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STRENGTH DEVELOPMENT OF CONCRETE EXPOSED TO OTTAWA TEMPERATURE EXTREMES

by

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MINERAL PROCESSING DIVISION

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SUMMARY OF RESULTS

Concrete columns, slabs and cylinders, cured for three days at 50 ± 10F (10 ± 6°C) and at about 80 per cent relative humidity, and then exposed to freezing temperatures continue to gain strength at these temperatures.

For concrete Mix Series I in which the average strength of 28-day moist-cured cylinders is 2520 psi (177 kg/cm^2), the corresponding strengths of field-cured cylinders and the cores drilled from columns and slabs range from 44 to 61 per cent of the above value. For Mix Series II to V in which the strength of 28-day moist-cured cylinders exceeds 4520 psi (323 kg/cm^2), the corresponding strengths of the cores and the field-cured cylinders range from 58 to 76 per cent.

There is a marked increase in the strength of field-cured cylinders and the cores drilled from columns and slabs as the ambient temperatures of exposure exceed 50°F (10°C). The core strengths generally exceed or equal the strength of field-cured cylinders at 355 days. At this age, the strength of the cores and the field-cured cylinders are higher than the compressive strength of moist-cured cylinders at 28 days.

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INTRODUCTION

In November 1971, the Mines Branch issued an investigation report (1) entitled, "Effect of Below Freezing Temperatures on Strength Development of Concrete". In that report data were presented on the relationships of the strength of standard laboratory-cured cylinders to the strength of concrete in structures cured under exposed winter conditions. The main conclusions were:

> Concrete, initially cured for three days at about 50°F (10°C) and 75 per cent relative humidity and then exposed to below-freezing temperatures, continues to gain strength; the rate of gain in strength of field-cured specimens shows a marked increase after the ambient temperature of exposure exceeds 50°F (10°C); at the age of 7 months, the compressive strength of the cores drilled from columns and slabs approach or exceed the compressive strengths of test cylinders cured under moist conditions.

Following the recommendations outlined in the above report and the fact that measurements on laboratory-cured test cylinders neither accurately nor consistently indicate the strength development in concrete structures (2-6), further field investigations were performed during the winter of 1971-1972. This report presents the new data and the relationships between the standard- and field-cured specimens and the cores taken from the slabs and columns cast and cured in the field during winter months.

This investigation is a part of research into the behaviour of concrete by the Mines Branch and the Department of Civil Engineering, University of Ottawa. This project has been especially designed to determine the effect of below-freezing temperatures on the strength development of concrete.

SCOPE OF INVESTIGATION

The nominal water/cement ratios of the five concrete mixes investigated were between 0.77 and 0.42; corresponding cement contents were between 360 and 700 lb/yd^3 (214 to 415 kg/m^3). From each mix, two 24 x 24 x 60-in. (0.61 x 0.61 x 1.52-meter) columns and one 36 x 48 x 8-in. (0.91 x 1.22 x 0.20-meter) slab were cast at the outdoor exposure site. Eighteen 4 x 8-in. (102 x 203-mm) cylinders were cast in the Civil Engineering Materials Behaviour Laboratory at the University of Ottawa, a short distance away. Ten of these cylinders, after one day curing at 70°F (21.1°C) and 50 per cent relative humidity, were taken to the outdoor exposure site. The columns, slabs, and the ten cylinders were left at the outdoor exposure site after the initial 3-day curing* at 40 to 60°F (4 to 16°C), achieved by the use of propane-gas heaters. The other cylinders were cured under standard conditions. The ambient temperatures during the casting and initial heating of the specimens, November 17-25, 1971, varied from 10°F to 55°F (-12.2 to 12.8°C). Cores were taken from the columns and slabs after 3, 14, 28, 120, and 355 days for compression testing. The companion field- and standard-cured cylinders were also tested at the same ages to obtain comparative compressive strengths.

Ninety 4 x 8-in. (102 x 203-mm) cylinders, and one hundred 4 x 8-in. (102 x 203-mm) drilled cores were tested.

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*For cylinders: One-day curing at 70°F (21.1°C) and 50 per cent relative humidity. Two-day curing at 40 to 60°F (4 to 16°C) and 80 per cent relative humidity.

PREPARATION AND CURING OF TEST SPECIMENS

The investigation was started in early November 1971. For each test series, a 2.5-yd^3 (1.91-m^3) batch of concrete was ordered from a local ready-mix concrete supplier. The columns and slabs were cast on a specially prepared area in the exposure plot situated at the University of Ottawa, Ottawa, Ontario (Figure 1). The large specimens were compacted by an internal vibrator.

The 4 x 8-in. (102 x 203-mm) cylinders were cast at the Materials Behaviour Laboratory, University of Ottawa, a short distance away, using procedures outlined in ASTM Standard C 31-69. This procedure was adopted to ensure that the small specimens would not be frozen because of failure of propane gas heaters.

Immediately after casting, the casting area was enclosed by tarpaulins and propane gas heaters were ignited inside the enclosure to bring the ambient temperature to between 40 and 60°F (4 and 16°C). This temperature was maintained during the next three days. Ten 4 x 8-in. (102 x 203-mm) one-day old cylinders were transported from the Materials Behaviour Laboratory and placed inside the enclosure for the remainder of the heating period. All test specimens were covered with burlap which was kept moist during the three days.

All cylindrical specimens had been compacted by hand rodding; the 4 x 8-in. (102 x 203-mm) cylinders were compacted in two equal layers using standard methods.

The laboratory cylinders were covered with wet burlap immediately after casting and were left in the laboratory for the next 24 hours. Then, eight 4 x 8-in. (102 x 203-mm) cylinders were removed to the moist-curing room for standard curing and the remaining ten 8 x 12-in.(102 x 203-mm) cylinders were transferred to the exposure plot and placed inside the heated enclosure for field curing.

Immediately before casting, the temperature, slump, unit weight, and air content of the fresh concrete were determined using ASTM Standard methods. The physical properties and chemical analyses of the normal portland cement (ASTM Type 1) used for the concrete mixes are given in Table 1. The mix-design data were supplied by the ready-mix concrete supplier, and the properties of the fresh concrete are shown in Table 2.

AIR TEMPERATURE VARIATIONS AT EXPOSURE STATION

As previously noted, each of the five series of exposed specimens consisted of two columns, a slab, and ten 4 x 8-in. (102 x 203-mm) cylinders.

Hourly dry-bulb temperatures - recorded by the Department of Transport Meteorological Office at Uplands Airport, Ottawa - were obtained during the tests between November 17, 1971 to November 7, 1972. The airport is about six miles south of the University of Ottawa, which is located in the downtown area of Ottawa.

During the first phase of this project ambient air temperature was continuously recorded between December 21, 1970, and July 27, 1971, by hygro-thermograph, in a standard Stephenson shelter at the University of Ottawa exposure station; this was 1.8°F higher than the Airport temperature and it varied between -3 and -3.8°F. It was felt that, due to the relatively small differences expected in the temperatures at the two sites, it would not be necessary to record ambient air temperatures at the University of Ottawa exposure station during the present investigation; so hourly dry-bulb temperatures recorded at the Uplands Airport have been used for this investigation, as plotted in Figure 2. The heavy shaded rectangles at the top left indicate the temperature range and duration of heating for each of the series.

The relative humidity during winter months in the Ottawa area generally varies between 65 and 75 per cent, whereas in April, May, and June the relative humidity varies between 50 and 60 per cent.

TESTING OF CONCRETE SPECIMENS

The laboratory - and field-cured cylinders were tested in pairs at 3, 14, 28, and 120 days. Originally the project duration was planned to be about six or seven months. This was extended to one year, with tests at about four months and one year, to get longer-range results. Two extra cylinders had been cast for field curing, due to the possible loss of or damage to these small specimens. Only field-cured cylinders were tested at 355 days, no extra laboratory-cured cylinders being available.

At each of the five ages, two 4 x 8-in. (102 x 203-mm) cores were drilled from the columns (one for each column) and the slab*. A view of the drilling operation is shown in Figure 3. The four cores for each series were transported to the Mines Branch Laboratory for testing. During the winter months (at ages 3, 14, 28, and 120 days), the drilled cores and field-cured cylinders were allowed to thaw in the laboratory air for about 6 hours to allow the inside of the specimens to reach a minimum temperature of about 60°F (15.5°C). The ends

*Further drilling of cores is planned at two years.

of the cores were sawn to get a smooth surface, and all cores and cylinders were capped with a sulphur-flint mixture for compression testing on an Amsler testing machine [600,000-lb (271,800-kg) capacity]. All cores were tested dry to simulate the concrete in exposed structures. The core size was 4 x 8 in. (102 x 203 mm) for a length:diameter ratio of 2, and no correction factors were needed for strengths (7). The compressive strengths for the four types of specimens of each series and for the five ages of the tests are given in Table 3.

At the ages of 28 days and four months, the densities of the standard-cured cylinders and of the cores drilled from the columns and slabs were determined (Table 4).

PRESENTATION OF TEST RESULTS

The typical relationships between age and compressive strength for 4 x 8-in. (102 x 203-mm) standard-cured cylinders are shown in Figure 4. The relationships between age and compressive strength as a percentage of the 28-day strength of the 4 x 8-in. (102 x 203-mm) standard-cured cylinders are shown in Figures 5 to 9 inclusive.

To determine the reproducibility of the test results, within-batch standard deviations and coefficients of variation have been computed for the test data. These are shown in Tables 5 to 8 inclusive.

STRENGTH DEVELOPMENT WITH AGE

Figures 5 to 9 relate the compressive strengths of concrete in the standard-cured cylinders, in columns, and in slabs. It should be pointed out that, in the Ottawa area, there are about 80 freeze-thaw cycles per year. These freeze-thaw phenomena were not expected to affect the performance of the field-cured concrete because all the concrete used had entrained air.

Mix Series I

Figure 5 shows the strength gain with age for concrete having a compressive strength of 2520 psi (177 kg/cm^2) at 28 days. The standard-cured cylinders show continuous gain in strength up to 120 days and reach a value of 107 per cent of the standard strength. Hereafter, the 28-day compressive strength of 4 x 8-in. (102 x 203-mm) standard-cured cylinders will be referred to as the standard strength. The curve for the strengths of the field-cured cylinders is almost a straight line between 3 and 28 days, where it reaches 61 per cent of the standard strength. After 28 days, a greatly reduced rate of strength gain is indicated which, at 120 days, reaches a strength that is only 63 per cent of the standard strength. The field-cured cylinders reach a value of 99.6 per cent of the standard strength at 355 days; the influence of predominantly higher than freezing temperatures, after the end of March, causes an increase of about 50 per cent over the 120-day strengths of the field specimens. The slab and column cores show an almost linear trend from 3 to 120 days. Following this, there is a marked increase in strength, the slab and column cores reaching a value of 91 and 106 per cent of the standard strength. The coefficient of variation for the 3-day results on the slab cores is 6.7 per cent whereas that of the column cores is 2.5 per cent. The effect of the experimental error coupled with a relatively low strength concrete would result in some scatter of the results at this early age. The slab core strengths average 10 per cent less than the column core strengths from 28 to 355 days.

Mix Series II

Test results of a concrete having a compressive strength of 4600 psi (323 kg/cm^2) at 28 days for the standard-cured cylinders are shown in Figure 6. The 3-day standard-cured cylinders show only 37 per cent of the 28-day standard strength value. The cylinders had been stored for the first 24 hours in the aggregate storage area where temperatures were between 50° and 60°F (10 and 15.6°C) instead of in the Materials Behaviour Laboratory itself where temperatures are normally about 73°F. The influence of these lower curing temperatures on the 3-day strength can readily be seen by comparing Figures 5 and 6 with the corresponding percentages for the standard-cured strengths in Table 3. A very similar trend can be seen in Figure 7 for the standard-cured cylinder 3-day test of Mix Series III, which was cast on the same day and underwent the same curing for the first 24 hours as Mix Series II. The field-cured cylinder test results generally lie above those for the cores except at 3 days where some scatter can be noted, with the cores giving slightly higher strengths. At 355 days, the column cores have the highest strength (106%), followed by the field-cured cylinders (102%) and then the slab cores (95%). Similar trends can be noted in Figure 5 for Mix Series I. For the field-cured cylinders the strength gain relation is almost a straight line over the full range of ages. The cores show a more gradual and almost linear strength gain relation up to 120 days reaching about 67 per cent of the standard strength. A sharp increase in strength from 120 to 355 days is noted for the cores.

Mix Series III

The strength-age relationship is shown in Figure 7 for Mix Series III. The compressive strength of the standard-cured cylinders at 28-days is 5180 psi (364 kg/cm^2). As noted previously for Mix Series II, the standard-cured cylinder strength is low at three days due to curing temperatures being between 50° to 60°F (10 and 15.6°C) instead of being about the normal temperature of 73°F (22.8°C). The standard-cured cylinders show a steady gain in strength up to 28 days after which the increase tapers off, reaching 112 per cent at 120 days. The field-cured cylinders gain strength at a slower rate from 14 to 120 days than the standard-cured cylinders but at a greater rate than the cores. The 3-day field-cured cylinder strength is also below the core strengths at this age. The field-cured cylinders reach 87 per cent, and the cores 68 and 69 per cent of the standard strength at 120 days. The rate of gain of strength after 120 days is greater for all specimens. The field-cured cylinders increase 23 per cent, the slab cores increase 56 per cent, and the column cores increase 72 per cent of their respective 120-day values. The column cores again show the largest gain in strength and would be closest to any projected standard-cured strength at 355 days.

Mix Series IV

Figure 8 shows the age-strength relations for Mix Series IV with a 28-day compressive strength of 5405 psi (380 kg/cm^2). The standard-cured cylinders show a steady increase in strength to 121 per cent of the standard strength at 120 days. The field-cured cylinders show an almost linear trend between 3 and 120 days reaching 83 per cent of the standard strength at 120 days. The slab cores show an almost parallel behaviour to the field-cured cylinders reaching 80 per cent of the standard strength at 120 days. The column cores show a much reduced gain of strength reaching only 67 per cent at 120 days. All specimens show very similar trends between 120 and 355 days. The field-cured cylinders increase 36 per cent, the slab cores increase 50 per cent, and the column cores increase the most, 61 per cent of their respective 120-day values. The slab cores show the highest strength at 355 days, 120 per cent of the standard strength.

Mix Series V

The development of strength with age for Mix Series V, which has a 28-day compressive strength of 6090 psi (428 kg/cm^2) is shown in Figure 9. There is a linear trend for the strength of standard-cured cylinders to 28 days. The behaviour after 28 days shows an increase in the rate of strength gain to 120 days where 130 per cent of the standard strength is reached. This is unusual. The 3-day strength of the field-cured cylinders is the lowest strength at this age, and the rate of gain of strength is almost linear between 3 and 120 days, reaching 80 per cent of the standard strength. The cores show very similar behaviour, the slab core strengths between 3 and 120 days are on the average 5 per cent higher than the column core strengths. The slab cores reach 76 and the column cores 71 per cent of the standard strength at 120 days. The behaviour between 120 and 355 days shows an increase of 41 per cent and 49 per cent in each case for the field-cured cylinders and the column cores over their respective 120-day strengths. The field-cured cylinders show a high of 113 per cent, and the column cores are 106 per cent of the standard strength at 355 days. The slab core test results were discarded. Due to the poor shape and unsatisfactory size of these cores, their strength was only 81 per cent of that of the 355-day results.

DENSITIES OF TEST CYLINDERS AND CORES

The 28-day and 4-month densities of 4 x 8-in. (102 x 203-mm) standard-cured cylinders and drilled cores from columns and slabs are given in Table 4. The densities of the cylinders vary from 147.18 to 151.90 lb/ft^3 (2358 to 2433 kg/m^3) and those of the cores from 142.35 to 148.71 lb/ft^3 (2280 to 2382 kg/m^3). The average densities, at 4 months, of standard-cured cylinders, slabs, and column cores are 150.44 lb/ft^3 (2410 kg/m^3), 145.90 lb/ft^3 (2337 kg/m^3), and 147.20 lb/ft^3 (2358 kg/m^3); the standard deviations are 1.88 lb/ft^3 (30 kg/m^3) for the standard-cured cylinders, 2.11 lb/ft^3 (34 kg/m^3) for the slab cores, and 1.68 lb/ft^3 (27 kg/m^3) for the column cores. Compaction of the cylinders had been by hand-rodding and of the slabs and columns by an internal vibrator. The statistical procedure that tests for the equality of the means of two sets of observations is the Student or t distribution test. Using the expression:

$$t_o = (\bar{X}_1 - \bar{X}_2) \Big/ \sqrt{(S_1^2/n_1 + S_2^2/n_2)} ,$$

it is assumed that the variances of the two samples cannot be combined; where $\bar{X}_1$ and $\bar{X}_2$ are the means and S_1 and S_2 the standard deviations of the two sets of observations. The test between the means of the slab and column cores results in no significant differences; $t_o = 1.08 < t_{0.95,4} = 2.776$, for the 95 per cent confidence limit and four degrees of freedom. Similar tests between the mean for the standard-cured cylinders and the mean for the slab and the column cores show significant differences in the densities of the cylinders and the cores. The results, ($t_o = 3.60 > t_{0.95,4}$) for the slab cores and ($t_o = 2.87 > t_{0.95,4}$) for the column cores, indicate significant differences between the densities of hand-rodded cylinders and cores. To what extent these differences in densities affect strengths is not known.

REPRODUCIBILITY OF TEST RESULTS

The within-batch standard deviation and coefficient of variation of the test results at 28 days and at four months are shown in Tables 5 and 6. For these ages, the average coefficient of variation for standard-cured cylinders is between 0.4 and 5.3 per cent with an over-all mean of 2.3 per cent which indicates excellent within-batch control of the concrete (8). The field-cured cylinders show an over-all mean coefficient of variation for these ages of 2.4 per cent. The slab cores, drilled vertically, show an over-all coefficient of variation of 3.9 per cent, with a range over the ages of 0.2 to 9.5 per cent. The column cores were drilled horizontally perpendicular to the column faces. The over-all average coefficient of variation of 4.2 per cent indicates only fair control of the concrete for the column cores. The probable reason for the greater variation in the column core test results is the strength variations between the two columns cast from each mix series. One core was taken from each column and the strengths combined in the average strengths reported. The slab cores were taken in closely adjacent areas of the slab and would therefore reflect a better reproducibility of the test results.

GENERAL COMMENTS

At 355 days, the core strengths exceed the field-cured cylinder strengths and the 28-day standard strength. Specimen type does not seem to influence these strengths at 355 days in that 4 x 8-in. (102 x 203-mm) cylinders, and cores from 8-in. (203-mm) slabs and 24 x 24-in. (609 x 609-mm) columns have similar strengths at this age. Maturity (9) calculations indicate that, at low temperatures, the maturity rule considerably underestimates the potential strength of the concrete. It was not possible to use thermocouples inside the test specimens because a heated hut for instrument reading was not available. The relationships between strength development and age confirm the test results reported in Phase I of the program with one major exception, i.e., field-cured cylinders have higher strengths than cores between 3 and 120 days. This observation is opposite to that noted in Phase I of the program (1). The heating enclosures in this investigation were better insulated and test specimens from each mix series were individually heated. This may have contributed to the higher strengths of field-cured cylinders. However, in both investigations, the cores drilled from columns and slabs were stronger than field-cured cylinders at 355 days and standard-cured cylinders at 28 days.

The scatter of results between the strengths of cores and field-cured cylinders is much smaller at all ages than the scatter in the corresponding strengths in Phase I of the investigation because there was better control than during Phase I of the project.

CONCLUSION AND RECOMMENDATION

The strength results of Phase II confirm those of Phase I of this project. The strength-gain relationship should be investigated after initial curings of 1, 2, 5, and 7 days.

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TABLE 1

Physical Properties and Chemical Analyses of Cement*

Description of Test	
Time of Set (Vicat Needle): Initial	150 min
Final	275 min
Fineness, minus 200 mesh	97.3 per cent
Autoclave expansion	0.13 per cent
Physical Tests - Mortar Strength	
Compressive Strength of 2-in. (51-mm) cubes	
3-day	2870 psi (202 kg/sq cm)
7-day	3680 psi (259 kg/sq cm)
Chemical Analysis	
Insoluble Residue	0.10 per cent
Silica (SiO_2)	20.90 per cent
Alumina (Al_2O_3)	5.40 per cent
Iron Oxide (Fe_2O_3)	2.70 per cent
Calcium Oxide (CaO) (Total)	63.30 per cent
Calcium Oxide (Free)	0.58 per cent
Magnesium Oxide (MgO)	3.00 per cent
Sulphur Trioxide (SO_3)	2.50 per cent
Loss on Ignition	0.42 per cent

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

TABLE 2

Mix Design Data and Properties of Fresh Concrete

Date Cast	Mix No.	Mix Design Data*				Properties of Fresh Concrete						
		Nominal Water/Cement Ratio by Wt	Cement Content		Aggregate/Cement Ratio by Weight	Temperature		Slump		Unit Weight		Air Content, Per Cent
			lb/yd^3	kg/m^3		°F	°C	in.	mm	lb/ft^3	kg/m^3	
1971 Nov. 17	1	0.77	360	214	9.46	60	16	** 2.0	52	144.8	2319	4.4
Nov. 19	2	0.67	410	243	8.25	74	23	2.75	70	148.0	2370	4.0
Nov. 19	3	0.56	500	297	6.76	72	22	2.5	64	148.8	2383	3.5
Nov. 22	4	0.46	630	374	5.06	68	20	3.5	89	145.2	3226	5.0
Nov. 22	5	0.42	700	415	4.39	68	20	3.5	89	***	***	***

* Supplied by the ready-mixed company which delivered the concrete.

** Slump taken 45 minutes after the truck arrived at site.

*** Air content and unit weight not determined due to faulty operation of the air meter.

TABLE 3

<u>Compressive Strength of Standard- and Field-Cured Cylinders, and Cores Drilled from Slabs, and Columns</u>

Mix No.	Compressive Strength at Various Ages of 4 x 8-in. (102 x 203-mm) Cylinders and Cores, psi (kg/cm^2)																			
	3-day				14-day				28-day				4-month				355-day			
	Standard Cured	Field Cured	Slab Cores	Column Cores	Standard Cured	Field Cured	Slab Cores	Column Cores	Standard Cured	Field Cured	Slab Cores	Column Cores	Standard Cured	Field Cured	Slab Cores	Column Cores	Standard Cured	Field Cured	Slab Cores	Column Cores
1	1210 (48)	980 (39)	995 (39)	850 (34)	2010 (80)	1325 (53)	1060 (42)	1120 (44)	2520 (100%)	1545 (61)	1120 (44	1305 (52)	2685 (107)	1590 (63)	1420 (56)	1585 (63)	***	2510 (99.6)	2295 (91)	2675 (106)
2	1715*+ (37)	2185 (48)	2280 (50)	2570 (56)	3795 (83)	2830 (62)	2690 (59)	2430 (53)	4600 (100%)	3445 (75)	2610 (57)	3060 (67)	5395 (117)	3880 (84)	3130 (68)	3000 (65)	***	4690* (102)	4365 (95)	4895 (106)
3	2115+ (41)	1960 (38)	2480 (48)	2740 (53)	4250 (82)	3370 (65)	2910 (56)	3100 (60)	5180 (100%)	3750 (72)	3040 (59)	3385 (65)	5800 (112)	4510 (87)	3600 (69)	3520 (68)	***	5525 (107)	5525 (107)	6110 (118)
4	3270 (61)	2605 (48)	2390 (44)	3130 (58)	4800 (89)	3540 (66)	3170 (59)	3150 (58)	5405 (100%)	3900 (72)	3475 (64)	3520 (65)	6530 (121)	4460 (83)	4340 (80)	3625 (67)	***	6110 (113)	6465 (120)	5815 (108)
5	4370 (72)	2855 (47)	3410 (56)	3205 (53)	5580 (92)	3740 (61)	3760 (62)	3440 (56)	6090 (100%)	4300 (71)	4025 (66)	3800 (62)	7890 (130)	4890 (80)	4621 (76)	4340 (71)	***	6890 (113)	**	6465 (106)

* Only one cylinder available for testing.
** Cores were discarded because of poor shape and unsatisfactory size.
*** Lab-cured cylinders not available due to change in project duration.
\+ Low standard-cured strength values are due to the temperature in the curing room being between 50° and 60° F for the first 24 hours.

TABLE 4

Densities of Concrete Cylinders and Cores

Mix No.	Density of Cylinders and Cores+											
	28-day						4-month					
	Standard-cured Cylinders		Drilled Cores				Standard-cured Cylinders		Drilled Cores			
	lb/ft^3	kg/m^3	lb/ft^3	kg/m^3	lb/ft^3	kg/m^3	lb/ft^3	kg/m^3	lb/ft^3	kg/m^3	lb/ft^3	kg/m^3
			slab		column				slab		column	
1	*	*	*	*	*	*	147.18	2358	142.35	2280	144.53	2315
2	151.37	2425	146.47	2346	147.49	2363	151.45	2426	147.29	2360	148.44	2378
3	151.64	2429	146.41	2345	148.21	2374	151.90	2433	147.52	2363	148.71	2382
4	*	*	147.37	2361	147.12	2357	150.70	2414	146.70	2350	147.60	2365
5	*	*	146.43	2346	146.82	2352	150.97	2419	145.64	2333	146.78	2351

+ Cylinder and core size = 4 x 8 in. (102 x 203 mm).

* Values not available.

TABLE 5

Within-Batch Standard Deviation and Coefficient of Variation of 28-day Test Results

Mix No.	Standard-Cured Cylinders*				Field-Cured Cylinders*				Slab Cores*				Column Cores*			
	Average+ Strength, psi(kg/cm²)	S.D.		C.V., %	Average+ Strength, psi(kg/cm²)	S.D.		C.V., %	Average+ Strength, psi(kg/cm²)	S.D.		C.V., %	Average Strength, psi	S.D.		C.V., %
		psi	kg/cm²			psi	kg/cm²			psi	kg/cm²			psi	kg/cm²	
1	2520 (177)	28	2.0	1.1	1545 (109)	18	1.3	1.1	1120 (79)	28	2.0	2.5	1305 (92)	70	4.9	5.2
2	4600 (323)	4	0.2	0.1	3445 (242)	81	5.7	2.4	2610 (184)	248	17.4	9.5	3060 (215)	96	6.7	3.1
3	5180 (364)	53	3.7	1.0	3750 (264)	173	4.6	4.6	3040 (214)	191	13.4	6.3	3385 (238)	117	8.2	3.5
4	5405 (380)	21	1.5	0.4	3900 (274)	67	4.7	1.7	3475 (244)	141	9.9	4.1	3520 (248)	240	16.9	6.8
5	6090 (428)	286	20.1	4.7	4300 (302)	170	11.9	4.0	4025 (283)	7	0.5	0.2	3800 (267)	141	9.9	3.7

*Size of cylinders and cores: 4 x 8 in. (102 x 203 mm).

+Each value is the average of tests on two specimens unless otherwise stated.

TABLE 6

Within-Batch Standard Deviation and Coefficient of Variation of 120-Day Test Results

Mix No.	Standard-Cured Cylinders*				Field-Cured Cylinders*				Slab Cores*				Column Cores*			
	Average+ Strength, psi(kg/cm^2)	S.D.		C.V., %	Average+ Strength, psi(kg/cm^2)	S.D.		C.V., %	Average+ Strength, psi(kg/cm^2)	S.D.		C.V., %	Average+ Strength, psi(kg/cm^2)	S.D.		C.V., %
		psi	kg/cm^2			psi	kg/cm^2			psi	kg/cm^2			psi	kg/cm^2	
1	2685 (189)	144	10.2	5.3	1590 (112)	57	4.0	3.6	1420 (100)	67	4.7	4.7	1585 (111)	35	2.5	2.2
2	5395 (379)	85	6.0	1.6	3880 (273)	127	8.9	3.3	3130 (220)	57	4.0	1.8	3000 (211)	18	1.2	0.6
3	5800 (408)	103	7.2	1.8	4510 (317)	7	0.5	0.2	3600 (253)	71	5.0	2.0	3520 (248)	141	9.9	4.0
4	6530 (459)	315	22.2	4.8	4460 (314)	59	4.2	1.3	4340 (305)	90	6.3	2.1	3625 (255)	355	25.0	9.8
5	7890 (555)	158	11.1	2.0	4892 (344)	85	6.0	1.7	4621 (325)	253	17.8	5.8	4340 (305)	135	9.5	3.1

+Each value is the average of tests on two specimens unless otherwise stated.

*Size of cylinders and cores = 4 x 8 in. (102 x 203 mm).

Fig. 1 - A view of the field specimens at exposure station.

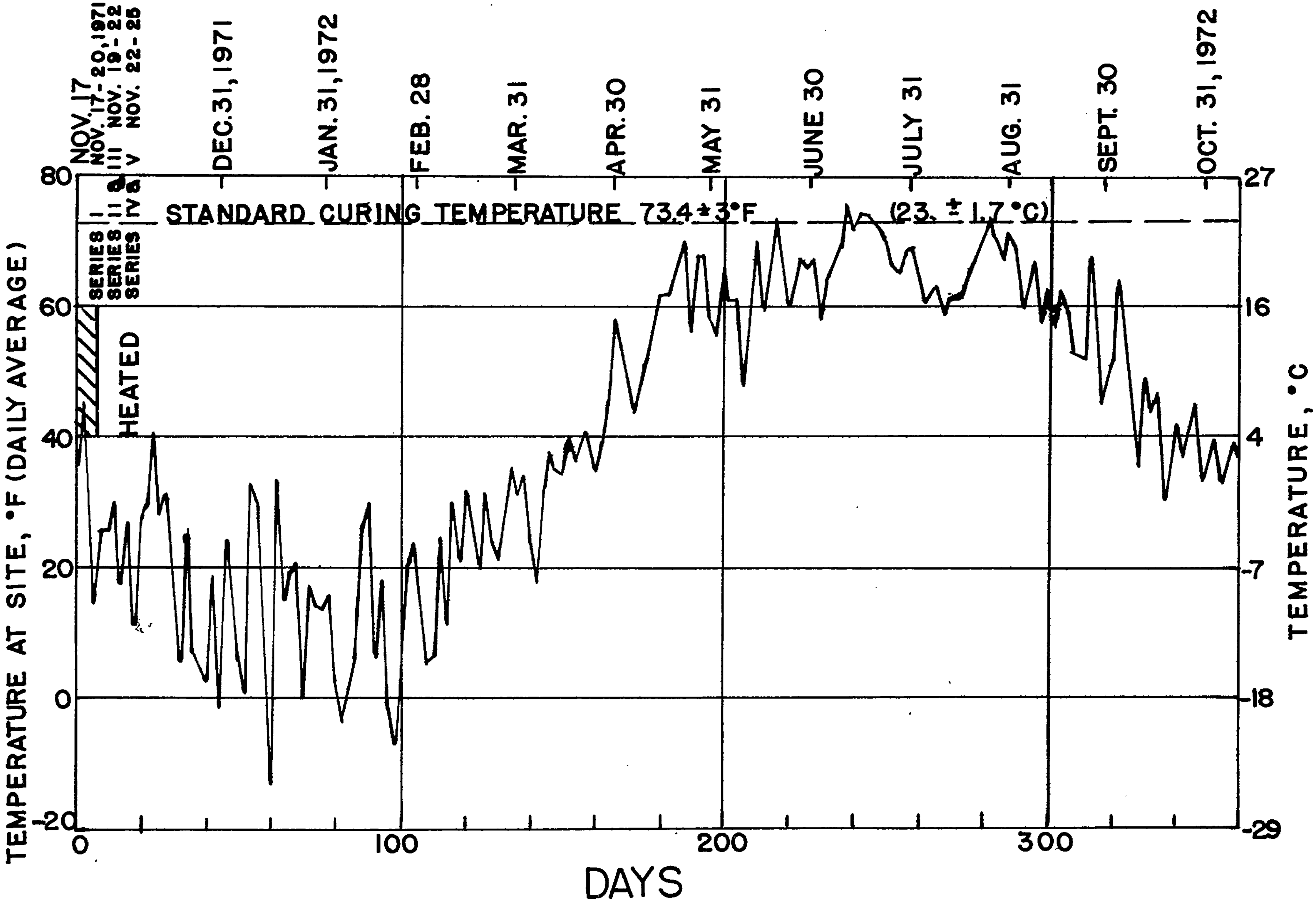

Fig. 2 - Average daily air temperature at Ottawa International Airport, Uplands, Ontario.

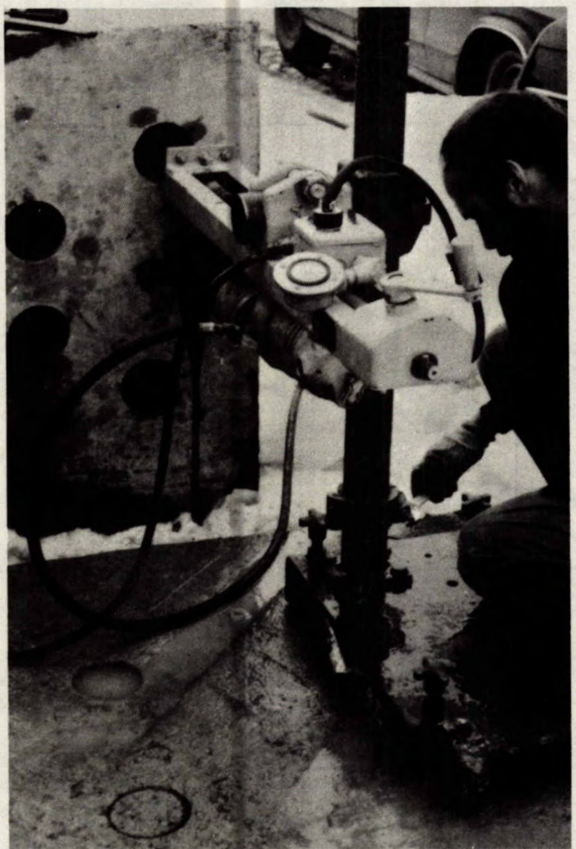

Fig. 3 - A view of the cores being drilled from columns.

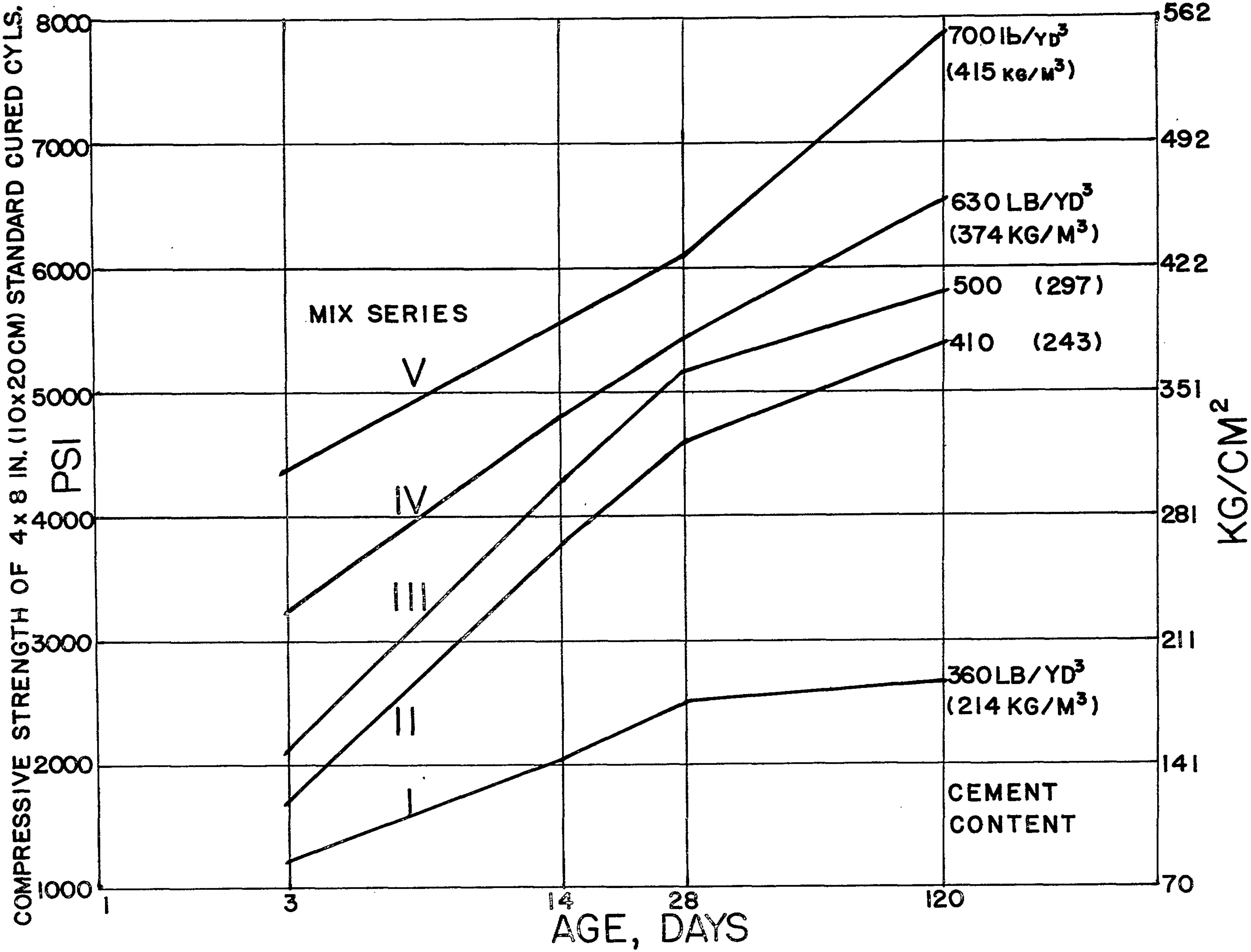

Fig. 4 - Relationship between age and compressive strength of standard-cured cylinders.

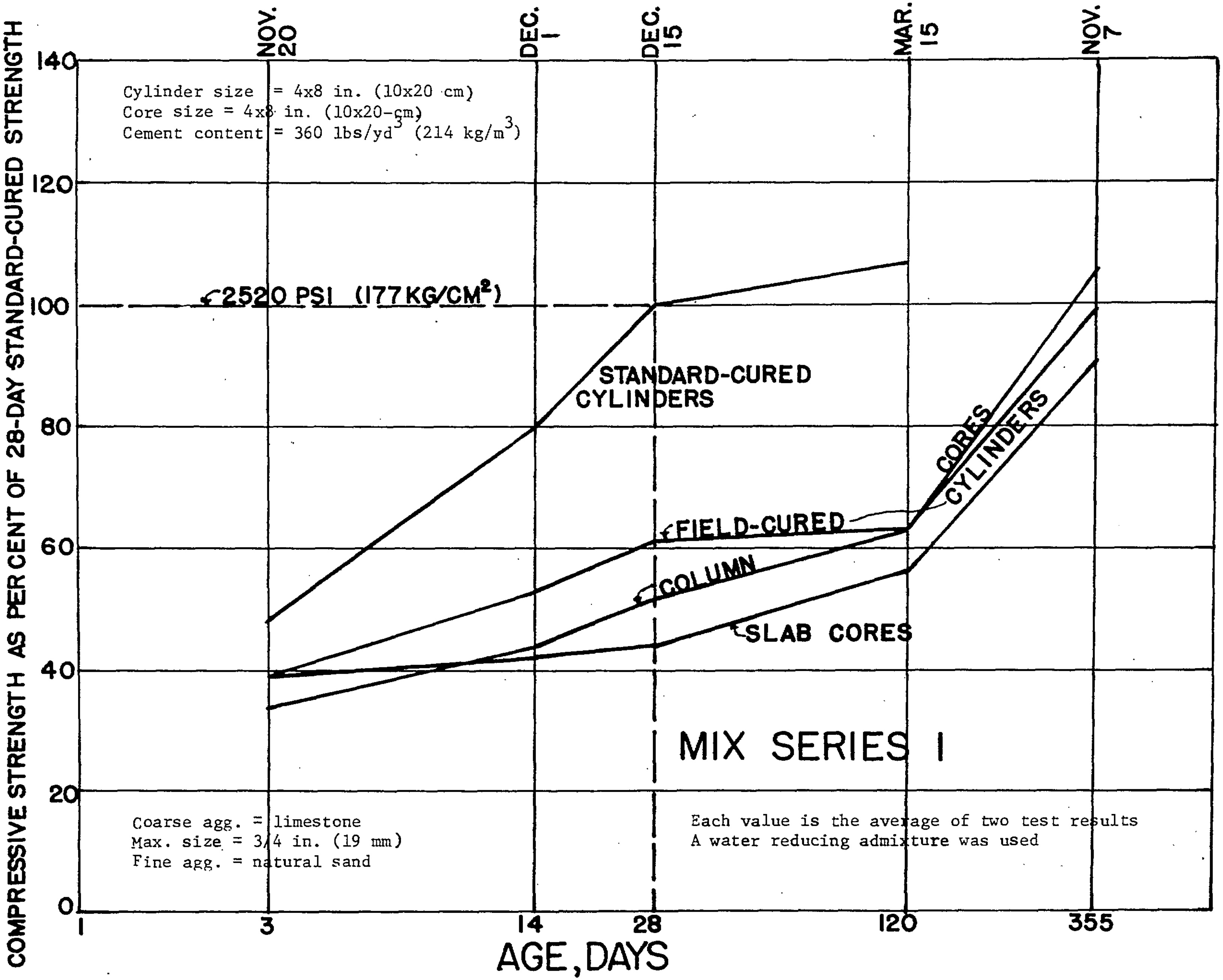

Fig 5 - Relationship between age and compressive strength of both laboratory- and field-cured test specimens - Mix Series 1.

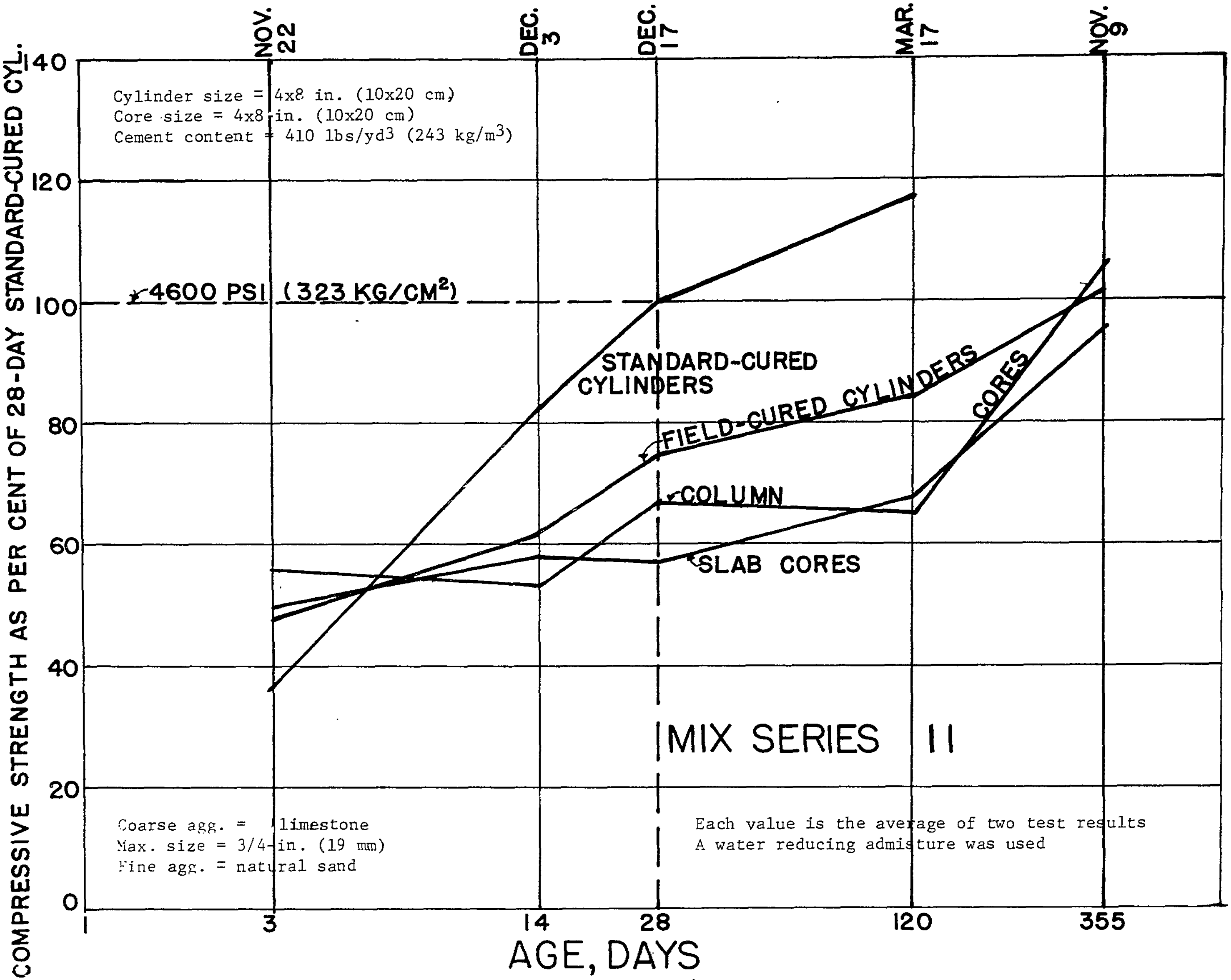

Fig. 6 - Relationship between age and compressive strength of both laboratory- and field-cured test specimens - Mix Series II

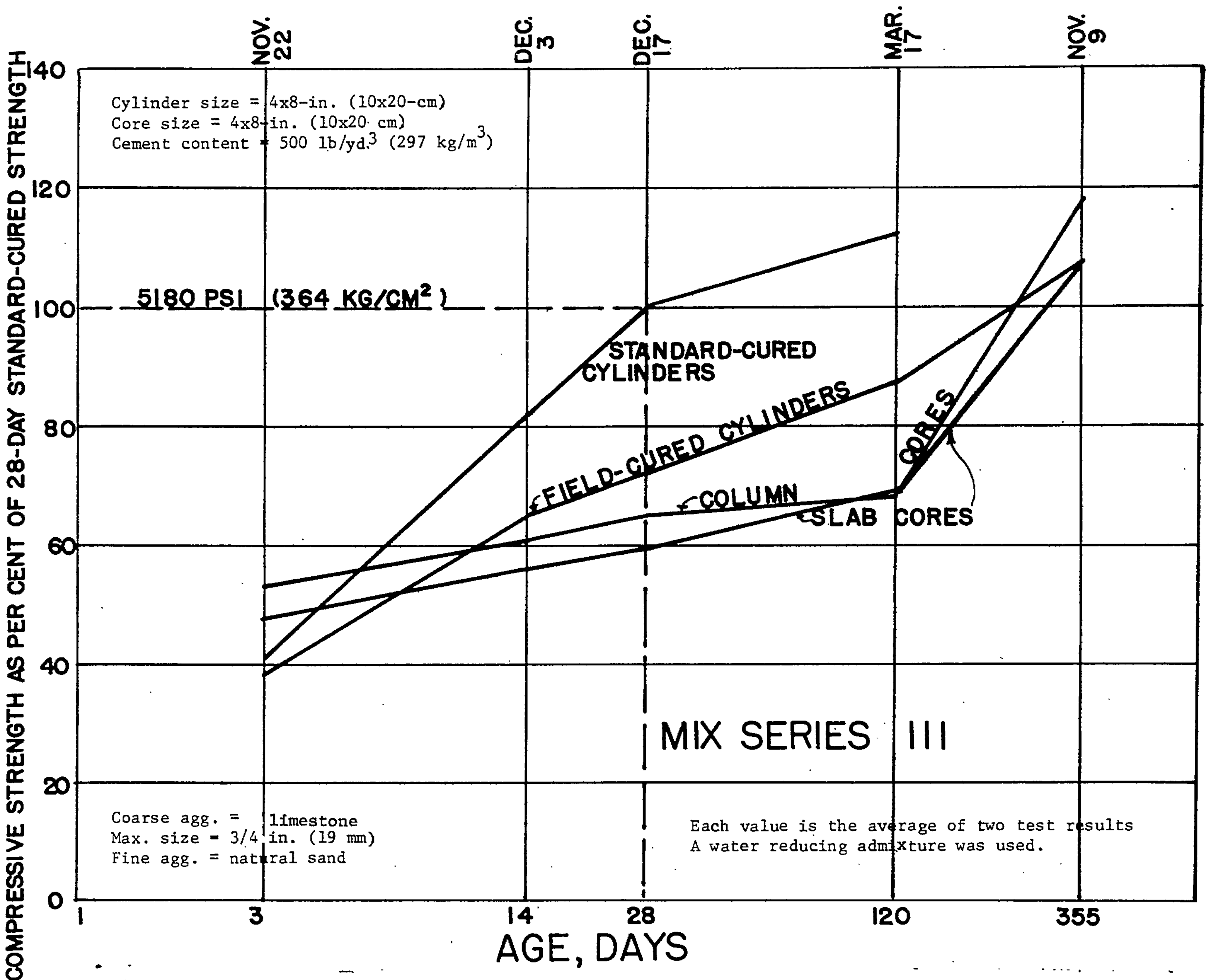

Fig. 7 – Relationship between age and compressive strength of both laboratory- and field-cured test specimens – Mix Series III

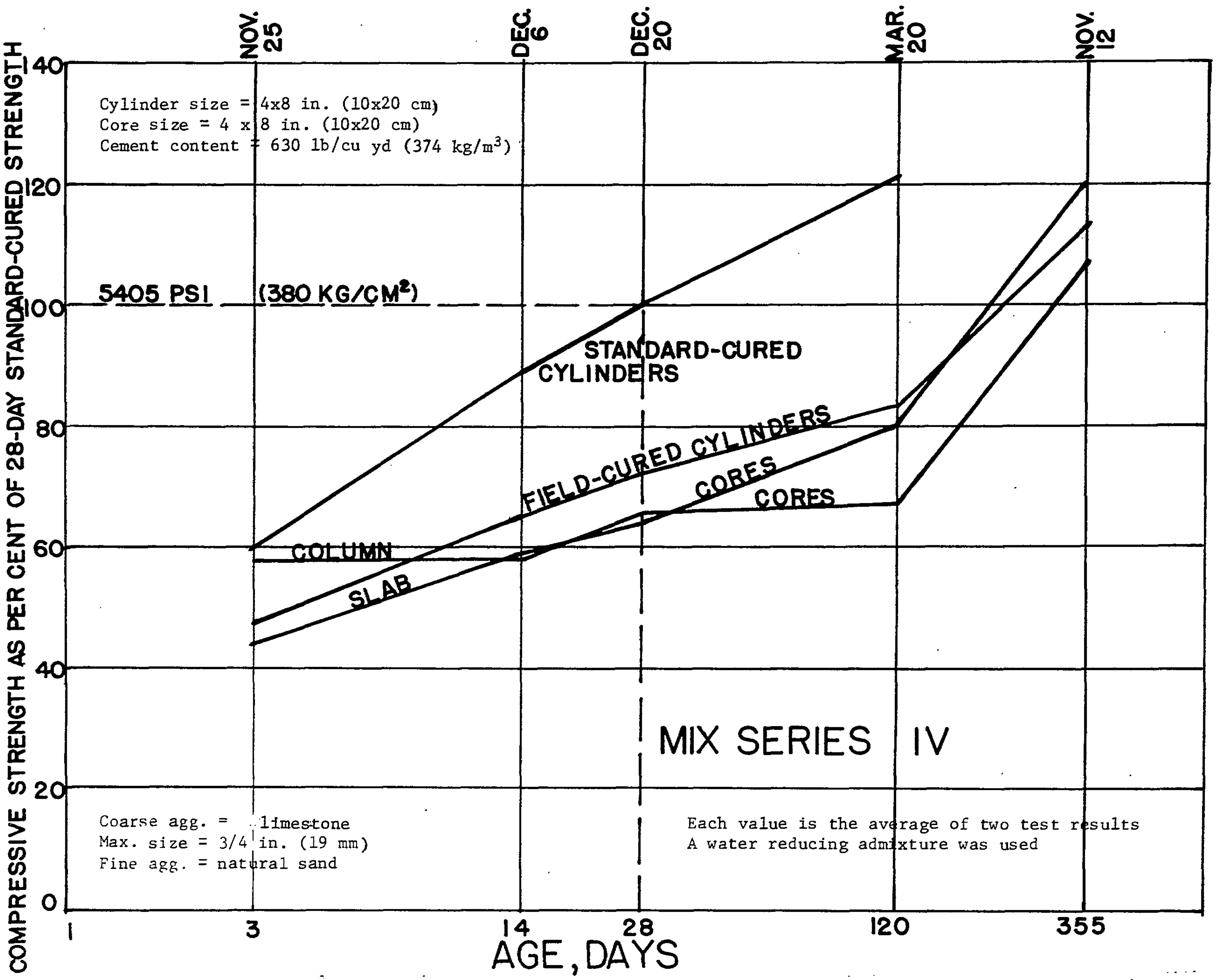

Fig. 8 - Relationship between age and compressive strength of both laboratory- and field-cured test specimens - Mix Series IV

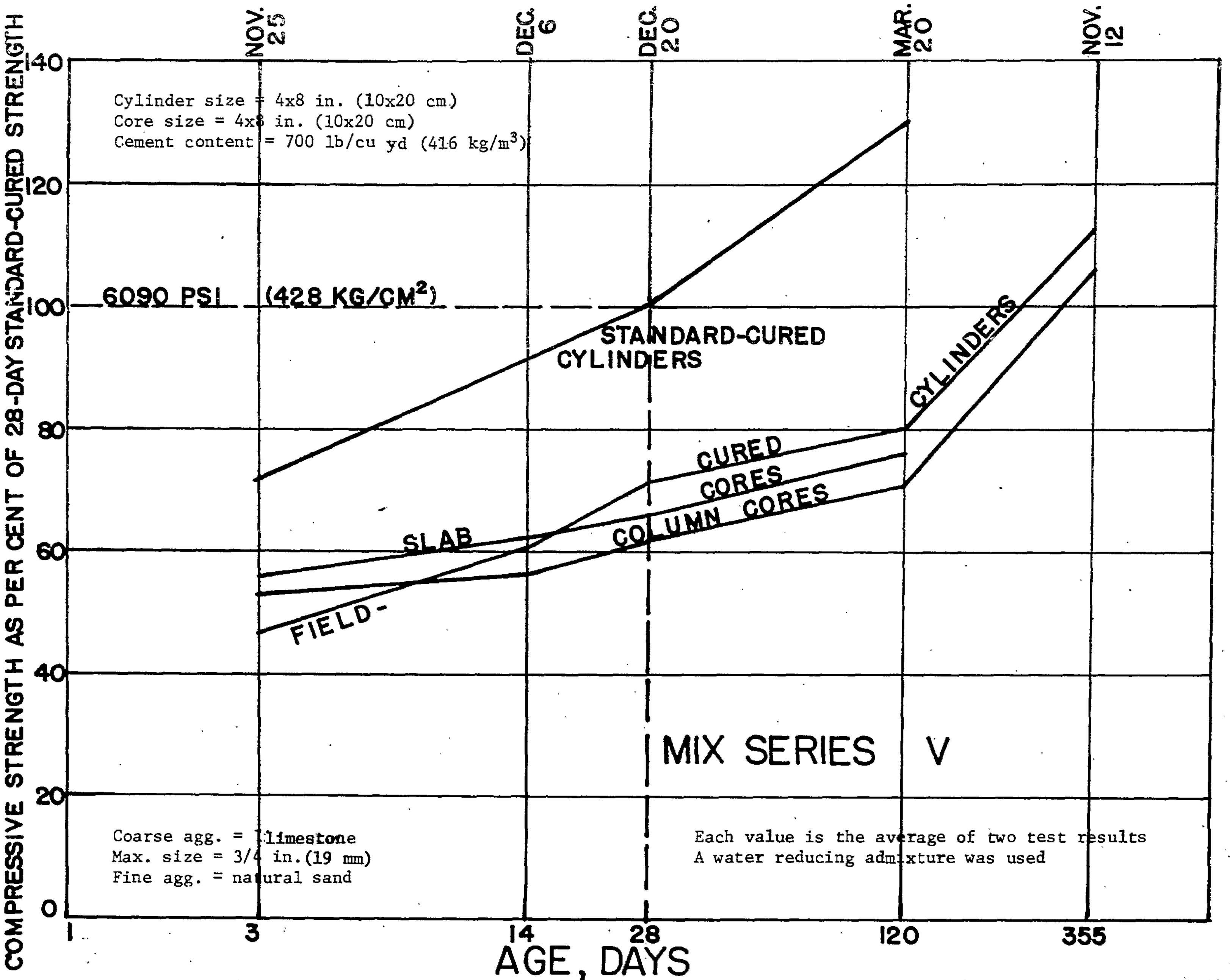

Fig. 9 - Relationship between age and compressive strength of both laboratory- and field-cured test specimens - Mix Series V