	850	
7 days	Comp.	3710	3700	3820	4010	3660	3780	0.82
	Tensile	391	360	383	406	398	388	
	Bond	970	945	905	890	915	925	
14 days	Comp.	4250	4600	4420	4510	4150	4386	0.95
	Tensile	415	435	418	440	425	427	
	Bond	970	1030	1050	1060	1040	1030	
28 days	Comp.	4745	4770	4670	4530	4450	4633	1.0
	Tensile	458	453	440	432	469	450	
	Bond	1075	1030	1050	1085	1110	1070	
3 mon.	Comp.	5750	5870	5520	5545	5300	5597	1.21
	Tensile	472	520	505	535	485	503	
	Bond	1150	1180	1160	1240	1320	1210	

Table 2b. Strength of concrete made with Type III cement cured 3 days @ 72°F then @ 55°F.

Age of Test	Kind of Test	Strength of Specimens						Actual
		No.1	No.2	No.3	No.4	No.5	Ave.	$f'_{c\ 28}$
1 day	Comp.							
	Tensile							
	Bond							
3 days	Comp.							
	Tensile							
	Bond							
7 days	Comp.	4270	3860	3980	4180	3860	4030	0.82
	Tensile	403	428	413	448	438	426	
	Bond	1090	978	1040	1010	982	1020	
14 days	Comp.	4750	4420	4650	4700	4295	4563	0.93
	Tensile	420	447	410	438	450	433	
	Bond	1040	1130	1050	1160	1120	1100	
28 days	Comp.	4670	4830	4870	5160	5050	4916	1.0
	Tensile	496	477	450	422	437	456	
	Bond	1055	1165	1150	1100	1180	1130	
3 mon.	Comp.	5800	5245	5530	5320	5270	5433	1.11
	Tensile	508	498	478	473	484	488	
	Bond	1120	1200	1170	1237	1225	1190	

Table 2c. Strength of concrete made with Type III cement cured 7 days @ 72°F than @ 55°F.

Age of Test	Kind of Test	Strength of Specimens						Actual
		No.1	No.2	No.3	No.4	No.5	Ave.	f'_c 28
1 day	Comp.	1170	1180	1090	1140	1170	1150	0.33
	Tensile	166	174	169	177	177	173	
	Bond	342	310	315	334	310	322	
3 days	Comp.	1680	1650	1720	1750	1800	1720	0.47
	Tensile	220	232	209	236	229	225	
	Bond	450	480	443	473	489	467	
7 days	Comp.	2240	2450	2400	2490	2320	2380	0.66
	Tensile	287	296	274	258	277	278	
	Bond	580	630	587	643	618	612	
14 days	Comp.	3290	3320	3260	3160	3130	3232	0.89
	Tensile	372	344	368	365	324	355	
	Bond	766	815	775	807	798	792	
28 days	Comp.	3790	3600	3540	3680	3405	3603	1.0
	Tensile	403	410	391	384	371	392	
	Bond	797	863	807	882	850	840	
3 mon.	Comp.	3770	4130	4050	4220	3910	4016	1.05
	Tensile	460	430	450	455	416	442	
	Bond	880	965	890	975	963	935	

Table 3a. Strength of concrete made with Type I cement cured one day @ 72°F then 35°F.

Age of Test	Kind of Test	Strength of Specimens						Actual
		No.1	No.2	No.3	No.4	No.5	Ave.	$f'_{c\,28}$
1 day	Comp. Tensile Bond							
3 days	Comp. Tensile Bond	1850 249 468	1790 233 513	1810 253 508	1880 267 473	1920 259 517	1850 252 496	0.51
7 days	Comp. Tensile Bond	2560 313 677	2580 319 626	2540 300 657	2460 283 662	2410 307 605	2510 304 645	0.69
14 days	Comp. Tensile Bond	3530 361 856	3310 383 796	3470 373 835	3500 395 802	3210 390 792	3404 380 816	0.94
28 days	Comp. Tensile Bond	3750 381 802	3820 412 902	3650 390 810	3390 422 872	3615 405 890	3645 402 855	1.0
3 mon.	Comp. Tensile Bond	4100 420 870	4030 461 902	3860 456 904	3820 432 960	3890 465 940	3940 447 915	1.08

Table 3b. Strength of concrete made with Type I cement cured 3 days @ 72°F then @ 35°F.

Age of Test	Kind of Test	Strength of Specimens						Actual
		No.1	No.2	No.3	No.4	No.5	Ave.	$f'_{c\,28}$
1 day	Comp.							
	Tensile							
	Bond							
3 days	Comp.							
	Tensile							
	Bond							
7 days	Comp.	2610	2540	2620	2700	2780	2650	0.71
	Tensile	319	340	325	349	346	336	
	Bond	692	768	702	750	763	735	
14 days	Comp.	3445	3720	3540	3440	3430	3515	0.95
	Tensile	381	415	390	422	406	403	
	Bond	872	812	856	872	790	840	
28 days	Comp.	3810	3760	3650	3570	3840	3726	1.0
	Tensile	398	432	423	441	406	420	
	Bond	935	847	882	850	834	870	
3 mon.	Comp.	3790	4080	3920	4010	3650	3890	1.05
	Tensile	426	422	417	438	447	430	
	Bond	893	873	885	927	947	905	

Table 3c. Strength of concrete made with Type I cement cured 7 days @ 72°F then 35°F.

Age of Test	Kind of Test	Strength of Specimens						Actual
		No.1	No.2	No.3	No.4	No.5	Ave.	f'_c 28
1 day	Comp.	1630	1610	1620	1680	1710	1650	0.38
	Tensile	228	221	208	195	199	210	
	Bond	493	458	482	480	464	475	
3 days	Comp.	2460	2680	2560	2620	2380	2540	0.58
	Tensile	260	249	278	246	269	260	
	Bond	650	732	657	707	720	693	
7 days	Comp.	3420	3240	3450	3660	3680	3490	0.80
	Tensile	325	332	321	356	324	332	
	Bond	930	910	872	860	880	890	
14 days	Comp.	3665	3980	3960	3760	4030	3879	0.89
	Tensile	380	350	369	372	340	362	
	Bond	1050	1020	960	902	918	970	
28 days	Comp.	4030	4280	4640	4420	4370	4348	1.0
	Tensile	388	425	392	430	413	410	
	Bond	990	1050	972	1025	1065	1020	
3 mon.	Comp.	5160	5050	4760	4560	4570	4820	1.11
	Tensile	427	453	436	468	467	450	
	Bond	1145	1125	1070	1100	1060	1100	

Su = 5363.63

Table 4a. Strength of concrete made with Type III cement cured one day @ 72°F then 35°F.

Age of Test	Kind of Test	Strength of Specimens						Actual
		No.1	No.2	No.3	No.4	No.5	Ave.	f'_c 28
1 day	Comp.							
	Tensile							
	Bond							
3 days	Comp.	2610	2790	2570	2760	2820	2710	0.63
	Tensile	293	310	304	327	310	309	
	Bond	828	742	792	762	755	776	
7 days	Comp.	3740	3660	3620	3450	3330	3560	0.80
	Tensile	360	337	353	358	326	347	
	Bond	1016	910	850	877	970	925	
14 days	Comp.	4080	4050	3920	3850	4150	4010	0.93
	Tensile	360	353	376	420	391	380	
	Bond	1045	1030	987	970	1020	1010	
28 days	Comp.	4250	4170	4230	4380	4470	4300	1.0
	Tensile	370	387	390	426	413	397	
	Bond	1035	1100	1052	1078	985	1050	
3 mon.	Comp.	4460	4880	4830	4650	4930	4750	1.1
	Tensile	447	405	437	418	405	422	
	Bond	1120	1130	1090	1078	1132	1110	

Su= 4531.70

Table 4b. Strength of concrete made with Type III cement cured three days at 72°F and then 35°F.

Age of Test	Kind of Test	Strength of Specimens No.1	No.2	No.3	No.4	No.5	Ave.	Actual f'_c 28
1 day	Comp.							
	Tensile							
	Bond							
3 days	Comp.							
	Tensile							
	Bond							
7 days	Comp.	3440	3730	3470	3800	3660	3620	0.83
	Tensile	380	390	365	410	405	390	
	Bond	930	978	910	970	960	950	
14 days	Comp.	3840	4215	4170	3960	4210	4079	0.94
	Tensile	425	395	416	420	383	408	
	Bond	1075	1110	1020	1030	990	1045	
28 days	Comp.	4430	4480	4465	4270	4170	4363	1.0
	Tensile	395	430	426	405	435	418	
	Bond	1020	980	1120	1100	1080	1060	
3 mon.	Comp.	4380	4750	4420	4850	4700	4620	1.06
	Tensile	440	462	435	398	406	428	
	Bond	1120	1060	1150	1030	1040	1080	

Sn = 4493.36

Table 4c. Strengths of concrete made with Type III cement, cured seven days at 72°F and then 35°F.

		Type I cured @ 55°F					
		1	3	7	14	28	90
1 day cured @ 72°F	expt.result	1140	1828	2570	3407	3761	4393
	expt./7 days @ 72°F	0.42	0.67	0.95	1.25	1.38	1.61
3 days cured @ 72°F	expt.result		1870	2650	3560	3680	4140
	expt./7 days @ 72°F		0.68	0.98	1.31	1.35	1.52
7 days cured @ 72°F	expt.result			2720	3573	3738	4033
	expt./7 days @ 72°F			1.0	1.31	1.37	1.48
Standard result		0.34	0.73	1.0	1.22	1.35	1.64

Table 5. The variation of cylinder strength with Type I cement cured at 55°F with respect to 7 days cured at 72°F cylinder strength.

		1	3	7	14	28	90
1 day cured @ 72°F	expt.result	2080	3050	4110	4750	5082	5750
	expt./7 days @ 72°F	0.52	0.76	1.02	1.18	1.26	1.43
3 days cured @ 72°F	expt.result		3140	3780	4386	4633	5597
	expt./7 days @ 72°F		0.78	0.94	1.09	1.15	1.39
7 days cured @ 72°F	expt.result			4030	4563	4916	5433
	expt./7 days @ 72°F			1.0	1.13	1.22	1.35
Standard result		0.41	0.81	1.0	1.12	1.27	1.47

Table 6. The variations of cylinder strength with Type III cement cured at 55°F with respect to 7 days cured at 72°F cylinder strength.

		Type I cured @ 35°F					
		1	3	7	14	28	90
1 day cured @ 72°F	expt.result	1150	1720	2380	3232	3603	4016
	expt./7 days @ 72°F	0.44	0.65	0.9	1.22	1.36	1.52
3 days cured @ 72°F	expt.result		1850	2510	3404	3645	3940
	expt./7 days @ 72°F		0.7	0.95	1.28	1.38	1.49
7 days cured @ 72°F	expt.result			2650	3515	3726	3890
	expt./7 days @ 72°F			1.0	1.33	1.41	1.47
standard result		0.34	0.73	1.0	1.22	1.35	1.64

Table 7. The variation of cylinder strength with Type I cement cured at 35°F with respect to the 7 days cured at 72°F cylinder strength.

		1	3	7	14	28	90
1 day cured @ 72°F	expt.result	1650	2540	3490	3879	4348	4820
	expt./7 days @ 72°F	0.46	0.70	0.97	1.07	1.20	1.33
3 days cured @ 72°F	expt.result		2710	3560	4010	4300	4750
	expt./7 days @ 72°F		0.75	0.99	1.11	1.19	1.32
7 days cured @ 72°F	expt.result			3620	4079	4363	4620
	expt./7 days @ 72°F			1.0	1.13	1.20	1.28
Standard result		0.41	0.81	1.0	1.12	1.27	1.47

Table 8. The variation of cylinder strength with Type III cement cured at 35°F with respect to the 7 days cured at 72°F cylinder strength.

	Bond Strength		Tensile Strength	
	a	b	a	b
Mix 1	0.92	0.48	0.74	0.72
Mix 2	0.75	1.99	0.68	1.48
Mix 3	1.06	0.17	0.77	0.78
Mix 4	0.86	0.84	0.78	0.65
Average	0.90	0.87	0.74	0.91

Table 9. Calculated values for 'a' and 'b' for concrete moist cured @ 72°F (for 1, 3, and 7 days only).

		Bond strength		Tensile strength	
		a	b	a	b
Mix 1 (Type I)	1 day cured @ 72° then 55°F	0.80	1.07	0.77	0.36
	3 days cured @ 72° than 55°F	0.78	1.47	0.73	0.48
	7 days cured @ 72°F than 55°F	0.65	3.9	1.02	0.06
Mix 2 (Type III)	1 day cured @ 72°F then 55°F	0.74	0.51	0.72	1.06
	3 days cured @ 72°F then 55°F	0.64	0.87	0.66	1.68
	7 days cured @ 72°F then 55°F	0.51	2.88	0.54	4.6
Mix 3 (Type I)	1 day cured @ 72°F than 35°F	0.82	1.01	0.72	1.29
	3 days cured at 72°F then 35°F	0.61	3.58	0.61	3.58
	7 days cured @ 72°F then 35°F	0.66	2.27	0.65	2.45
Mix 4 (Type III)	1 day cured @ 72°F then 35°F	0.72	1.98	0.87	0.14
	3 days cured @ 72°F then 35°F	0.64	4.94	0.61	1.16
	7 days cured @ 72°F then 35°F	0.57	1.37	0.4	5.60

Table 10. Detailed results for 12 curing conditions for 'a' and 'b'.

	Bond Strength		Tensile Strength	
	a	b	a	b
Type 1 cement cured at 55°F	0.78	1.44	0.84	0.42
Type 3 cement cured at 55°F	0.69	3.23	0.64	2.03
Type 1 cement cured at 35°F	0.70	2.77	0.66	1.75
Type 3 cement cured at 35°F	0.68	3.57	0.63	2.09
Average =	0.71	2.74	0.69	1.57

Table 11. Calculated values for 'a' and 'b' for 4 concrete mixes.

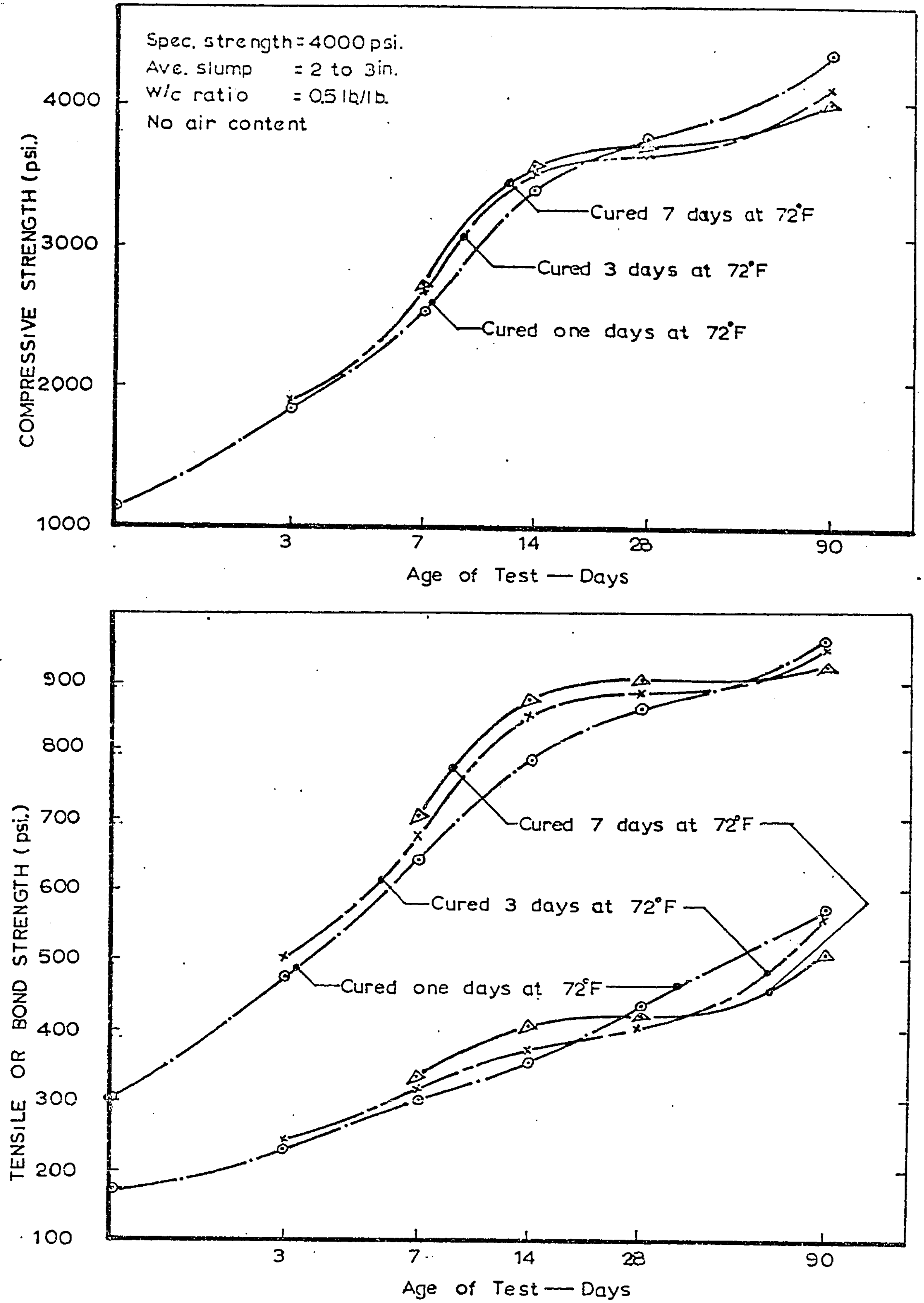

FIG.4 —— VARIATION OF CONCRETE STRENGTH WITH TEMPERATURE
TYPE I CEMENT CURED AT 55°F

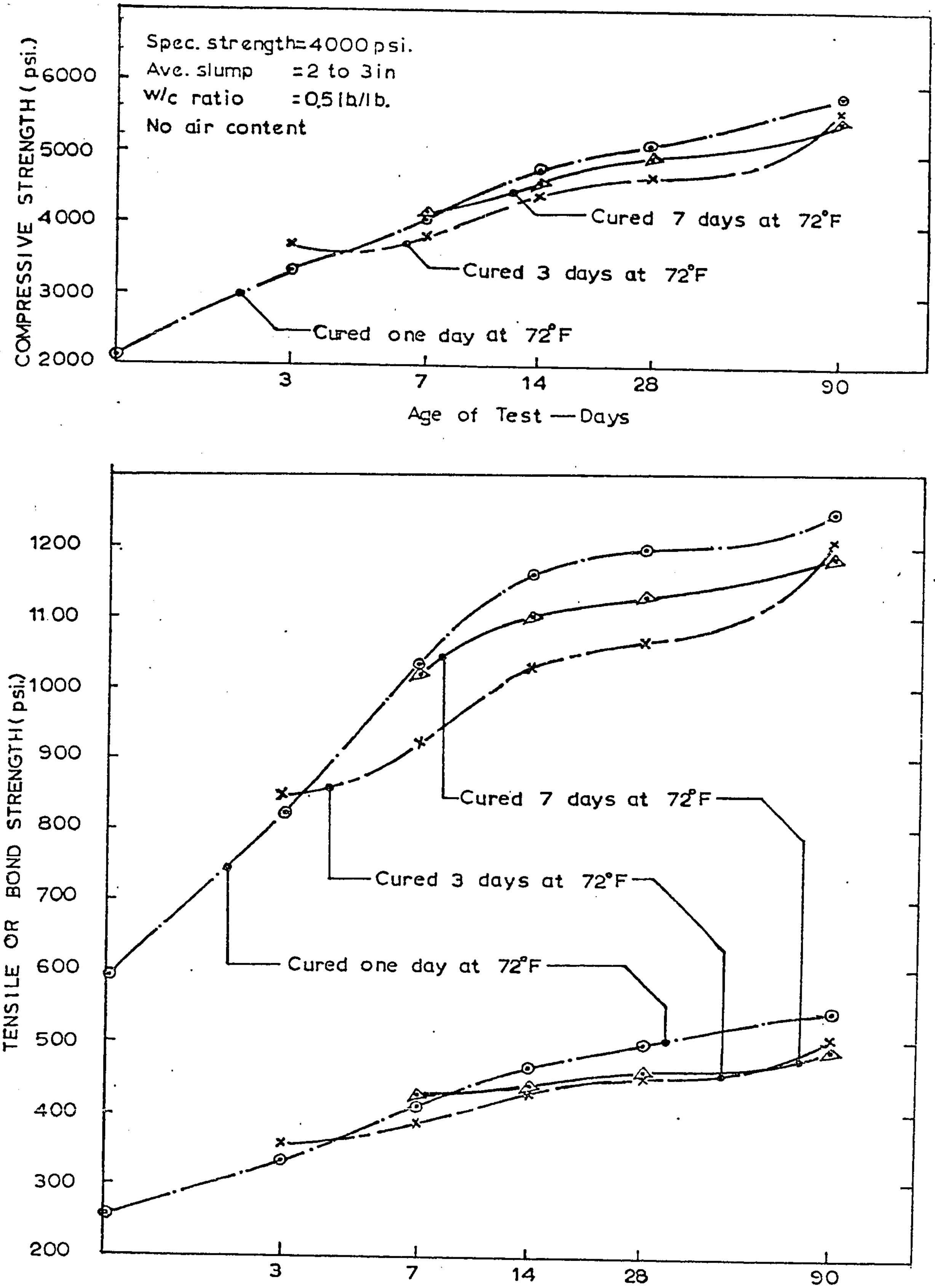

FIG.5 — VARIATION OF CONCRETE STRENGTH WITH TEMPERATURE
TYPE III CEMENT CURED AT 55°F

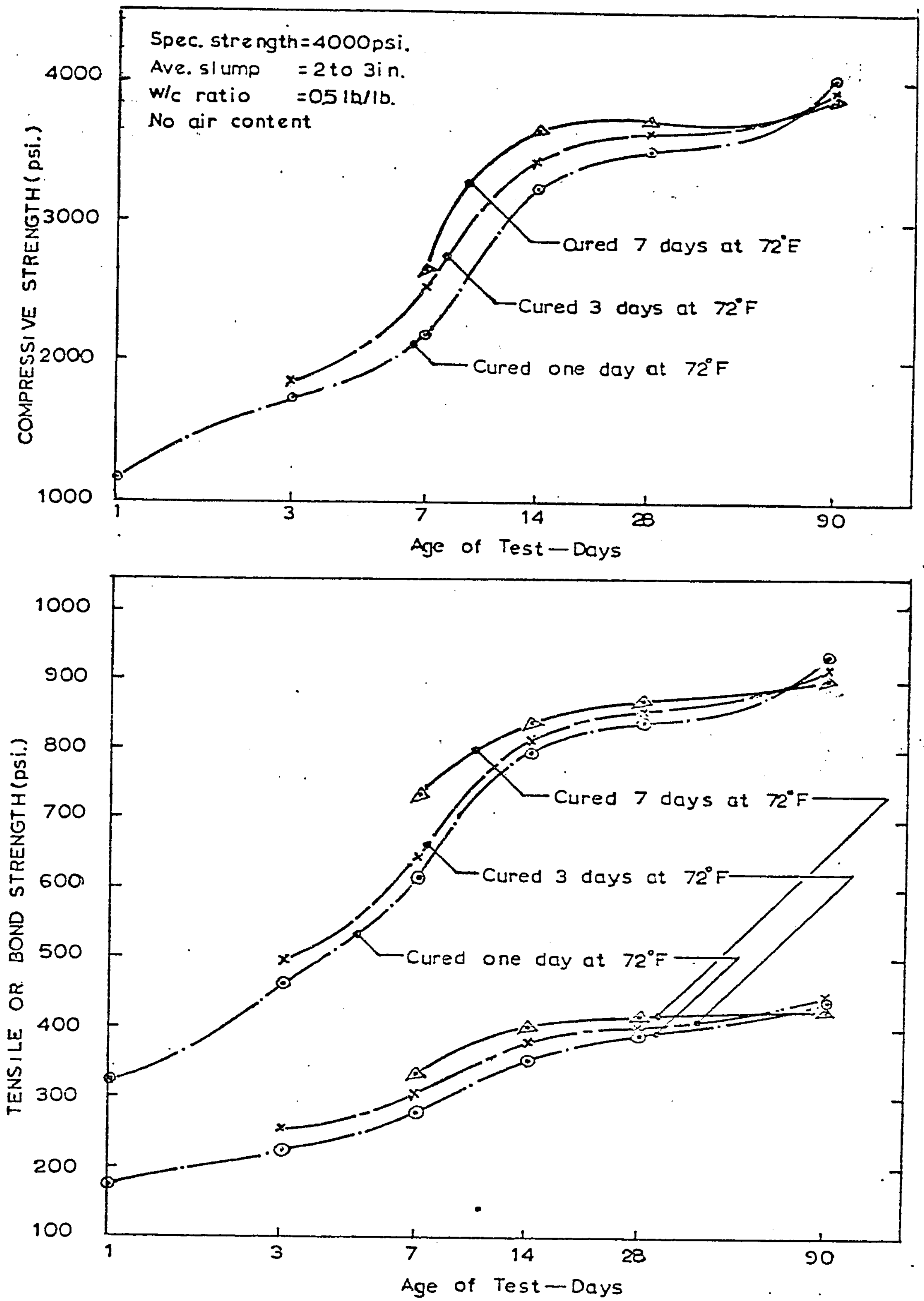

FIG.6.— VARIATION OF CONCRETE STRENGTH WITH TEMPERATURE TYPE I CEMENT CURED AT 35°F

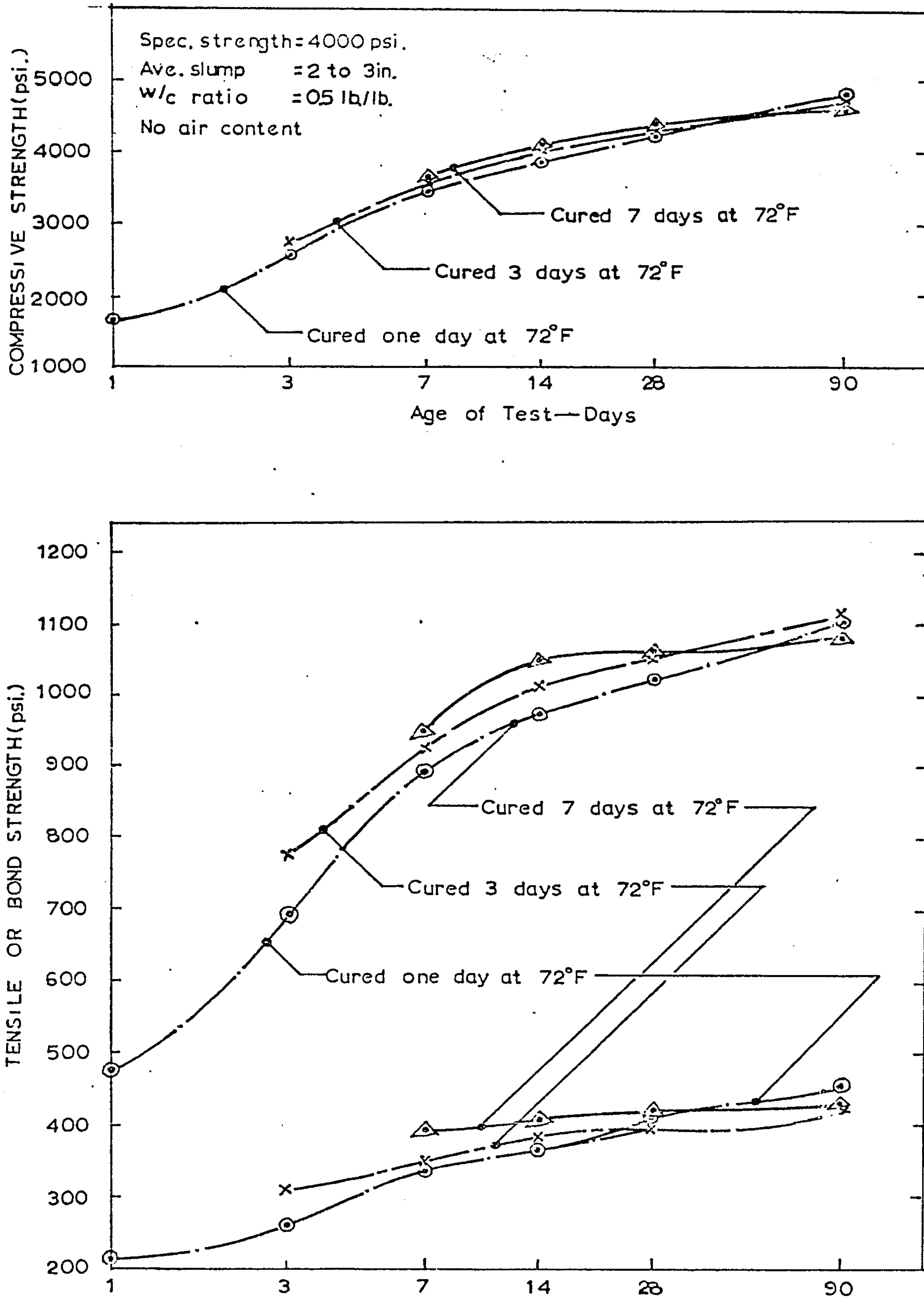

FIG.7 — VARIATION OF CONCRETE STRENGTH WITH TEMPERATURE
TYPE III CEMENT CURED AT 35°F

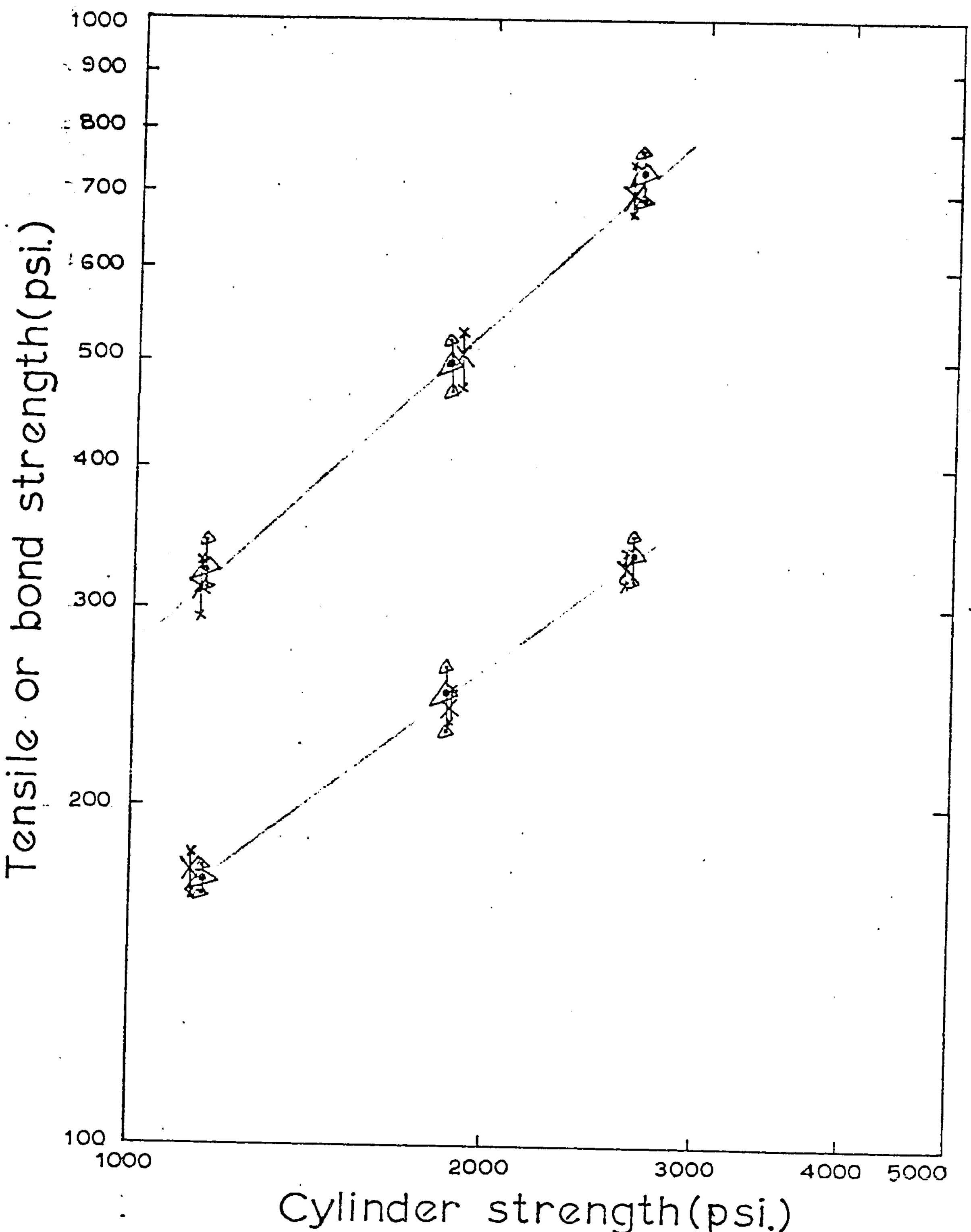

FIG.8a.—Log-log plot of variation of tensile or bond strength with cylinder strength Type I cement cured at 72°F (for 1,3. and 7 days only)

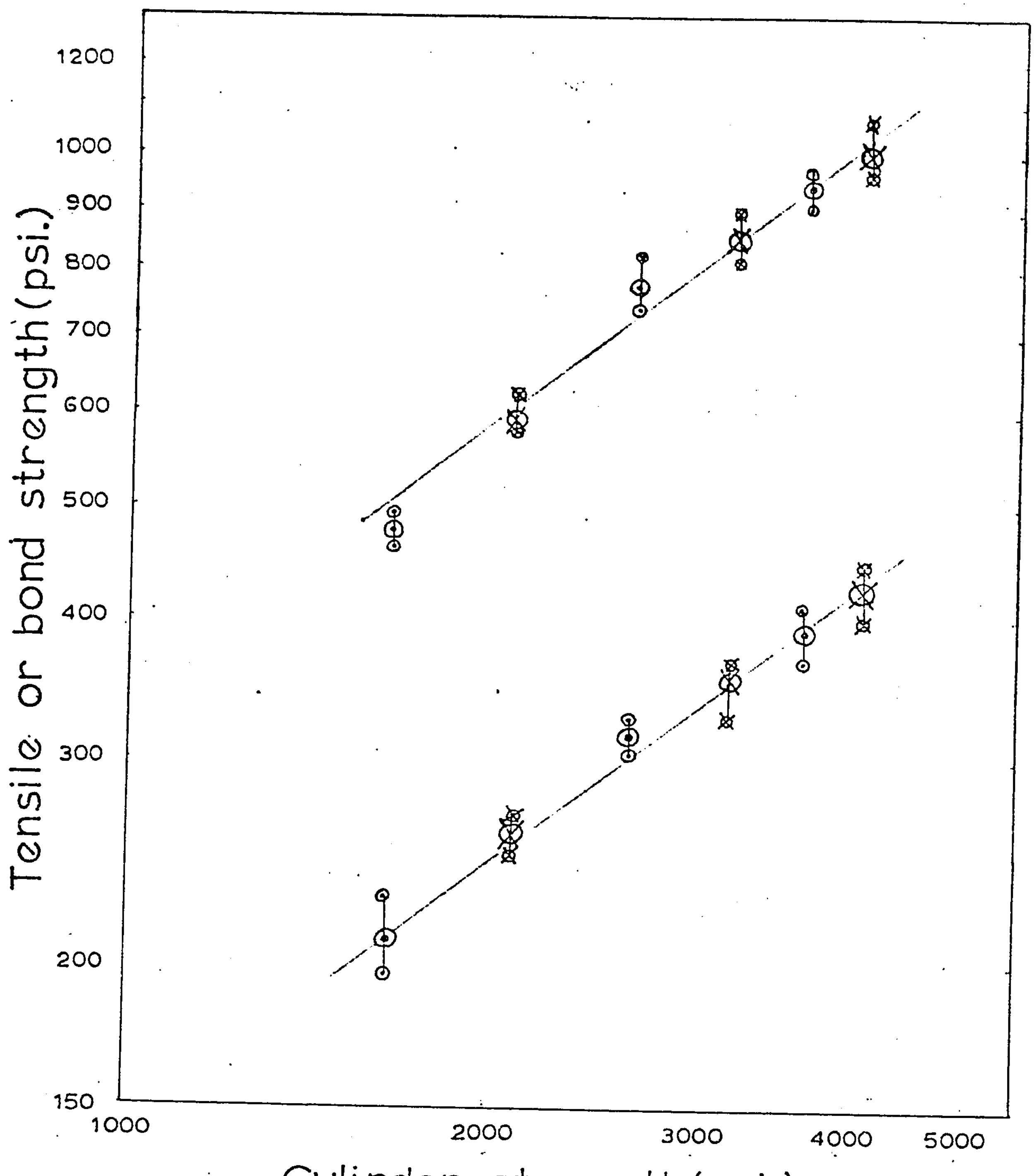

FIG.8b.—Log-log plot of variation of tensile or bond strength with cylinder strength Type III cement cured at 72°F (for 1,3 and 7 days only)

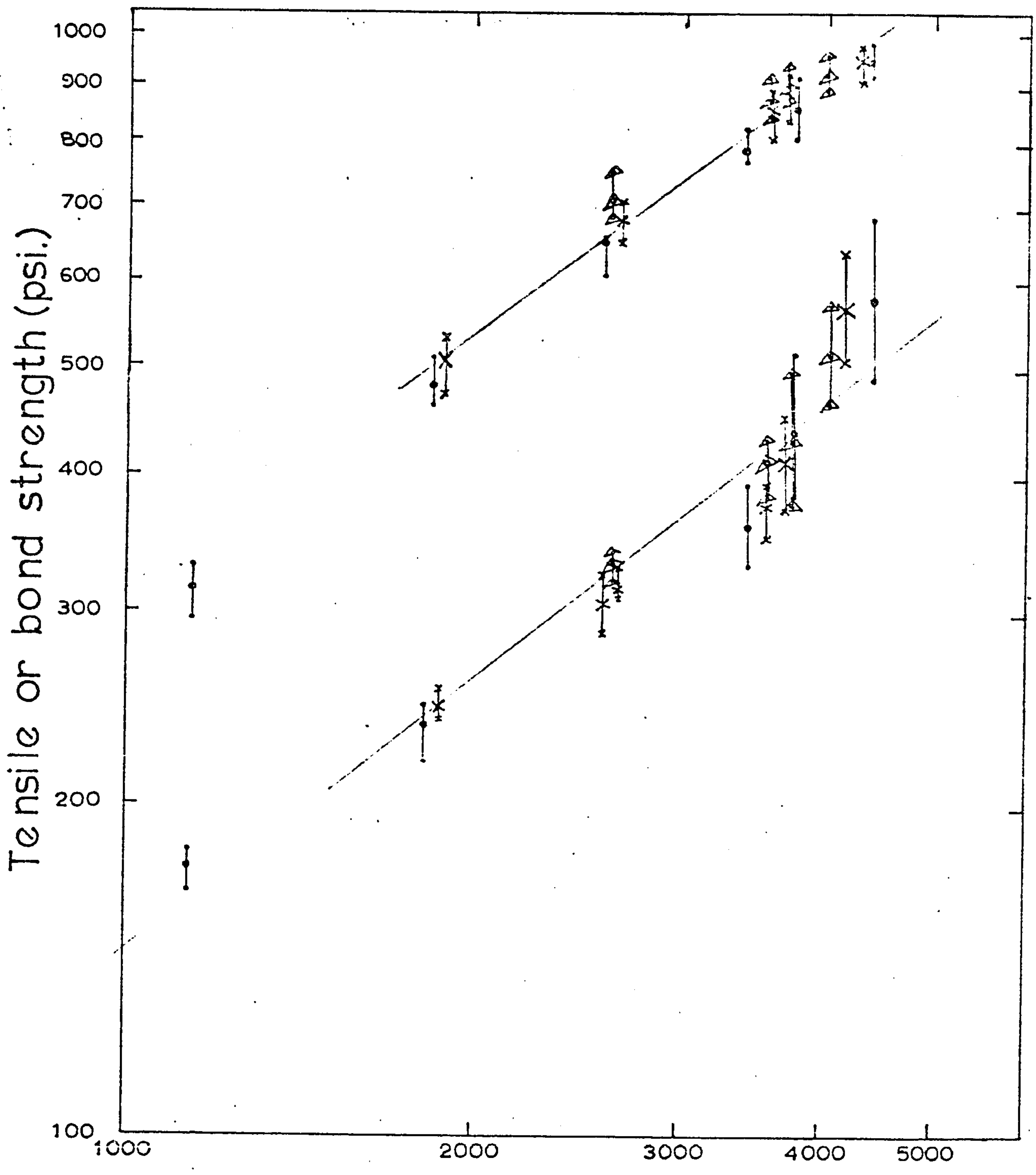

FIG.9 — Log-log plot of variation of tensile or bond strength with cylinder strength Type I cement cured at 55°F

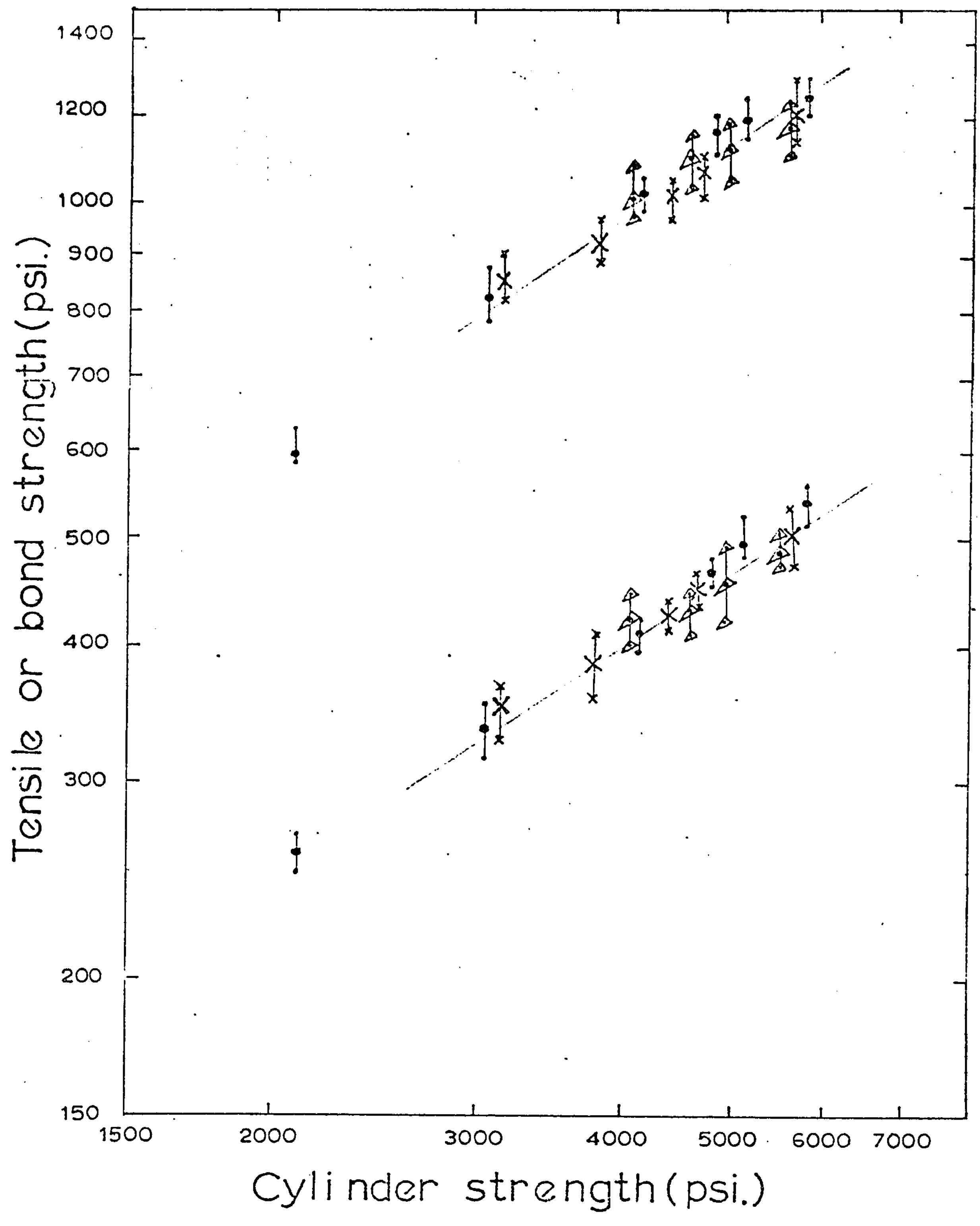

FIG.10—Log-log plot of variation of tensile or bond strength with cylinder strength Type III cement cured at 55°F

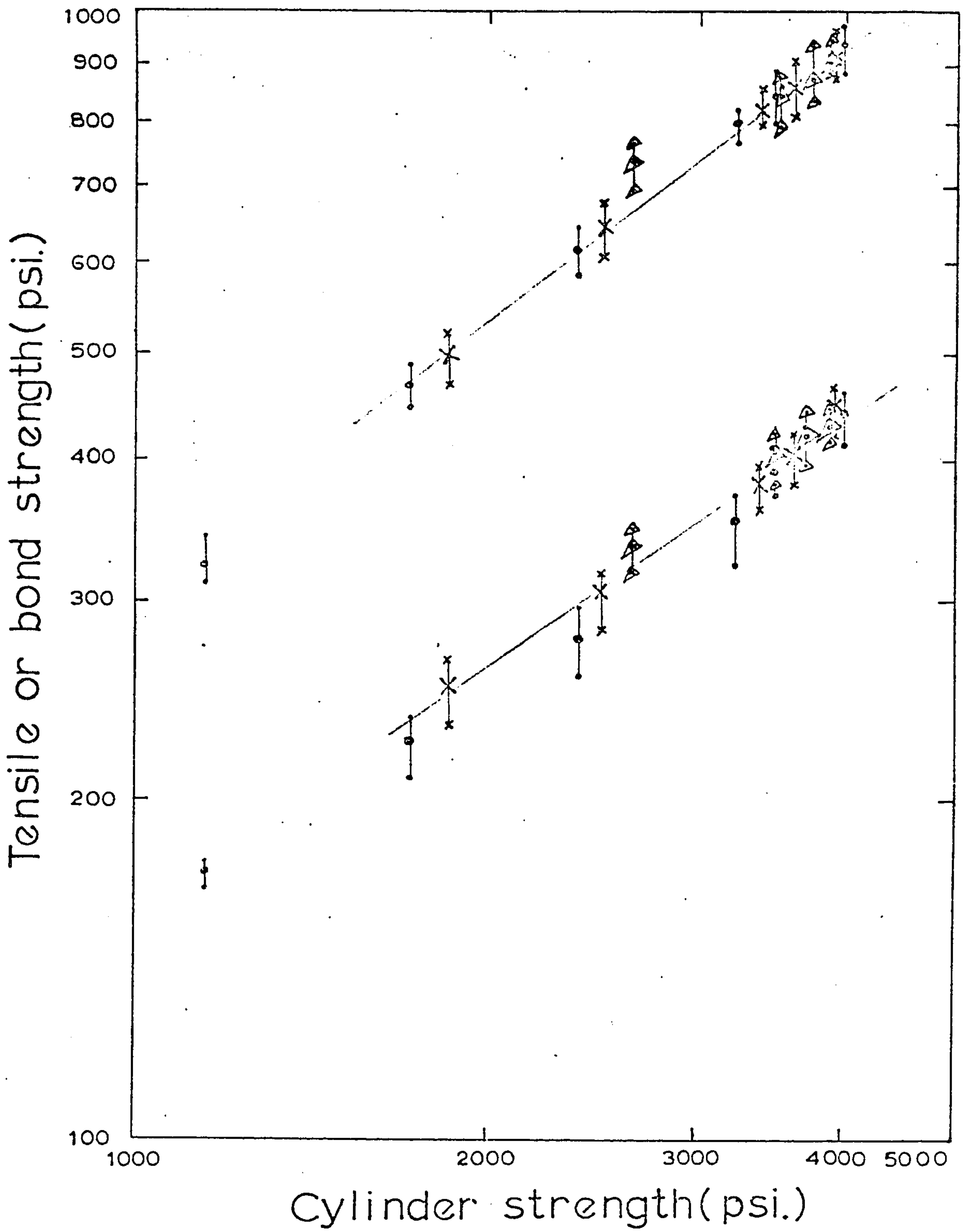

FIG.11 —Log-log plot of variation of tensile or bond strength with cylinder strength Type I cement cured at 35°F

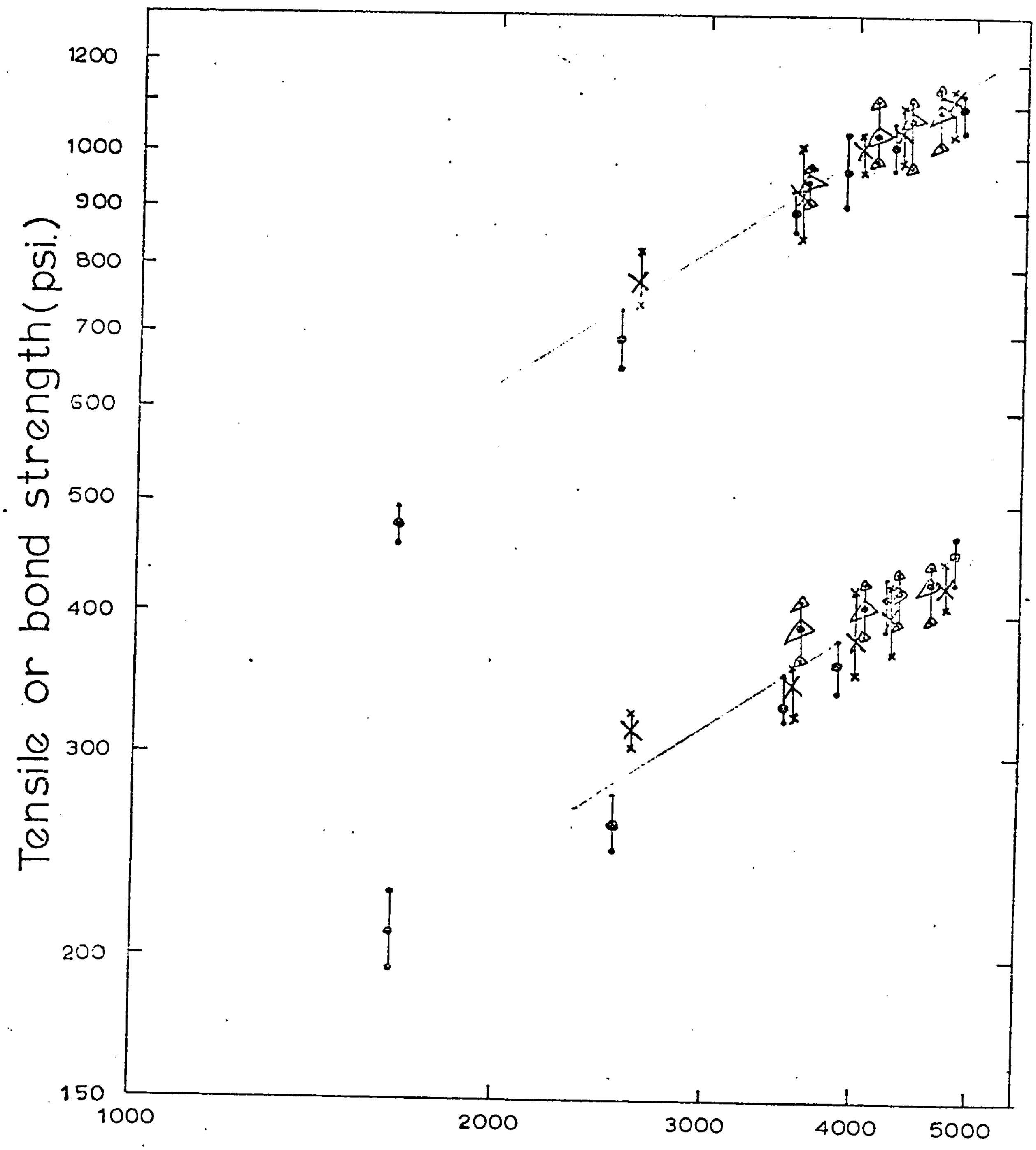

FIG.12— Log-log plot of variation of tensile or bond strength with cylinder strength Type III cement cured at 35°F