MIX DESIGN PARAMETERS FOR CONCRETE CONTAINING CHEMICAL ADMIXTURES

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Elwood L. Ore
USBR (retired)

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16. ABSTRACT

Concrete samples having water to cement ratios ranging from 0.35 to 0.65 with various quantities of WRA (water-reducing and set-controlling admixtures) ranging from 0.00 to 0.40 percent at three temperatures were prepared and periodically tested at intervals up to 1 year. An average quality aggregate was used to produce adequately conservative concrete design data. The effect was evaluated for each condition of WRA on the rate of hardening at early ages, as shown by the resistance to penetration of the wet-screened mortar, and at extended aging, as shown by the compressive strength. The influence of WRA's on the water requirement was analyzed, as was the W/C (water-cement ratio) and temperature. The computer was used to analyze and plot the data. The use of WRA's was most effective in concrete with lower W/C's and higher temperatures. Use of WRA's at lower temperatures is not recommended unless a nonretarding WRA is available.

17. KEY WORDS AND DOCUMENT ANALYSIS

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by

Elwood L. Ore

USBR (retired)

Prepared Under Contract No. 0-07-DV-00109 with E. L. Ore

December 1981

Concrete Laboratory
Fifty Years

Concrete and Structural Branch
Division of Research
Engineering and Research Center
Denver, Colorado

SI METRIC

UNITED STATES DEPARTMENT OF THE INTERIOR * BUREAU OF RECLAMATION

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. administration.

CONTENTS

TABLES

FIGURES

INTRODUCTION

Chemical admixtures, commonly referred to as WRA (water reducing agents), may serve two functions in a concrete mix:

1. These may be water reducing agents, defined by ACI (American Concrete Institute) Committee 116 as, "A material which either increases slump of freshly mixed mortar or concrete without increasing water content or maintains workability with a reduced amount of water, the effect being due to factors other than air entrainment."

2. These may accelerate or retard setting time, and frequently in conjunction with this they also act as water reducers.

From our experience we have found that chemical admixtures also enhance other qualities.

The admixture required by current Bureau (U.S. Bureau of Reclamation) specifications may or may not retard hardening characteristics of concrete as indicated by penetration tests on wet-screened mortar. However, numerous tests conducted at the Bureau laboratories have demonstrated several advantages obtained from the use of WRA:

- The admixture effects a reduction in the amount of water required to produce concrete with a given slump. Since mix design is based upon W/C (water-cement ratio), significant cement savings result.

- The admixture usually increases the compressive strength of the concrete even though the W/C is held constant.

- Some admixtures which retard the hardening of concrete minimize problems due to delays and high temperature during placement.

- Inherent with the use of less cement in the concrete is a reduction in the heat of hydration, especially important in massive placements.

- Admixtures will sometimes enhance the workability of concrete at the same particular slump.

The first important use of WRA by the Bureau came during the construction of Glen Canyon Dam. In this massive structure, 3×10^6 m^3 (4×10^6 yd^3) of concrete contained WRA. Tests at the construction site showed that mass concrete containing WRA had greater strength with a significantly lower cement content. The effectiveness of vibration was also better with the admixture. The success at Glen Canyon prompted specifying the use of WRA at Morrow Point Dam. In this thin-arch structure, higher strength requirements made this usage especially attractive. A WRA was also used in the major portion of canal lining concrete for the San Luis Canal in California. Here, 0.99×10^6 m^3(1.3×10^6 yd^3) of concrete contained WRA. As a result of these experiences, a WRA is required by specifications in all Bureau contracts where the quantity exceeds 1500 m^3 (2000 yd^3) of concrete, and WRA is permitted in all smaller contracts.

There have been cases in more recent work where some degree of incompatibility has occurred between the admixture and other concrete ingredients which resulted in a rapid slump loss. This problem and the increased use of WRA have resulted in a need for basic mix design information. This report documents Bureau guides as contained in the *Concrete Manual*[1] for mix proportioning data for concrete using WRA. For example, compressive strengths shown in table 16, and water requirements shown in table 14 of the *Concrete Manual*, were derived from this study. For comparisons, generally the use of WRA is expressed as a ratio to concrete without WRA. Relationship between the W/C and compressive strength needs to be more accurately defined. What effect various amounts of WRA have on early strength and the rate of hardening needs to be established. The retarding influence can have a significant effect on 1- and 3-day strengths. The temperature effects on concrete properties were briefly studied.

CONCLUSIONS

1. The larger dosages of WRA generally resulted in lower water requirements; however, concrete with 0.10-percent WRA required slightly more water than the reference concrete.

[1] *Concrete Manual,* A Water Resources Technical Publication, Bureau of Reclamation, eighth edition, revised reprint, U.S. Government Printing Office, Washington, DC, 1981.

2. The amount of water reduction due to WRA decreased as the W/C increased; consequently, at 0.65 W/C the amount of water reduction was insignificant.

3. The water requirement relative to temperature was unchanged from 10 to 21 °C (50 to 70 °F); however, from 21 to 32 °C (70 to 90 °F), the water requirement increased 4.5 percent for each 5.5 °C (10 °F) temperature change.

4. The setting time of mortar, wet-screened from concrete, increased as the size of WRA dosage increased.

5. A longer setting time resulted from increases in W/C when less WRA was used. When the amount of WRA was 0.30 to 0.40 percent, differences in W/C did not affect initial set as greatly as it did final set.

6. A temperature decrease from 32 to 21 °C (90 to 70 °F) delayed the initial set 2.5 hours for concrete with a W/C of 0.50. An additional decrease to 10 °C (50 °F) of the same mix delayed initial set 4.25 hours. Equal increments in WRA dosages produced equal retardation increments at 21 and 32 °C, although the retardation was somewhat greater at 10 °C.

7. Larger amounts of WRA resulted in 1-day compressive strengths which were lower than the reference concrete, but by 3 days all concrete samples with WRA were stronger than the reference concrete.

8. For lower W/C concrete, smaller amounts of WRA increased the strength; but for higher W/C concrete, larger amounts of WRA increased the strength.

9. Increased compressive strength attributable to WRA was apparently maximum between 7 and 28 days of curing; however, later in the curing this strength difference diminished somewhat.

10. In this study, all concretes containing WRA were stronger than those without WRA, except for the 0.40 percent WRA concrete where the 1-day strengths were slightly less.

11. A comparison of concretes with equal 28-day strengths but different W/C ratios showed that the concrete without WRA was stronger at 90 days and 1 year than that with WRA.

12. Strengths of control concrete at 1, 3, 7, 90, and 365 days' age averaged 22.3, 44.2, 62.6, 120.0, and 129.6 percent, respectively, of given 28-day strengths of 17-, 34-, 48-MPa (2500-, 5000-, and 7000-lb/in^2) levels. These averages were 16.9, 40.4, 62.6, 114.6, and 119.3 percent for concrete containing 0.30 percent WRA, at 21 °C.

MATERIALS

The Clear Creek aggregate used in the concrete for this study was a local, natural, stream-worn aggregate of average quality. The aggregate has been described as a schistose granitic gneiss. The particles vary in shape from rounded to angular, and the physical properties and gradings are given (table 1). The aggregate was washed and separated into individual fractions by laboratory screening equipment. The coarse aggregate was stored in bins after washing and screening, where it was allowed to reach a laboratory-dry condition. The sand was dried in the laboratory kiln and separated into six sizes by vibratory screens. Different sizes were selected individually so that a constant fineness modulus could be maintained.

The cements used in this study were type II, low-alkali cements obtained from several sources, subsequently blended in the laboratory, and stored in metal drums until used. The physical properties and chemical analysis were recorded (table 1).

The WRA used in this study was an unaltered lignin type which met the Bureau requirements for water reduction, retardation, and compressive strength, and was selected for convenience, not for brand. The WRA was furnished in a solution containing 40 percent solids, by mass.[2]

The air-entraining admixture was a laboratory-formulated, neutralized, vinsol resin solution containing 5 percent solids.

[2] All ratios of quantities of materials given as percent of the whole will be by mass (weight) throughout this report.

MIXING AND TESTING PROCEDURES

Concrete mixes were made with varying W/C ratios and WRA dosages. The W/C ratios used were 0.35, 0.45, 0.50, 0.55, and 0.60. Since most concrete used in Bureau work is made with W/C of 0.45 to 0.55, the mixes within this range were repeated to furnish more complete and reliable data. At each W/C, the WRA was applied at 0.0 (control), 0.10, 0.20, 0.30, and 0.40 percents of lignin solids.

The concrete was designed for 75-mm (3-in) slump and 5.0 percent entrained air. Most concrete was prepared at a temperature close to 21 °C (70 °F); however, two sets of mixes with W/C of 0.50 were made, one at 10 °C (50 °F) and one at 32 °C (90 °F). The original test plan included more mixes at corresponding W/C ratios and WRA dosages, but these were never completed. Air entrainment was accomplished by use of a neutralized vinsol resin solution alone, and in combination with the WRA when required. Both admixtures were included in separate parts of the mixing water. As the W/C was increased, generally the percent sand was also increased, and more sand was used in the WRA concrete to compensate for fewer fines due to cement reduction.

All ingredients were carefully weighed and mixed in a 0.10-m^3 (3.5-ft^3) revolving, tilting, drum mixer. Each batch was mixed for 5 minutes after all ingredients had been added. Entrained air, slump, and temperature were measured as soon as each batch was discharged, and if all the measured values were within the standard tolerances, test specimens were fabricated. Compressive strength test specimens were cast in 150- by 300-mm (6- by 12-in) molds, and simultaneously two wet-screened mortar specimens were cast for the time of setting tests using a penetrometer as described later. Most of the compressive strength cylinders were fog cured at 23 °C (73 °F) until tested at ages of 1, 3, 7, 28, 90, and 365 days. Cylinders were stripped after about 24 hours of curing; however, the groups of concrete cylinders made at 10 and 32 °C were held at these temperatures for 48 hours and then standard cured until test age.

Mortar obtained from wet-screening the parent concrete on a No.4 sieve was used to determine the hardening characteristics of the concrete during the first few hours of hydration process. The development of the hardening process was measured by the resistance of the mortar to penetration using the standard needles of a penetrometer. The lapsed time for penetration resistances of 3.5 and 28 MPa (500 and 4000 lb/in^2) were recorded. The occurrence of these two conditions corresponds roughly with similar conditions labeled "initial set" and "final set" when cement mortar is used. The mortar specimens were stored at 10, 21, and 32 °C, as appropriate, until "final set." The concrete was under test and test results recorded (table 2) from the time of mixing, through the fluid state, and at intervals throughout the hardening process until it had aged for 1 full year.

MIXING WATER REQUIREMENT

The 75-mm-slump concrete with various dosages of WRA at 0.35, 0.45, 0.50, 0.55, and 0.65 and various mixing water requirements to produce the correct W/C ratios was tested (table 2). Most of the data is for concrete made at approximately 21 °C; however, similar data are also shown for sets of mixes made at approximately 10 and 32 °C. The slump ranged from 63.5 to 94 mm (2.5 to 3.7 in) with a standard deviation of 7 mm (0.28 in). The relationship between water requirement and W/C ratio, and the effect of various dosages of WRA at 21 °C are shown (fig. 1). The water requirements were highest for the concrete having a 0.35 W/C and lowest for concrete with a 0.50 W/C ratio.

As the amount of WRA increased, the water required was generally less. This trend was quite regular and without exception for concretes having 0.45, 0.50, and 0.55 W/C ratios. The effect of the WRA was a bit irregular at a W/C of 0.35 where the water requirement of concrete with 0.10 percent WRA was slightly greater than that of the control; and 0.30 percent WRA lowered the requirement more than the 0.40 percent dosage did. At 0.65 W/C ratio, the WRA appears to have little ability to affect the water requirement. There was only a 1.8-kg (4-lb) difference between the high and low values, with the effect somewhat variable. The water reduction was noticeably greater at the 0.35 W/C than at the 0.65 W/C.

The water requirements are shown (fig. 2) as percentages of the reference concrete. In the middle range of W/C ratios, the amount of water reduction obtained was greatest with the highest amount. At the 0.45 W/C, for instance, the 0.10 percent WRA concrete had the same water requirement as the reference concrete; however, as the amount increased, the water reduction also increased to 5 percent at a 0.40 percent WRA dosage. At 0.50 and 0.55 W/C ratios, the behavior was quite normal with a maximum reduction of 7 percent. From the behavior of the lean 0.65 structural concrete, there was little reason to recommend the use of WRA except possibly for retardation.

In addition to the effect of W/C and WRA, the effect of temperature is important (fig. 3). As mentioned previously, five mixes were made at approximately 10 °C and five at 32 °C and compared with mixes made at 21 °C. It is evident that as the temperature rose from 21 to 32 °C the water requirement for the control increased approximately 4.5 percent for each 5.5 °C (10 °F). The same general trend held true for the WRA concrete. When the temperature was dropped from 21 to 10 °C the water requirement was hardly affected. This was somewhat contrary to trends shown in figure 118, page 256, of the *Concrete Manual* previously mentioned. The water reduction is appreciably greater for the 0.30 and 0.40 percent dosages at 32 °C than at 21 or 10 °C.

RATE OF HARDENING

Three factors appear to affect the hardening rate, just as they do the water demand. The most striking influence is the amount of WRA, followed in decreasing importance by temperature and W/C ratio. The rate of hardening was determined by noting the resistance to penetration of mortar, wet-screened from the parent mixture. This method was developed to study its early behavior when the compressive strength varied from zero to about 0.69 MPa (100 lb/in²). Thus, it was desirable to know how long after mixing that the concrete could be vibrated. This was found to occur when the resistance to penetration had reached 3.5 MPa (500 lb/in²). When the resistance had reached 28 MPa (4000 lb/in²), the specimens could be stripped and tested in compression. Instead of sulfur, the specimens were "shot capped" on the rough or trowelled end, and the other end was tested as stripped. Penetration resistance at 3.5 MPa and 28 MPa corresponds roughly to the initial and final set noted on cement test reports.

The time required for the mortar to harden at 20 °C, so that resistance to penetration was 3.5 MPa (initial set), is plotted (fig. 4) as a function of the W/C ratio and WRA dosage. As expected, the higher amount of WRA resulted in greater time elapsed to reach the vibration limit. The results are such that general trends are not readily evident. However, if the data for the 0.10 percent WRA dosage are omitted (fig. 4), the remaining data for dosages of 0.20-, 0.30-, and 0.40-percent WRA show an average delay for each W/C in reaching initial set as follows:

W/C	Time (hours)
0.35	1.58
0.45	1.33
0.50	1.25
0.55	1.17
0.65	1.25

The WRA apparently produced greater retardation at 0.35 W/C and linear regression analyses indicate that as the W/C ratio increases, the retardation also increases. This trend increases for the control concrete and decreases as the amount of WRA increases. Data for the effect of WRA and W/C ratio on final set at 21 °C are shown in figure 5 in the same manner as for figure 4. A superficial examination of these data shows about the same trends as for the initial set.

The effect of temperature on the initial and final sets at a W/C ratio of 0.50 is shown (figs. 6 and 7). As the temperature decreases from 32 to 21 °C, the initial set is delayed by about 2.5 hours and the final set by 3.75 hours. If the temperature is lowered from 21 to 10 °C, the initial set is retarded by 4.25 hours and the final set by about 8 hours. Increments in dosages produce about the same increments in retardation at 21 and 32 °C, but at 10 °C each increment results in greater retardation. This trend should discourage the use of WRA at lower temperatures and encourage it at higher temperatures.

COMPRESSIVE STRENGTH

The compressive strengths were plotted as functions of the amount of WRA dosages and the W/C ratios (figs. 8 and 9). In Abram's general strength equation, $y = A/B^x$, the constants A and B were determined from the test results by the least-squares method (table 3). In all cases the correlation coefficient of 1.000 would indicate that the computed y for each W/C ratio, or x would equal the actual test values.

After the first 24 hours curing time, the compressive strength of the 0.40 percent WRA concrete (fig. 8) was less than the reference concrete at 0.35, 0.45, 0.55, and 0.65 W/C ratios. To avoid confusion, curves for the 0.50, W/C ratio are not shown. The 0.30 percent WRA concrete (fig. 8) had about the same strength as the reference concrete at each W/C ratio, and the 0.20 and 0.10 percent concrete (fig. 9) had greater strengths than the reference concrete. By the time the concrete had cured for 3 days, all test samples containing any WRA had greater strength than the reference concrete. Evidently, at some time between 1 and 3 days, the effect of the retardation is no longer detrimental to the strength.

It is interesting to observe the effect of WRA on compressive strength throughout the entire testing program. As mentioned previously, at 1 day's age the smaller amounts gave greater strength because of the retardation, but at 3 days this relationship was reversed. Generally, from 7 through 28 days the higher amounts produced greater strengths. When the concrete reached 90 days and on through 365 days, the effect of increased amounts appeared less advantageous. Another interesting trend that occurs between 90 and 365 days of cure is that at the lower W/C, smaller amounts of WRA gave the best strength, but at higher W/C, larger amounts of WRA gave the best strength. At 1 and 3 days, the curves tend to converge as the W/C increases, and the WRA was more effective at lower W/C ratios. At 7 days the tendency was less obvious, and at 28 days and older there was not a significant difference in effectiveness of the WRA as the W/C changed.

Compressive strength benefits attributable to WRA appear to be maximum in the age interval from the 7th through the 28th day (figs. 8 and 9), but at 90 days and older the difference from the reference concrete had diminished. Compressive strengths of concrete containing various amounts of WRA and various W/C ratios are shown in a somewhat different manner (figs. 10 and 11). With W/C ratios computed from $y=A/B^x$ for equal 28-day strengths ranging from 17 to 52 MPa (2500 to 7500 lb/in²), strengths at 1, 3, 7, 90, and 365 days' age were determined for appropriate A and B values (table 3) for these ages and all percent WRA contents (table 4, figs. 10 and 11). These calculations were done so that the 28-day strengths were in the range of 17.2 to 51.7 MPa (2500 to 7500 lb/in²) at 3.4 MPa (500 lb/in²) increments. With the exception of the 0.10 percent WRA, concrete made with W/C ratios sufficiently higher than the control concrete had the same 28-day strengths, but had lower strengths at 1, 3, 90, and 365 days. The W/C ratio required to produce concrete with a given 28-day compressive strength increased as the WRA was increased. For instance, for the concrete to have a 31 MPa (4500 lb/in²) 28-day strength, the W/C without WRA would be 0.48 (tabulations, figs. 10 and 11). When the WRA was 0.10 percent, the W/C would be 0.51; when the WRA was 0.30 percent, the W/C would be 0.53. This difference in W/C ratio for a given strength was greater at the lower strengths than at the higher strengths. To produce concrete with 52 MPa (7500 lb/in²) at 28 days' age, a 0.31 W/C without WRA would be required; and 0.34 with 0.40 percent WRA. Whereas, to produce concrete with 17 MPa (2500 lb/in²) at 28 days' age, a 0.67 W/C without WRA would be required; and 0.77 W/C with 0.40 percent WRA.

A study of the strength development of the concrete with a 31-MPa 28-day strength was interesting (figs. 10 and 11). This strength level was selected merely as an example; however, other strength levels generally followed this same relationship as described. At 7 days' age, regardless of the amount of WRA, the compressive strengths were the same in most instances. At 1 day, the retarding effect of the WRA resulted in a significant reduction in strength when above 0.10 percent; however, at 90 days it had less strength than the control concrete. Evidently concrete made with a WRA at a W/C to produce a 28-day strength of 31 MPa had less strength at 1, 90, and 365 days than concrete at the lower W/C ratio required by the concrete without WRA.

Frequently, it is very advantageous to know the relationship of early strength to 28-day strength. The Bureau *Concrete Manual,* previously mentioned, alludes to this relationship (*Manual* fig. 10, p. 25), but for non-air-entrained concrete with 359 kg/m^3 (606 lb/yd^3) of cement having a single strength level. In comparison, this study shows the strengths at 1, 3, 7, 90, and 365 days for WRA dosages of 0.10, 0.20, 0.25, 0.30, and 0.40 percent as percents of their 28-day values (table 5). Some of these relationships are shown graphically (fig. 12) at the 17-, 34-, and 52-MPa (2500-, 5000-, and 7500-lb/in^2) levels. At 1 day's age, the strengths vary between a low of 15.1 percent to a high of 28.9 percent of their 28-day strengths for the control concrete. Similarly, for 0.30 percent WRA concretes, at the same age, the relationships vary between 10.2 to 23.4 percent. At 3 and 7 days, the relationships of the WRA and control concrete strengths are approximately the same. At 90 and 365 days, the relationship with the 28-day concrete increases to 130 ± 2.5 percent for the control concrete, whereas the WRA concrete percentage increases through 90 days and then levels off somewhat to 365 days.

Table 1.—*Physical properties of aggregate and cement*

CLEAR CREEK AGGREGATE

SAND

Sieve Number					Pan	Fineness modulus	Specific gravity	Absorption percent
8	16	30	50	100				
Grading, percent retained								
15	15	25	25	15	5	2.75	2.67	0.60

COARSE AGGREGATE

5 mm (3/16-in)	10 mm (3/8-in)	20 mm (3/4 in)	40 mm (1 1/2-in)	Specific gravity	Absorption percent
Grading, percent retained					
22	33	45	0	2.63	0.58

LABORATORY BLEND CEMENT (M-5500)

CHEMICAL ANALYSIS

Oxide Analysis	Percent	Compound Composition	Percent
SiO_2	22.58	C_3S	46.36
Al_2O_3	4.39	C_2S	29.85
Fe_2O_3	3.63	C_4AF	11.04
CaO	63.52	C_3A	5.50
MgO	2.11	$CaSO_4$	3.50
SO_3	2.06		
Loss on ignition	1.36		
Insoluble residue	0.13		
Na_2O	0.19		
K_2O	0.46		
Alkalies as Na_2O	0.49		

PHYSICAL PROPERTIES

Specific gravity, 3.18
Autoclave expansion, 0.023%
Normal consistency, 25.2%
Initial set, 3 hrs. 30 min.
Final set, 5 hrs. 15 min.
Compressive strength of 50-mm (2-in) cubes: 3 days – 14 MPa (2096 lb/in²)
7 days – 20 MPa (2971 lb/in²)
28 days – 33 MPa (4721 lb/in²)
Air in mortar, 7.6 percent
False set: Initial, 1/2-min. penetration, 38 mm (1.5 in)
5-min. penetration, 30 mm (1.2 in)
Blaine surface 3470 cm²/gm

Table 2.—*Concrete mix quantities and properties of fresh and hardened concrete*

			MIX QUANTITIES PER CUBIC YARD/METER							PROPERTIES OF FRESH CONCRETE					SETTING TIME		COMPRESSIVE STRENGTH, PSI/MPa					
MIX NO.	W/C	S/A %	AEA cc	WRA %	WRA cc	WATER lbs / kgs	CEMENT lbs / kgs	SAND lbs / kgs	C. AGGR. lbs / kgs	TEMP °F / °C	SLUMP ins / mm	UNIT WT. lbs/cu ft / kgs/cu m.	PERCENT AIR GRAV. %	PERCENT AIR PRESS. %	INITIAL hrs.min	FINAL hrs.min	6-X 12-INCH CYLINDERS MADE AND CURED AS SHOWN: 1 DAY	3 DAY	7 DAY	28 DAY	90 DAY	1 YEAR
MADE AND CURED AT 70°F (21.1°C)																						
21	0.35	32	1,397	0.0	0	273	775	918	1,919	69	3.7	143.9	5.5	4.9	4:40	6:15	1,950	3,600	5,060	6,950	7,700	8,320
			1,062			162.0	459.8	544.6	1,138.5	20.6	94	2,305.1					13.5	24.8	34.9	48.0	53.1	57.4
22	.35	33	371	.1	735	277	786	961	1,921	69	3.3	146.1	4.0	4.0	4:45	6:30	2,400	4,330	5,710	7,430	8,360	9,080
			282		559	164.3	466.3	570.1	1,139.7	20.6	84	2,340.3					11.6	29.9	39.4	51.3	57.7	62.7
23	.35	33	237	.2	1,401	264	746	984	1,967	69	3.1	146.7	4.0	4.2	6:00	7:45	2,260	4,200	5,750	7,370	8,130	9,340
			180		1,064	156.6	442.6	583.8	1,167.0	20.6	79	2,349.9					15.6	29.0	39.7	50.9	56.1	64.4
24	.35	33	88	.3	2,023	252	720	994	1,987	69	3.0	146.4	4.5	4.2	7:30	9:25	1,980	4,060	5,970	7,570	8,610	9,190
			67		1,537	149.5	427.1	589.7	1,178.8	20.6	76	2,345.1					13.7	28.0	41.2	52.2	59.4	63.4
25	.35	33	0	.4	2,785	260	743	981	1,961	69	3.7	146.1	4.5	4.8	9:30	11:15	1,860	4,240	5,900	7,550	8,410	8,720
					2,117	154.2	440.8	582.0	1,163.4	20.6	94	2,340.3					12.8	29.3	40.7	52.1	58.0	60.2
51	.45	33	595	0.0	0	246	547	1,041	2,081	69	3.3	145.0	4.9	4.7	4:55	7:00	1,190	2,300	3,250	5,310	6,130	6,900
			452			145.9	324.5	617.6	1,234.6	20.6	84	2,322.6					8.2	15.8	22.4	36.6	42.2	47.6
52	.45	34	291	.1	509	243	540	1,077	2,062	70	3.4	145.3	4.9	4.5	5:35	7:25	1,350	2,580	3,650	5,610	6,560	7,210
			221		387	144.1	320.3	638.9	1,223.3	21.1	86	2,327.4					9.3	17.8	25.1	38.7	45.2	49.7
53	.45	34	148	.2	995	239	531	1,096	2,098	69	3.3	146.8	4.0	4.1	6:15	8:10	1,280	2,750	4,280	6,260	6,960	7,130
			112		756	141.7	315.0	650.2	1,244.7	20.6	84	2,351.5					8.8	18.9	29.5	43.1	48.0	49.1
54	.45	34	74	.3	1,459	234	521	1,094	2,092	70	3.4	145.9	4.7	4.5	7:30	9:35	1,200	2,690	4,240	6,150	6,530	7,130
			56		1,109	138.8	309.1	649.0	1,241.1	21.1	86	2,337.0					8.3	18.6	29.3	42.4	45.0	49.2
55	.45	34	41	.4	1,904	228	507	1,089	2,086	70	3.3	144.8	5.5	5.0	9:05	11:10	980	2,600	4,090	5,920	6,900	7,030
			31		1,447	135.2	300.8	646.1	1,237.6	21.1	84	2,319.4					6.8	17.9	28.2	40.8	47.6	48.5
51.2	.45	33	542	0.0	0	235	522	1,065	2,129	70	3.2	146.3	4.4	4.2	5:25	7:40	1,100	2,030	3,220	4,600	5,760	6,220
			412			139.4	309.7	631.8	1,263.1	21.1	81	2,343.8					7.6	14.0	22.2	31.7	39.7	42.9
52.2	.45	34	303	.1	500	240	534	1,093	2,094	70	3.2	146.7	4.0	4.0	5:40	7:55	1,260	2,390	3,510	5,300	6,220	6,380
			230		380	142.3	316.8	648.4	1,242.3	21.1	81	2,350.3					8.7	16.5	24.2	36.6	42.9	44.0
53.2	.45	34	164	.2	984	236	526	1,091	2,092	70	3.1	146.2	4.5	4.1	6:55	9:05	1,150	2,410	3,710	5,440	6,070	6,100
			125		748	140.0	312.0	647.2	1,241.1	21.1	79	2,341.9					7.9	16.6	25.5	37.5	41.8	42.0
54.2	.45	34	91	.3	1,441	231	514	1,097	2,101	70	3.0	146.0	4.7	4.1	7:55	9:55	1,000	2,430	3,790	5,770	6,460	6,620
			69		1,095	137.0	304.9	650.8	1,246.5	21.1	76	2,338.7					6.9	16.7	26.1	39.8	44.5	45.6
55.2	.45	34	33	.4	1,902	229	508	1,097	2,102	69	2.9	145.8	4.9	4.6	9:20	11:30	880	2,370	3,770	5,540	6,500	6,560
			25		1,446	135.8	301.3	650.8	1,247.1	20.6	74	2,335					6.1	16.3	26.0	38.2	44.8	45.2
76	.50	35	563	0.0	0	234	469	1,136	2,076	69	3.4	145.0	5.1	4.9	6:05	9:00	780	1,470	2,120	4,140	4,930	5,510
			428			138.8	278.2	673.9	1,231.6	20.6	86	2,322.6					5.4	10.1	14.6	28.5	34.0	38.0
77	.50	36	298	.1	430	230	461	1,172	2,053	68	2.8	145.0	5.2	4.8	6:40	9:40	910	1,860	2,690	4,530	5,700	6,110
			226		327	136.4	273.5	695.3	1,218.0	20.0	71	2,322.6					6.3	12.8	18.5	31.2	39.3	42.1
78	.50	36	190	.2	833	224	445	1,179	2,065	68	3.0	145.0	5.3	5.0	7:30	10:35	900	1,980	2,950	4,820	5,570	6,070
			144		633	132.8	264.0	699.5	1,225.1	20.0	76	2,322.6					6.2	13.6	20.3	33.2	38.4	41.8
79	.50	36	124	.3	1,230	218	436	1,189	2,083	69	2.5	145.4	5.3	5.2	8:20	11:40	880	2,170	3,410	5,060	5,860	6,350
			94		935	129.3	258.6	705.4	1,235.8	20.6	64	2,329.0					6.1	14.9	23.5	34.9	40.4	43.8
80	.50	36	83	.4	1,592	213	426	1,196	2,094	68	2.5	145.5	5.4	5.1	10:30	14:10	720	1,840	2,960	4,770	5,710	6,180
			63		1,210	126.3	252.7	709.5	1,242.3	20.0	64	2,330.6					5.0	12.6	20.4	32.9	39.3	42.6
76.2	.50	35	539	0.0	0	234	468	1,138	2,080	70	3.2	145.2	5.0	4.9	5:50	8:35	810	1,670	2,380	3,900	4,780	5,160
			409			138.8	277.6	675.1	1,234.0	21.1	81	2,325.8					5.9	11.5	16.4	26.9	32.9	35.6
77.2	.50	36	315	.1	444	236	471	1,162	2,036	70	3.3	144.6	5.2	5.0	5:50	8:20	950	1,900	2,790	4,560	5,460	5,800
			239		337	140.0	279.4	689.4	1,207.9	21.1	84	2,316.2					6.6	13.1	19.2	31.4	37.6	40.0
78.2	.50	36	171	.2	881	236	472	1,174	2,058	70	2.9	145.9	4.5	4.0	6:55	9:20	900	1,920	2,860	4,680	5,350	5,940
			130		670	140.0	280.0	696.5	1,221.0	21.1	74	2,337.0					6.2	13.2	19.7	32.2	36.9	40.9
79.2	.50	36	115	.3	1,286	229	458	1,179	2,066	70	3.0	145.6	4.9	5.2	7:55	10:25	770	1,940	2,960	4,760	5,480	5,870
			87		977	135.8	271.7	699.5	1,225.7	21.1	76	2,332.2					5.3	13.3	20.4	32.8	37.8	40.5
80.2	.50	36	69	.4	1,683	225	449	1,176	2,061	70	3.3	144.8	5.4	5.0	9:15	11:55	650	1,810	2,970	4,660	5,050	5,430
			52		1,279	133.4	266.3	697.7	1,222.7	21.1	84	2,319.4					4.5	12.4	20.4	32.1	34.8	37.4
111	.55	36	412	0.0	0	248	451	1,177	2,062	69	2.9	145.9	4.0	4.0	5:15	7:15	730	1,480	2,280	3,870	5,100	5,250
			313			147.1	267.5	698.3	1,223.3	20.6	74	2,337.0					5.0	10.2	15.7	26.7	35.1	36.2
112	.55	37	260	.1	414	244	444	1,215	2,037	69	3.0	146.0	4.1	4.0	5:30	7:25	890	1,600	2,530	4,250	4,970	5,250
			198		315	144.7	263.4	720.8	1,208.5	20.6	76	2,338.7					6.1	11.0	17.4	29.3	34.2	36.2
113	.55	37	154	.2	811	238	434	1,213	2,034	70	3.3	145.2	4.8	4.5	6:00	8:00	820	1,730	2,760	4,230	4,900	5,340
			117		616	141.2	257.4	719.6	1,206.7	21.1	84	2,325.8					5.7	11.9	19.0	29.1	33.8	36.8
114	.55	37	81	.3	1,218	239	434	1,213	2,035	70	3.1	145.2	4.7	4.5	7:30	9:30	660	1,650	2,560	4,240	4,780	4,960
			61		926	141.7	257.4	719.6	1,207.3	21.1	79	2,325.8					4.6	11.3	17.6	29.2	32.9	34.2
115	.55	37	65	.4	1,545	227	412	1,215	2,038	70	2.6	144.2	5.7	5.0	8:45	10:55	645	1,870	2,960	4,700	5,290	5,310
			49		1,174	134.6	244.4	720.8	1,209.1	21.1	66	2,309.8					4.5	12.9	20.4	32.4	36.5	36.6
111.2	.55	36	369	0.0	0	240	435	1,182	2,069	66	2.9	145.4	4.5	---	6:25	10:15	590	1,310	1,970	3,490	4,430	4,540
			280			142.3	258.0	701.3	1,227.5	18.9	74	2,329.1					4.1	9.0	13.5	24.0	30.5	31.3
112.2	.55	37	149	.1	407	240	436	1,215	2,036	66	3.2	145.5	4.5	---	6:25	9:20	690	1,320	2,090	3,770	4,470	4,640
			113		309	142.3	258.6	720.8	1,207.9	18.9	81	2,330.3					4.8	9.1	14.4	26.0	30.8	32.0
113.2	.55	37	100	.2	808	238	433	1,218	2,041	66	3.2	145.6	4.5	---	7:00	9:50	640	1,500	2,130	3,930	4,600	4,860
			76		614	141.2	256.8	722.6	1,210.9	18.9	81	2,332.3					4.4	10.3	14.6	27.1	31.7	33.5
114.2	.55	37	50	.3	1,194	234	426	1,211	2,030	66	3.2	144.6	5.2	---	8:30	11:20	570	1,480	2,240	4,030	4,510	4,870
			38		907	138.8	252.7	718.4	1,204.3	18.9	81	2,316.3					3.9	10.2	15.4	27.8	31.1	33.6
115.2	.55	37	0	.4	1,555	228	415	1,222	2,047	66	3.3	145.0	5.2	---	10:00	13:05	510	1,490	2,360	4,300	4,680	5,000
					1,182	135.2	246.2	725.0	1,214.4	18.9	84	2,322.7					3.5	10.2	16.2	29.6	32.2	34.5
141	.65	38	390	0.0	0	242	372	1,253	2,014	68	3.3	143.7	5.2	4.8	5:55	9:05	465	920	1,380	2,720	3,210	3,370
			296			143.5	220.7	743.4	1,194.9	20.0	84	2,301.8					3.2	6.3	9.5	18.7	22.1	23.2
142	.65	39	248	.1	347	238	366	1,291	1,990	68	3.3	143.9	5.3	4.9	6:00	9:05	500	990	1,450	2,800	3,290	3,430
			188		264	141.2	217.1	765.9	1,180.6	20.0	84	2,305.0					3.5	6.8	10.0	19.3	22.7	23.6
143	.65	39	124	.2	700	242	372	1,286	1,983	68	3.1	143.9	5.2	4.5	7:10	9:50	465	930	1,600	3,070	3,520	3,760
			94		532	143.5	220.7	762.9	1,176.5	20.0	79	2,305.0					3.2	6.4	11.0	21.1	24.2	25.9
144	.65	39	58	.3	1,030	239	368	1,298	2,001	68	2.5	144.7	4.8	4.3	7:45	10:40	460	1,120	1,830	3,370	4,110	3,950
			44		783	141.7	218.3	770.1	1,187.1	20.0	64	2,317.8					3.2	7.7	12.6	23.2	28.3	27.2
145	.65	39	0	.4	1,390	241	371	1,308	2,016	67	2.8	145.8	4.1	4.0	9:40	12:55	380	1,100	1,710	3,440	3,880	3,780
					1,056	142.9	220.1	776.0	1,196.0	19.4	71	2,335.4					2.6	7.5	11.7	23.7	26.7	26.0
MADE AND CURED AT 90°F (32.2°C)																						
86	.50	35	643	0.0	0	256	513	1,114	2,038	92	3.3	145.2	4.3	4.5	3:30	5:05	1,270	2,120	2,740	4,430	5,360	6,140
			489			151.2	304.1	660.9	1,209.1	33.3	84	2,325.8					8.8	14.6	18.9	30.5	36.9	42.3
87	.50	36	336	.1	480	255	511	1,142	2,002	92	3.3	144.8	4.6	4.6	4:00	5:35	1,250	2,140	2,900	4,550	5,350	5,930
			255		365	151.2	303.1	677.5	1,187.7	33.3	84	2,319.4					8.6	14.7	20.0	31.3	36.9	40.9
88	.50	36	201	.2	954	253	507	1,145	2,005	92	3.2	144.8	4.7	4.6	4:35	5:55	1,110	2,130	3,050	4,600	5,530	5,980
			153		725	151.1	300.8	679.3	1,189.5	33.3	81	2,319.4					7.7	14.6	21.0	31.7	38.1	41.2
89	.50	36	147	.3	1,365	244	487	1,166	2,044	93	2.7	146.0	4.2	4.9	5:20	6:36	1,070	2,420	3,280	4,870	5,670	6,310
			112		1,037	144.7	288.9	691.7	1,212.7	33.9	69	2,338.7					7.4	16.6	22.6	33.6	39.1	43.5
90	.50	36	82	.4	1,731	231	462	1,176	2,061	91	2.2	145.5	4.9	4.8	6:40	8:15	1,110	2,500	3,660	5,160	5,920	6,800
			62		1,316	137.0	274.1	697.7	1,222.7	32.8	56	2,330.6					7.7	17.2	25.2	35.6	40.8	46.9
MADE AND CURED AT 50°F (10°C)																						
81	.50	35	347	0.0	0	235	469	1,148	2,099	52	3.1	146.4	4.3	4.6	10:15	17:25	180	1,280	2,430	4,690	5,670	5,750
			264			139.4	278.2	681.1	1,245.3	11.1	79	2,345.1					1.2	8.8	16.7	32.3	39.1	39.6
82	.50	36	163	.1	431	230	461	1,186	2,095	53	3.0	146.4	4.4	4.7	11:00	18.00	160	1,360	2,520	5,070	5,750	6,380
			124		328	136.4	273.5	703.6	1,242.9	11.7	76	2,345.1					1.1	9.3	17.3	34.9	39.6	44.0
83	.50	36	106	.2	841	224	448	1,192	2,086	51	3.1	146.3	4.6	4.9	12:30	19:45	150	1,360	2,870	4,930	5,740	6,210
			81		639	132.8	265.7	707.2	1,237.6	10.6	79	2.343.5					1.0	9.3	19.8	34.0	39.6	42.8
84	.50	36	0	.3	1,263	225	449	1,196	2,094	53	3.1	146.8	4.3	4.8	14:30	21:10	100	1,520	2,980	4,980	5,480	6,090
					960	133.4	266.3	709.5	1,242.3	11.7	79	2,351.5					0.7	10.4	20.5	34.3	37.8	42.0
85	.50	36	0	.4	1,601	219	428	1,180	2,065	53	3.0	143.1	6.4	5.9	15:40	23:55	70	1,330	2,730	4,460	5,340	5,790
					1,217	129.9	253.9	700.0	1,225.1	11.7	76	2,292.2					0.5	9.1	18.8	30.7	36.8	39.9

Table 3.—*Abram's equation values for various W/C ratios, ages, and WRA dosages. (recorded in MPa)*

W/C	1 Day		3 Day		7 Day		28 Day		90 Day		1 Year	
	Compressive strength MPa	% control	Compressive strength MPa	% control	Compressive strength MPa	% control	Compressive strength MPa	% control	Compressive strength MPa	% control	Compressive strength MPa	% control
Control												
35	12.55	100	23.23	100	33.23	100	46.33	100	53.57	100	59.29	100
40	9.79	100	18.55	100	26.82	100	39.64	100	46.61	100	51.02	100
45	7.65	100	14.82	100	21.58	100	33.99	100	40.54	100	43.92	100
50	6.00	100	11.79	100	17.44	100	29.09	100	35.23	100	37.78	100
55	4.69	100	9.44	100	14.06	100	24.96	100	30.61	100	32.54	100
60	3.65	100	7.51	100	11.31	100	21.37	100	26.61	100	27.99	100
65	2.83	100	6.00	100	9.10	100	18.27	100	23.17	100	24.13	100
70	2.21	100	4.76	100	7.38	100	15.65	100	20.13	100	20.75	100
A	–	10 242	–	16 400	–	21 818	–	19 856	–	20 639	–	24 561
B	–	139	–	92	–	74	–	22	–	16	–	20
Standard error	–	0.55	–	1.00	–	1.40	–	1.73	–	2.01	–	2.20
0.1% WRA												
35	15.17	121	28.27	121	38.68	116	51.57	111	59.78	112	64.67	109
40	11.72	119	21.99	119	30.82	115	43.92	111	51.16	110	55.02	108
45	9.03	117	17.17	116	24.54	114	37.37	110	43.85	108	46.81	107
50	6.96	116	13.37	113	19.58	112	31.78	109	37.58	107	39.78	105
55	5.38	115	10.41	110	15.58	111	27.10	109	32.20	105	33.85	104
60	4.14	113	8.07	108	12.41	109	23.03	108	27.58	104	28.82	103
65	3.17	112	6.27	105	9.93	108	19.58	107	23.58	102	24.54	102
70	2.48	110	4.89	103	7.86	107	16.68	107	20.20	100	20.89	101
A	–	13 628	–	23 566	–	27 507	–	23 115	–	25 617	–	29 078
B	–	182	–	148	–	94	–	25	–	22	–	25
Standard error	–	0.67	–	0.87	–	0.93	–	1.07	–	1.47	–	2.11
0.2% WRA												
35	14.41	114	29.03	125	40.47	122	52.40	113	57.98	108	63.09	106
40	11.03	113	22.61	122	32.47	121	45.02	114	50.26	108	54.47	107
45	8.48	111	17.65	119	26.06	121	38.68	114	43.57	107	47.02	107
50	6.55	109	13.79	117	20.96	120	33.23	114	37.78	107	40.54	107
55	5.03	107	10.75	114	16.82	120	28.54	115	32.75	107	34.96	108
60	3.86	106	8.41	112	13.51	119	24.48	115	28.41	107	30.20	108
65	2.96	104	6.55	109	10.82	119	21.03	115	24.61	106	26.06	108
70	2.27	103	5.10	107	8.69	118	18.06	115	21.37	106	22.48	108
A	–	13 097	–	23 925	–	27 303	–	22 018	–	22 828	–	25 714
B	–	190	–	143	–	81	–	21	–	17	–	19
Standard error	–	0.61	–	0.76	–	1.73	–	1.85	–	1.92	–	2.18
0.25% WRA												
35	13.44	107	28.13	121	40.61	122	52.54	114	57.85	108	63.22	107
40	10.34	106	22.27	120	32.82	122	45.30	114	50.47	108	54.61	107
45	8.00	105	17.58	119	26.47	123	39.09	115	43.99	108	47.16	107
50	6.20	104	13.93	118	21.37	123	33.71	116	38.33	109	40.75	108
55	4.83	102	11.03	117	17.30	123	29.09	117	33.44	109	35.16	108
60	3.72	101	8.76	116	13.93	123	25.10	118	29.16	110	30.40	109
65	2.89	100	6.89	115	11.24	123	21.65	118	25.44	110	26.27	109
70	2.21	99	5.45	114	9.10	124	18.68	119	22.20	110	22.86	109
A	–	11 765	–	21 051	–	26 326	–	21 436	–	21 896	–	25 586
B	–	171	–	108	–	72	–	19	–	15	–	19
Standard error	–	.77	–	0.79	–	1.65	–	1.70	–	1.82	–	1.91
0.3% WRA												
35	12.48	100	27.30	117	40.82	122	52.67	114	57.71	108	63.36	107
40	9.72	99	21.92	118	33.09	123	45.64	115	50.61	109	54.74	107
45	7.58	99	17.58	119	26.89	124	39.57	116	44.40	109	47.37	108
50	5.86	98	14.06	119	21.86	125	34.27	118	38.95	111	40.95	108
55	4.55	98	11.31	120	17.72	126	29.72	119	34.13	111	35.37	109
60	3.58	97	9.10	121	14.41	127	25.72	120	29.92	112	30.61	109
65	2.76	97	7.31	122	11.72	128	22.27	122	26.27	113	26.47	110
70	2.14	96	5.86	122	9.51	129	19.30	123	23.03	114	22.89	110
A	–	10 569	–	18 523	–	25 383	–	20 868	–	21 002	–	25,459
B	–	153	–	82	–	64	–	18	–	14	–	18
Standard error	–	0.63	–	0.77	–	1.46	–	1.40	–	1.64	–	1.57
0.4% WRA												
35	11.17	89	26.82	115	40.06	120	50.68	109	57.98	109	61.09	103
40	8.62	88	21.51	116	32.68	122	44.54	112	50.81	109	53.16	104
45	6.69	87	17.30	117	26.61	123	39.09	115	44.54	110	46.26	105
50	5.10	85	13.86	117	21.65	125	34.40	118	38.95	111	40.26	107
55	3.93	84	11.10	118	17.65	126	30.20	121	34.13	111	35.02	108
60	3.03	83	8.89	119	14.41	127	26.54	124	29.92	112	30.47	109
65	2.34	82	7.17	120	11.72	129	23.30	128	26.20	113	26.54	110
70	1.79	81	5.72	120	9.58	130	20.48	131	22.96	114	23.10	111
A	–	10 054	–	18 155	–	24 393	–	18 153	–	21 272	–	23 469
B	–	183	–	82	–	60	–	13	–	14	–	16
Standard error	–	0.70	–	1.34	–	1.41	–	1.51	–	2.13	–	1.71

Table 3.—*Abram's equation values for various W/C ratios, ages, and WRA dosages.*—Continued (recorded in lb/in²)

W/C	1 Day		3 Day		7 Day		28 Day		90 Day		1 Year	
	Compressive strength psi	% control	Compressive strength psi	% control	Compressive strength psi	% control	Compressive strength psi	% control	Compressive strength psi	% control	Compressive strength psi	% control
Control												
35	1820	100	3370	100	4820	100	6720	100	7770	100	8600	100
40	1420	100	2690	100	3890	100	5750	100	6760	100	7400	100
45	1110	100	2150	100	3130	100	4930	100	5880	100	6370	100
50	870	100	1710	100	2530	100	4220	100	5110	100	5480	100
55	680	100	1370	100	2040	100	3620	100	4440	100	4720	100
60	530	100	1090	100	1640	100	3100	100	3860	100	4060	100
65	410	100	870	100	1320	100	2650	100	3360	100	3500	100
70	320	100	690	100	1070	100	2270	100	2920	100	3010	100
A	–	10 242	–	16 400	–	21 818	–	19 856	–	20 639	–	24 561
B	–	139	–	92	–	74	–	22	–	16	–	20
Standard error	–	80	–	145	–	203	–	251	–	291	–	319
0.1% WRA												
35	2200	121	4100	121	5610	116	7480	111	8670	112	9380	109
40	1700	119	3190	119	4470	115	6370	111	7420	110	7980	108
45	1310	117	2490	116	3560	114	5420	110	6360	108	6790	107
50	1010	116	1940	113	2840	112	4610	109	5450	107	5770	105
55	780	115	1510	110	2260	111	3930	109	4670	105	4910	104
60	600	113	1170	108	1800	109	3340	108	4000	104	4180	103
65	460	112	910	105	1440	108	2840	107	3420	102	3560	102
70	360	110	710	103	1140	107	2420	107	2930	100	3030	101
A	–	13 628	–	23 566	–	27 507	–	23 115	–	25 617	–	29 078
B	–	182	–	148	–	94	–	25	–	22	–	25
Standard error	–	98	–	127	–	135	–	156	–	214	–	306
0.2% WRA												
35	2090	114	4210	125	5870	122	7600	113	8410	108	9150	106
40	1600	113	3280	122	4710	121	6530	114	7290	108	7900	107
45	1230	111	2560	119	3780	121	5610	114	6320	107	6820	107
50	950	109	2000	117	3040	120	4820	114	5480	107	5880	107
55	730	107	1560	114	2440	120	4140	115	4750	107	5070	108
60	560	106	1220	112	1960	119	3550	115	4120	107	4380	108
65	430	104	950	109	1570	119	3050	115	3570	106	3780	108
70	330	103	740	107	1260	118	2620	115	3100	106	3260	108
A	–	13 097	–	23 925	–	27 303	–	22 018	–	22 828	–	25 714
B	–	190	–	143	–	81	–	21	–	17	–	19
Standard error	–	89	–	111	–	251	–	269	–	279	–	317
0.25% WRA												
35	1950	107	4080	121	5890	122	7620	114	8390	108	9170	107
40	1500	106	3230	120	4760	122	6570	114	7320	108	7920	107
45	1160	105	2550	119	3840	123	5670	115	6380	108	6840	107
50	900	104	2020	118	3100	123	4890	116	5560	109	5910	108
55	700	102	1600	117	2510	123	4220	117	4850	109	5100	108
60	540	101	1270	116	2020	123	3640	118	4230	110	4410	109
65	420	100	1000	115	1630	123	3140	118	3690	110	3810	109
70	320	99	790	114	1320	124	2710	119	3220	110	3290	109
A	–	11 765	–	21 051	–	26 326	–	21 436	–	21 896	–	25 586
B	–	171	–	108	–	72	–	19	–	15	–	19
Standard error	–	112	–	115	–	239	–	247	–	264	–	277
0.3% WRA												
35	1810	100	3960	117	5920	122	7640	114	8370	108	9190	107
40	1410	99	3180	118	4800	123	6620	115	7340	109	7940	107
45	1100	99	2550	119	3900	124	5740	116	6440	109	6870	108
50	850	98	2040	119	3170	125	4970	118	5650	111	5940	108
55	660	98	1640	120	2570	126	4310	119	4950	111	5130	109
60	520	97	1320	121	2090	127	3730	120	4340	112	4440	109
65	400	97	1060	122	1700	128	3230	122	3810	113	3840	110
70	310	96	850	122	1380	129	2800	123	3340	114	3320	110
A	–	10 569	–	18 523	–	25 383	–	20 868	–	21 002	–	25,459
B	–	153	–	82	–	64	–	18	–	14	–	18
Standard error	–	92	–	112	–	212	–	203	–	238	–	228
0.4% WRA												
35	1620	89	3890	115	5810	120	7350	109	8410	109	8860	103
40	1250	88	3120	116	4740	122	6460	112	7370	109	7710	104
45	970	87	2510	117	3860	123	5670	115	6460	110	6710	105
50	740	85	2010	117	3140	125	4990	118	5650	111	5840	107
55	570	84	1610	118	2560	126	4380	121	4950	111	5080	108
60	440	83	1290	119	2090	127	3850	124	4340	112	4420	109
65	340	82	1040	120	1700	129	3380	128	3800	113	3850	110
70	260	81	830	120	1390	130	2970	131	3330	114	3350	111
A	–	10 054	–	18 155	–	24 393	–	18 153	–	21 272	–	23 469
B	–	183	–	82	–	60	–	13	–	14	–	16
Standard error	–	102	–	195	–	204	–	219	–	309	–	248

Note: Correlation coefficients varied from 0.994 to 0.999

Table 4.—*Compressive strengths computed for each age and WRA dosage.*

W/C	Age: 1 Day		3 Day		7 Day		28 Day		90 Day		1 Year	
	Compressive Strength MPa (lb/in²)											
Control												
0.31	15.0	(2171)	27.3	(3960)	38.8	(5624)	51.7	(7500)	59.1	(8579)	65.9	(9566)
0.34	13.4	1945	24.7	3581	35.2	5109	48.3	7000	55.6	8061	61.7	8948
0.36	11.9	1728	22.2	3214	31.8	4608	44.8	6500	52.0	7540	57.4	8328
0.39	10.5	1521	19.7	2859	28.4	4122	41.4	6000	48.4	7015	53.1	7707
0.41	9.1	1325	17.4	2518	25.2	3651	37.9	5500	44.7	6486	48.8	7084
0.45	7.8	1138	15.1	2191	22.0	3198	34.5	5000	41.0	5952	44.5	6460
0.48	6.6	962	12.9	1879	19.0	2761	31.0	4500	37.3	5412	40.2	5833
0.52	5.5	797	10.9	1582	16.2	2344	27.6	4000	33.6	4867	35.9	5204
0.56	4.4	645	9.0	1302	13.4	1946	24.1	3500	29.7	4315	31.5	4573
0.61	3.5	504	7.2	1040	10.8	1570	20.7	3000	25.9	3755	27.1	3939
0.67	2.6	377	5.5	797	8.4	1218	17.2	2500	22.0	3186	22.7	3301
0.10% WRA												
0.35	15.3	2215	28.4	4115	38.8	5631	51.7	7500	59.9	8691	64.8	9405
0.37	13.6	1981	25.5	3697	35.2	5110	48.3	7000	56.1	8133	60.5	8776
0.39	12.1	1758	22.7	3296	31.7	4603	44.8	6500	52.2	7575	56.2	8147
0.42	10.6	1545	20.1	2911	28.3	4112	41.4	6000	48.3	7014	51.8	7519
0.45	9.2	1342	17.5	2544	25.1	3637	37.9	5500	44.5	6452	47.5	6891
0.47	7.9	1151	15.1	2194	21.9	3180	34.5	5000	40.6	5887	43.2	6263
0.51	7.7	971	12.8	1864	18.9	2741	31.0	4500	36.7	5321	38.8	5635
0.54	5.5	803	10.7	1552	16.0	2322	27.6	4000	32.8	4752	34.5	5007
0.59	4.5	647	8.7	1262	13.3	1924	24.1	3500	28.8	4180	30.2	4379
0.63	3.5	504	6.8	994	10.7	1548	20.7	3000	24.8	3605	35.9	3752
0.69	2.6	376	5.2	749	8.2	1197	17.2	2500	20.9	3026	21.5	3125
0.20% WRA												
0.35	14.1	2040	28.4	4122	39.7	5761	51.7	7500	57.3	8305	62.3	9041
0.38	12.5	1811	25.4	3683	35.9	5215	48.3	7000	53.7	7784	58.3	8455
0.40	11.0	1593	22.5	3263	32.3	4685	44.8	6500	50.1	7261	54.2	7868
0.43	9.6	1387	19.7	2863	28.8	4174	41.4	6000	46.4	6736	50.2	7280
0.46	8.2	1194	17.1	2484	25.4	3681	37.9	5500	42.8	6207	46.1	6691
0.49	7.0	1013	14.6	2126	22.1	3207	34.5	5000	39.1	5676	42.0	6100
0.52	5.8	844	12.3	1790	19.0	2754	31.0	4500	35.4	5141	38.0	5507
0.56	4.7	689	10.2	1477	16.0	2323	27.6	4000	31.7	4603	33.9	4912
0.60	3.8	547	8.9	1188	13.2	1916	24.1	3500	28.0	4061	29.7	4315
0.66	2.9	419	6.4	923	10.6	1533	20.7	3000	24.2	3514	25.6	3715
0.72	2.1	306	4.7	686	8.1	1178	17.2	2500	20.4	2961	21.5	3113
0.25% WRA												
0.36	13.0	1892	27.4	3981	39.7	5758	51.7	7500	57.0	8266	62.2	9028
0.38	11.6	1678	24.6	3569	35.9	5211	48.3	7000	53.5	7754	58.1	8431
0.40	10.2	1475	21.9	3173	32.3	4681	44.8	6500	49.9	7239	54.0	7833
0.43	8.8	1283	19.3	2795	28.7	4169	41.4	6000	46.3	6721	49.9	7235
0.46	7.6	1103	16.8	2435	25.3	3675	37.9	5500	42.7	6200	45.8	6637
0.49	6.4	934	14.4	2093	22.1	3202	34.5	5000	39.1	5675	41.6	6038
0.53	5.4	778	12.2	1771	18.9	2749	31.0	4500	35.5	5147	37.5	5439
0.57	4.4	634	10.1	1469	16.0	2318	27.6	4000	31.8	4614	33.4	4839
0.61	3.5	502	8.2	1189	13.2	1911	24.1	3500	28.1	4077	29.2	4239
0.67	2.6	384	6.4	931	10.5	1529	20.7	3000	24.3	3533	25.1	3638
0.73	1.9	280	4.8	697	8.1	1174	17.2	2500	20.6	2984	20.9	3036
0.30% WRA												
0.36	12.1	1755	26.5	3848	39.7	5756	51.7	7500	56.7	8232	62.1	9015
0.38	10.7	1555	23.9	3461	35.9	5208	48.3	7000	53.3	7728	57.9	8406
0.41	9.4	1365	21.3	3089	32.2	4678	44.8	6500	49.8	7221	53.7	7797
0.43	8.2	1187	18.8	2732	28.7	4165	41.4	6000	46.3	6711	49.6	7189
0.46	7.0	1019	16.5	2390	25.3	3671	37.9	5500	42.7	6197	45.4	6581
0.50	5.9	862	14.2	2064	22.0	3198	34.5	5000	39.2	5680	41.2	5975
0.53	4.9	716	12.1	1756	18.9	2745	31.0	4500	35.6	5158	37.0	5369
0.58	4.0	583	10.1	1466	15.9	2314	27.6	4000	31.9	4631	32.8	4764
0.62	3.2	461	8.2	1194	13.1	1906	24.1	3500	28.2	4098	28.7	4161
0.68	2.4	352	6.5	942	10.5	1525	20.7	3000	24.5	3559	24.5	3558
0.74	1.7	255	4.9	712	8.1	1170	17.2	2500	20.8	3012	20.4	2957
0.40% WRA												
0.34	11.7	1693	27.8	4028	41.4	6005	51.7	7500	59.2	8593	62.5	9061
0.37	10.1	1473	24.7	3581	37.1	5383	48.3	7000	55.2	8006	58.0	8413
0.40	8.7	1269	21.8	3157	33.0	4786	44.8	6500	51.1	7420	53.5	7768
0.43	7.4	1080	19.0	2754	29.1	4216	41.4	6000	47.1	6836	49.1	7126
0.46	6.2	906	16.4	2375	25.3	3672	37.9	5500	43.1	6252	44.7	6489
0.50	5.1	748	13.9	2019	21.8	3157	34.5	5000	39.1	5670	40.4	5856
0.54	4.2	605	11.6	1687	18.4	2672	31.0	4500	35.1	5089	36.0	5228
0.59	3.3	477	9.5	1381	15.3	2216	27.6	4000	31.1	4510	31.7	4606
0.64	2.5	364	7.6	1100	12.4	1793	24.1	3500	27.1	3933	27.5	3989
0.70	1.8	267	5.8	846	9.7	1405	20.7	3000	23.1	3358	23.3	3379
0.77	1.3	185	4.3	620	7.2	1052	17.2	2500	19.2	2785	19.1	2777

Strengths computed for each age and percent WRA from *A* and *B* values shown in table 3 so that the 28 day strengths were in the range of 17.2 to 51.7 MPa (2500 to 7500 lb/in²) at 3.4 MPa (500 lb/in²) increments.

Table 5.—*Compressive strengths expressed as a percent of the 28-day strength*

W/C Age:	1 Day	3 Day	7 Day	28 Day	90 Day	1 Year
Control						
0.31	28.9	52.8	75.0	100.0	114.4	127.6
0.34	27.8	51.2	73.0	100.0	115.2	127.8
0.36	26.6	49.4	70.9	100.0	116.0	128.1
0.39	25.4	47.7	68.7	100.0	116.9	128.5
0.41	24.1	45.8	66.4	100.0	117.9	128.8
0.45	22.8	43.8	64.0	100.0	119.0	129.2
0.48	21.4	41.8	61.4	100.0	120.3	129.6
0.52	19.9	39.6	58.6	100.0	121.7	130.1
0.56	18.4	37.2	55.6	100.0	123.3	130.7
0.61	16.8	34.7	52.3	100.0	125.2	131.3
0.67	15.1	31.9	48.7	100.0	127.4	132.0
0.10% WRA						
0.35	29.5	54.9	75.1	100.0	115.9	125.4
0.37	28.3	52.8	73.0	100.0	116.2	125.4
0.39	27.0	50.7	70.8	100.0	116.5	125.3
0.42	25.7	48.5	68.5	100.0	116.9	125.3
0.45	24.4	46.2	66.1	100.0	117.3	125.3
0.47	23.0	43.9	63.6	100.0	117.7	125.3
0.51	21.6	41.4	60.9	100.0	118.2	125.2
0.54	20.1	38.8	58.1	100.0	118.8	125.2
0.59	18.5	36.1	55.0	100.0	119.4	125.1
0.63	16.8	33.1	51.6	100.0	120.2	125.1
0.69	15.0	30.0	47.9	100.0	121.0	125.0
0.20% WRA						
0.35	27.2	55.0	76.8	100.0	110.7	120.5
0.38	25.9	52.6	74.5	100.0	111.2	120.8
0.40	24.5	50.2	72.1	100.0	111.7	121.1
0.43	23.1	47.7	69.6	100.0	112.3	121.3
0.46	21.7	45.2	66.9	100.0	112.9	121.6
0.49	20.3	42.5	64.1	100.0	113.5	122.0
0.52	18.8	39.8	61.2	100.0	114.3	122.4
0.56	17.2	36.9	58.1	100.0	115.1	122.8
0.60	15.6	33.9	54.7	100.0	116.0	123.3
0.66	14.0	30.8	51.1	100.0	117.1	123.8
0.72	12.2	27.4	47.1	100.0	118.4	124.5
0.25% WRA						
0.36	25.2	53.1	76.8	100.0	110.2	120.4
0.38	24.0	51.0	74.4	130.0	110.8	120.4
0.40	22.7	48.8	72.0	100.0	111.4	120.5
0.43	21.4	46.6	69.5	100.0	112.0	120.6
0.46	20.0	44.3	66.8	100.0	112.7	120.7
0.49	18.7	41.9	64.0	100.0	113.5	120.8
0.53	17.3	39.4	61.1	100.0	114.4	120.9
0.57	15.8	36.7	58.0	100.0	115.4	121.0
0.61	14.3	34.0	54.6	100.0	116.5	121.1
0.67	12.8	31.0	51.0	100.0	117.8	121.3
0.73	11.2	27.9	47.0	100.0	119.3	121.4
0.30% WRA						
0.36	23.4	51.3	76.8	100.0	109.8	120.2
0.38	22.2	49.4	74.4	100.0	110.4	120.1
0.41	21.0	47.5	72.0	100.0	111.1	120.0
0.43	19.8	45.5	69.4	100.0	111.9	119.8
0.46	18.5	43.5	66.8	100.0	112.7	119.7
0.50	17.2	41.3	64.0	100.0	113.6	119.5
0.53	15.9	39.0	61.0	100.0	114.6	119.3
0.58	14.6	36.6	57.8	100.0	115.8	119.1
0.62	13.2	34.1	54.5	100.0	117.1	118.9
0.68	11.7	31.4	50.8	100.0	118.6	118.6
0.74	10.2	28.5	46.8	100.0	120.5	118.3
0.40% WRA						
0.34	22.6	53.7	80.1	100.0	114.6	120.8
0.37	21.0	51.2	76.9	100.0	114.4	120.2
0.40	19.5	48.6	73.6	100.0	114.2	119.5
0.43	18.0	45.9	70.3	100.0	113.9	118.8
0.46	16.5	43.2	66.8	100.0	113.7	118.0
0.50	15.0	40.4	63.1	100.0	113.4	117.1
0.54	13.4	37.5	59.4	100.0	113.1	116.2
0.59	11.9	34.5	55.4	100.0	112.8	115.1
0.64	10.4	31.4	51.2	100.0	112.4	114.0
0.70	8.9	28.2	46.8	100.0	111.9	112.6
0.77	7.4	24.8	42.1	100.0	111.4	111.1

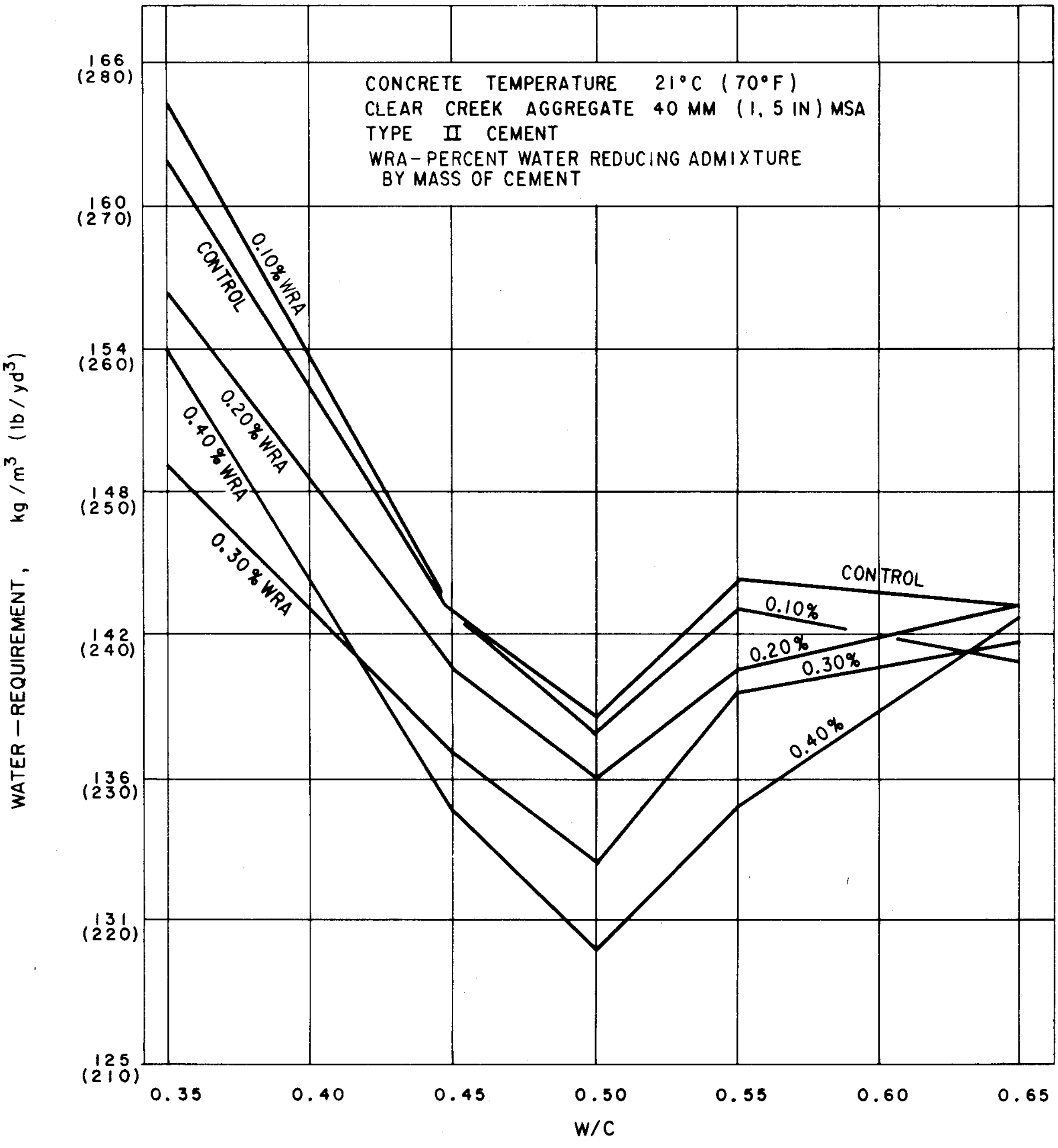


Figure 1.—Effect of water-cement ratio and admixture dosage on the water requirement. Water requirement is lowest at 0.50 W/C. Concretes with higher and lower W/C ratios have higher water requirements.

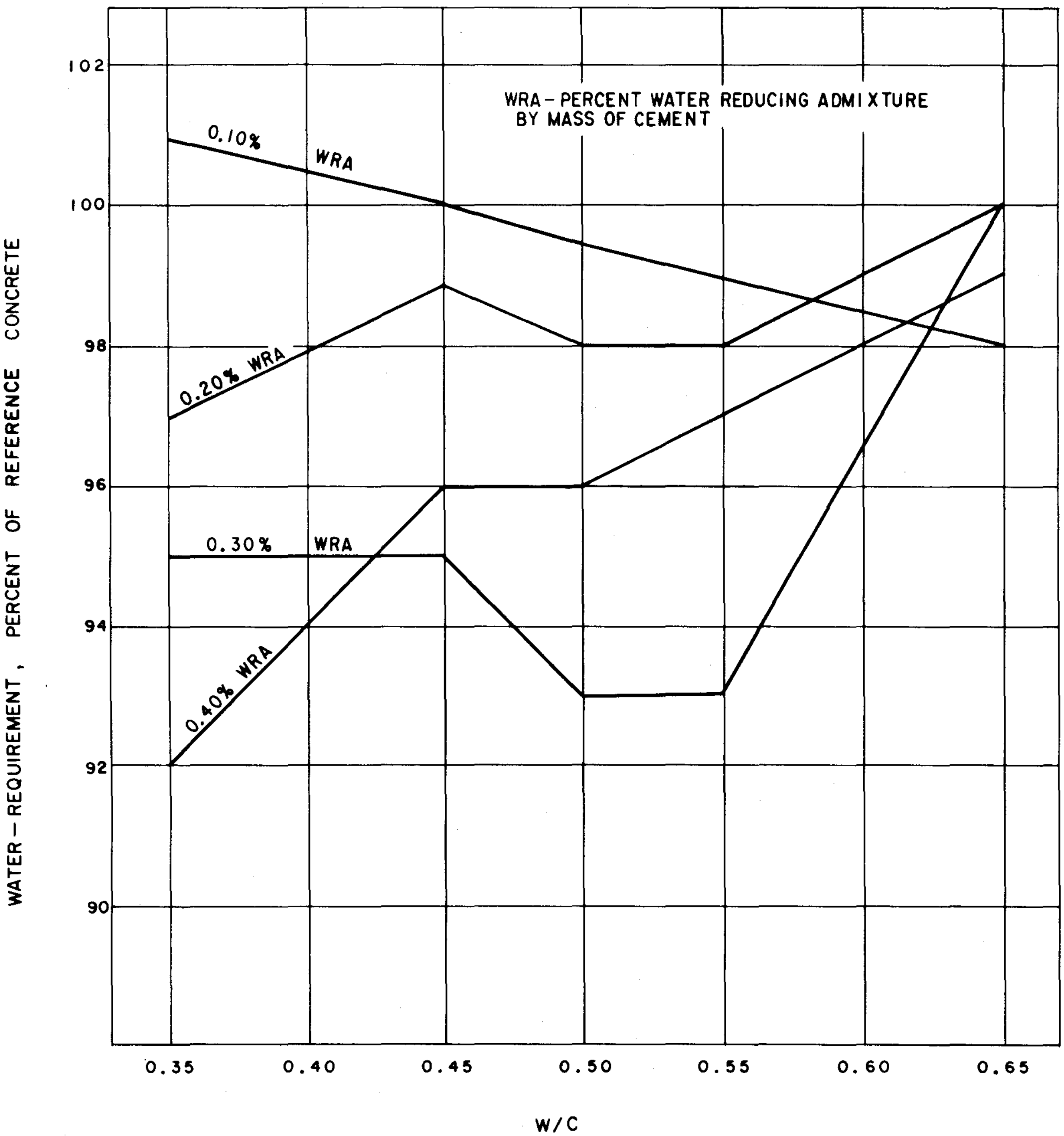


Figure 2.—Effect of water-cement ratio and admixture dosage on water reduction. With WRA additions of 0.20 percent or greater, the water reduction was greatest at W/C ratios less than 0.65. WRA's are of very little benefit at 0.65 W/C.

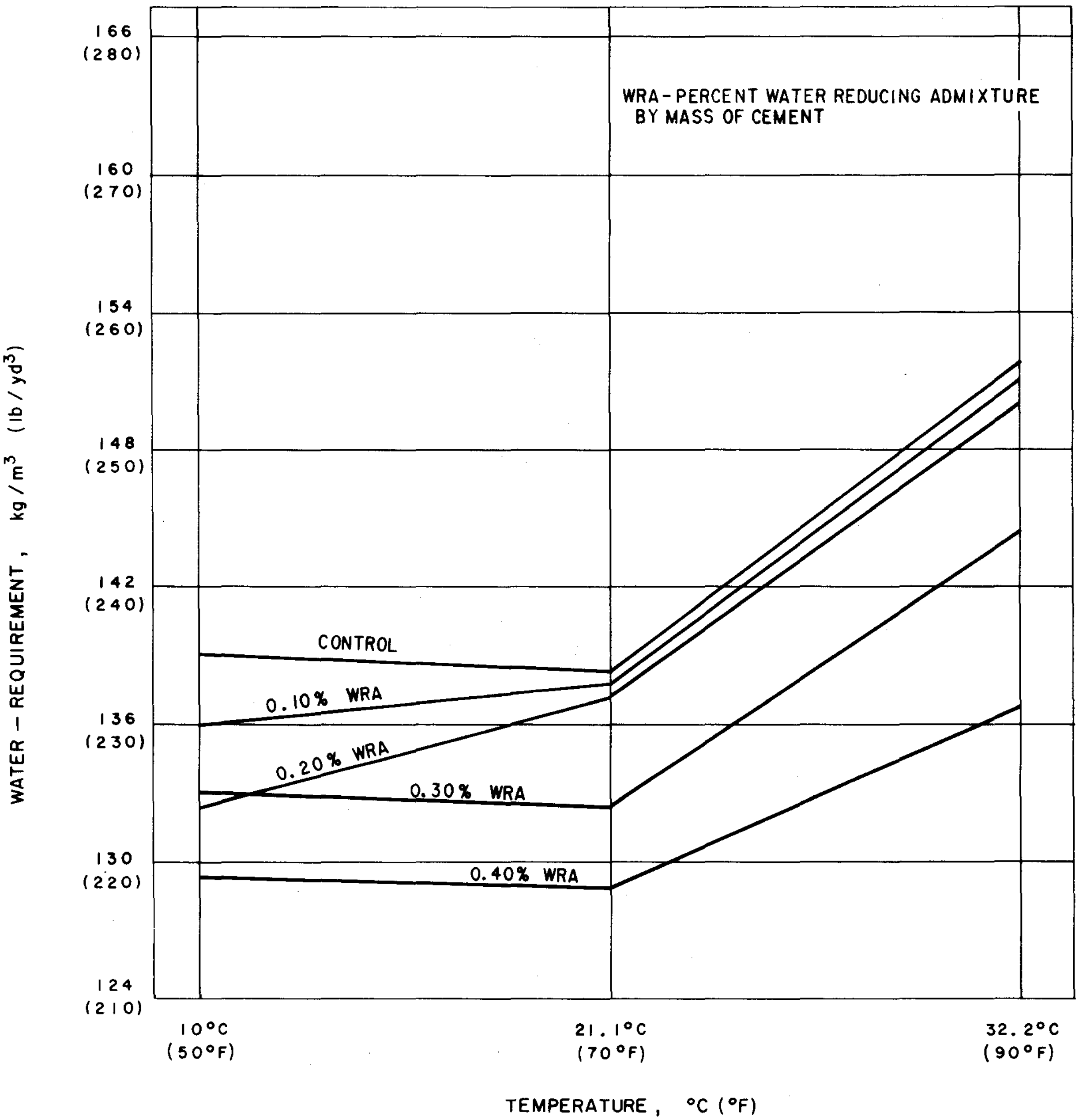


Figure 3.—Effect of temperature and admixture dosage on the water requirement. Water requirement rose 4.5 percent for each 5.5 °C (10 °F) rise in temperature between 21 and 32 °C. Between 10 and 21 °C the water required for a 75-mm (3-in) slump was unaffected.

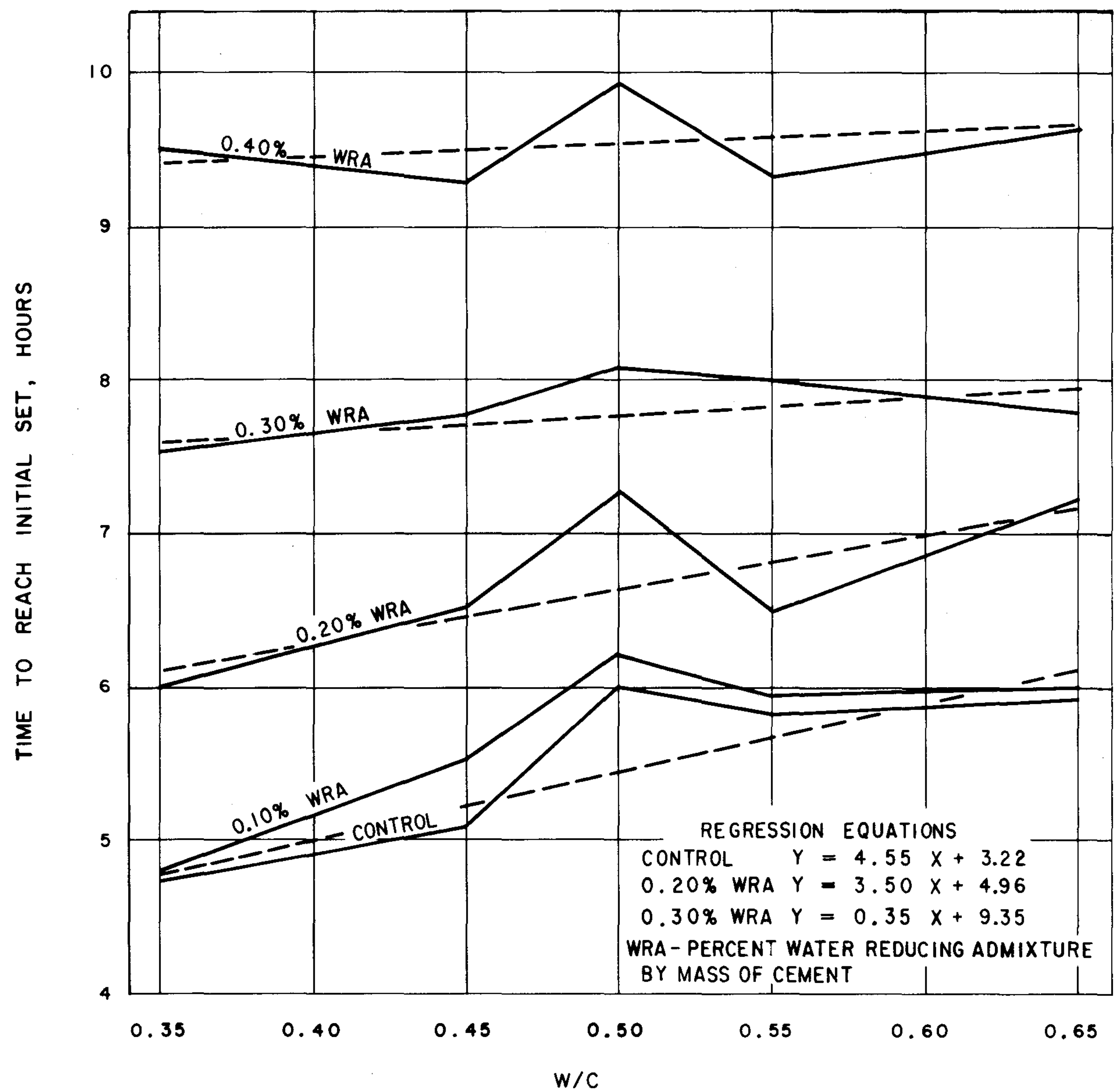


Figure 4.—Effect of water-cement ratio and admixture dosage on time of initial set. The group of concretes with W/C of 0.65 reached initial set later than concretes with lower W/C ratios. Omitting the 0.10 percent dosage, equal WRA increments produced slightly greater retardation at 0.35 W/C than at 0.65.

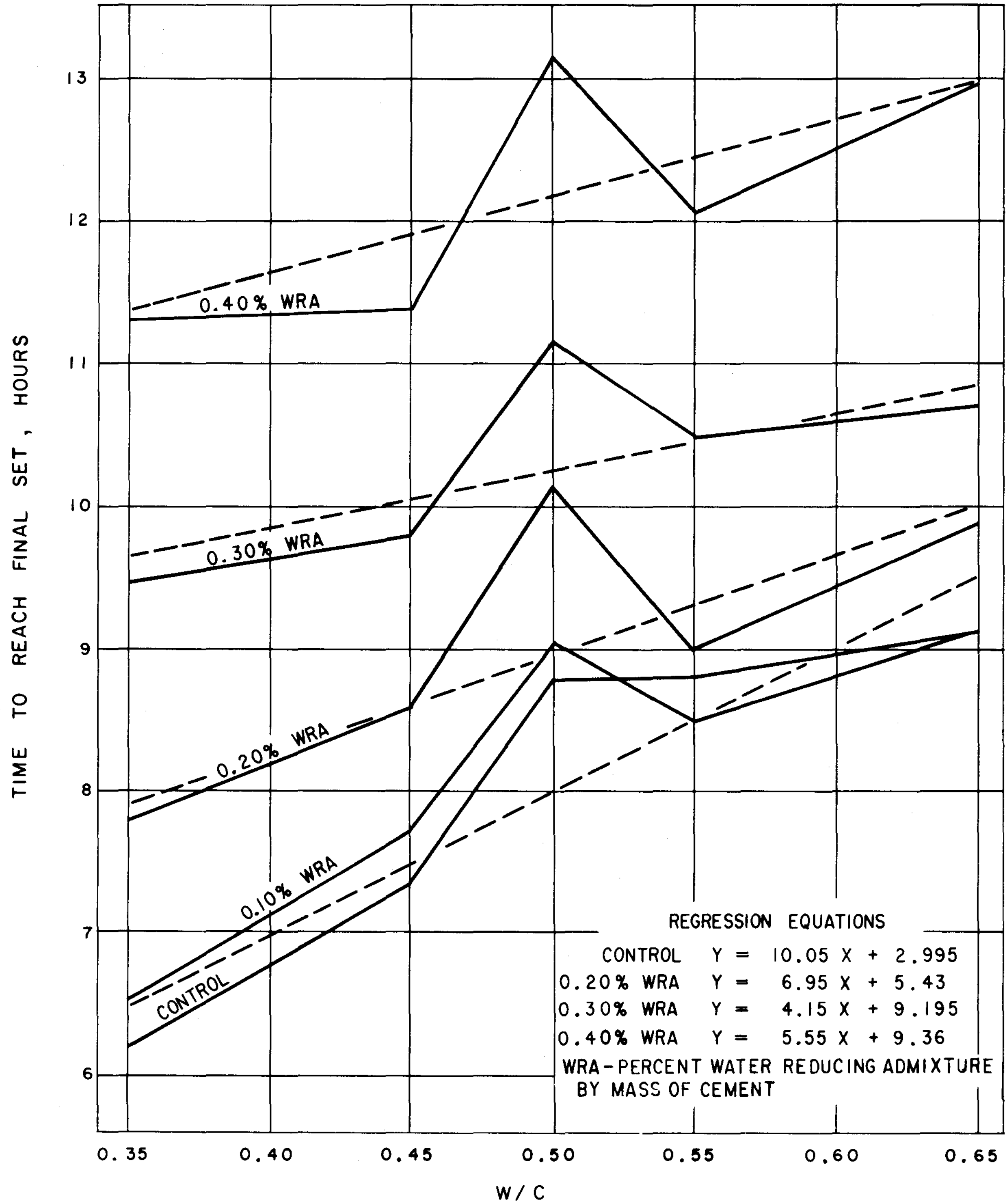


Figure 5.—Effect of water-cement ratio and admixture dosage on time of final set. Groups of mixes with W/C of 0.65 reached final set later than mixes with lower W/C ratios. Omitting the 0.10 percent dosage, equal WRA increments produced greater retardation at 0.35 W/C than at 0.65. Trends shown by final set were more acute than those shown by the initial set.

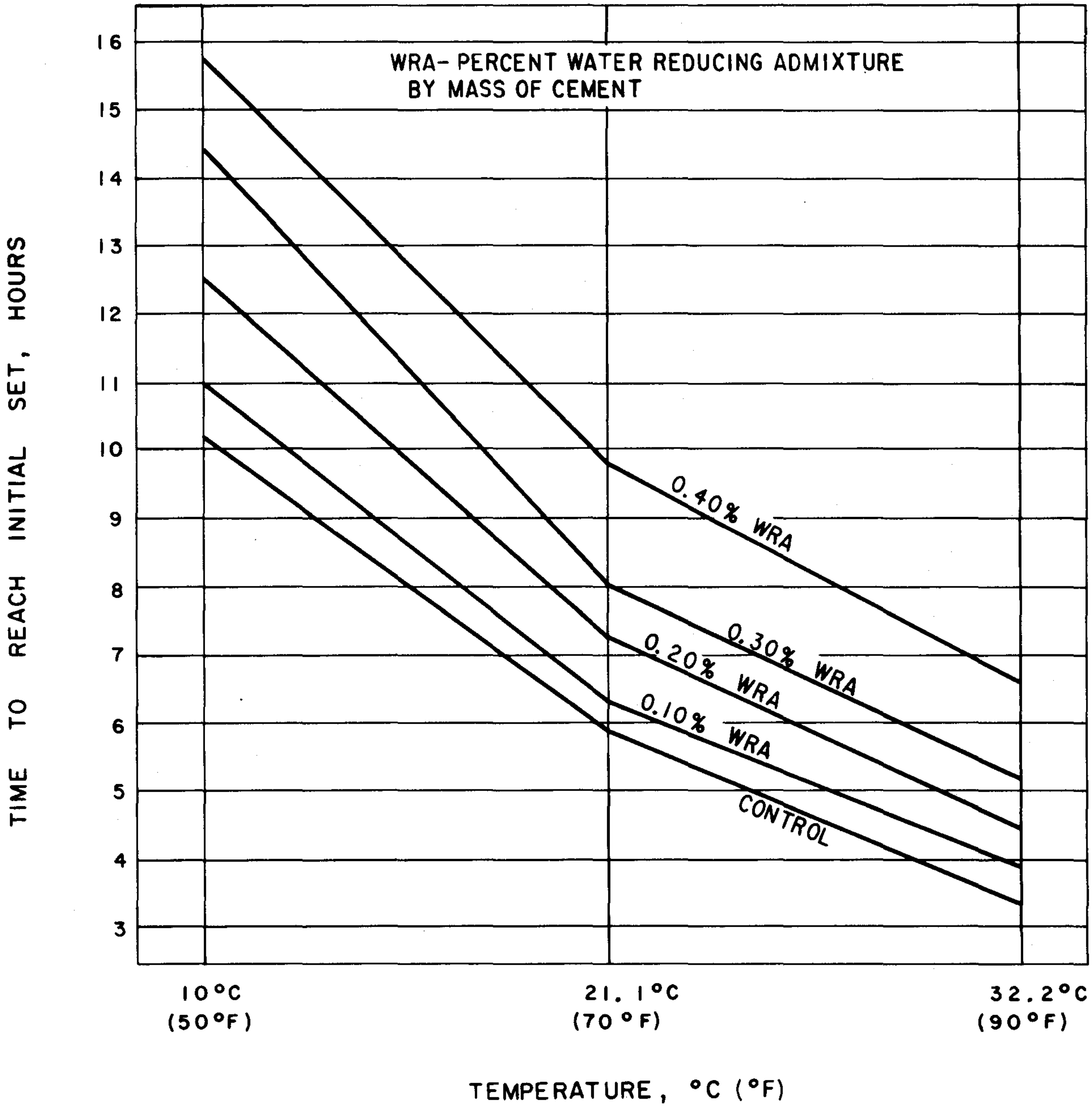


Figure 6.—Effect of temperature and admixture dosage on time of initial set. When temperature increased from 10 to 21 °C and then to 32 °C, time to reach initial set was reduced by 4.25 and 2.50 hours at a 0.50 W/C. Equal increments of WRA produced greater retardation at 10 °C.

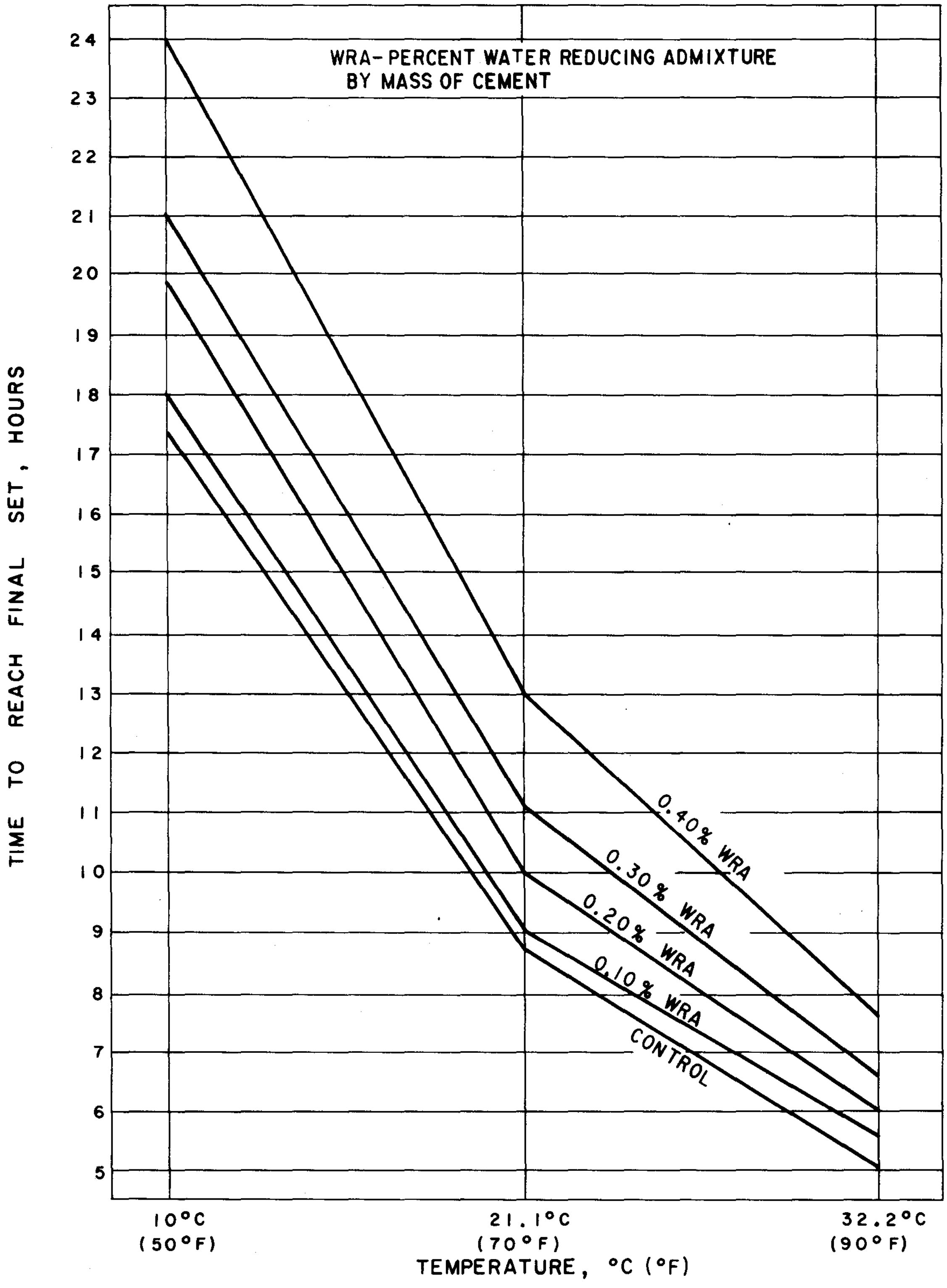


Figure 7.—Effect of temperature and admixture dosage on time of final set. When temperature increased from 10 to 21 °C and then to 32 °C, time to reach final set was reduced 8.25 and 3.75 hours. Equal WRA increments produced greater retardation at 10 °C than at 21 °C or 32 °C.

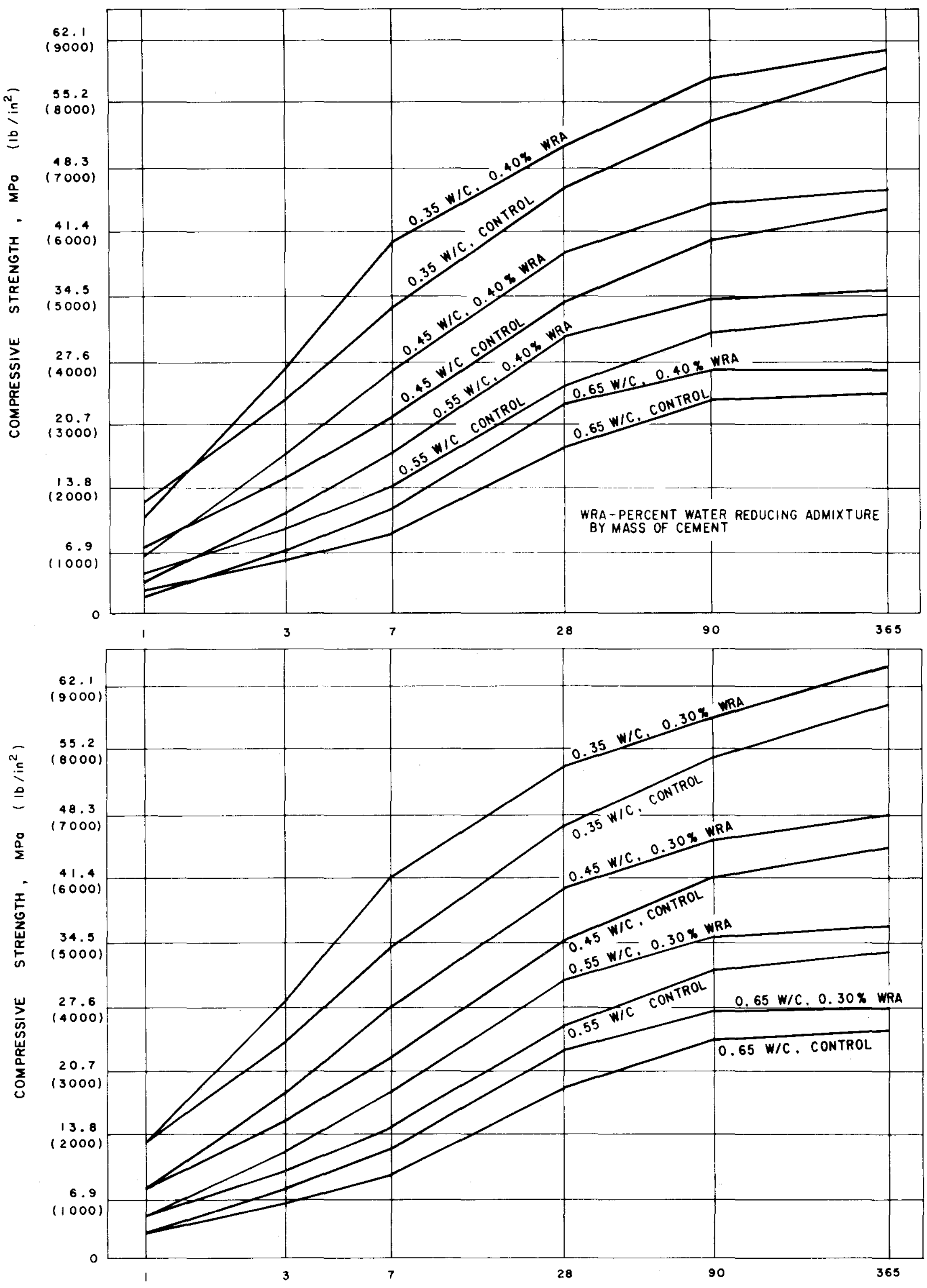


Figure 8.—Effect of water-cement ratio and admixture dosage (0.40 and 0.30 percent) on compressive strength development. Concretes with 0.30 and 0.40 percent WRA had lower strengths at 1 day and: (1) were higher at later ages than the control, (2) were more effective at lower W/C ratios; and (3) had the maximum effect at 7 and 28 days' age.

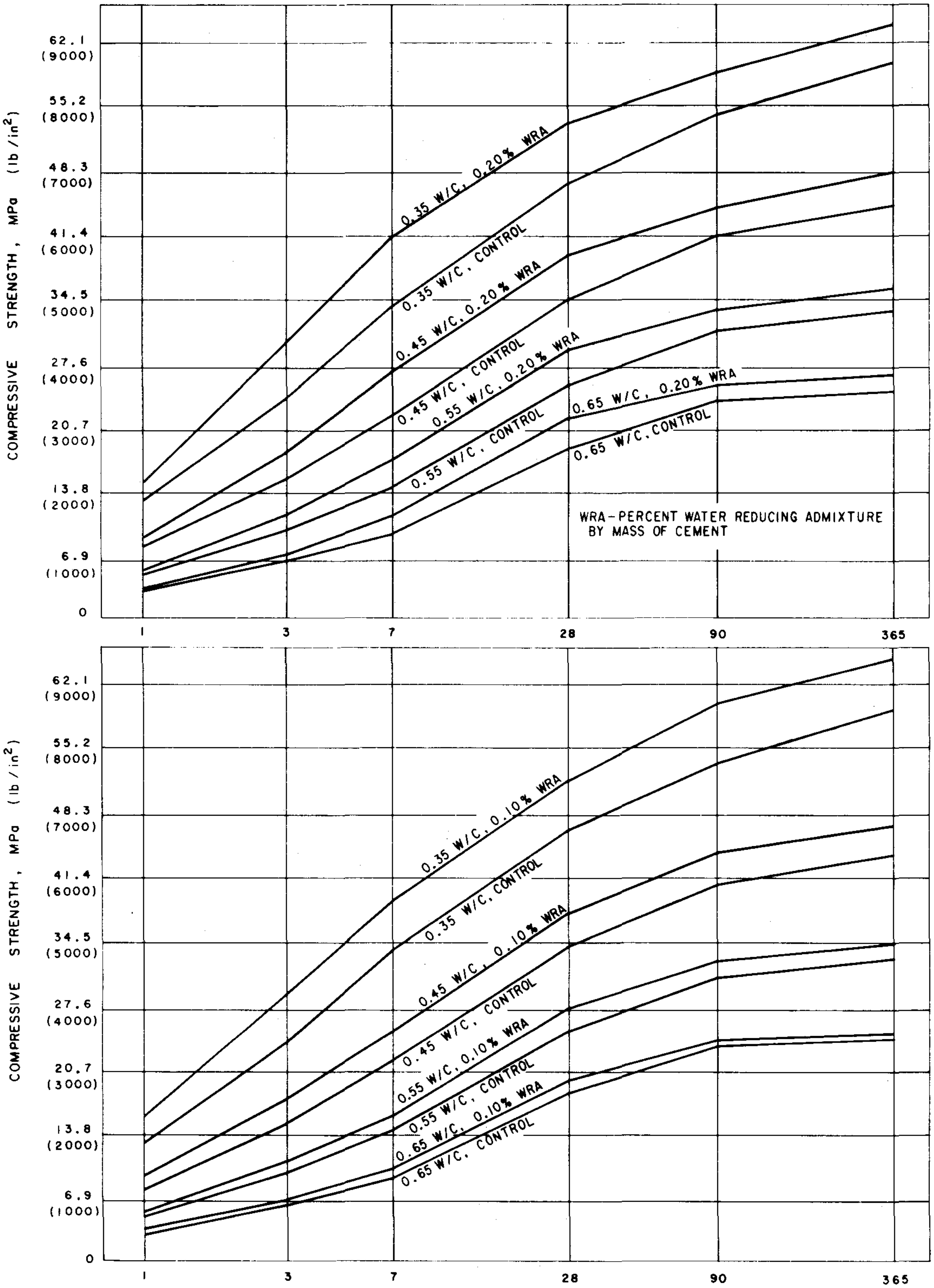


Figure 9.—Effect of water-cement ratio and admixture dosage (0.20 and 0.10 percent) on compressive strength development. Concretes with 0.10 and 0.20 percent WRA had higher strengths at all ages and were more effective as the W/C ratio increased, maximizing at 7 and 28 days' age.

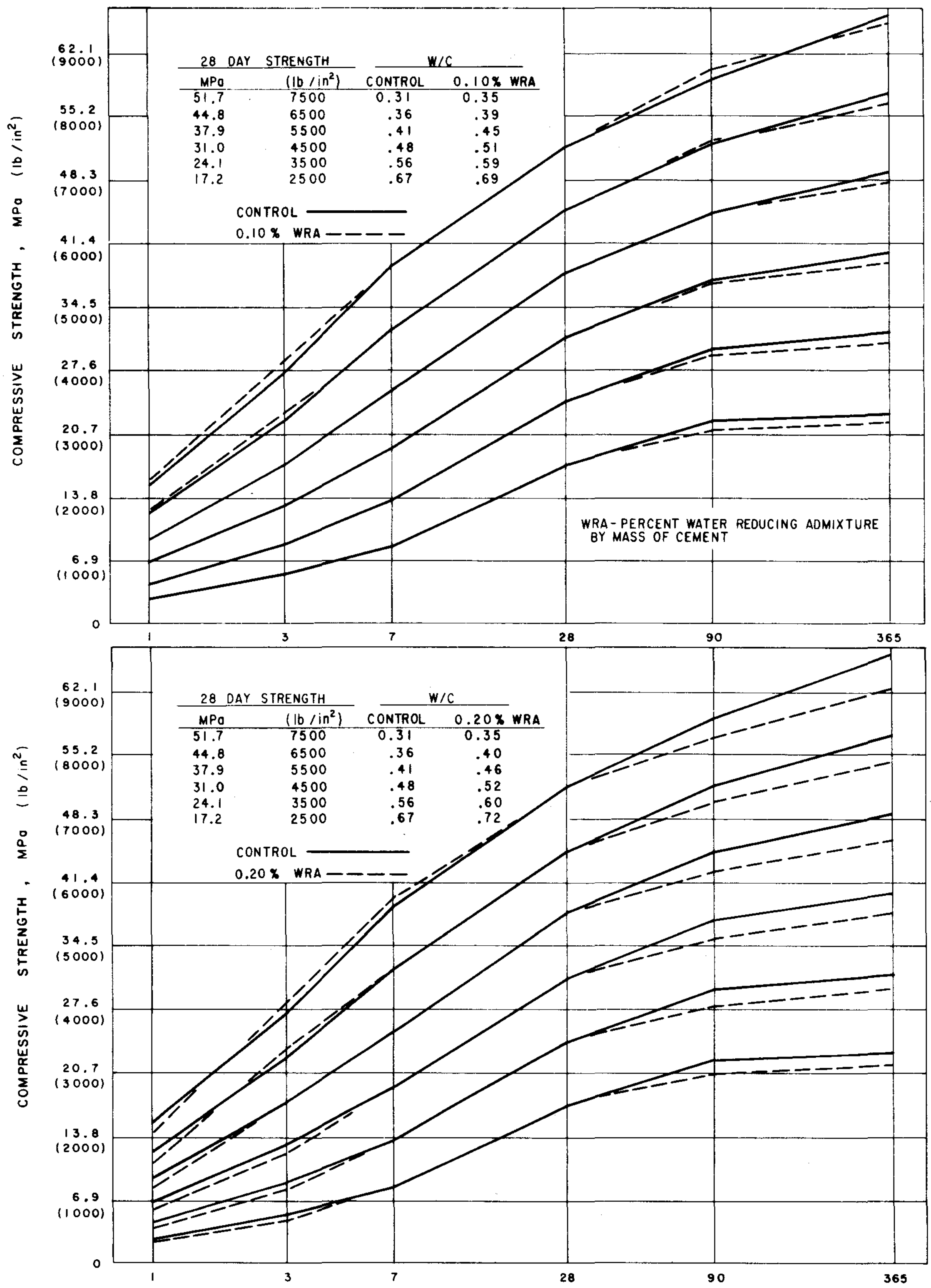


Figure 10.—Comparison of compressive strength development for control and admixture (0.10 and 0.20) concretes. Concretes made with WRA at W/C ratios sufficiently higher than the control to have the same 28-day strengths of 51.7, 44.8, and 37.9 MPa had lower strengths at 1, 3, 90, and 365 days' age. (exception, 0.10 percent WRA dosage).

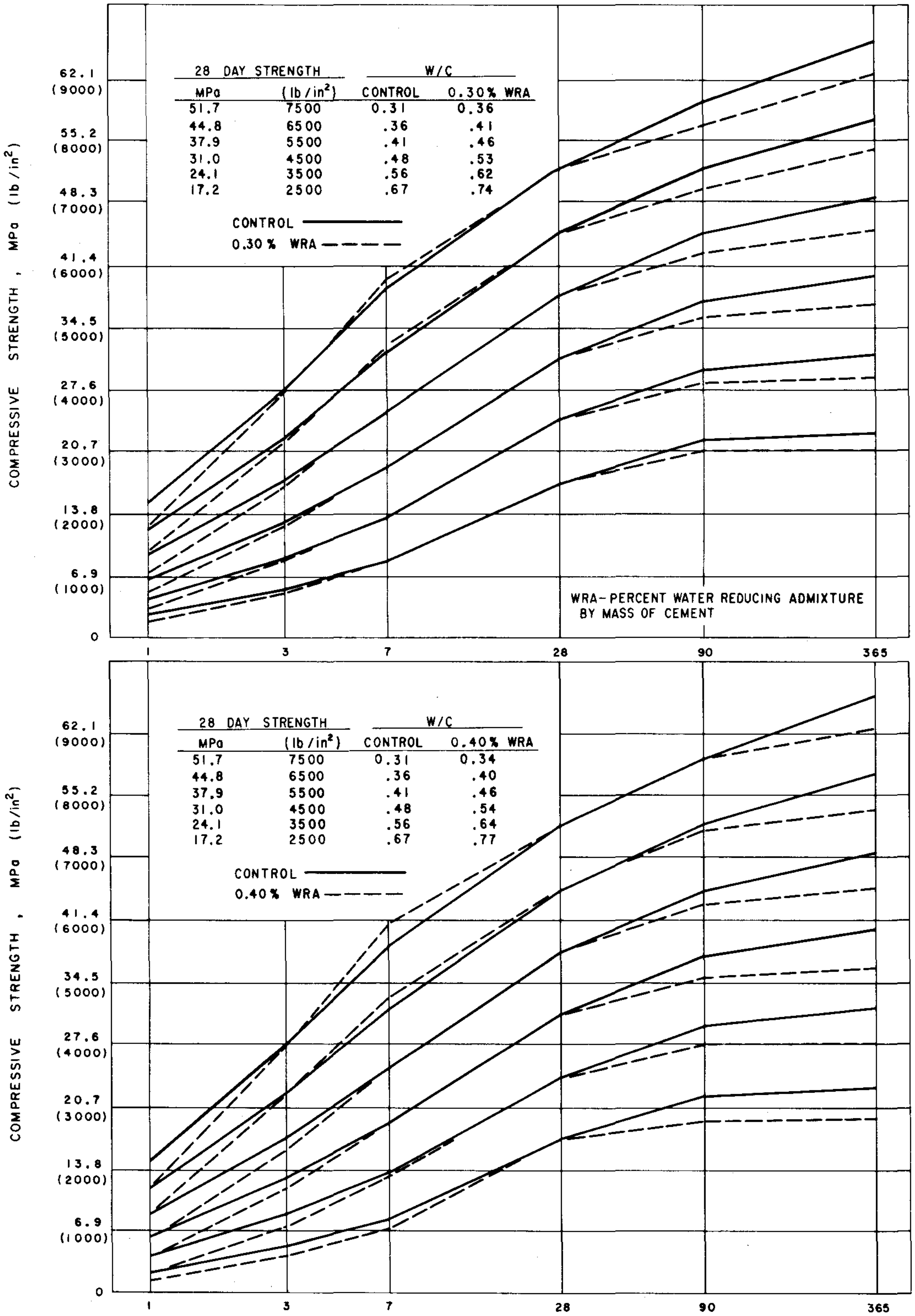
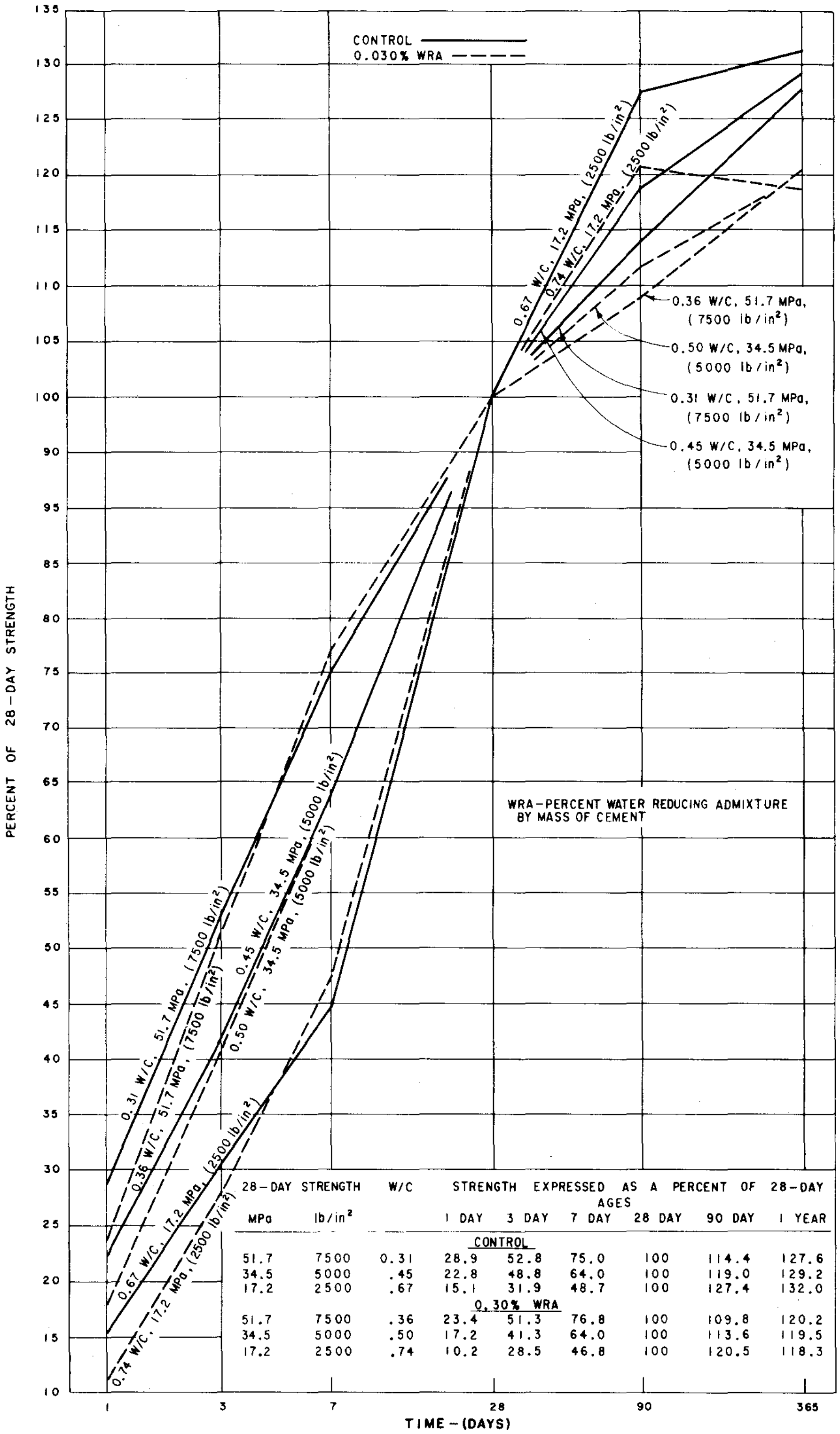


Figure 11.—Comparison of compressive strength development for control and admixture (0.30 and 0.40 percent) concretes. Concretes made with WRA at W/C ratios sufficiently higher than the control concrete to have the same 28-day strengths (51.7, 44.8, and 37.9 MPa) had lower strengths at 1, 3, 90, and 365 days' age.



28-DAY STRENGTH MPa	28-DAY STRENGTH lb/in²	W/C	STRENGTH EXPRESSED AS A PERCENT OF 28-DAY AGES: 1 DAY	3 DAY	7 DAY	28 DAY	90 DAY	1 YEAR
			CONTROL					
51.7	7500	0.31	28.9	52.8	75.0	100	114.4	127.6
34.5	5000	.45	22.8	48.8	64.0	100	119.0	129.2
17.2	2500	.67	15.1	31.9	48.7	100	127.4	132.0
			0.30% WRA					
51.7	7500	.36	23.4	51.3	76.8	100	109.8	120.2
34.5	5000	.50	17.2	41.3	64.0	100	113.6	119.5
17.2	2500	.74	10.2	28.5	46.8	100	120.5	118.3

Figure 12.—Compressive strength development as a function 28-day strengths for control and admixture (0.30 percent) concretes. Strengths at 1, 3, 7, 90, and 365 days are an average of 22.3, 44.5, 62.6, 120, and 129.6 percent of their 28-day values for non-WRA concretes at 17.2, 34.5, and 51.7 MPa levels. For concretes containing 0.30 percent WRA, these values averaged 16.9, 40.4, 62.6, 114.6. and 119.3 percent.

GPO 835-503

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