DASA-13.0181

R 447

Technical Report

DYNAMIC PROPERTIES OF PLAIN PORTLAND CEMENT CONCRETE

June 1966

NAVAL FACILITIES ENGINEERING COMMAND

U. S. NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

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DYNAMIC PROPERTIES OF PLAIN PORTLAND CEMENT CONCRETE

Technical Report

Y-F008-08-03-401, DASA-13.0181

by

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ABSTRACT

Two concrete mixes (a medium- and a high-strength mix), each cured under two different conditions (73°F, 100% relative humidity for 26 days followed by 2 days in a 20% RH environment or 73°F, 100% RH for 28 days followed by 21 days in a 20% RH environment) were tested to determine the effect of differences in moisture content and rate of loading on their compressive and tensile strengths.

The compressive tests showed the values for mechanical properties increased as the rate of loading increased. At the maximum rate of loading (approximately 2×10^6 psi/sec), the increases in compressive strength over the values for static loading for the moist, 28-day concrete were 45% for the medium-strength and 39% for the high-strength concrete. The increases for the drier, 49-day, medium- and high-strength concretes were 35% and 24%.

In the splitting tensile-strength tests, at a stress rate of 3×10^5 psi/sec the increases in tensile strength over the static values for the 28-day concrete were 70% for the medium-strength and 67% for the high-strength mix. For the 49-day concretes, the increases were 53% for the medium-strength and 40% for the high-strength mix.

Recommended percentage increases in compressive strength are given for concretes subjected to high strain rates.

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The Laboratory invites comment on this report, particularly on the results obtained by those who have applied the information.

This work sponsored by the Defense Atomic Support Agency

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INTRODUCTION

The Naval Civil Engineering Laboratory is conducting studies to determine the dynamic properties of basic structural materials for which such data are incomplete or lacking. This will provide fundamental information for the design of structures to resist blast or other dynamic loads. The present tests were conducted to determine the effects of dynamic loading on the mechanical properties of concrete.

TEST PROGRAM

General

Two basic concrete mixes were used in this program: one to represent a medium-strength concrete and another to represent a high-strength concrete. Each strength of concrete was tested at two ages — 28 days and 49 days. The age differential was incidental to the actual purpose for which these two ages were selected. The 28-day age was selected to test the concrete in a condition as near moisture saturation as possible. The 49-day age was selected to test the concrete in a dry condition. For each strength of concrete the following curing conditions were used: (1) 26 days at 100% RH and 2 days at 20% RH, age at test 28 days; and (2) 28 days at 100% RH and 21 days at 20% RH, age at test 49 days. The temperature used for both curing conditions was 73°F. The 28-day test specimens were removed from the 100% RH curing at 26 days to permit the surface to dry sufficiently for installation of strain gages.

Compression tests were conducted with 3-inch-diameter by 9-inch-long cylinders. Splitting tensile tests were conducted with 3-inch-diameter by 6-inch-long cylinders.

Compression-test specimens for each strength were cast in two batches. Because of the length of time involved in conducting the tests, each group of cylinders from one casting was divided into two test groups: one comprising the 28-day-old and one comprising the 49-day-old cylinders. The following table shows the distribution of test cylinders subjected to static and dynamic compressive tests from each batch:

Test Age (days)	Batch No.	Number of Cylinders Tested			
		Static	Dynamic		
			Approximate Test Rate (psi/sec)		
			10^3	10^5	10^6
Medium Strength					
28	1	3	6	-	3
	2	3	-	6	3
49	1	3	6	-	3
	2	3	-	6	3
High Strength					
28	1	6	6	-	-
	2	3	-	6	6
49	1	6	6	-	-
	2	3	-	6	6

All of the tensile-test cylinders for one age and strength of concrete were obtained from one batch of concrete. Both the static and dynamic tests were conducted during the course of 1 day's testing.

Materials

The materials used were type II portland cement and San Gabriel sand and gravel. The maximum size of the aggregate was 3/4 inch. The proportions used in the two concrete mixes are given below:

Concrete Strength	Type of Test	Proportions by Weight			Gallons per Sack of Cement	Sacks per Cubic Yard of Concrete
		Cement	Sand	Gravel		
Medium	Compression	1	3.9	3.3	8.56	4.63
High	Compression	1	2.0	2.2	5.40	7.37
Medium	Tensile	1	3.9	3.3	8.35	4.83
High	Tensile	1	2.0	2.2	5.30	7.40

Specimen Instrumentation

Half of the compression-test specimens were instrumented with strain gages. Longitudinal strain was measured with type A-9 electrical resistance strain gages cemented to the surface of each specimen on diametrically opposite gage lines parallel to the longitudinal axis of the specimen. These gages had a nominal gage length of 6 inches. The gages were connected in series in the measuring arm of the Wheatstone bridge to obtain the average strain of the two sides of the specimen. Lateral strain was measured by a single 2-1/2-inch (nominal gage length) type A-9-4 gage cemented on the specimen surface at the midheight and normal to the longitudinal axis.

Half of the specimens for splitting tensile tests were instrumented with type A-12 strain gages mounted in the center of each end face of the specimen and normal to the axis of load application. (See Figure 1.) These gages have a nominal gage length of 1 inch. Each gage was recorded independently.

Recording Instrumentation

Test data were recorded by means of an oscillograph and system D, 3-kc amplifiers. Basic information obtained during compression-strength testing was load, longitudinal strain, and transverse strain — each as a function of time. Information obtained during tensile-strength testing was load and transverse strain on each end of the cylinder. As a check on the frequency response of the oscillograph system, several tests were recorded by means of an oscilloscope and a polaroid camera. The values for maximum load determined by each recording system were within the limits of error which might be expected in reducing the data.

Dynamic Testing Machine

The testing machine used to conduct the dynamic tests is shown in Figure 2. This is a pneumatic-hydraulic machine that utilizes air pressure in hydraulic accumulators to supply the energy necessary to conduct a test. Just before the machine is fired, the hydraulic pressure is equalized on the top and on the bottom of the main piston. The head velocity is varied by regulating the rate of flow of hydraulic fluid from beneath the main piston. Since the main piston operates downward only, compression tests are conducted in the lower section of the machine. The specimen is centered on the load cell and the bearing head, attached to the lower piston rod, is screwed down upon the specimen. The bearing head contains a spherical seat. A more detailed description of the machine and its operation can be found in Reference 1.

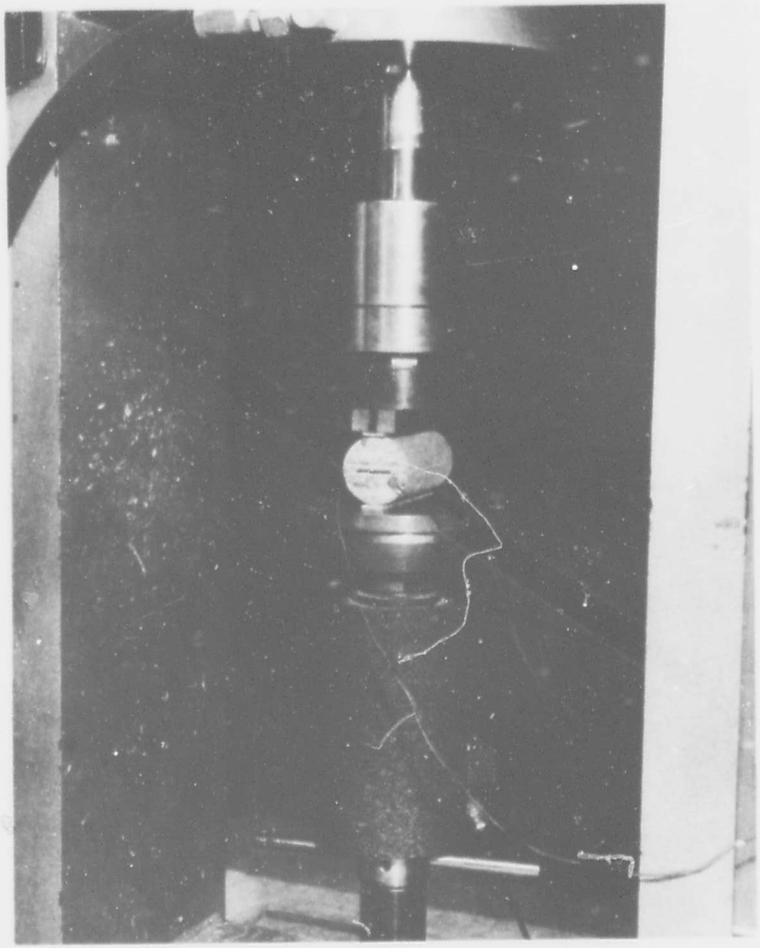


Figure 1. Equipment setup for conducting dynamic splitting tensile-strength tests.

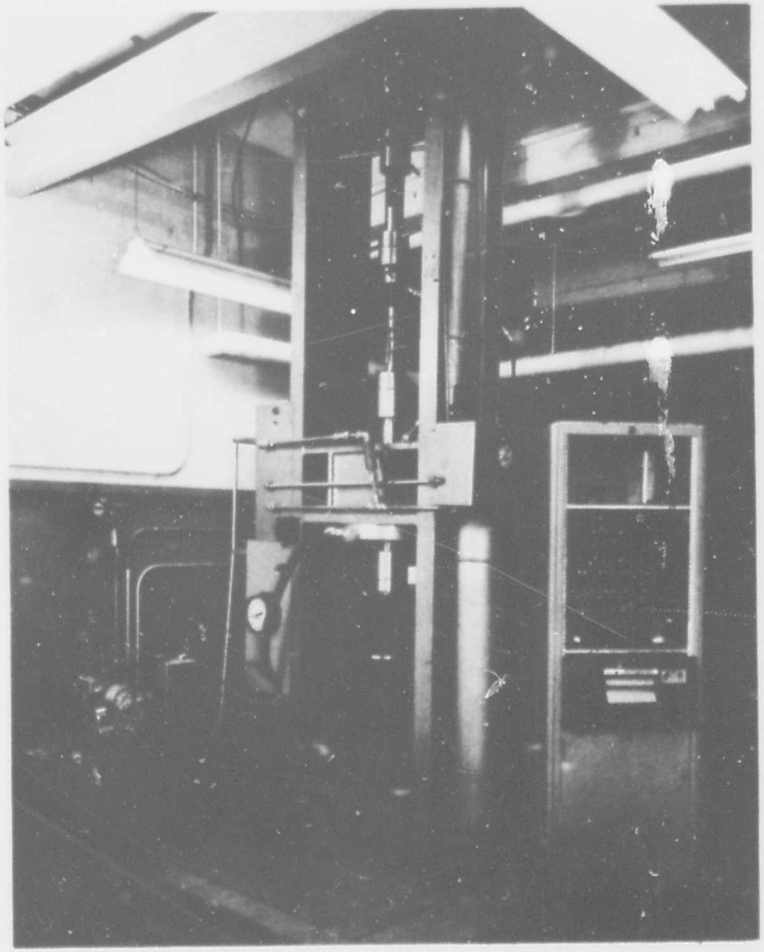


Figure 2. NCEL dynamic testing machine.

TEST PROCEDURE AND APPARATUS

Static Tests

Tests to determine static values for compressive and splitting tensile strength were conducted with a universal testing machine. For those specimens equipped with strain gages, the oscillographic recording equipment was used to maintain a record of the load and strain in the specimen. An example of this arrangement may be seen in Figure 3. The compression loading rate was 30 psi/sec and the tensile loading rate was approximately 3 psi/sec.

Sonic Tests

Just prior to capping, the modulus of elasticity and Poisson's ratio were determined by the sonic method on each of the cylinders instrumented with strain gages. The sonic values were computed from the fundamental longitudinal and torsional frequencies of each cylinder. The method and apparatus used conformed with American Society for Testing Materials (ASTM) Designation C215-60: "Standard Method of Testing for Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens."

Dynamic Tests

Compression test specimens with strain gages in place were initially preloaded in the universal testing machine. Longitudinal and transverse strain readings were taken with an electronic strain indicator. The maximum static load was 1,130 psi for the medium-strength concrete and 2,120 psi for the high-strength concrete. After the static loading, the specimens were taken to the dynamic testing machine and broken. The test arrangement for dynamic testing is illustrated in Figure 4.

The dynamic splitting tensile test arrangement is illustrated in Figure 1. When a compressive load is applied along the circumference of the cylinder as shown in Figure 1, it sets up a uniform tensile stress over the diametral plane containing the applied load and tensile fracture occurs along this plane. Special care was taken to center the test specimen in the testing machine. Cardboard bearing strips (1/32 inch thick by 3/4 inch wide by 6-1/4 inches long) were used to distribute the compressive load on the cylinder. The decision to use cardboard instead of the 1/8-inch-thick plywood normally recommended for a bearing surface was made after considerable difficulty was experienced with the plywood. The splitting tensile strength indicated with plywood strips was approximately 180 psi higher than the values obtained with the cardboard bearing strips. (See Appendix.)

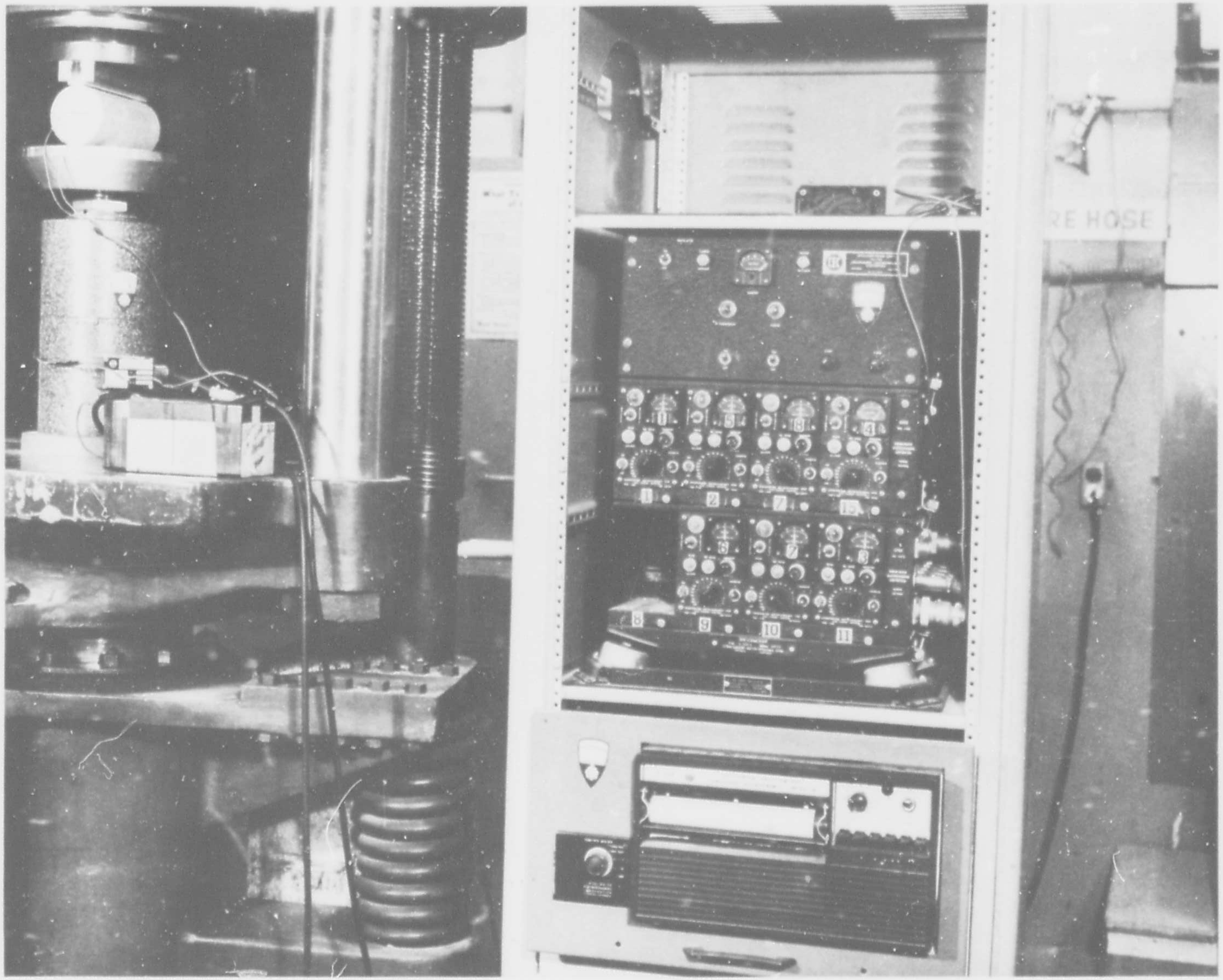


Figure 3. Equipment setup for conducting static tensile-strength tests.

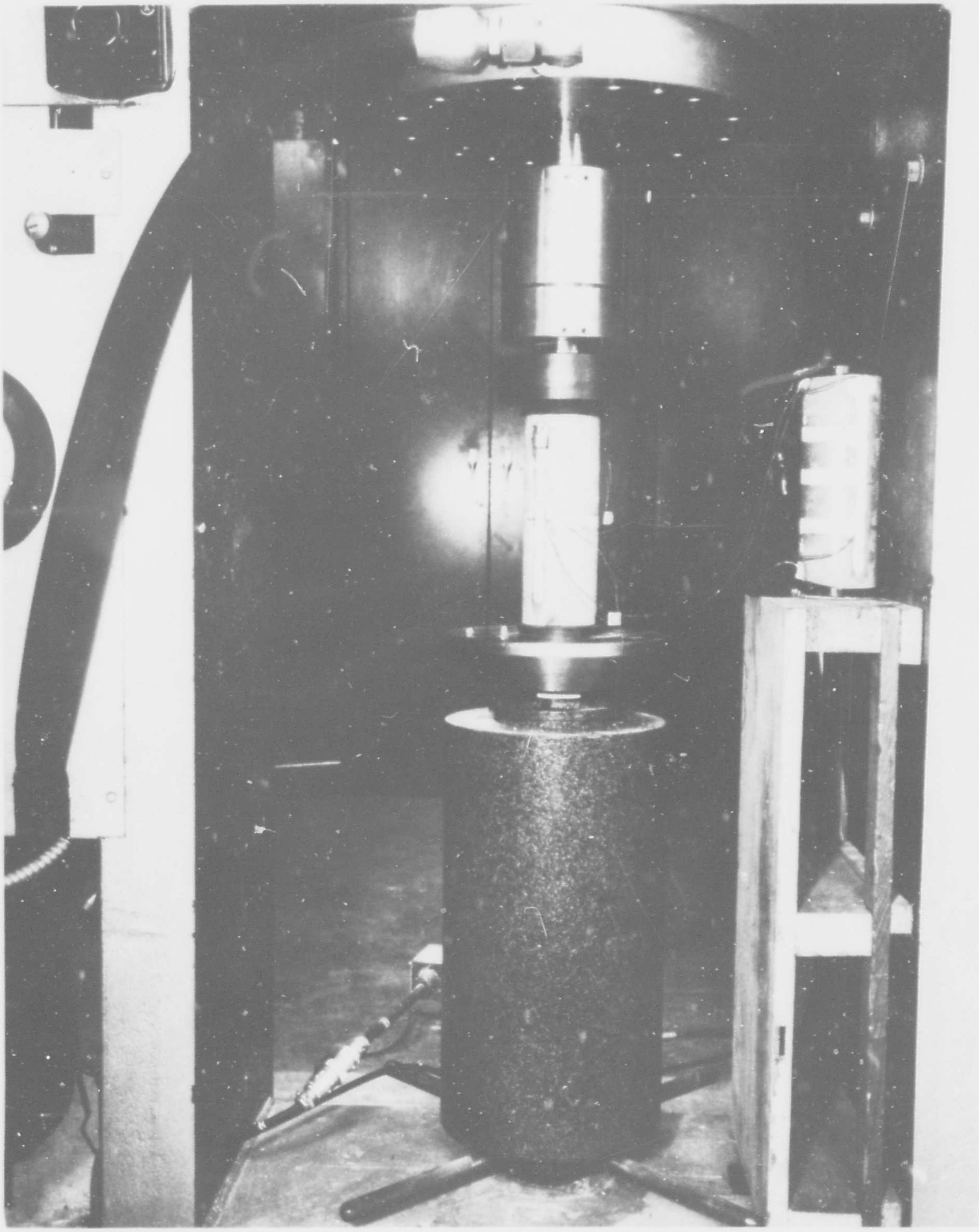


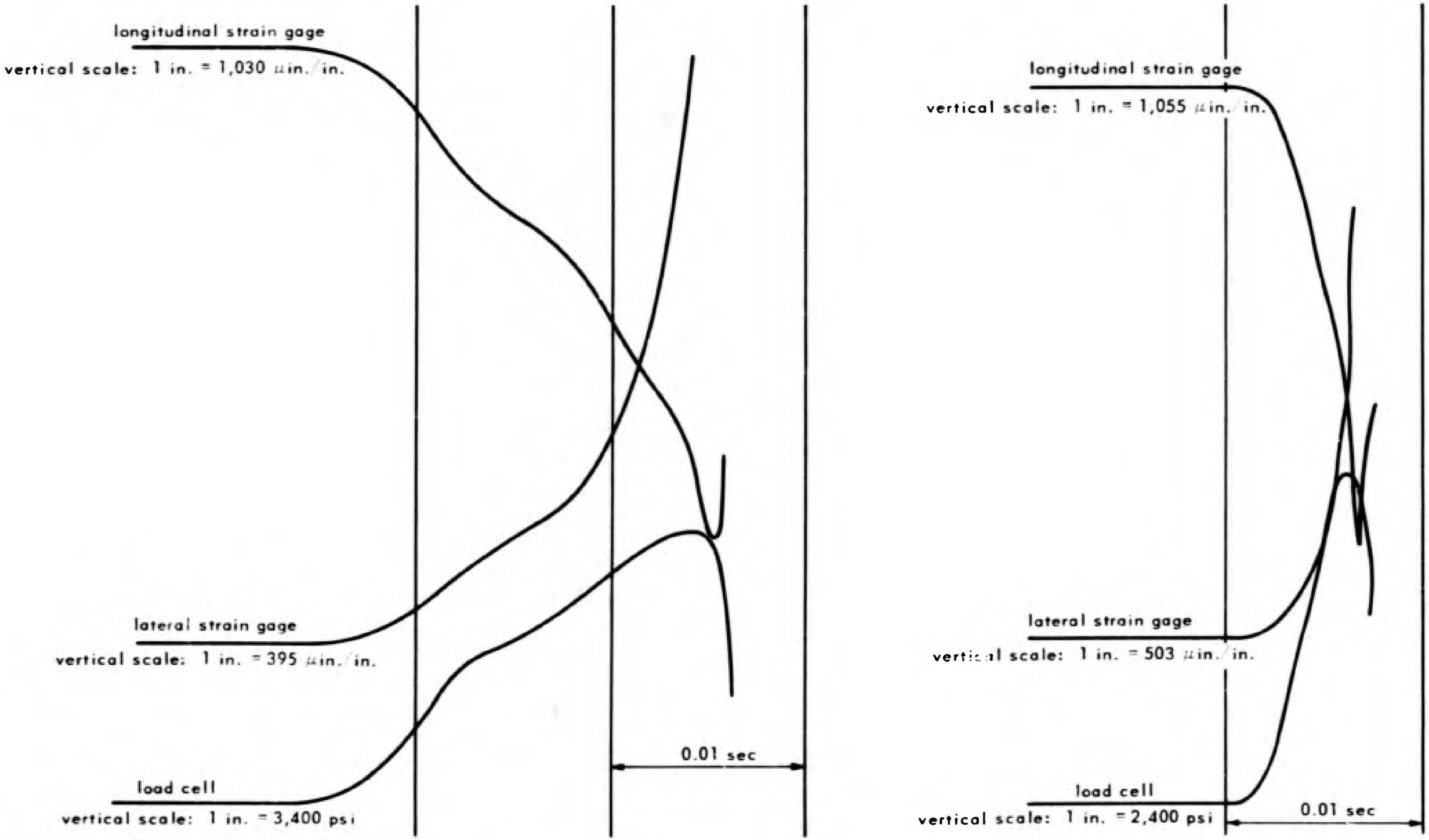
Figure 4. Equipment setup for conducting dynamic compressive-strength tests.

TEST RESULTS

The results of all tests conducted on compression test specimens are shown in Tables 1, 2, 3, and 4. Typical oscillograph records of compression tests are shown in Figure 5. The stress and strain rates listed for cylinders tested in the 10^3 psi/sec range are average rates for the whole test. A linear relationship with time did not exist for the stress or strain at the low rates of loading. At the two highest rates of loading the stress rate was reasonably uniform (see Figure 5b) after an initial acceleration. The linear portion of the load curve just prior to maximum stress was selected to calculate the stress rate. In two groups of tests, the rate of increase in the first part of the load curve was much greater than the rate of increase in the remainder of the test. (See Figure 5a.) As noted above, the last part of the curve was used to calculate the stress rate.

Determination of the longitudinal strain rate was much more arbitrary than determination of stress rate. The strain rate became reasonably linear at a later stage of the test and the rate of strain at this linear portion of the test was selected as representative. The average rates both for stress and strain (zero load to maximum load) were computed for comparison with the selected rates. Although the difference between the selected and average rates for any one specimen was high in some cases, the effect on the relationships developed is negligible.

The results of the splitting tensile tests are shown in Tables 5 and 6. Typical oscillograms of the tensile tests are shown in Figure 6.



(a) (b)

Figure 5. Typical oscillograms of dynamic compressive-strength tests.

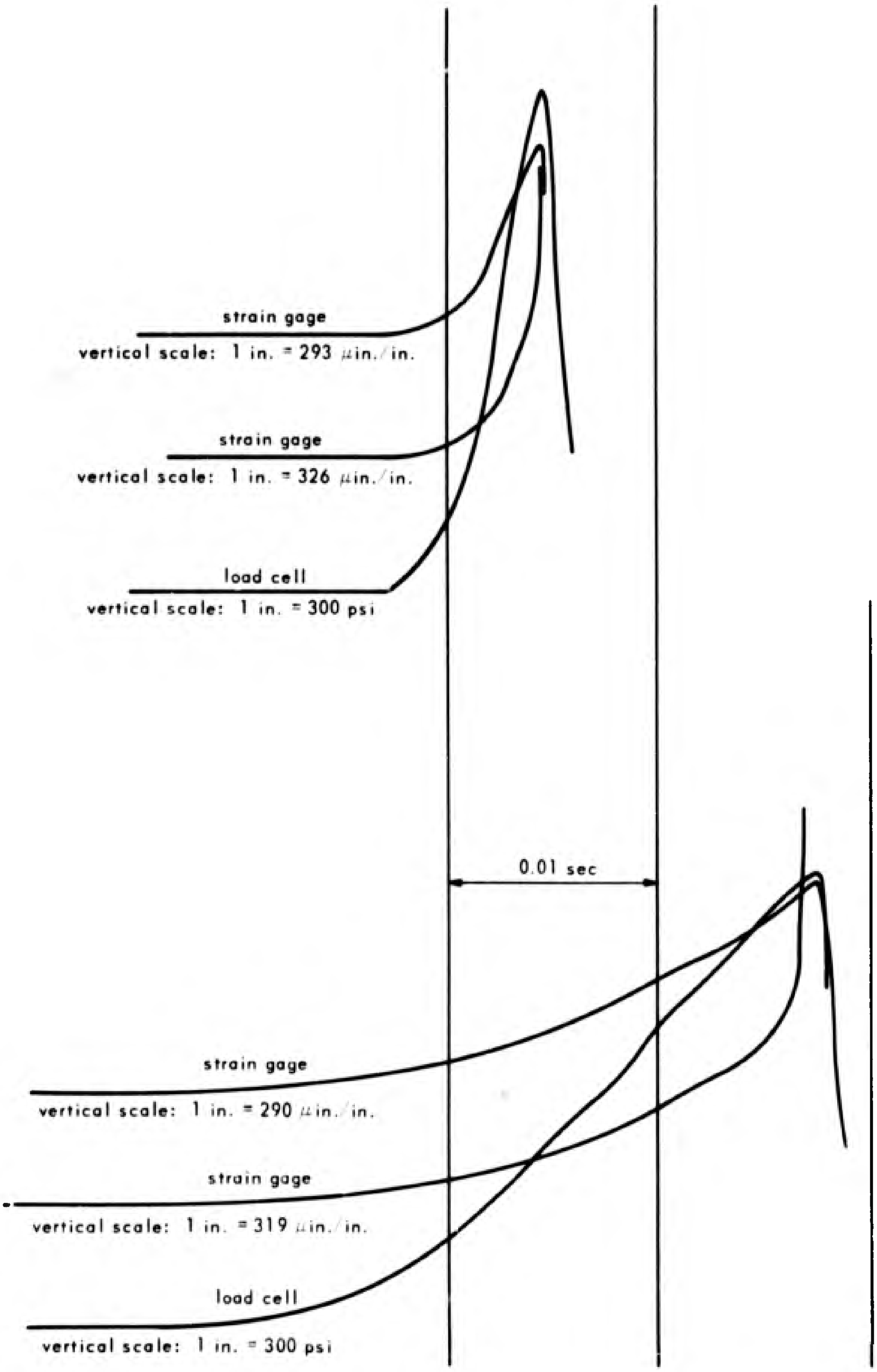


Figure 6. Typical oscillograms of dynamic tensile-strength tests.

Table 1. Summary of Compression Test Results for Medium-Strength Concrete at 28 Days of Age

Cylinder No.	Stress Rate (psi/sec)	Strain Rate (in./in./sec)	Compressive Strength (psi)	Modulus of Elasticity (E)			Poisson's Ratio		Strain at Maximum Stress (in./in. x 10^{-6})	Maximum Strain (in./in. x 10^{-6})	Strain Energy (in.-lb/in.^{3})
				E_1[1] (psi x 10^6)	E_{secant} (psi x 10^6)	E_{sonic} (psi x 10^6)	Test	Sonic			
Static Tests											
1M-216	30	Approximately 6×10^{-6}	3,960	3.26	2.48	4.13	0.15	0.18	—	3,620	5.6
217	30		3,920	3.13	—	4.18	—		—	2,900	—
218	30		4,150	3.27	2.55	4.12	0.18	0.16	—	2,540	6.4
2M-234	30		3,820								
235	30		3,790								
236	30		3,760								
Average	30		3,900		2.52		0.165				5.8
Dynamic Tests											
1M-213	1.91×10^3	11.5×10^{-4}	4,400	3.07	2.82	4.14	0.15	0.16	2,470	—	7.1
214	1.73×10^3	9.1×10^{-4}	4,050	3.00	2.72	4.07	0.20	0.16	2,380	2,880	6.5
215	1.78×10^3	9.7×10^{-4}	4,450	3.03	2.80	4.13	0.17	0.16	2,680	2,890	8.2
1M-207	2.54×10^3		4,300								
208	0.30×10^3		3,720								
209	2.30×10^3		4,470								
2M-240	1.63×10^6	—	5,550	3.09	—	4.14	0.31	0.16	—	—	—
241	1.73×10^6	0.54	5,070	3.01	3.15	4.07	0.23	0.16	2,480	3,070	8.2
242	1.68×10^6	0.54	5,090	3.01	3.25	4.08	0.22	0.16	2,480	2,970	8.4
2M-237	1.55×10^6		5,530								
238	1.57×10^6		5,340								
239	1.68×10^6		5,160								
2M-243	1.88×10^6	0.77	5,660	2.91	3.10	4.08	0.20	0.18	2,640	3,640	9.3
244	1.64×10^6	0.77	5,900	3.12	3.22	4.16	0.22	0.14	2,520	3,150	9.0
245	1.95×10^6	0.72	5,620	3.06	3.30	4.16	0.20	0.14	2,270	2,720	7.7
1M-210	1.06×10^6		5,730								
211	8.70×10^4		5,010								
212	7.90×10^5		5,390								

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[1] Determined by static loading and an electronic strain indicator.

Table 2. Summary of Compression Test Results for Medium-Strength Concrete at 49 Days of Age.

Cylinder No.	Stress Rate (psi/sec)	Strain Rate (in./in./sec)	Compressive Strength (psi)	Modulus of Elasticity (E)			Poisson's Ratio		Strain at Maximum Stress (in./in. x 10^{-6})	Maximum Strain (in./in. x 10^{-6})	Strain Energy (in.-lb/in.^{3})
				E_1[1] (psi x 10^6)	E_{secant} (psi x 10^6)	E_{sonic} (psi x 10^6)	Test	Sonic			
					Static Tests						
1M-228	30	Approximately 6 x 10^{-6}	4,580	—	2.81	4.03	0.23	0.16	2,710	2,980	8.3
229	30		5,200	3.54	3.08	4.10	0.21	0.16	—	—	—
230	30		5,080	3.60	3.11	4.21	0.22	0.14	2,730	3,380	9.4
2M-246	30		4,730								
247	30		4,620								
248	30		4,860								
Average			4,840		3.00		0.22				8.8
					Dynamic Tests						
1M-225	7.36 x 10^3	3.4 x 10^{-3}	5,120	3.35	3.09	4.02	0.16	0.16	2,610	3,300	8.7
226	5.18 x 10^3	2.4 x 10^{-3}	4,880	3.59	3.20	4.09	0.21	0.15	2,260	2,830	7.0
227	6.44 x 10^3	2.8 x 10^{-3}	5,190	3.50	3.18	4.04	0.24	0.16	2,540	2,890	8.6
1M-220	6.48 x 10^3		5,190								
221	6.35 x 10^3		5,020								
2M-252	2.90 x 10^5	0.114	6,000	3.53	3.30	4.13	0.21	0.17	2,740	3,010	10.4
253	3.03 x 10^5	0.126	5,820	3.50	3.25	4.06	0.22	0.16	2,740	3,140	9.6
254	2.96 x 10^5	0.128	6,000	3.61	3.42	4.11	0.25	0.16	2,730	3,180	10.3
2M-249	2.66 x 10^5		5,310								
250	3.07 x 10^5		5,820								
251	3.07 x 10^5		5,900								
2M-255	2.39 x 10^6	0.92	—	3.58	3.85	4.19	0.25	0.17	—	—	—
256	2.06 x 10^6	0.92	6,500	3.53	3.67	4.13	0.32	0.16	2,960	3,390	12.2
257	1.95 x 10^6	0.89	6,580	3.52	3.40	4.07	0.19	0.17	2,980	3,420	12.2
1M-222	1.93 x 10^6		6,650								
223	2.17 x 10^6		6,580								
224	2.27 x 10^6		6,270								

[1] Determined by static loading and an electronic strain indicator.

Table 3. Summary of Compression Test Results for High-Strength Concrete at 28 Days of Age

Cylinder No.	Stress Rate (psi sec)	Strain Rate (in. in. sec)	Compressive Strength (psi)	Modulus of Elasticity (E)			Poisson's Ratio		Strain at Maximum Stress (in. in. × 10^{-6})	Maximum Strain (in. in. × 10^{-6})	Strain Energy (in.-lb in.^{3})
				E_1[1] (psi × 10^6)	E_{secant} (psi × 10^6)	E_{sonic} (psi × 10^6)	Test	Sonic			
Static Tests											
1H-278	30	Approx-imately 6 × 10^{-6}	7,630	3.74	3.60	5.07	0.24	0.20	—	2,900	11.0
279	30		7,350	3.71	3.50	4.94	0.22	0.18	—	2,770	11.8
280	30		7,450	3.68	3.45	4.94	0.16	0.19	—	3,060	11.1
1H-272	30		7,640								
273	30		7,660								
274	30		7,200								
2H-299	30		7,660								
300	30		7,350								
301	30		7,030								
Average			7,420		3.52		0.21				
Dynamic Tests											
1H-281	3.66 × 10^3	1.8 × 10^{-3}	7,400	3.74	3.80	4.93	0.20	0.19	2,430	2,545	9.7
282	4.28 × 10^3	1.5 × 10^{-3}	8,140	3.64	3.75	4.90	0.20	0.19	2,825	3,010	13.4
283	4.64 × 10^3	1.6 × 10^{-3}	8,070	3.72	3.80	4.97	0.25	0.18	2,510	—	11.2
1H-284	0.95 × 10^3		7,810								
285	5.10 × 10^3		7,910								
286	4.18 × 10^3		8,140								
2H-311	4.91 × 10^5	0.147	9,900	3.84	4.07	4.96	0.22	0.19	3,150	3,310	18.0
312	4.57 × 10^5	0.135	9,150	3.69	4.22	4.82	0.30	0.16	2,865	2,920	15.6
313	4.77 × 10^5	0.140	9,500	3.72	4.18	4.85	0.29	0.17	3,010	3,050	16.8
2H-302	4.50 × 10^5		9,520								
303	4.84 × 10^5		9,190								
304	4.77 × 10^5		9,480								
2H-308	2.81 × 10^6	0.75	10,100	3.74	4.15	4.87	0.23	0.15	2,610	2,610	13.6
309	2.79 × 10^6	0.75	10,300	3.80	4.30	4.92	0.25	0.18	3,090	3,090	18.7
310	2.71 × 10^6	0.76	10,350	3.52	3.76	4.76	0.17	0.17	3,160	3,160	18.0
2H-305	2.64 × 10^6		10,550								
306	2.84 × 10^6		10,350								
307	3.01 × 10^6		10,450								

[1] Determined by static loading and an electronic strain indicator.

Table 4. Summary of Compression Test Results for High-Strength Concrete at 49 Days of Age

Cylinder No.	Stress Rate (psi/sec)	Strain Rate (in./in./sec)	Compressive Strength (psi)	Modulus of Elasticity (E)			Poisson's Ratio		Strain at Maximum Stress (in./in. × 10^{-6})	Maximum Strain (in./in. × 10^{-6})	Strain Energy (in.-lb/in.^{3})
				E_1 1/ (psi × 10^6)	E_{secant} (psi × 10^6)	E_{sonic} (psi × 10^6)	Test	Sonic			
Static Tests											
1H-290	30	Approximately 5×10^{-6}	9,000	4.30	4.00	5.17	0.20	0.20	3,000	3,040	16.0
291	30		9,380	4.36	4.00	5.11	0.17	0.17	3,140	3,140	16.6
292	30		8,600	4.14	3.95	5.04	0.17	0.19	2,970	2,970	15.3
1H-287	30		8,440								
288	30		8,480								
289	30		8,700								
2H-315	30		8,650								
Average			8,750		3.98		0.18				
Dynamic Tests											
1H-293	5.00×10^3	0.00152	9,350	4.34	4.20	5.15	0.22	0.17	—	—	—
294	5.85×10^3	0.00176	9,060	4.15	4.15	4.98	0.25	0.18	2,730	2,840	14.9
295	8.50×10^3	0.00259	9,000	4.15	4.18	5.03	0.22	0.18	2,800	2,970	14.7
1H-296	5.25×10^3		9,040								
297	4.78×10^3		9,510								
298	4.60×10^3		9,880								
2H-323	1.59×10^5	0.051	9,680	4.24	4.25	4.97	0.15	0.18	3,100	3,270	17.4
324	1.70×10^5	0.048	9,380	4.23	4.27	5.00	0.22	0.18	—	—	—
325	1.58×10^5	0.047	9,960	4.18	4.38	5.05	0.20	0.18	2,960	3,180	17.2
2H-317	1.41×10^5		9,610								
318	1.43×10^5		10,150								
319	1.41×10^5		10,300								
2H-326	2.98×10^6	0.77	11,320	4.20	4.50	5.03	0.26	0.18	3,150	3,150	20.7
327	2.76×10^6	0.76	11,300	4.10	4.90	5.03	0.22	0.19	2,840	2,840	18.7
328	2.80×10^6	0.78	10,850	4.06	4.43	4.94	0.21	0.17	2,950	2,950	20.2
2H-320	2.79×10^6		10,800								
321	2.78×10^6		10,600								
322	2.94×10^6		10,700								

1/ Determined by static loading and an electronic strain indicator.

Table 5. Splitting Tensile Strengths for Medium-Strength Concrete at 28 and 49 Days of Age

28-Day Concrete[1]				49-Day Concrete[2]			
Cylinder No.	Stress Rate (psi/sec)	Strain Rate (in./in./sec)	Tensile Strength (psi)	Cylinder No.	Stress Rate (psi/sec)	Strain Rate (in./in./sec)	Tensile Strength (psi)
145	3	4×10^{-6}	560	258	3	3×10^{-6}	555
146	3	4×10^{-6}	430[3]	259	3	6×10^{-6}	630
147	3	4×10^{-6}	475	260	3	9×10^{-6}	535
148	3		565	261	3		560
149	3		470	262	3		580
150	3		480	263	3		605
Average			515	Average			575
163	650	4.8×10^{-4}	670	264	650	3.8×10^{-4}	660
164	680	5.0×10^{-4}	665	265	670	3.2×10^{-4}	715
165	700	5.8×10^{-4}	610	266	660	3.5×10^{-4}	710
166	1,460		610	267	670		550
167	670		615	268	670		610
168	660		670				
				270	37×10^{3}	1.8×10^{-2}	775
169	46×10^{3}	3.4×10^{-2}	750	271	38×10^{3}	2.3×10^{-2}	750
170	41×10^{3}	2.6×10^{-2}	775	272	38×10^{3}	2.0×10^{-2}	665
171	47×10^{3}	2.7×10^{-2}	820	273	39×10^{3}		790
172	45×10^{3}		705	274	37×10^{3}		745
173	46×10^{3}		720	275	39×10^{3}		700
174	46×10^{3}		680				
				276	210×10^{3}	0.11	790
157	250×10^{3}	0.16	890	277	210×10^{3}	0.10	845
158	240×10^{3}	0.14	865	278	210×10^{3}	0.08	860
159	260×10^{3}	0.18	900	279	130×10^{3}		850
160	260×10^{3}		880	280	180×10^{3}		835
161	260×10^{3}		805	281	200×10^{3}		835
162	270×10^{3}		860				
				282	610×10^{3}	0.16	970
151	700×10^{3}	0.28	—	283	620×10^{3}	0.20	1,045
152	$1{,}060 \times 10^{3}$	0.27	—	284	630×10^{3}	0.18	1,010
153	750×10^{3}	0.27	—	285	600×10^{3}		995
154	560×10^{3}		1,010	286	620×10^{3}		1,040
155	560×10^{3}		—	287	600×10^{3}		995
156	770×10^{3}		—				

[1] Compressive strength (four cylinders) = 4,570 psi.
[2] Compressive strength (four cylinders) = 5,520 psi.
[3] Not used in average.

Table 6. Splitting Tensile Strengths for High-Strength Concrete at 28 and 49 Days of Age

28-Day Concrete[1]			
Cylinder No.	Stress Rate (psi/sec)	Strain Rate (in./in./sec)	Tensile Strength (psi)
212	3	1.7×10^{-6}	740
213	3	2.4×10^{-6}	740
214	3	2.4×10^{-6}	760
215	3		690
216	3		660
217	3		655
Average			710
218	660	3.8×10^{-4}	870
219	680	3.2×10^{-4}	770
220	640	4.0×10^{-4}	880
221	710		820
223	670		900
224	45×10^{3}	2.0×10^{-2}	1,130
225	44×10^{3}	2.1×10^{-2}	1,020
226	45×10^{3}	2.0×10^{-2}	1,130
227	50×10^{3}		965
228	45×10^{3}		975
229	46×10^{3}		1,065
230	230×10^{3}	0.13	850
231	125×10^{3}	0.14	1,080
232	130×10^{3}	0.07	1,090
234	224×10^{3}		985
235	137×10^{3}		1,115
236	610×10^{3}	0.23	1,225
237	590×10^{3}	0.20	1,215
240	580×10^{3}		1,260
241	610×10^{3}		1,300

49-Day Concrete[2]			
Cylinder No.	Stress Rate (psi/sec)	Strain Rate (in./in./sec)	Tensile Strength (psi)
294	3	2.7×10^{-6}	895
295	3	2.9×10^{-6}	815
296	3	3.3×10^{-6}	810
297	3		775
298	3		720
299	3		670[3]
Average			805
300	700	2.6×10^{-4}	945
301	690	4.7×10^{-4}	745
302	660	2.6×10^{-4}	980
303	700		770
304	700		900
305	670		940
306	42×10^{3}	1.9×10^{-2}	1,030
307	38×10^{3}	1.4×10^{-2}	940
308	43×10^{3}	1.8×10^{-2}	1,105
309	43×10^{3}		1,030
311	42×10^{3}		1,220
312	220×10^{3}	0.08	1,010
313	210×10^{3}	0.09	1,090
314	230×10^{3}	0.10	1,140
315	250×10^{3}		930
316	200×10^{3}		1,135
317	270×10^{3}		1,010
318	580×10^{3}	0.15	1,205
319	530×10^{3}	0.16	1,195
320	550×10^{3}	0.21	1,155
321	620×10^{3}		1,405
322	610×10^{3}		1,115
323	630×10^{3}		1,245

[1] Compressive strength (four cylinders) = 8,310 psi.

[2] Compressive strength (four cylinders) = 9,080 psi.

[3] Not used in average.

OBSERVATIONS

Compression Tests

The effect of increased stress rate on the compressive strength of concrete is illustrated in Figure 7; when compressive strength is plotted against the stress rate on a log scale, a curvilinear relationship exists for all of the concretes tested.

Figure 8 shows the numeric increase in compressive strength as a function of stress rate. For a given curing condition, the high-strength concretes generally have the greatest rate of increase in compressive strength. Drying the concrete lowers the rate of increase in compressive strength at the lower stress rates for both strengths of concrete. The effect of drying seems to be more pronounced in the high-strength concrete.

Figure 9 shows the percentage increase in compressive strength as a function of the compressive stress rate for each concrete mix. The 28-day, medium-strength concrete exhibits the greatest percentage increase, primarily because of its lower static strength. Increases of 45% and 39% for the 28-day medium- and high-strength concretes, respectively, were obtained at the maximum stress rates. For the 49-day concretes the increase was 35% and 24% for the medium- and high-strength concretes, respectively.

The results of tests conducted by Watstein[2] are shown in Figure 9 for comparison with the values obtained in the present tests. The rate of static loading used by Watstein was 6 psi/sec compared to the 30 psi/sec used in the NCEL tests. The lower static-loading rate would give a slightly lower static strength and in turn this would raise the computed percentage increase in compressive strength at higher testing rates. Tests by the Bureau of Reclamation[3] and by Jones and Richart[4] show that a reduction in loading rate from 30 psi/sec to 6 psi/sec could lower the compressive strength by 4% to 5%. Watstein[2] tabulated the maximum stress rate as well as the average stress rate for each test. A significant change in the curve representing his data exists at the higher stress rates when the maximum stress rate is used instead of the average stress rate. Curves representing both sets of data are displayed in Figure 9.

Figure 10 illustrates the effect of strain rate on the compressive strength of concrete. The curves generally are much the same as those shown in Figure 7 for the effect of stress rate on compressive strength. Because more test specimens were involved in the stress-rate tests than in the strain-rate tests, the curve for the 49-day, high-strength concrete was adjusted to more closely fit the test result groupings (ordinate) illustrated in Figure 7. Other ordinate values in Figure 10 corresponding to those in Figure 7 are in close agreement. Because the tests are reasonably consistent in rate of loading, the strain-rate grouping should also be consistent. Figure 11 shows the percentage increase in compressive strength as a function of the strain rate for each concrete mix. Watstein's[2] test results are also included for comparison.

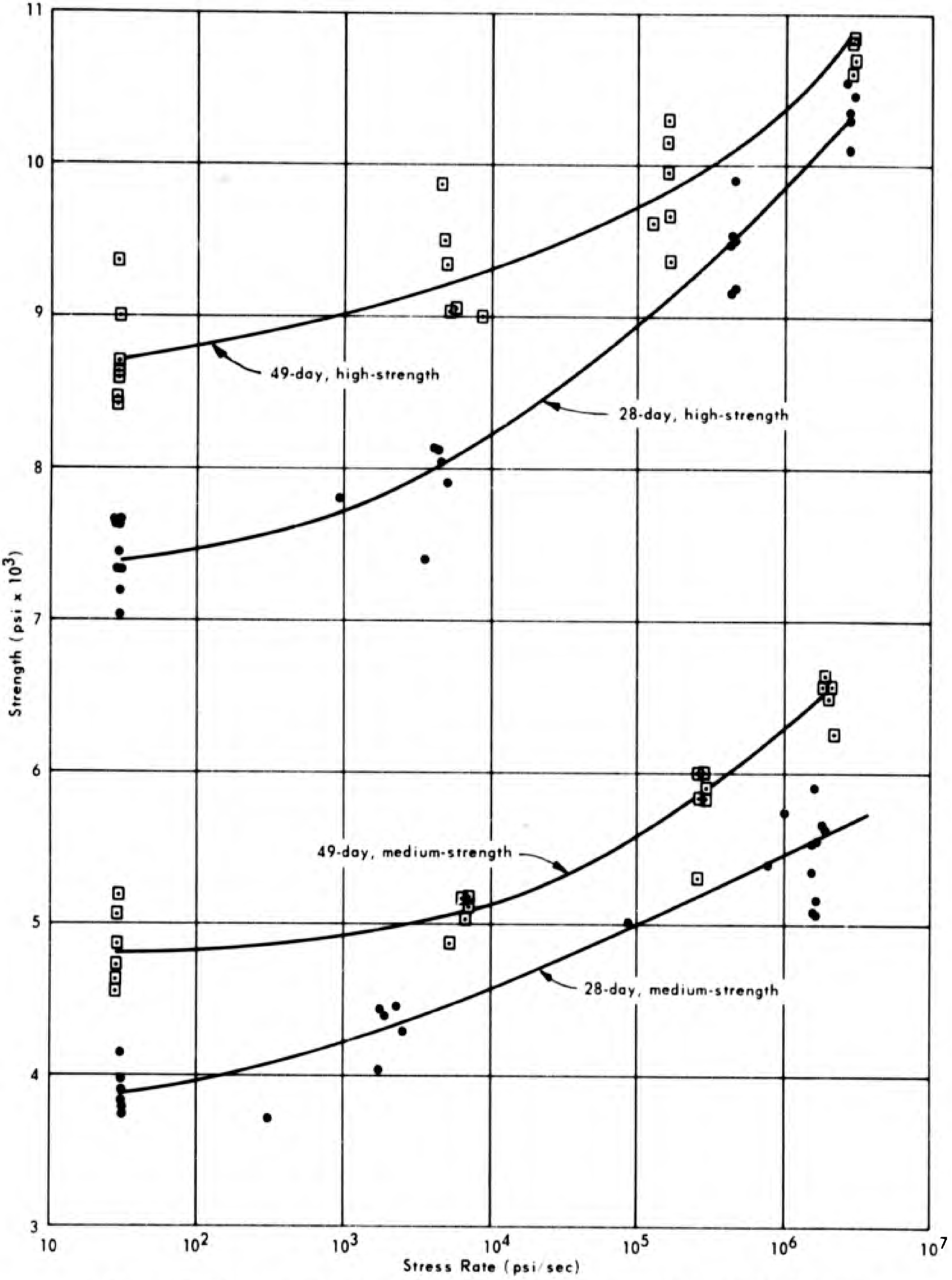


Figure 7. Compressive-stress rate versus compressive strength of concrete.

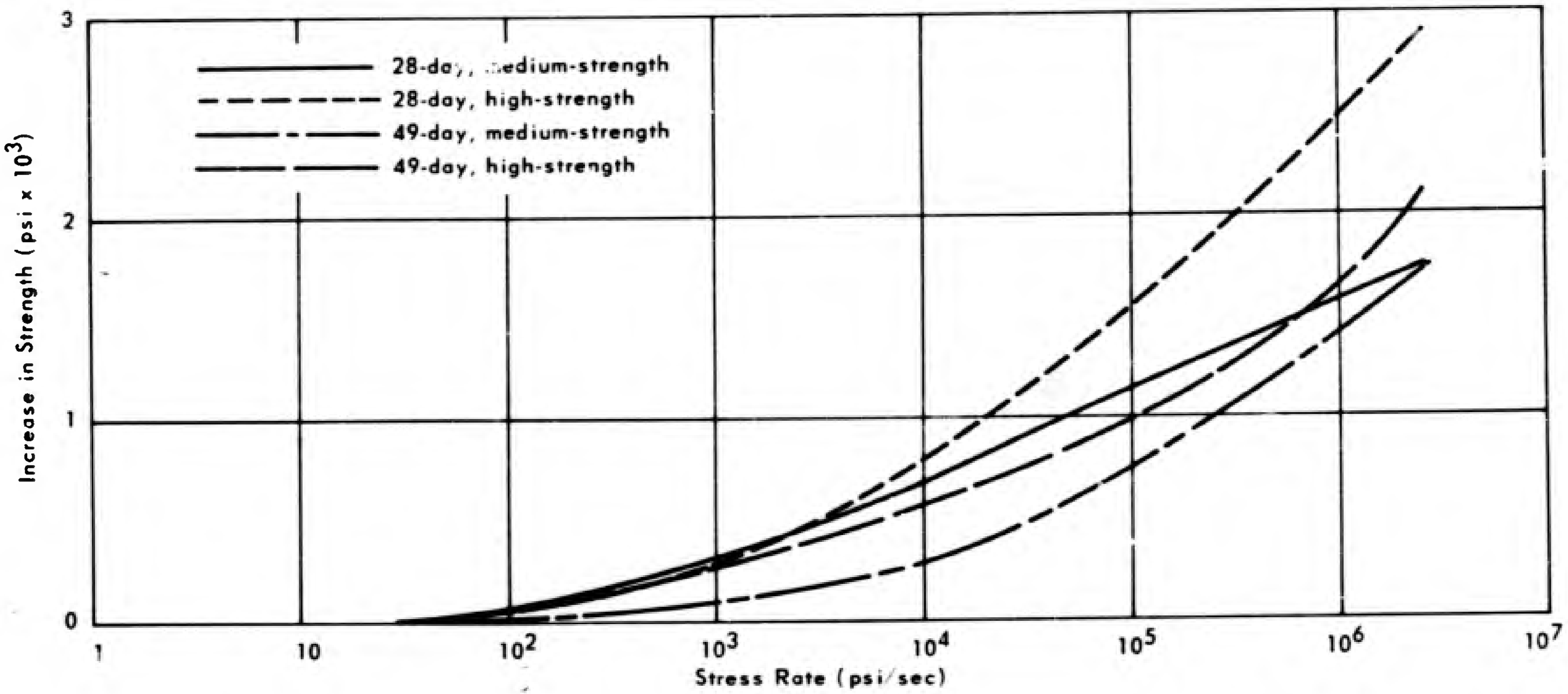


Figure 8. Compressive-stress rate versus increase in compressive strength of concrete.

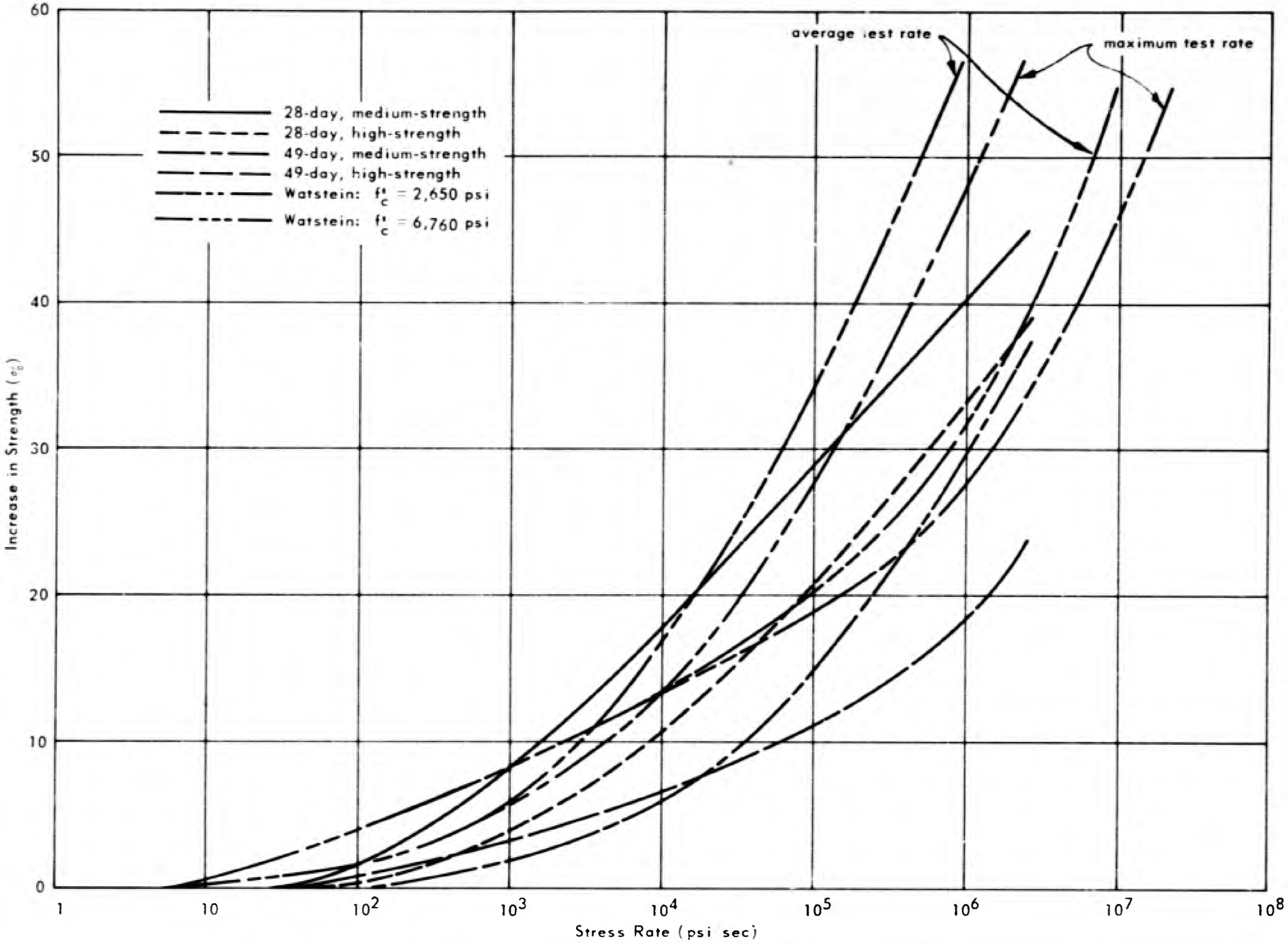


Figure 9. Compressive-stress rate versus percentage increase in compressive strength of concrete.

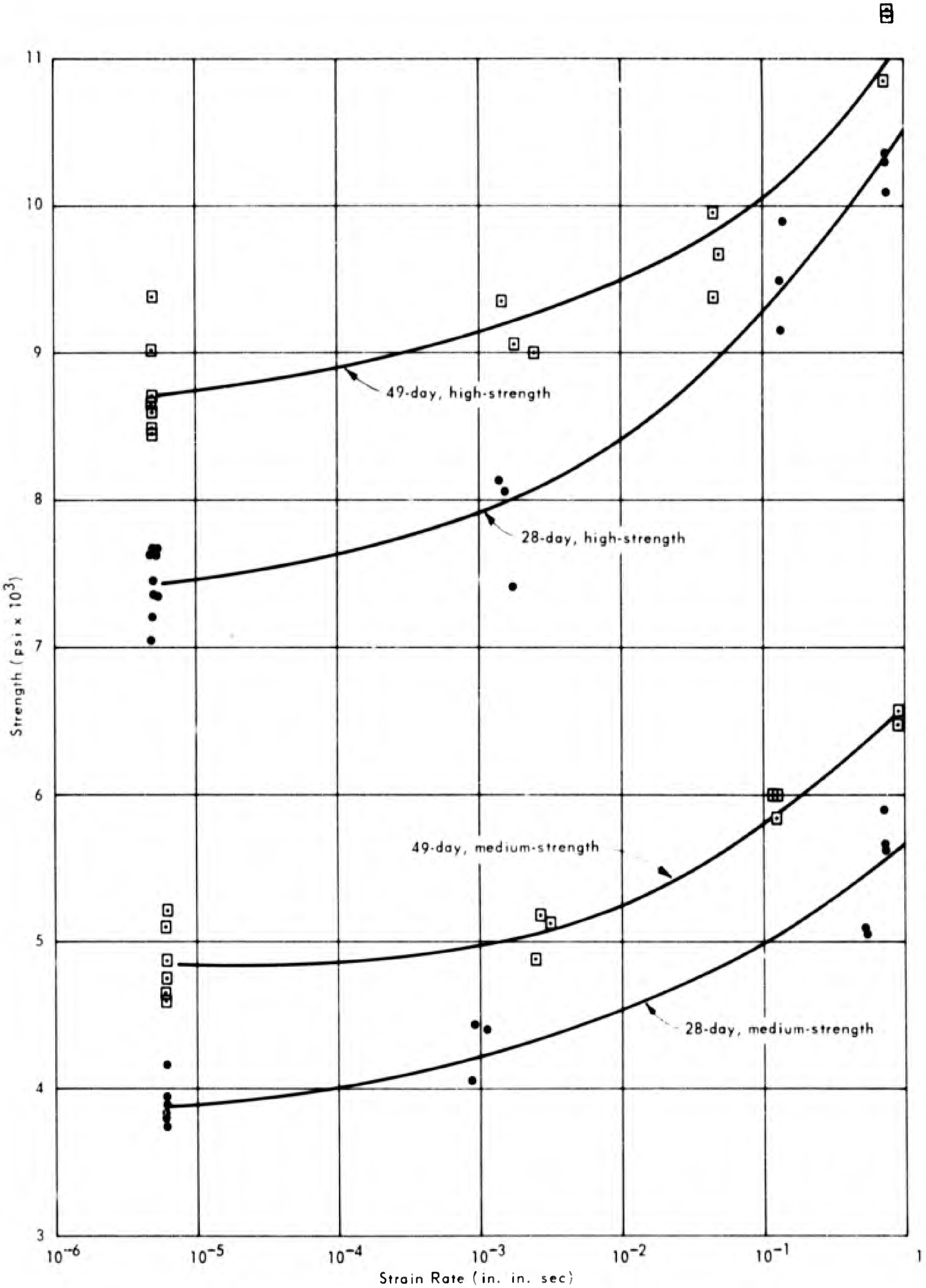


Figure 10. Strain rate versus compressive strength of concrete.

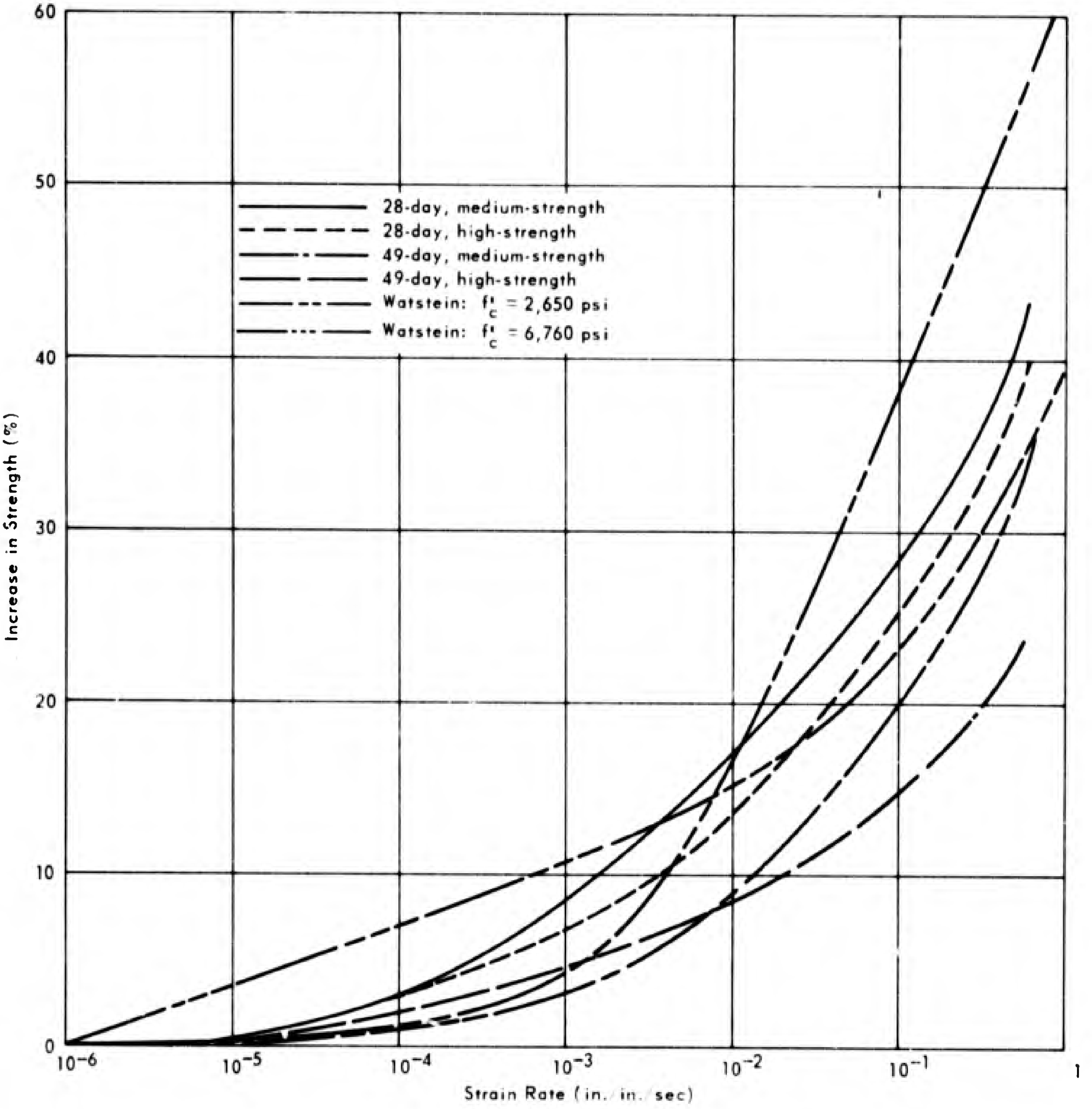


Figure 11. Strain rate versus percentage increase in compressive strength of concrete.

Figures 12 and 13 show the effect of stress rate on the secant modulus of elasticity for both strengths and for both curing conditions of the concrete. Average values for specimens at each test rate were used. The 28-day, high-strength concrete cylinders and the 49-day, medium-strength concrete cylinders had load-versus-time curves similar to the trace shown in Figure 5a when the cylinders were tested at the 10^5 psi/sec load rate. The initial phase of the test had a much higher stress rate; the average stress rates for these two groups have been adjusted to conform to the stress rate experienced by the cylinders at the strain value used for computing the modulus of elasticity. Of the concretes tested, the 28-day, medium-strength concrete had the largest percentage increase in modulus of elasticity. The primary cause of the difference in the percentage increase curves is the lower static value for the 28-day, medium-strength concrete. The actual numeric increase in modulus of elasticity is similar for the 28-day concretes and 49-day concretes. Drying the concrete reduced the rate of increase at the lower stress rates but appears to have had very little effect at the maximum stress rate. Watstein's[2] results are shown in Figure 12 for comparison with the NCEL tests.

Figures 14 and 15 show the effect of high stress rate on the stress-strain curve of concrete. These figures were prepared by averaging, at progressively higher strain increments, the stress of the cylinders tested at a given stress rate. The linear portion of the stress-strain curve becomes longer as the stress rate increases. It is doubtful that the increase in linearity exhibited is significant when compared to the increase in compressive strength. The slope of the stress-strain curve becomes slightly steeper with increasing stress rates. This increase in slope is represented by the increase in modulus shown in Figures 11 and 12. As stress rate increases, the increase in strain at maximum stress appears small; however, the test results were quite erratic and no definite conclusions can be made as to the extent of this apparent increase in strain. The increase in strain energy with rate of loading shown in Tables 1 through 4 is due primarily to the increase in compressive strength of the concrete.

The values of sonic modulus of elasticity as computed from the resonant frequency of each cylinder exceeded both the static and dynamic modulus of elasticity in all tests (Tables 1 through 4). An effort was made to correlate the sonic modulus with the initial tangent modulus of elasticity under dynamic loading. However, the tangent modulus was not well defined and therefore its value was subject to individual interpretation.

Poisson's ratio was determined by dividing the lateral strain by the longitudinal strain at a longitudinal strain of 0.001 in./in. Although no consistent relationship with rate of loading could be determined, there was a significant increase in Poisson's ratio at the higher loading rates.

No difference could be seen between the appearance of the fractures of static test specimens and the appearance of fractures of dynamic test specimens. However, the broken fragments of the 49-day, medium-strength specimens appeared dry, whereas those of the 49-day high-strength specimens had a damp appearance.

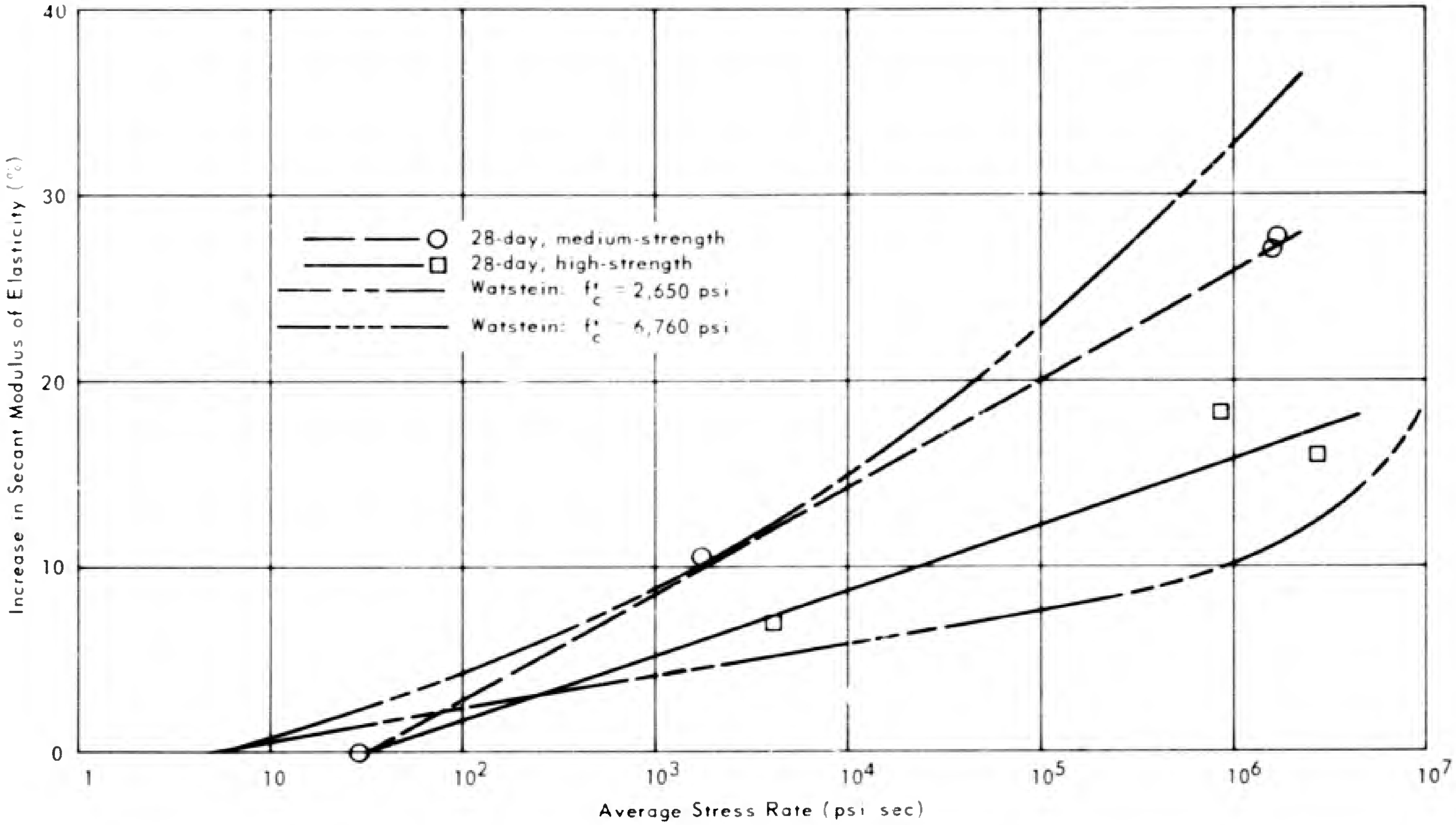


Figure 12. Stress rate versus percentage increase in secant modulus of elasticity (0.001 in./in. strain) for 28-day concretes.

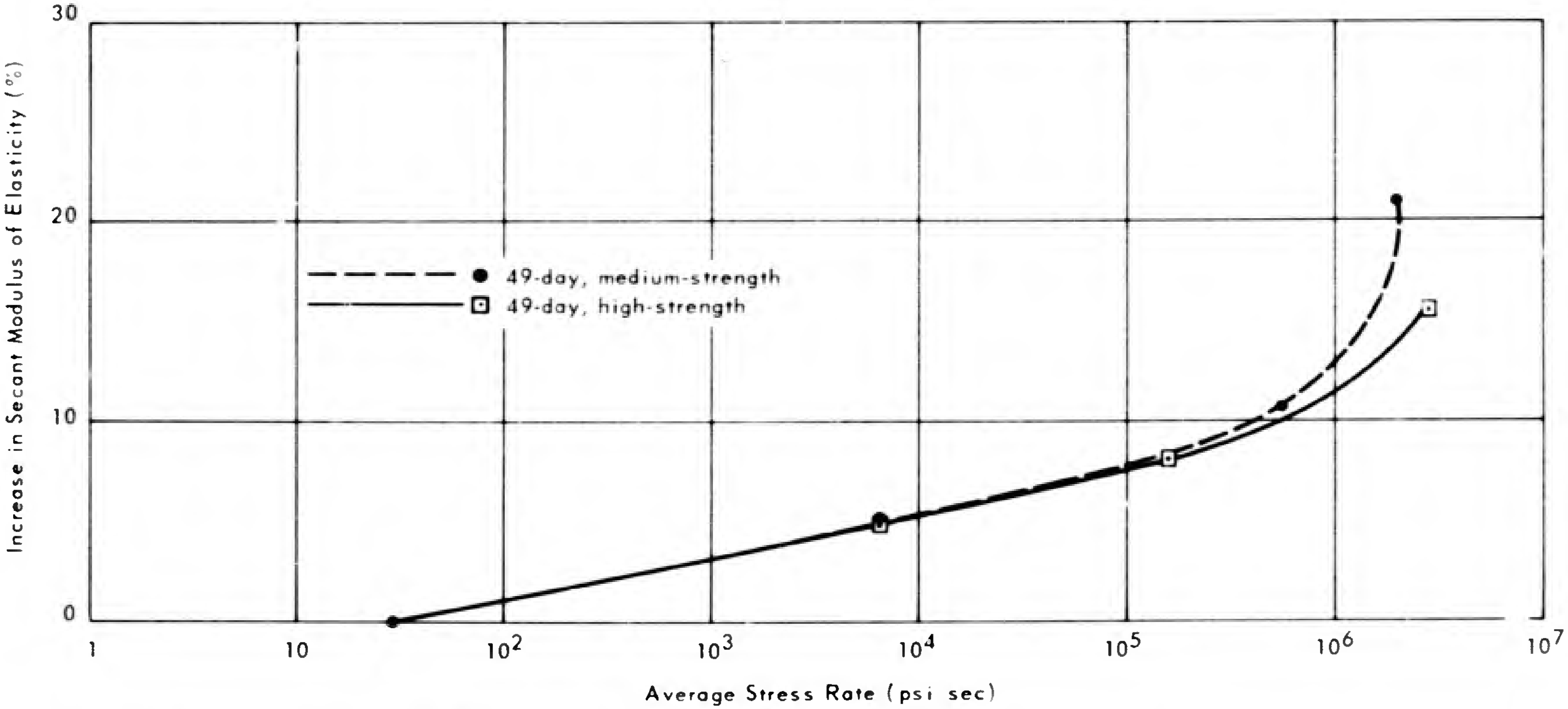
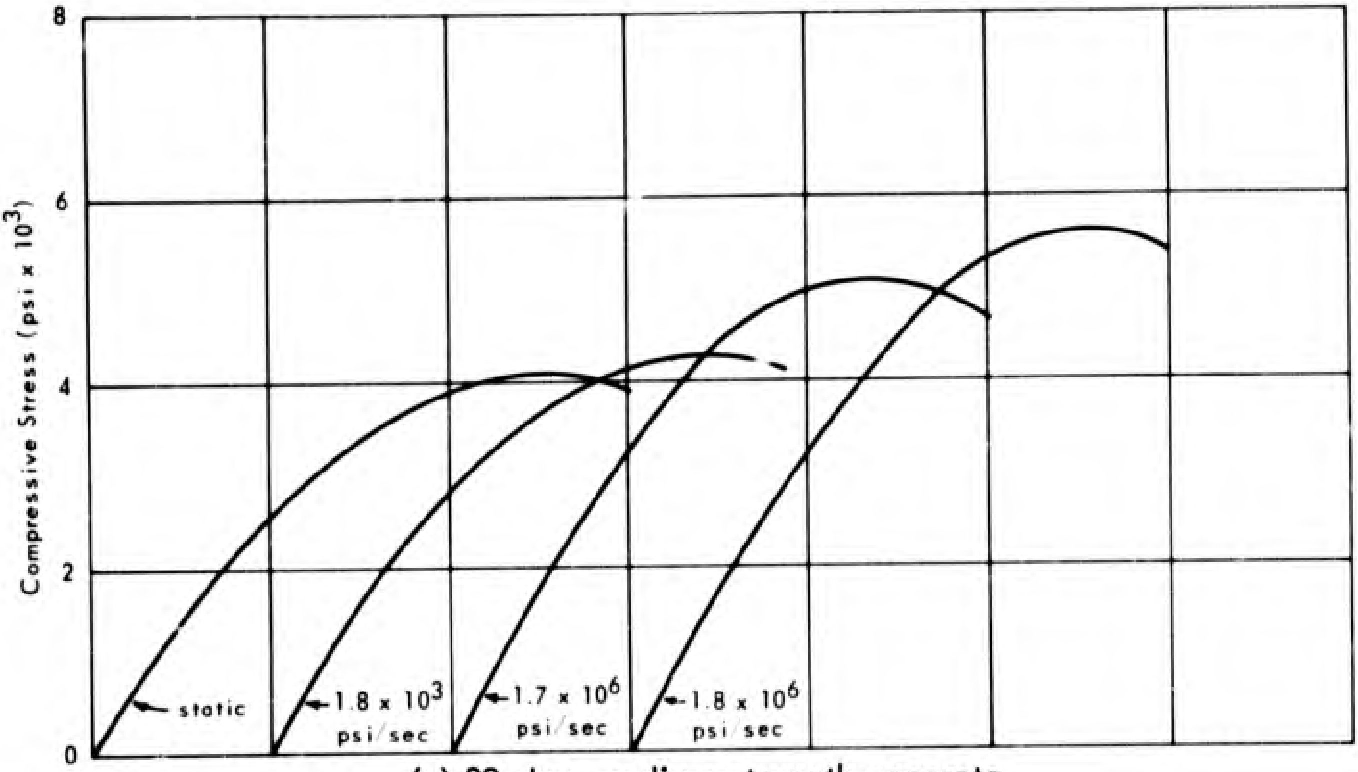
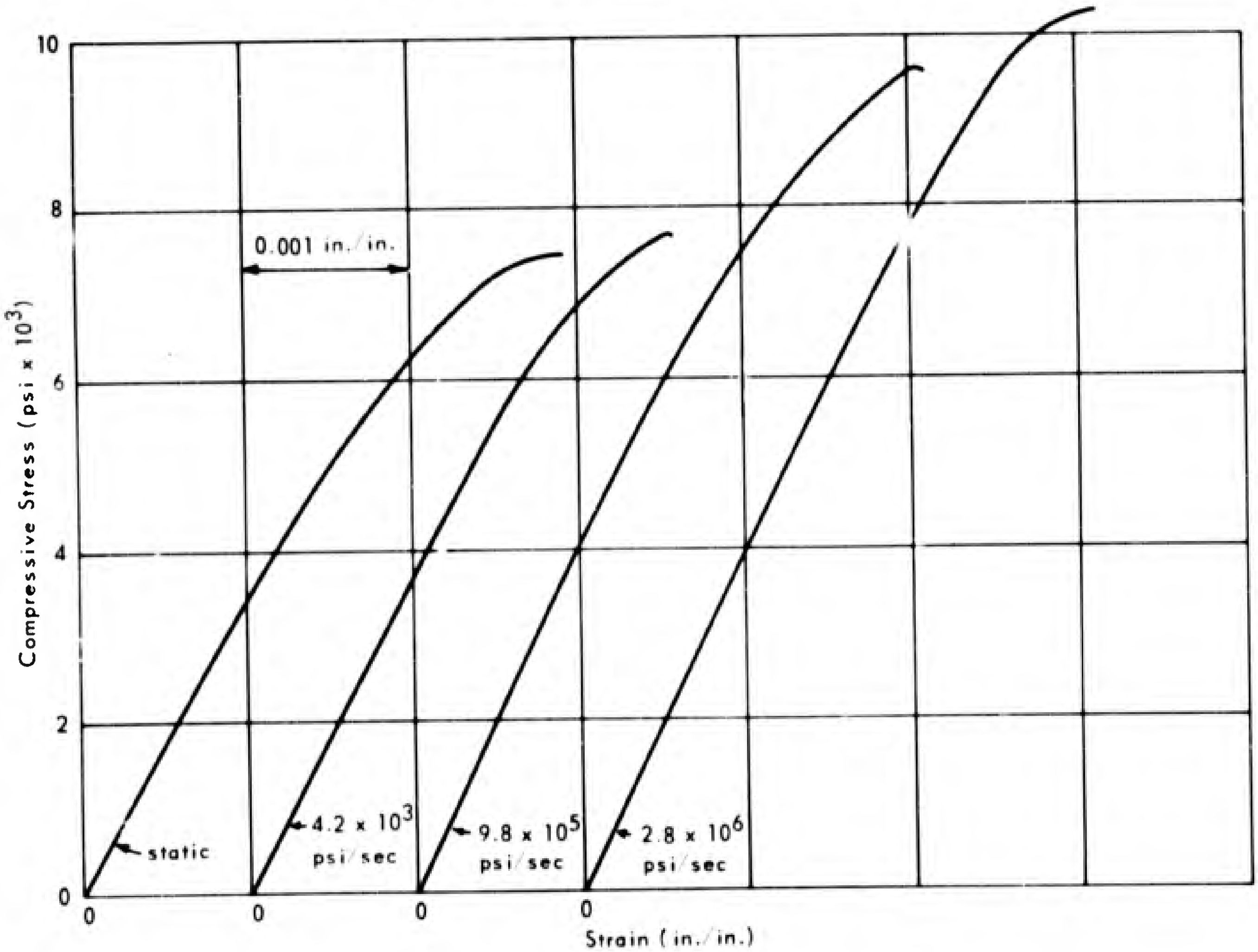


Figure 13. Stress rate versus percentage increase in secant modulus of elasticity (0.001 in./in. strain) for 49-day concretes.

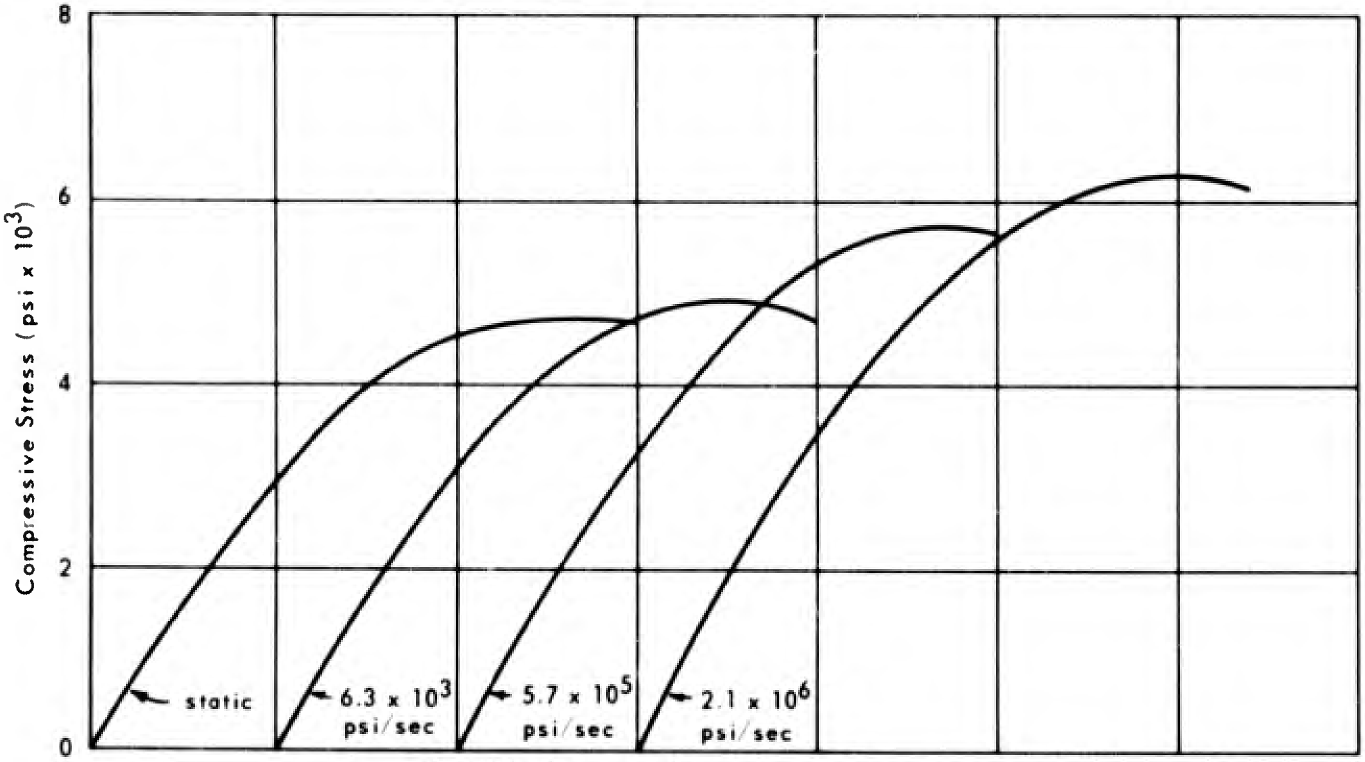


(a) 28-day, medium-strength concrete.

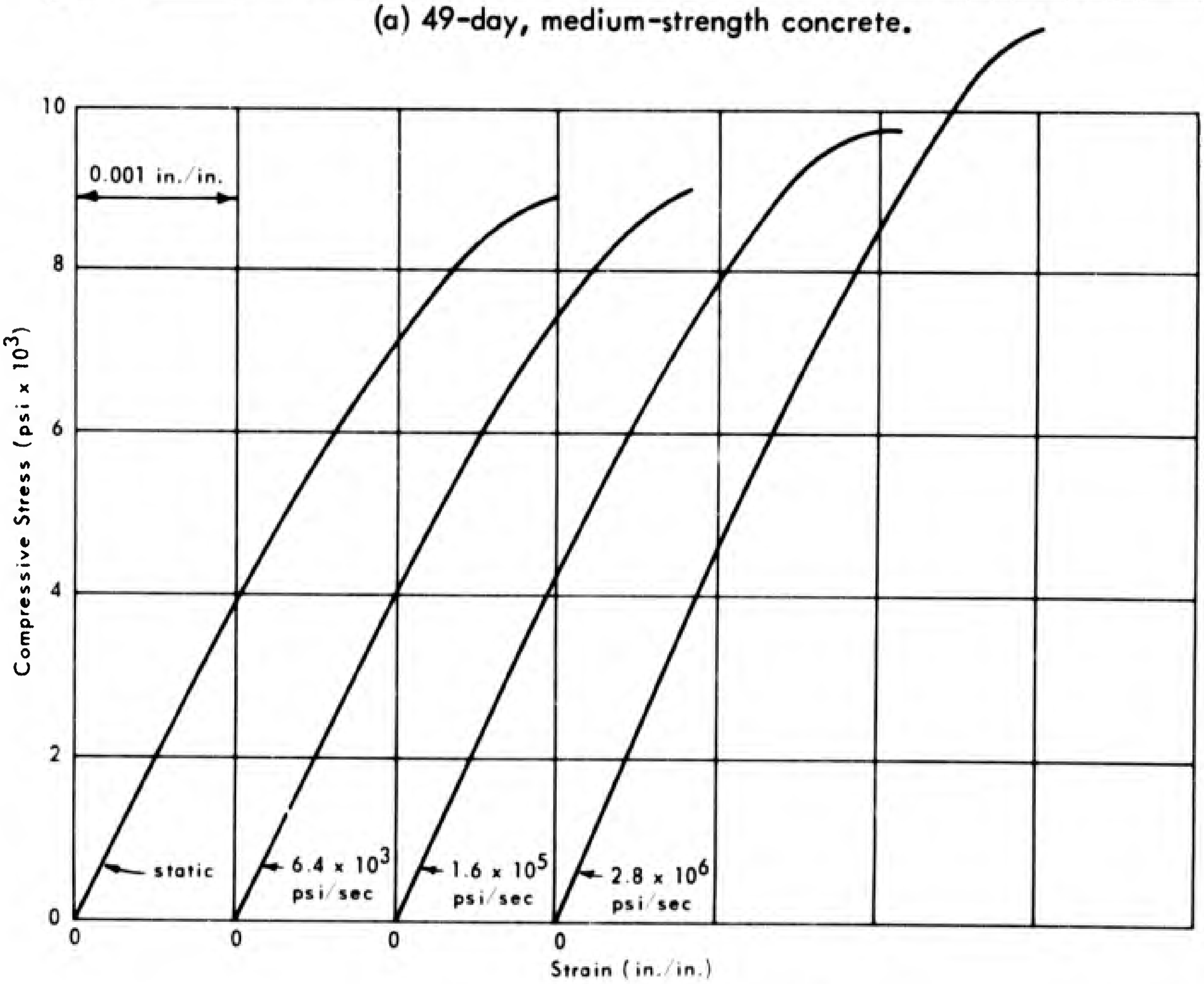


(b) 28-day, high-strength concrete.

Figure 14. Consolidated stress - strain curves for 28-day concrete.



(a) 49-day, medium-strength concrete.



(b) 49-day, high-strength concrete.

Figure 15. Consolidated stress-strain curves for 49-day concrete.

Splitting Tensile Tests

The effect of stress rate on the splitting tensile strength of concrete is shown in Figures 16 and 17. The stress was computed from the applied load as shown in the Appendix. The same general trend was exhibited by the concrete in the splitting tensile tests as in the compression tests. The splitting tensile-strength properties of all of the concretes showed considerable sensitivity to increasing stress rates. The rate of increase in splitting tensile strength is slightly greater for the 28-day, high-strength concrete than that observed for the 28-day, medium-strength concrete. There were not sufficient data to clearly define the increase in splitting tensile strength of the 28-day, medium-strength concrete at the maximum stress rate (Figure 16). Electrical noise in the recording system at or about the maximum load was believed to have distorted the load trace on all but one of the tests. However, the relationships are well defined up to a stress rate of 2 x 10^5 psi/sec. The effect of drying the concrete was similar to that experienced in the compression tests in that the rate of increase in splitting tensile strength was reduced. At the maximum test rate, the 49-day, medium-strength concrete exhibited a very large increase in splitting tensile strength; this result seems to be at variance with the general trend of the dry concretes.

Figure 18 shows the percentage increase in splitting tensile strength with increasing stress rate. The medium-strength concrete shows the greatest increase, primarily because of its lower values for static strength. The 28-day concretes and 49-day concretes appear similar when the increase in splitting tensile strength is presented as a percentage of their static tensile strength. Up to stress rates of 10^5 psi/sec, each age group could be represented by one curve with a maximum deviation of ±3% from either curve in the age group. At stress rates above 10^5 psi/sec, the rate of increase in splitting tensile strength for the two concretes appears to change and the above relationship no longer exists. The maximum increase in splitting tensile strength for the 28-day, medium-strength concrete was 64% at a stress rate of 2.5 x 10^5 psi/sec. The 28-day, high-strength concrete increased 74% in splitting tensile strength over the static value at the maximum stress rate (6.25 x 10^5 psi/sec), while the 49-day, medium- and high-strength concretes showed increases of 64% and 46%, respectively.

The increase in load with time was reasonably linear for the splitting tensile tests. The increase in strain with time was slightly curvilinear. The strains registered at each end of a cylinder were not equal despite the care taken in centering and vertically aligning the cylinders in the testing machine. In most tests, one gage would show a reduction in strain at failure while the other gage continued to show an increase in strain. These unequal strain values apparently were caused by the crack initiating at one end of the cylinder and progressing through the cylinder to the opposite end. As the crack progresses, the uncracked end may tend to pinch together, indicating a reduction in strain. This effect was much more pronounced when the plywood bearing strips were used. Most tensile strains at failure were between 300 and 400 μin./in., regardless of either the rate of loading or the strength of the concrete.

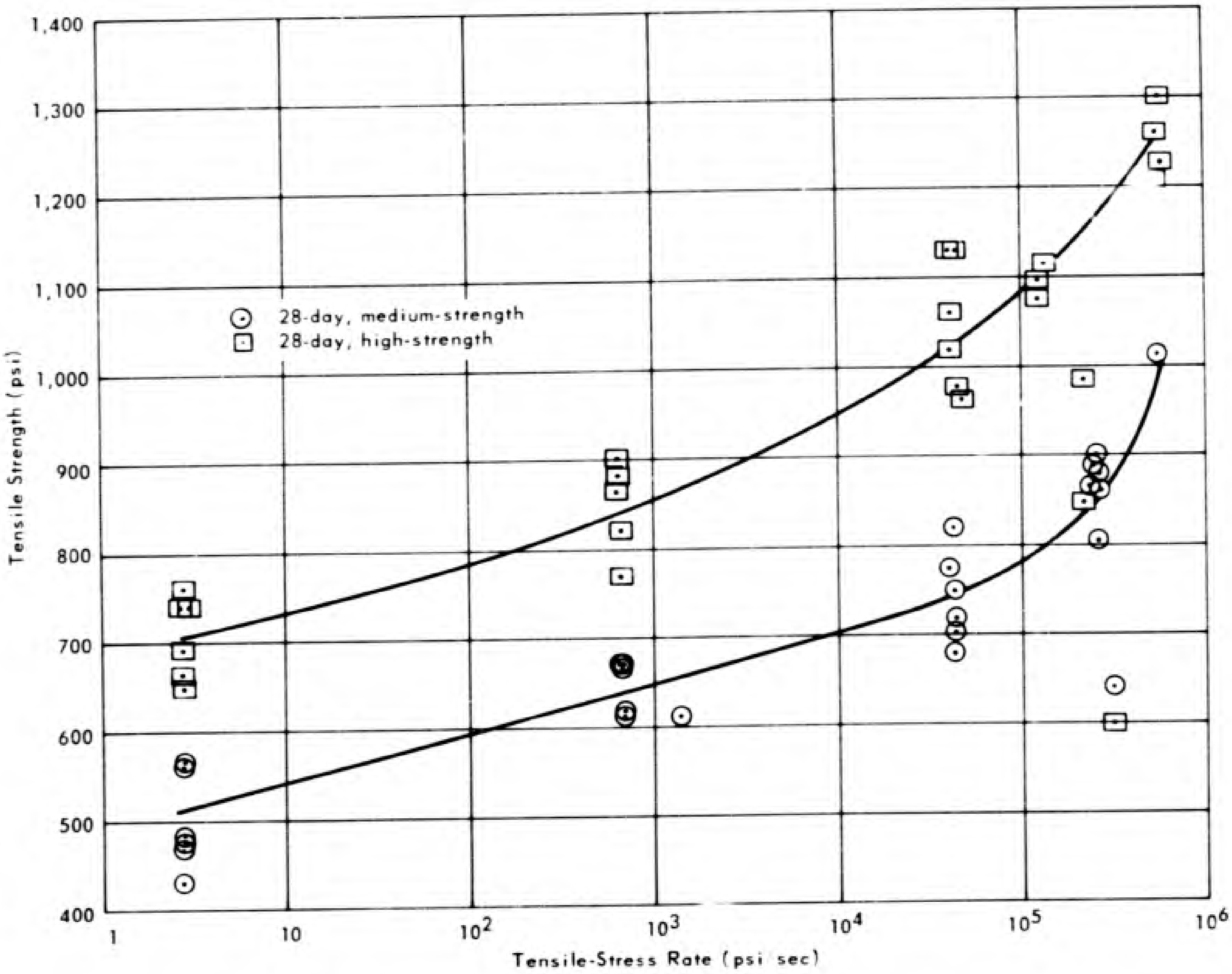


Figure 16. Tensile-stress rate versus tensile strength for 28-day concrete.

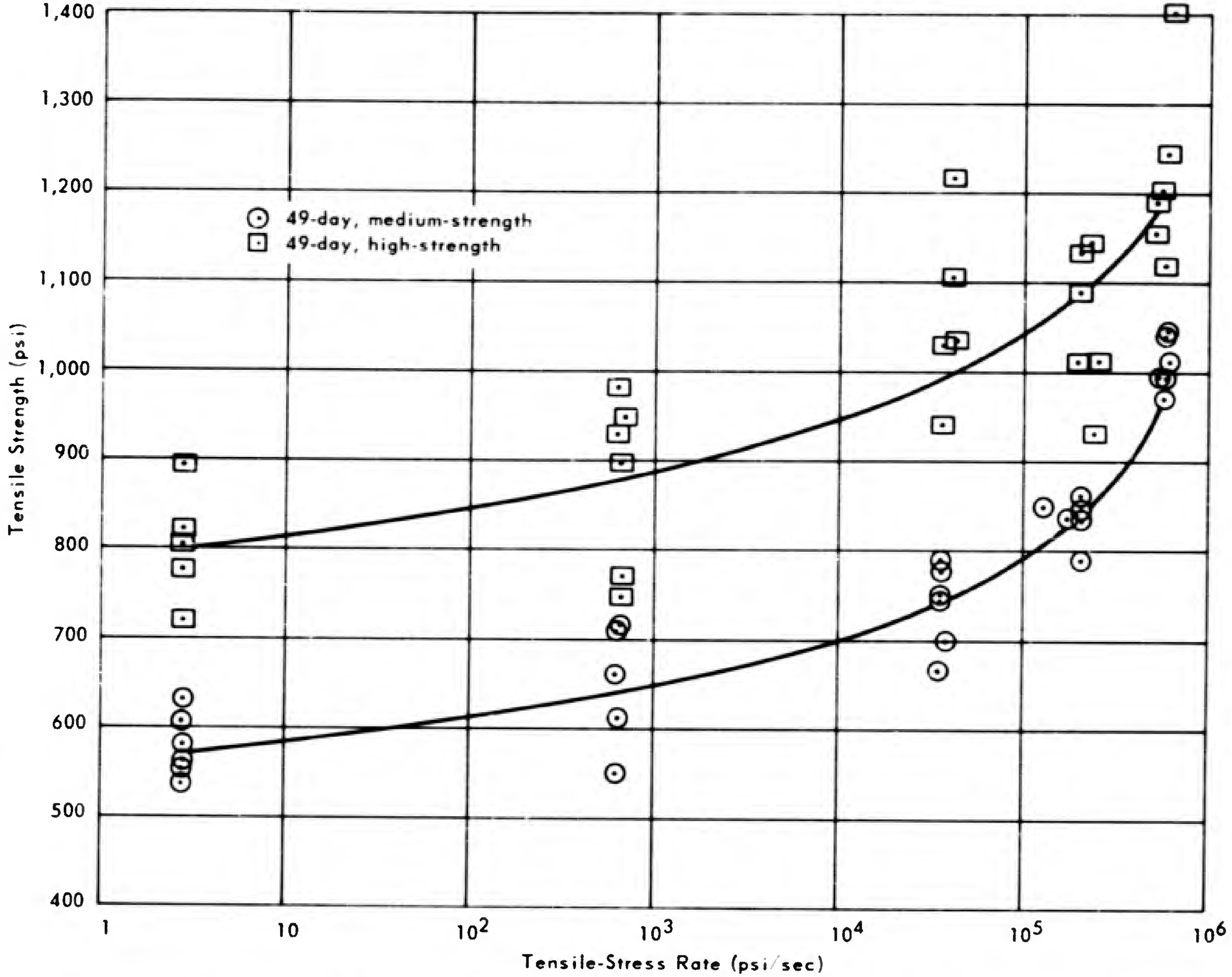


Figure 17. Tensile-stress rate versus tensile strength for 49-day concrete.

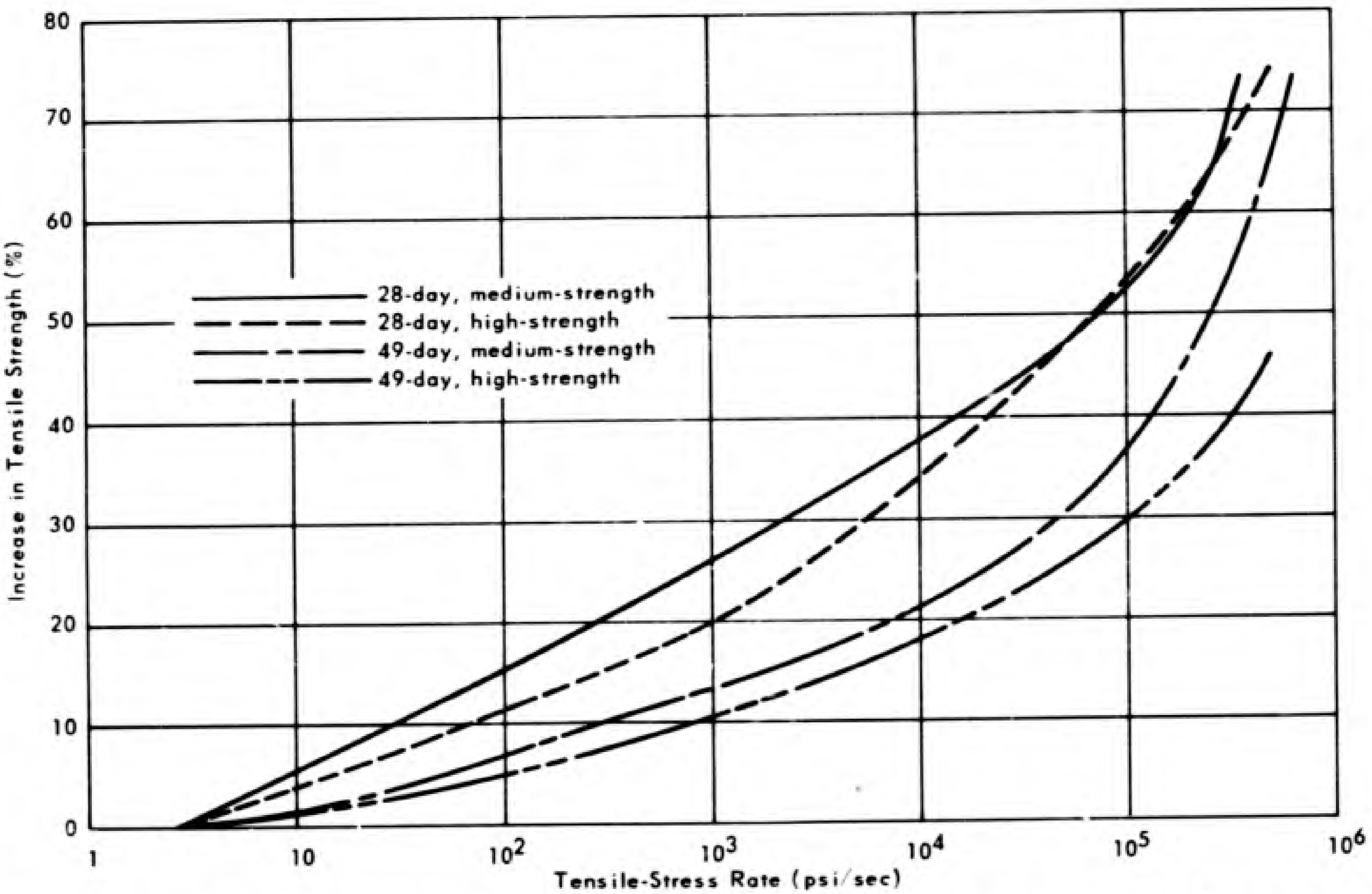


Figure 18. Tensile–stress rate versus increase in tensile strength for 28–day and 49–day medium– and high–strength concretes.

The effect of strain rate on the splitting tensile strength of concrete is shown in Figures 19 and 20. The plotted points represent the average strain rate of the two gages. The curves are generally similar to those shown for stress rate. The stress-rate test groupings were used to obtain a more representative curve for strain-rate effects. Figure 21 shows the percentage increase in splitting tensile strength as a function of the strain rate. Up to a strain rate of 0.1 in./in./sec the percentage increase for concretes of the same age (and therefore the same moisture condition) are in very close agreement. The agreement is even closer than that illustrated in Figure 18 for stress rate.

DISCUSSION

With increased rates of loading, both the medium- and high-strength concrete showed an increase in compressive strength, modulus of elasticity, and Poisson's ratio. For a given curing condition, the rate of increase in compressive strength with increasing load rates appears to be a function of the static compressive strength. The high-strength concretes show a more rapid rate of increase in compressive strength with increasing load rates than do the low-strength concretes. When the increase in compressive strength is computed as a percentage of the static strength, the curves for the high- and medium-strength concretes are quite similar. The relationship shown for percentage increase in compressive strength as a function of strain rate (see Figure 11) indicates that the dynamic strength of the two concretes can be reliably estimated by means of a single curve. The strain-rate curves for the 28-day, medium- and high-strength concretes do not vary from each other by more than 4%. Drying the concrete lowers the percentage increase in compressive strength for both strengths of concrete. The correlation between various 49-day (dry) concretes is not as good as that demonstrated by the 28-day (wet) concretes. The maximum difference between the strain-rate curves for 49-day, medium- and high-strength concretes is 10% at the maximum strain rate.

Figure 22 has been prepared to compare NCEL test results with the recommended values extracted from the Corps of Engineers Manual (CEM)[5] and the Air Force Manual (AFM).[6] The CEM and AFM curves are primarily based upon Watstein's work.[2] The variation between the two curves is undoubtedly due to individual variations in interpretation of Watstein's data by the two services. The AFM has assigned an unrealistically high value of 6.95×10^{-5} in./in./sec as the strain rate for static tests. The CEM indicates this same strain rate for 0% increase in compressive strength but also indicates a more reasonable value of approximately 1.2×10^{-5} in./in./sec as the rate of strain for standard compression tests on 28-day concrete. For comparison, the curves for the 28-day strengths were combined and the 49-day strengths were combined; the AFM value of 6.95×10^{-5} in./in./sec is used as the strain rate at 0% increase. The curve for the 28-day concrete agrees quite closely with the CEM curve. The curve for the 49-day concrete shows a slower rate of increase in strength. At the maximum strain rate, the reduction is approximately 10% below the average for the 28-day concrete.

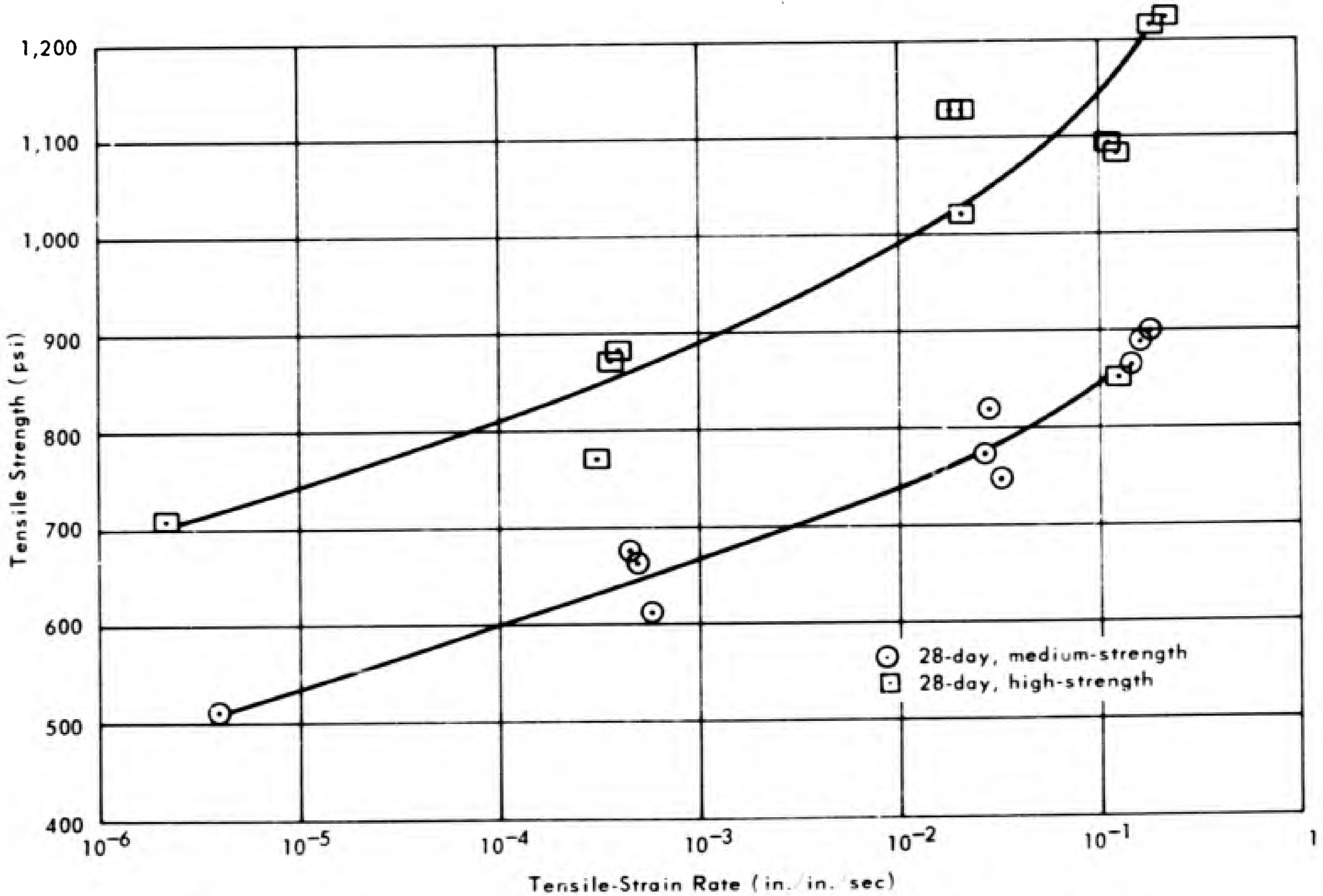


Figure 19. Tensile-strain rate versus tensile strength for 28-day concrete.

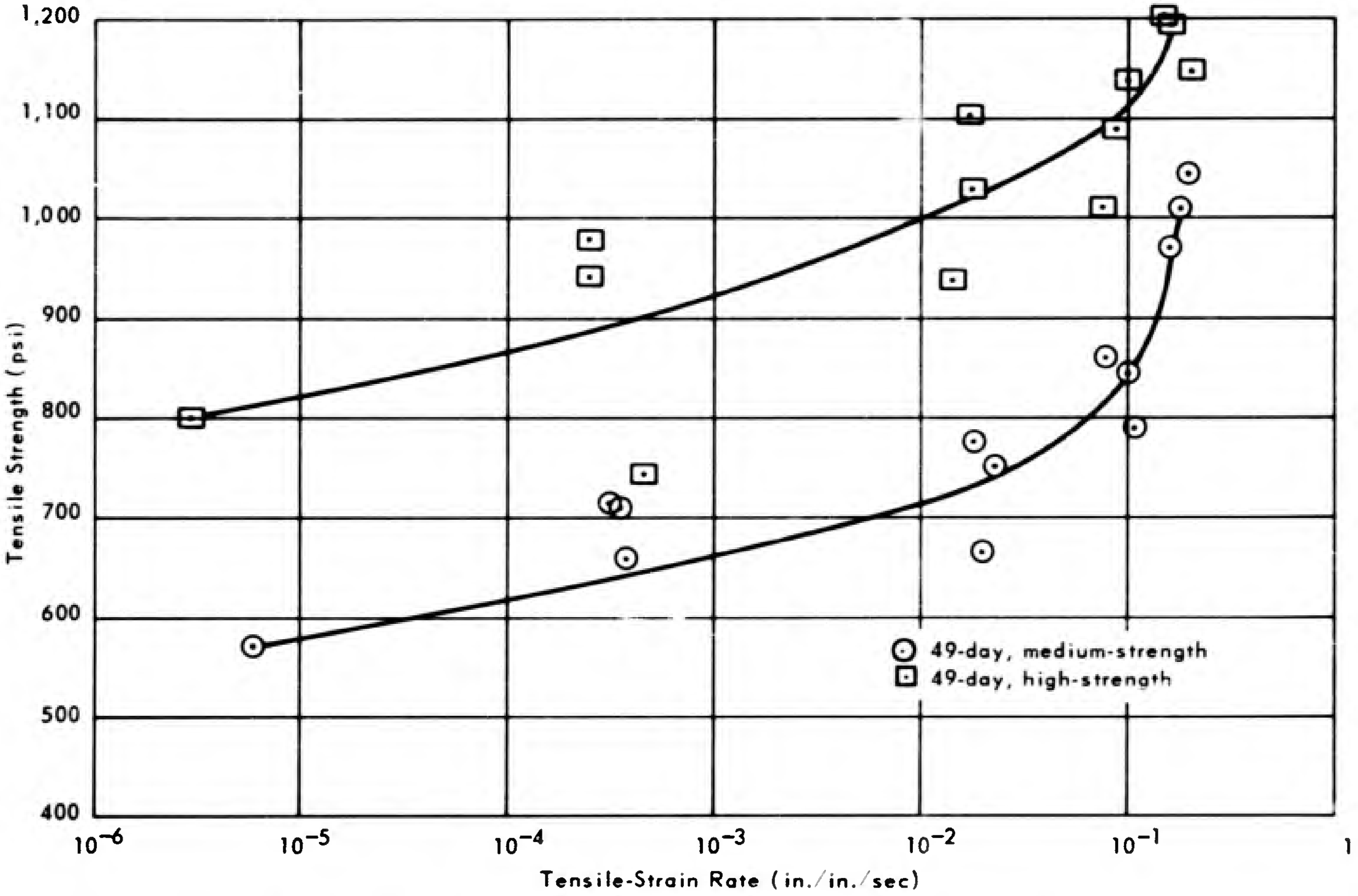


Figure 20. Tensile–strain rate versus tensile strength for 49–day concrete.

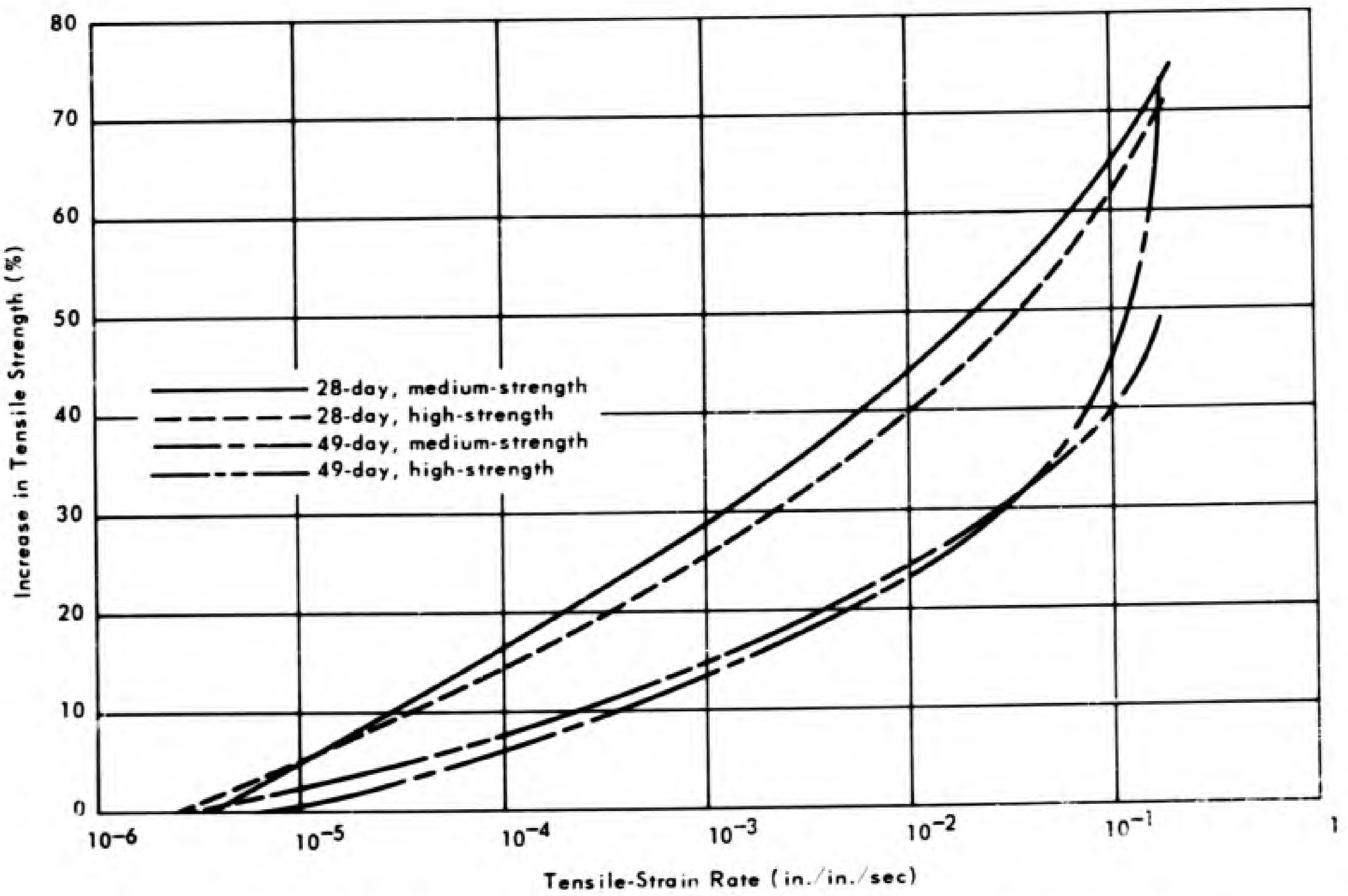


Figure 21. Tensile-strain rate versus increase in tensile strength.

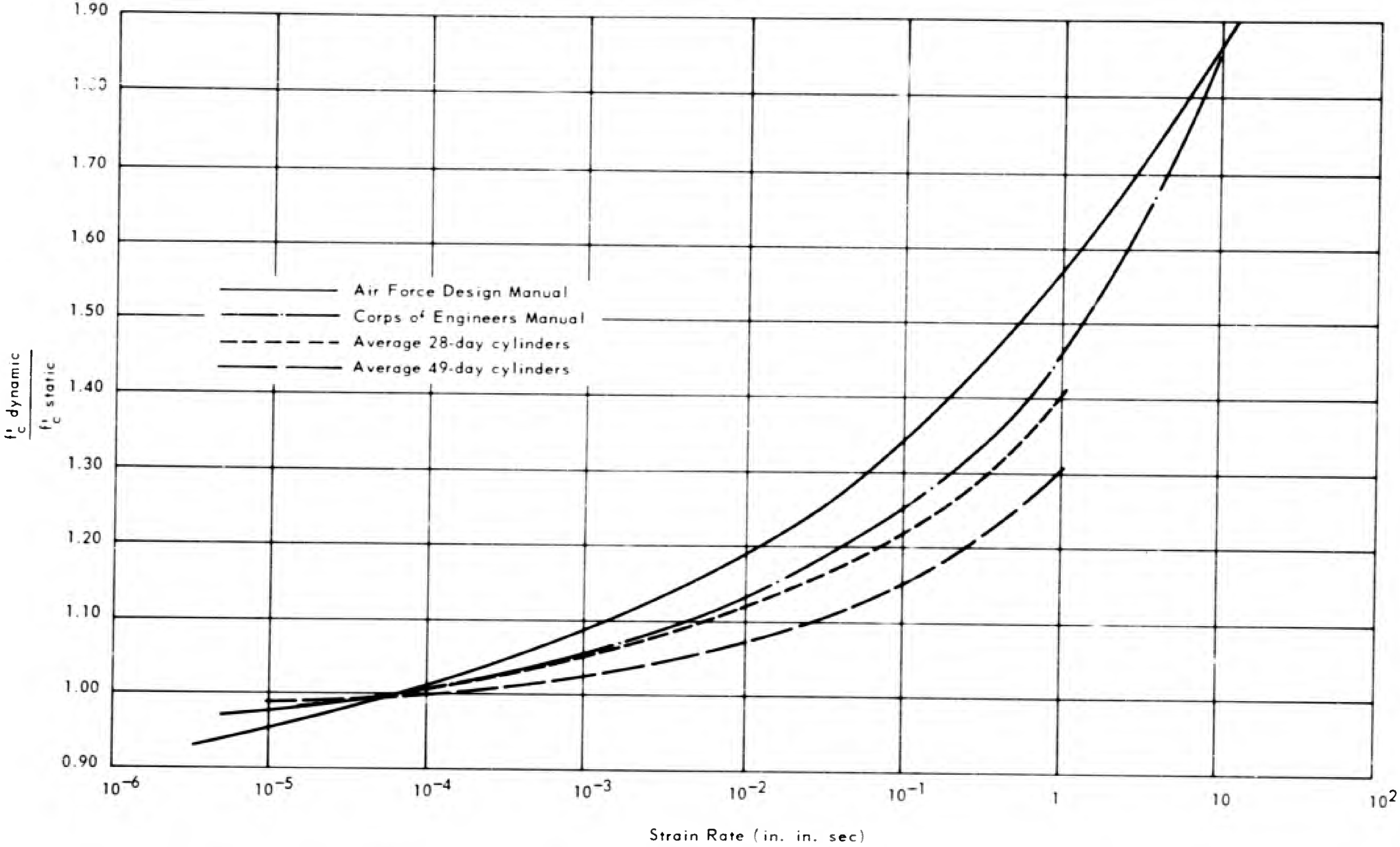


Figure 22. A comparison of currently recommended values for the increase in compressive strength of portland cement concrete due to dynamic loading.

Data is available on only two other sets of dynamic tests. One was conducted by R. H. Evans,[7] who used concrete cubes fabricated with aluminous cement. Evans did not find any appreciable increase in compressive strength until the rate of stressing approached 10^5 psi/sec. Because of the marked difference in chemical composition between aluminous and portland cements, it is not surprising that the test results are not in closer agreement. Another set of tests was conducted at the Waterways Experiment Station (WES)[8] on 1-1/2-inch-diameter by 3-inch-long cylinders. Because of the design of the testing machine, the dynamic tests were conducted at one speed. Test results showed there was approximately the same percentage increase regardless of the static strengths. The three strengths of concrete (1,960, 2,770 and 3,920 psi static compressive strength) showed increases in compressive strength of 37%, 39%, and 33%, respectively, at stress rates ranging from 3×10^6 to 5.9×10^6 psi/sec. Even though the tests were conducted at a faster loading rate than that used in the present test group, the percentage increases are much smaller. A possible explanation may be the smaller maximum size of the aggregate (3/8 inch versus 3/4 inch in the present tests) and the smaller cylinder size. The cylinders at WES were removed from fog curing at 21 days of age and remained at ambient room temperature and humidity until tested at 28 days of age. It is likely that drying the small cylinders also caused a reduction in the percentage increase in compressive strength at the high stress rate. As observed in the NCEL tests, the WES tests show that the increase in compressive strength becomes greater as the static compressive strength increases.

It is apparent that the increase in compressive strength at a given strain rate is much greater for concretes tested in a saturated or near-saturated condition than for concretes in a dry or semidry condition. Therefore, a factor to take into consideration when estimating the increase in compressive strength due to blast loading is the type and length of curing given the concrete up to its age at testing. If the concrete is maintained in a saturated condition and then allowed to dry out as was done in the present test series, no real risk would result from using either the 28-day or CEM curves shown in Figure 22. Because drying increases the strength of concrete, medium-strength concrete and high-strength concrete were 24% and 18% stronger, respectively, at 49 days of age than at 28 days. This increase in compressive strength more than compensates for the reduced rate of increase in compressive strength due to rate of loading exhibited by the dry concretes. However, it is unlikely that a structure will be moist cured for the full 28 days. It is more reasonable to assume that the structure will be moist cured for 7 days or cured with a protective membrane to reduce evaporation. For either condition of curing, the moisture condition of the concrete will probably be closer to that of the 49-day cylinders than to that of saturated concrete.

The curves shown in Figure 23 for 28-day and 49-day concretes are recommended for design purposes. The decision as to which curve to use in estimating the probable increase in compressive strength under dynamic loading will depend on the design and curing conditions, but the curve for the dry condition seems to be the most realistic. The effect of age on the dynamic characteristics of the concrete is not known. Both the medium- and high-strength concretes were still losing weight after 21 days in a 20% RH environment. It is possible that a further reduction in moisture content might further reduce the rate of increase in compressive strength.

The application of the splitting tensile-strength test data to the design of blast-resistant structures would most logically be in the design of beams to resist diagonal tension. As stated in CEM[5]: "The ultimate strength of concrete in tension, shear, and bond may also increase under rapid rates of strain. However, due to lack of data on the effects of strain rate, the ultimate static test values of shear stress, tensile stress, and bond stress should be used in dynamic design." The present tests have shown that concrete in splitting tension exhibits considerable sensitivity to strain rate. Present studies at NCEL on shear resistance of beams will help in determining the safe application of this information as a modification to present criteria on blast-resistant design.

The WES[8] tests also included a group of splitting tensile-strength tests for each concrete. The low-, medium-, and high-strength concretes had increases in tensile strength of 75%, 74%, and 73%, respectively, at stress rates ranging from 6×10^5 to 1.1×10^6 psi/sec. These values are very close to those determined in the present NCEL tests.

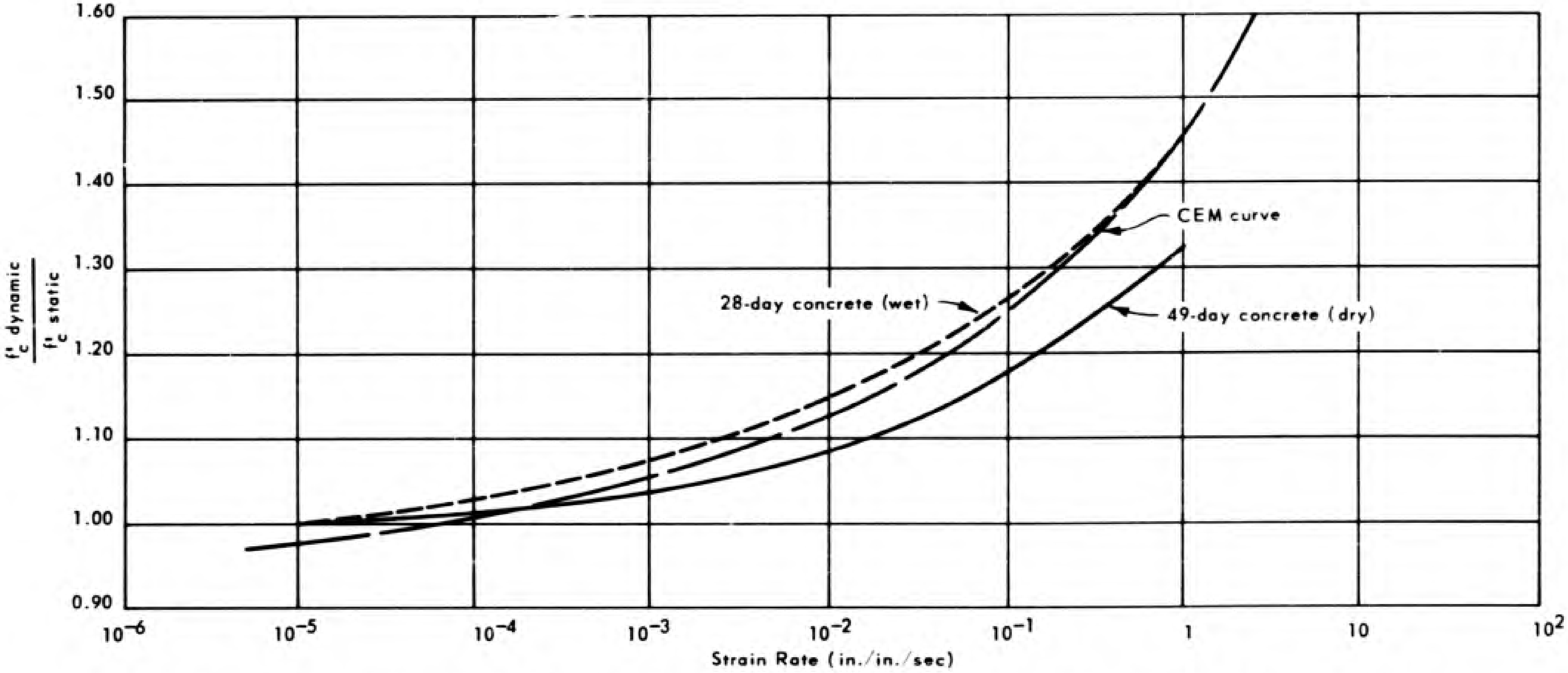


Figure 23. Recommended values for the increase in compressive strength of portland cement concrete due to dynamic loading.

FINDINGS AND CONCLUSIONS

Compression Tests

1. Both strengths of concrete (medium and high) exhibited an increase in values for mechanical properties over the static values as the rate of loading increased. Mechanical properties measured were compressive strength, modulus of elasticity, and Poisson's ratio.

2. The high-strength concrete showed the greater sensitivity to stress rate. For the 28-day-old concrete, the high-strength concrete increased in strength over static values by 2,900 psi (39%) compared to 1,750 psi (45%) for the medium-strength concrete at the maximum stress rate.

3. Allowing the concrete to dry out reduced the rate of increase in strength over static values at the low and intermediate stress rates. The reduction was most pronounced in the high-strength concrete. For the 49-day-old concrete, the high-strength concrete increased in strength 2,080 psi (24%) at the maximum stress rate compared to 1,710 psi (35%) for the medium-strength concrete.

4. The secant modulus of elasticity increased 28% and 17% over static values for the 28-day medium- and high-strength concretes, respectively, at the maximum stress rates. The increase in secant modulus of elasticity was slightly less for the dry, 49-day concretes at the maximum stress rate. The reduction in rate of increase was most evident at the intermediate stress rates for the dry concretes.

Splitting Tensile Tests

1. The splitting tensile strength of concrete shows considerable sensitivity to the rate of loading. The maximum increase in strength over static values for the 28-day, medium-strength concrete was 64% at a stress rate of 2.5×10^5 psi/sec. The 28-day, high-strength concrete increased in strength by 74% at the maximum stress rate of 6.25×10^5 psi/sec.

2. Drying the concrete reduces the rate of increase in strength over static values, both for the medium- and high-strength concrete. At the maximum stress rate (6.25×10^5 psi/sec) the percentage increases were 64% and 46% for the 49-day, medium- and high-strength concretes, respectively.

RECOMMENDATION

The recommended permissible increases in compressive strength for concrete subjected to high strain rates are shown in Figure 23.

ACKNOWLEDGMENTS

Kenneth DeBord, former engineer-in-training at NCEL, assisted in planning and conducting the compression test phase of this program. David Fuss, Structures Division at NCEL, assisted in conducting the splitting tensile-strength test phase of this program. Engineering Technician Valente Hernandez installed the strain gages used in the tests and assisted in data reduction.

Appendix

INVESTIGATION OF BEARING-PAD MATERIAL FOR USE IN SPLITTING TENSILE-STRENGTH TESTS

Results of splitting tensile-strength tests are dependent on the tensile stress developed when a cylinder is compressed on its circumference between two diametrically opposite longitudinal generators on its surface. The stress at any point can be calculated by elastic theory. The maximum tensile stress acts normal to the loaded diametrical plane of the specimen and can be computed with the following equation:

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

where T = splitting tensile stress

P = applied load

d = specimen diameter

l = length of specimen

The derivation of this equation can be found in References 9 and 10.

The primary function of a bearing pad between the cylinder and the loading heads of the testing machine is to redistribute the load from a line bearing longitudinally along the circumference of the cylinder, which produces excessively high compressive stresses, to a larger area. Several studies (References 9, 11, 12, 13 and 14) have been made on the types and widths of bearing materials necessary to adequately distribute the load and prevent crushing of the concrete. The best material and size of bearing pad has not yet been determined. The stress distribution with various pad widths has been calculated by various individuals.[9, 10, 15] Rudnick et al[12] refer to an analysis in which Peltier's[15] results indicate that the tensile stresses can be held uniform over a reasonable proportion of the loaded diameter if the width of the bearing area, b, is less than one-fifth the specimen diameter, d. Hondros[10] and Wright[9] used b/d ratios of 1/10 and 1/12, respectively. A large bearing area does not alter the maximum tensile stress on the cylinder but it does reduce the effective area over which the uniform tensile stress acts within the cylinder.

When small cylinders (3-inch diameter) were used in this NCEL study, it became evident that the 1/8-inch-thick by 1-inch-wide plywood bearing strips specified by ASTM 496-64T were not giving the correct tensile stress at failure. The static splitting tensile strength appeared to be much too high when compared to tensile strength values shown in the literature for equivalent compressive strengths. It was noticed that the load trace during a test had a distinctive hesitation or a slight dip as it approached ultimate. This dip was believed to have been caused by the initial cracking of the specimen. Careful visual observation during static testing did not reveal a correlation with the first visible crack with the load dip in all of the tests. The depression in the plywood caused by loading the cylinder definitely prevented the cylinder from separating after it had failed in tension. Because reduction of the bearing width of the plywood strips used in the dynamic testing machine proved unsatisfactory, tests were conducted to determine the suitability of cardboard pads.

To select the proper cardboard thickness, a test series was conducted in which the effect of thickness and width of bearing material could be observed on 3-inch by 6-inch cylinders. The bearing width in these tests was limited by the pad thickness. The following table shows the results of this test series:

Pad Material	Size of Pad		Average Stress[1] (psi)	Standard Deviation (psi)	Coefficient of Variation (%)
	Thickness (in.)	Width (in.)			
None	–	–	524	35	6.5
Cardboard	0.06	1.0	579	40	7.0
Cardboard	0.04	1.0	574	40	6.9
Cardboard	0.06	0.3	521	66	12.7
Cardboard	0.04	0.3	568	38	6.8
Plywood	0.125	1.0	748[2]	32	4.3
Plywood	–	–	686[3]	–	–
Plywood	–	–	710[4]	–	–

[1] Average of five cylinders (3 by 6 inches).
[2] Stress at maximum load.
[3] Stress at first visible crack.
[4] Stress at load hesitation or load dip.

Average compressive strength of five cylinders was 5,580 psi.

An analysis of variance showed that at the 0.90 probability level no significant effect was caused by variations in the width or thickness of the cardboard bearing material.

Another function of the bearing pad is to fill in irregularities along the cylinder surface caused by the mold. This was not a problem in this series of tests because the cylinders were cast in steel molds of uniform cross section.

On the basis of these tests of bearing pads, a thin, wide cardboard bearing pad was selected for use in the splitting tensile-strength tests.

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DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY *(Corporate author)*

U. S. Naval Civil Engineering Laboratory
Port Hueneme, California 93041

2a REPORT SECURITY CLASSIFICATION
Unclassified

2b GROUP

3 REPORT TITLE

Dynamic Properties of Plain Portland Cement Concrete

4 DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Not final

5 AUTHOR(S) *(Last name, first name, initial)*

Cowell, Walter L.

6 REPORT DATE
June 1966

7a. TOTAL NO. OF PAGES
56

7b. NO. OF REFS
15

8a. CONTRACT OR GRANT NO. DASA-13.0181

b. PROJECT NO. Y-F008-08-03-401

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
TR-447

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited. Copies available at the Clearinghouse (CFSTI) $3.00

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Defense Atomic Support Agency — Naval Facilities Engineering Command

13. ABSTRACT

Two concrete mixes (a medium- and a high-strength mix), each cured under two different conditions (73°F, 100% relative humidity for 26 days followed by 2 days in a 20% RH environment or 73°F, 100% RH for 28 days followed by 21 days in a 20% RH environment) were tested to determine the effect of differences in moisture content and rate of loading on their compressive and tensile strengths.

The compressive tests showed the values for mechanical properties increased as the rate of loading increased. At the maximum rate of loading (approximately 2×10^6 psi/sec), the increases in compressive strength over the values for static loading for the moist, 28-day concrete were 45% for the medium-strength and 39% for the high-strength concrete. The increases for the drier, 49-day, medium- and high-strength concretes were 35% and 24%.

In the splitting tensile-strength tests, at a stress rate of 3×10^5 psi/sec the increases in tensile strength over the static values for the 28-day concrete were 70% for the medium-strength and 67% for the high-strength mix. For the 49-day concretes, the increases were 53% for the medium-strength and 40% for the high-strength mix.

Recommended percentage increases in compressive strength are given for concretes subjected to high strain rates.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Concrete						
Static loading						
Dynamic loading						
Compressive strength						
Tensile strength						

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