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EFFECT OF BELOW-FREEZING TEMPERATURES ON STRENGTH DEVELOPMENT OF CONCRETE

by

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MINERAL PROCESSING DIVISION

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SUMMARY OF RESULTS

Concrete specimens cured for three days at about 50°F (10°C) and at 80 per cent relative humidity and then immediately exposed to freezing temperatures continue to gain strength at sub-zero temperatures. The rate of gain in strength appears to be higher for columns and slabs than it is for field-cured cylinders.

Field-cured specimens rapidly gain strength after ambient temperature exceeds 50°F (10°C).

The difference in the strength of 4 x 8-in. (10 x 20-cm) and 6 x 12-in. (15 x 30-cm) cylinders increases with increase in the strength level of the concrete, the strength of larger cylinders being generally lower than that of smaller cylinders.

For the maturity concept to be applicable to large concrete sections cured in the field, allowance should be made for their size because of different temperature conditions inside large concrete sections.

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INTRODUCTION

During the winter months, in both Canada and the northern parts of the United States, concrete is often placed when the ambient air temperature is below freezing. Concrete placed under these conditions during the construction of buildings is usually cured for about three days using plastic enclosures, inside which the temperature is maintained sufficiently high to keep the floor slab above from freezing. Following this, the heated enclosures are removed and the concrete structure is allowed to cure exposed to winter temperature extremes. Few data are available regarding the strength development of concrete in exposed structures during the winter months, when the ambient air temperatures vary between $-20^{\circ}F$ and $32^{\circ}F$ (-29 to $0^{\circ}C$). The published data (1-5) indicate that measurements on laboratory-cured test cylinders neither accurately nor consistently indicate the strength development in concrete structures. The present study has been undertaken to investigate the relationship of the strength of standard laboratory-cured cylinders to the strength of concrete in structures cured under exposed winter conditions.

This investigation report is part of a co-operative research into the behaviour of concrete jointly undertaken 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

In this study, five concrete mixes were investigated. The nominal water/cement ratio varied from 0.75 to 0.42 and corresponding cement contents varied from 360 to 700 lb/cu yd (214 to 415 kg/m^3). From each mix, one 24 x 24 x 66-in. (0.61 x 0.61 x 1.68-meter) column*, one 24 x 24 x 8-in. (61 x 61 x 20-cm) slab, sixteen 6 x 12-in. (15 x 30-cm) cylinders and sixteen 4 x 8-in. (10 x 20-cm) cylinders were cast on an outdoor exposure platform. The columns, prisms, slabs, and half of the cylinders were left on the outdoor exposure platform after an initial 3-day curing at 50±10°F (10±6°C), achieved by the use of propane-gas heaters. The other cylinders were cured under standard conditions. The ambient temperature during the casting and initial heating of the specimens, December 10-24, 1970, varied from -15°F to 25°F (-26.2 to -4.0°C). Test cores were taken from the columns, prisms, and slabs after 7, 14, 28, and 91 days, and finally at about 7 months. The cores were tested in compression to determine the development of strength of the concrete. The companion field-cured and standard-cured test cylinders were also tested at the same ages to obtain comparative compressive strengths.

Eighty each of 6 x 12-in. (15 x 30-cm) cylinders, 4 x 8-in. (10 x 20-cm) cylinders, and 4 x 8-in. (10 x 20-cm) drilled cores were tested.

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* In Mix IV and V, one 24 x 24 x 66-in. (0.61 x 0.61 x 1.68-m) horizontal prism was cast instead of the column.

PREPARATION AND CURING OF TEST SPECIMENS

The investigation was started in early December 1970 and was terminated late in July 1971 after almost 8 months. For each test series, a 1.5-yd^3 (1.15-m^3) batch of concrete was ordered from a local ready-mix concrete supplier. The columns/prisms and slabs were cast on a specially built platform erected in an exposure plot situated at the University of Ottawa, Ottawa, Ontario (Figure 1). The large specimens were compacted by an internal vibrator.

For Mix Series I, II, and III, the 6 x 12-in. (15 x 30-cm) and 4 x 8-in. (10 x 20-cm) cylinders were also cast at this exposure site using procedures outlined in ASTM Standard C 31-69. Immediately after casting, the platform was enclosed by tarpaulins (Figure 1 b) and propane-gas heaters were ignited inside the enclosure to bring the ambient temperature to 50±10^{o}F (10±6^{o}C). This temperature was maintained for the next 3 days. The history of the ambient temperature for the exposed specimens is described in the next section of this report. For concrete Mix Series IV and V, sufficient concrete was taken from the field to the Civil Engineering Materials Behaviour Laboratory at the University of Ottawa, a short distance away, where the 6 x 12-in. (15 x 30-cm) and 4 x 8-in. (10 x 20-cm) cylinders were cast. This procedure was adopted to ensure that the small specimens would not be frozen in case of break-down of the propane-gas heaters.

All cylindrical specimens were compacted by hand rodding; the 6 x 12-in. (15 x 30-cm) cylinders were compacted in three equal layers and the 4 x 8-in. (10 x 20-cm) cylinders were compacted in two equal layers using standard methods. For any particular mix, it was ensured that the same operator carried out the hand rodding of the specimens.

For Mix Series I, II, and III, all test specimens were left in the heated enclosure for the first 24 hours, following which the eight 6 x 12-in. (15 x 30-cm) and eight 4 x 8-in. (10 x 20-cm) cylinders were removed to the moist-curing room for curing at 73.4±3°F (23±1.7°C) and 100 per cent relative humidity. For Mix Series IV and V, all the test specimens were covered with wet burlap immediately after casting and were left in the laboratory for the next 24 hours. Following this, eight 6 x 12-in. (15 x 30-cm) and eight 4 x 8-in. (10 x 20-cm) cylinders were removed to the moist-curing room for standard curing while the remaining eight 6 x 12-in. (15 x 30-cm) and eight 4 x 8-in. (10 x 20-cm) 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 a column (Mixes I, II, and III), a horizontal prism (Mixes IV and V), a slab, and eight of each of 6 x 12-in. (15 x 30-cm) and 4 x 8-in. (10 x 20-cm) cylinders.

A continuous record of the ambient air temperatures was made from December 21, 1970 to July 27, 1971.

A hygro-thermograph was placed in the standard Stephenson shelter shown in Figure 2, which was obtained from the Department of Transport, Meteorological Branch, Toronto, Ontario. The shelter was placed a short distance from the platform at the exposure station.

The calibration of the hygro-thermograph was checked for a few weeks, at the start of the tests, and periodically later on. The hygro-thermograph device consisted of a 7-day clock mechanism which rotated a drum on which a chart was fixed. The recording pen was activated by the flexing of a bimetallic arm.

The continuous record of temperatures from the field station was compared to the hourly dry-bulb temperatures recorded by the DOT Meteorological Office, International Airport, Uplands, Ottawa. The accuracy of the continuous record was confirmed by comparing the average daily temperatures computed for these two stations. The difference between these computed average daily temperatures was taken in order to determine any significant relationship. The field station is in the downtown area of Ottawa, and the airport is about ten miles south of it, just outside the city. The airport average temperatures were found to be consistently lower; its average computed value was 1.8^{o}F lower, and the average range of its variation was from -0.3^{o} to -3.8^{o}F. The average daily air temperatures at the exposure station given by the above analysis have been plotted in Figure 3; the heavy shaded rectangles at the top left indicate the temperature range and duration for each test series.

It was not possible to completely isolate the specimens of earlier castings during the heating stage of later series because space on the exposure platform was restricted. All specimens of Test Series I and II underwent the same heating as the specimens of Series III between 16 and 19 December, 1970. The column specimens for Series I, II, and III were exposed to the ambient temperatures while the remaining specimens of these series underwent the heating of Series IV and V between 21 and 24 December, 1970. With regard to humidity inside the heated enclosure, all test specimens were covered with burlap, kept moist for three days.

TESTING OF CONCRETE SPECIMENS

The laboratory- and field-cured cylinders were tested in pairs at 7*, 14, 28, 91, and 218 days. At each of these ages, two 4 x 8-in. (10 x 20-cm) cores were drilled from each column, prism, and slab. The four cores for each series were transported to the Mines Branch laboratory for testing. During the winter months, i.e., for ages of 7, 14, 28, and 91 days, the drilled cores and field-cured cylinders were allowed to thaw in the laboratory air for about 6 hours. It was estimated from the limited laboratory studies available that this would allow the inside of the specimens to reach a minimum temperature of about 60^{o}F (15.5^{o}C). The ends of the cores were sawn to get a reasonably smooth surface. All cores and cylinders were capped with a sulphur-flint mixture, and the compression testing was done on an Amsler testing machine of 600,000-lb (271,800-kg) capacity. It should be emphasized that all cores were tested dry in order to simulate the condition of the concrete in exposed structures. The size of the cores was 4 x 8 in. (10 x 20 cm) giving a $\frac{\text{length}}{\text{diameter}}$ ratio of 2, and no correction factors were needed for core strengths[6].

At the ages of 91 and 218 days, the densities of the standard-cured cylinders and of the cores drilled from slabs and columns/prisms were determined.

A view of the drilling operation is shown in Figure 4. A summary of the test results is given in Tables 3 to 5.

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*For Mix Series I and II, testing was done starting at 7 days instead of at 14 days; for the Mix Series III, IV, and V, the testing was started at 14 days.

PRESENTATION OF TEST RESULTS

The typical relationships between age and compressive strength for 4 x 8-in. (10 x 20-cm) standard-cured cylinders are shown in Figure 5. The relationships between age and compressive strength as a percentage of the 28-day strength of 4 x 8-in. (10 x 20-cm) standard-cured cylinders are shown in Figures 6 to 10. In order to avoid size effects in the analysis, the 4 x 8-in. (10 x 20-cm) cylinder was selected for comparison with the drilled cores. However, to facilitate comparison of the strengths of 6 x 12-in. (15 x 30-cm) standard-cured and/or field-cured cylinders and the drilled cores, Figure 11 has been prepared to relate the strengths of the two sizes of cylinders.

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 6, 7, and 8.

STRENGTH DEVELOPMENT WITH AGE

Figures 6 to 10 relate the compressive strengths of concrete in the standard-cured cylinders, in columns or prisms, and in slabs. It should be pointed out that, in the Ottawa area, the annual freeze-thaw cycles number about 80. These freeze-thaw phenomena are not expected to affect the performance of the field-cured concrete because all the concrete was air-entrained. The relative humidity during winter months in the Ottawa area generally varies from 30 to 80 per cent, whereas in April, May and June the relative humidity varies between 50 and 60 per cent.

Mix Series I

Figure 6 shows the strength gain with age for concrete having a compressive strength of 4025 psi (283 kg/cm^2) at 28 days, as measured on 4 x 8-in. (10 x 20-cm) cylinders. The standard-cured cylinders show continuous gain in strength up to 218 days and reach a value of 155.0 per cent of the standard strength*. There is no evidence of a levelling-off of the strength at 218 days, which is unusual. The field-cured cylinders show some gain in strength, between 7 and 28 days, reaching to a value of 34.9 per cent of the standard strength. After 28 days, there is a rapid gain in strength and this continues up to 218 days, though at a slower rate after 91 days, to reach a maximum of 105.5 per cent of the standard strength at 218 days. The cores from the slab and columns show rapid gains in strength up to 28 days, reaching 78.5 and 91.5 per cent of the standard strength, respectively. It should be noted that the cores from the slabs had 7-day strengths of only 28.4 per cent of the standard strength. Both slab and column cores continue to gain strength after 28 days and the rate of strength gain accelerates after 91 days. At 218 days, the cores just surpass the strengths reached by standard-cured cylinders at that age; the highest strength, 162.5 per cent of the standard strength, was obtained for the cores from the columns. The increased rate of strength gain between 91 and 218 days is due to higher ambient temperatures during this period.

Mix Series II

For the low-strength concrete (Figure 7), the standard-cured cylinders show continuous strength gain up to 91 days after which the compressive strength levels off. The test specimens appear to have received their ultimate strength of 136.2 per cent of the standard strength at 218 days. The field-cured cylinders

*Hereafter the 28-day compressive strength of 4 x 8-in. (10 x 20-cm) standard-cured cylinders will be referred to as the standard strength.

and the cores from both columns and slabs show rapid gain in strength up to 28 days, although lagging behind the standard-cured cylinders. Between 28 and 91 days, the strength gain for these specimens continues less rapidly. After 91 days, during which there is a change in curing conditions due to changed environmental temperatures, the cores from both slabs and columns show accelerated strength gain. The cores from the columns surpass the strength of standard-cured cylinders but those from the slabs barely reach the standard strength. A column strength, 188.7 per cent of the standard strength at 218 days, appears too high. The field-cured cylinders also show somewhat accelerated rate of strength gain but, at 218 days, reach a value of only 97.5 per cent of the standard strength.

Mix Series III

The strength-age relationship for Mix Series III [compressive strength of 4430 psi (310 kg/cm^2) at 28 days] is shown in Figure 8. The standard-cured cylinders show a steady gain in strength up to 218 days after which the gain tapers off; 126.0 per cent of the standard strength is reached at this age. The field-cured cylinders gain strength at a slower rate between 14 and 28 days but the strength gain accelerates after 28 days and shows steady increase up to 218 days to reach 103.1 per cent of the standard strength. The slab and column cores show very slow gain in strength between 14 and 28 days but, like the field-cured cylinders, the strength gain accelerates after 28 days and continues until 218 days. Compressive strength values of 114 and 105 per cent of the standard strength are reached at 218 days by the cores drilled from slabs and columns, respectively. There appears to be no change in rate of gain-in-strength after 91 days as is the case with Mix Series I and II. This is unexplained.

Mix Series IV

Figure 9 shows the age-strength relations for Mix Series IV with 28-day compressive strength of 5045 psi (355 kg/cm^2). The standard-cured cylinders show steady increase in strength to 120.5 per cent of the standard strength at 217 days. The field-cured cylinders show almost no gain in strength between the ages of 14 and 28 days. This is followed by a rapid gain in strength and 95.2 per cent of the standard strength is reached at 91 days. The two 4 x 8-in. (10 x 20-cm) cylinders for testing at 217 days were lost at the outdoor exposure plot, hence no strength values are available for this age.

The cores drilled from the slabs and prisms show steady gain in strength to 95.5 and 88.0 per cent of the standard strength, respectively, up to 91 days. After 91 days, the cores drilled from prisms show accelerated gain in strength to 115 per cent of the standard strength at 217 days. However, the cores from the slabs gain less rapidly in strength reaching 101 per cent of the standard strength at 217 days.

Mix Series V

Figure 10 shows the development of strength with age for Mix Series V with 28-day compressive strength of 6215 psi (437 kg/cm^2). As expected, the standard-cured cylinders show continuous gain to 108 per cent of the standard strength at 217 days. The field-cured cylinders show a rapid gain in strength between 28 and 91 days and almost reach the standard strength at 91 days. However, after this, there is a slight drop in strength but 94.5 per cent of the standard strength is reached at 217 days; the drop in strength is unusual. The cores drilled from both slab and prisms show modest gain in strength up to 91 days. After this, the rate of gain in strength accelerates. The cores drilled from the prisms reach 111.1 per cent of the standard strength at 217 days. This is a few points higher than reached by the standard-cured cylinders.

The cores drilled from slabs follow the cores from the prism reaching a value of 107.0 per cent of the standard strength at 217 days. In fact, it could be stated that in this series the strengths of the cores at 217 days are of the same order as those reached by the standard-cured cylinders.

DENSITIES OF TEST CYLINDERS AND CORES

The 28- and 91-day densities of 4 x 8-in. standard-cured cylinders and drilled cores from columns and slabs are given in Table 5. The densities of the cylinders vary from 137.33 to 151.03 lb/ft^3 (2200 to 2420 kg/m^3), but those of cores vary from 134.22 to 150.04 lb/ft^3 (2150 to 2404 kg/m^3); the cylinders had been compacted by hand-rodding, whereas the slabs and columns had been compacted by an internal vibrator. There appear to be no significant differences between the densities of cores drilled from columns and those drilled from slabs.

REPRODUCIBILITY OF TEST RESULTS

The within-batch standard deviation and coefficient of variation of the test results at 28, 91, and 218 days are shown in Tables 6, 7, and 8. The analyses indicate that at 28 days the field-cured cylinders have the poorest reproducibility with an average C.V. value of 10.7 per cent; the corresponding value for the standard-cured cylinders is 5.5 per cent. The C.V. values for the compressive strength of drilled cores from slabs and columns are 6.9 and 4.8 per cent respectively.

At 91 days, the within-batch C.V. for compressive strengths of field-cured cylinders shows marked decreases whereas those for the standard-cured cylinders and the drilled cores are of the same order as at 28 days. No positive conclusions can be drawn for the within-batch variation for 218-day test results because too few results are available.

STRENGTH DEVELOPMENT AND MATURITY CONCEPT

The combined effect of time and temperature is generally referred to as maturity (7). Often, this concept has been correlated with compressive strength, particularly if the curing history of the specimen changes or if the strengths of concrete specimens, cured under two different curing regimes, are being compared. An attempt was made to see if this concept could explain the strength gain of the concrete under investigation. It is seen from the data in Table 3 that at all ages, the strength of field-cured cylinders is considerably lower than the strength of cores drilled from the large specimens. Specifically, at 218 days, the difference in strength varies from a low of 475 psi (33 kg/cm^2) for Mix Series V to a high of 2250 psi (158 kg/cm^2) for Mix Series III. Again, the cores drilled from slabs have generally lower strengths than those from the prisms or columns, though the strength difference is much less marked. This illustrates that, for the maturity concept to be applicable to large concrete sections cured in the field, allowance must be made for their size because of different temperature conditions inside the large concrete section. Furthermore, maturity calculations indicate that at low temperatures the maturity rule considerably underestimates the potential strength of concrete. Unfortunately, because of poor working conditions at the exposure station, it was not possible to install thermocouples inside the large test specimens.

RELATIONSHIP BETWEEN THE COMPRESSIVE STRENGTHS OF DIFFERENT-SIZED SPECIMENS

The relationships shown in Figures 6 to 10 are for cylinders and drilled cores having a diameter of 4 in. (10 cm) and length/diameter ratio of 2. The above size was selected in order to have direct comparison between the compressive strength of the drilled cores and the standard- and field-cured cylinders. However, 6 x 12-in. (15 x 30-cm) cylinders were also cast and tested for both standard- and field-curing conditions. Figure 11 shows this relationship between the 28-day compressive strength of the different-sized cylinders. There is an indication that the difference in the strength of cylinders, 4 and 6 in. (10 and 15 cm) in diameter, increases with increase in the strength level of the concrete, the strength of 6-in. (15-cm) cylinders being generally lower than the 4-in. (10-cm) cylinders.

CONCLUDING REMARKS

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 gain in compressive strength is considerably more rapid by column and slab concrete than by field-cured concrete cylinders.

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)

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* Estimated value only. All specimens were covered with wet burlap kept moist for the duration of three days.

Concrete cured below freezing has a reserve potential strength which is realized when the ambient air temperature and humidity conditions approach the conditions for standard moist-curing.

At the age of 7 months, the compressive strengths of the cores drilled from columns and slabs approach or exceed the compressive strengths of test cylinders cured under standard moist conditions.

At temperatures below 30°F (-1°C), the concept of maturity cannot be applied to estimate the compressive strength of concrete because the maturity rule considerably underestimates the potential strength of concrete and, for the same maturity, different-sized specimens have different strengths.

RECOMMENDATIONS

It is recommended that additional field data be obtained to confirm the findings of this report. Further, it is suggested that this project be extended to determine the compressive strength of field-cured test specimens at below-freezing temperatures after initial curing of 1, 2, 3, 4, 5, and 6 days at 55°F (12.8°C) and at 70 to 100 per cent relative humidity.

VMM/am

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TABLE 1

Physical Properties and Chemical Analyses of Cement*

Description of Test	
Time of Set (Vicat needle): Initial	3 hr 55 min
Final	- -
Specific Surface (Blaine)	3245 cm^2/g
Soundness - Autoclave	0.12
Physical Tests - Mortar Strength	
Compressive Strength of 2-in. (5-cm) cubes	
3-day	2810 psi(197 kg/cm^2)
7-day	3900 psi(274 kg/cm^2)
28-day	5190 psi(365 kg/cm^2)
Chemical Analysis	
Insoluble Residue	0.22 per cent
Tricalcium Silicate (C_3S)	51.1 per cent
Tricalcium Aluminate (C_3A)	9.9 per cent
Magnesium Oxide (MgO)	3.50 per cent
Sulphur Trioxide (SO_3)	2.61 per cent
Loss on Ignition	0.65 per cent

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

TABLE 2

Mix Design Data and Properties of Fresh Concrete

Mix No.	Mix Design Data*: Nominal Water/Cement Ratio by Weight	Mix Design Data*: Cement Content, lb/yd³	Mix Design Data*: Cement Content, kg/m³	Mix Design Data*: Aggregate/Cement Ratio by Weight	Properties of Fresh Concrete: Temperature, °F	Temperature, °C	Slump, in.	Slump, cm	Unit Weight, lb/ft³	Unit Weight, kg/m³	Air Content, Per Cent
1	0.67	410	243	8.25	64	18	2.0	5.1	148.4	2377	3.8
2	0.77	360	214	9.46	50	10	2.5	6.4	141.6	2268	3.6
3	0.56	500	297	6.76	62	17	**	**	133.2	2134	9.5
4	0.46	630	374	5.06	52	11	5.0	12.7	140.4	2249	7.0
5	0.42	700	415	4.39	64	18	3.5	8.9	145.6	2333	5.0

* Supplied by the ready-mixed company which delivered the concrete.
** Slump exceeded 6 in. (15 cm).

TABLE 3

Compressive Strength of Standard- and Field-Cured Cylinders, and Cores Drilled from Slabs, Prisms, and Columns

Mix No.	Compressive Strength at Various Ages of 4 x 8 in. (10 x 20-cm) Cylinders or Cores, psi (kg/cm²)																			
	7-day				14-day				28-day				91-day				218-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	Prism Cores	Standard Cured	Field Cured	Slab Cores	Prism Cores
1	3405 (186)	1105 (78)	1140 (80)	2695 (189)	-	-	-	-	4025 (283)	1415 (99)	3155 (222)	3670 (258)	5370 (378)	3425 (241)	4960 (349)	5050 (355)	6220* (437)	4260 (300)	6470* (455)	6510 (458)
2	1680 (118)	710 (50)	465 (33)	1330 (94)	-	-	-	-	1895 (133)	1460 (103)	1280 (90)	1605 (113)	2440 (172)	1640 (115)	1450 (102)	1760 (124)	2580++ (181)	1850* (130)	2430 (171)	3540 (249)
3	-	-	-	-	3735 (263)	1395 (98)	2760 (194)	2110 (148)	4430 (311)	1770 (124)	2850 (200)	2140 (150)	5310 (373)	3495 (246)	3935 (277)	3585 (252)	5580 (392)	4565 (321)	5040 (354)	4645 (327)
4	-	-	-	-	4520 (318)	3015 (212)	3440 (242)	3810 (268)	5045 (355)	2990 (210)	3965 (279)	4095 (288)	***	4780 (336)	4805 (338)	4425 (311)	6055 (426)	**	5099 (358)	5800 (408)
5	-	-	-	-	5540 (390	4095	3640 (256)	4250 (299)	6215 (437)	3420 (240)	4325 (304)	4620 (325)	***	6180 (435)	5040 (354)	5685 (400)	6710 (472)	5890 (414)	6150 (432)	6850 (482)

* Only one cylinder available for testing.
** Test cylinders were lost.
*** Test results not available.
\+ For Mix Series 4 and 5, age at testing was 217 days.
++ Strength estimated from 6 x 12-in (15 x 30-cm) cylinders which had strength of 2545 psi.

TABLE 4

Compressive Strength of Standard- and Field-Cured Test Cylinders of Different Sizes

Mix No.	Curing Condition	7-day		14-day		28-day		91-day		218-day*	
		6x12-in. (15x30-cm)	4x8-in. (10x20-cm)	6x12-in. (15x30-cm)	4x8-in. (10x20-cm)	6x12-in. (15x30-cm)	4x8-in. (10x20-cm)	6x12-in. (15x30-cm)	4x8-in. (10x20-cm)	6x12-in. (15x30-cm)	4x8-in. (10x20-cm)
1	Standard	3920 (276)	3405**	-	-	4660 (328)	4025 (283)	5300 (373)	5370 (378)	5550 (390)	6220** (437)
	Field	1570 (110)	1105 (78)	-	-	2000 (141)	+	+	3425** (241)	+	4260 (299)
2	Standard	1905 (134)	1680 (118)	-	-	2265 (159)	1895 (133)	2550 (179)	2440 (172)	2545 (179)	+
	Field	475 (34)	710 (50)	-	-	1140 (80)	1460 (103)	1010 (71)	1640 (115)	2475 (174)	+
3	Standard	-	-	3655 (257)	3735 (263)	4110 (289)	4430 (311)	4320 (304)	5310 (373)	4880 (343)	5580 (392)
	Field	-	-	1225 (86)	1395 (98)	1565 (110)	1770 (124)	2780 (195)	3495 (246)	4305 (303)	4565 (321)
4	Standard	-	-	3995 (281)	4520 (318)	4100 (288)	5045 (355)	5130 (361)	+	5200 (366)	6055 (426)
	Field	-	-	2740 (193)	3015 (212)	2355 (166)	2990 (210)	4150 (292)	4780 (336)	5625 (395)	+
5	Standard	-	-	4965 (349)	5540* (389)	5565 (391)	6215 (437)	6350 (446)	+	7000 (492)	6710 (472)
	Field	-	-	3855 (271)	4095** (288)	3330 (234)	3420 (240)	5200 (366)	6180 (435)	6820 (479)	5890** (414)

* For Mix Series 4 and 5, age at testing was 217 days.
** Only one cylinder available for testing.
\+ Test results not available.

TABLE 5

Densities of Concrete Cylinders and Cores

Mix No.	Density of Cylinders and Cores											
	28-day						91-day					
	Standard-cured Cylinders 4x8-in. (10x20-cm)		Drilled Cores 4x8-in. (10x20-cm)				Standard-cured Cylinders 4x8-in. (10x20-cm)		Drilled Cores 4x8-in. (10x20-cm)			
			slab		column				slab		column*	
	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
1	150.94	2418	147.79	2368	149.79	2400	147.78	2367	148.67	2382	150.04	2404
2	137.33	2200	136.54	2187	135.44	2170	138.37	2217	137.06	2196	134.22	2150
3	150.81	2416	147.61	2365	148.23	2375	151.03	2420	149.23	2391	149.12	2389
4	141.54	2268	139.54	2235	139.57	2236	141.29	2264	140.75	2255	139.04	2227
5	147.01	2355	143.89	2305	142.76	2287	147.47	2363	143.64	2301	143.52	2299

* For Mix Series 4 and 5, the values refer to cores taken from prisms.

TABLE 6

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

Mix No.	Standard-Cured Cylinders 4x8-in. (10x20-cm)				Field-Cured Cylinders 4x8-in. (10x20-cm)				Slab Cores 4x8-in. (10x20-cm)				Column Cores* 4x8-in. (10x20-cm)			
	Average+ Strength, psi (kg/cm^2)	S.D., psi	S.D., kg/cm^2	C.V., %	Average+ Strength, psi (kg/cm^2)	S.D., psi	S.D., kg/cm^2	C.V., %	Average+ Strength, psi (kg/cm^2)	S.D., psi	S.D., kg/cm^2	C.V., %	Average+ Strength, psi	S.D., psi	S.D., kg/cm^2	C.V., %
1.	4025 (283)	672	47.2	16.7	1415 (100)	421	29.6	29.7	3155 (222)	21	1.5	0.7	3670 (258)	187	13.1	5.1
2.	1895 (133)	21	1.5	1.1	1460 (103)	240	16.9	16.5	1280 (90)	272	19.1	21.3	1605 (113)	134	9.4	8.4
3.	4430 (311)	195	13.7	4.4	1770 (124)	28	2.0	1.6	2850 (200)	127	8.9	4.5	2140 (150)	110	7.7	5.1
4.	5045 (355)	573	40.3	11.4	2990 (210)	71	5.0	2.4	3965 (288)	233	16.4	5.9	4095 (288)	159	11.2	3.9
5.	6215 (437)	233	16.4	3.8	3420 (240)	113	7.9	3.3	4325 (304)	99	7.0	2.3	4620 (325)	64	4.5	1.4
				Avg = 5.5				Avg = 10.7				Avg = 6.9				Avg. = 4.8

+ Each value is the average of tests on two specimens unless otherwise stated.
* For Mix Series 4 and 5, the values refer to cores taken from prisms.

TABLE 7

Within-Batch Standard Deviation and Coefficient of Variation of 91-Day Test Results

Mix No.	Standard-Cured Cylinders 4x8-in. (10x20-cm)				Field-Cured Cylinders 4x8-in. (10x20-cm)				Slab Cores 4x8-in. (10x20-cm)				Column Cores** 4x8-in. (10x20-cm)			
	Average+ Strength, psi (kg/cm²)	S.D., psi	S.D., kg/cm²	C.V., %	Average+ Strength, psi (kg/cm²)	S.D., psi	S.D., kg/cm²	C.V., %	Average+ Strength, psi (kg/cm²)	S.D., psi	S.D., kg/cm²	C.V., %	Average+ Strength, psi (kg/cm²)	S.D., psi	S.D., kg/cm²	C.V., %
1.	5370 (378)	212	14.9	4.0	3425* (241)	-	-	-	4960 (349)	382	26.9	7.7	5050 (355)	28	2.0	0.6
2.	2440 (172)	127	8.9	5.2	1640 (115)	14	1.0	0.9	1450 (102)	127	8.9	8.8	1760 (124)	371	26.1	21.1
3.	5310 (373)	57	4.0	1.1	3495 (246)	7	0.5	0.2	3935 (277)	106	7.5	2.7	3585 (252)	92	6.5	2.6
4	-	-	-	-	4780 (336)	50	3.5	1.0	4805 (338)	163	11.5	3.4	4425 (311)	177	12.4	4.0
5	-	-	-	-	6180 (435)	159	11.2	2.6	5040 (354)	378	26.6	7.5	5685 (400)	35	2.5	0.6

+ Each value is the average of tests on two specimens unless otherwise stated.
* One cylinder available for testing.
** For Mix Series 4 and 5, the values refer to cores taken from prisms.

TABLE 8

Within-Batch Standard Deviation and Coefficient of Variation of218-Day Test Results

Mix No.	Standard-Cured Cylinders 4x8-in. (10x20-cm)				Field-Cured Cylinders 4x8-in. (10x20-cm)				Slab Cores 4x8-in. (10x20-cm)				Column Cores*** 4x8-in. (10x20-cm)			
	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 (kg/cm²)	S.D.,		C.V.,
		psi	kg/cm²	%		psi	kg/cm²	%		psi	kg/cm²	%		psi	kg/cm²	%
1	6220* (437)	-	-	-	4260 (300)	-	-	-	6470* (455)	-	-	-	6510 (458)	304	21.4	4.7
2	2580++ (181)	-	-	-	1850* (130)	-	-	-	2430 (171)	305	21.4	4.1	3540	-	-	-
3	5580 (392)	113	7.9	2.0	4565 (321)	361	25.4	7.9	5040 (354)	644	45.3	12.8	4645 (327)	106	7.5	2.3
4	6055 (426)	658	46.3	10.9	- **	-	-	-	5099 (359)	163	11.5	3.2	5800 (408)	283	19.9	4.9
5	6710 (472)	262	18.4	3.9	5890* (414)	-	-	-	6150 (432)	-	-	-	6850 (482)	354	24.9	5.2

* Only cylinder available for testing.
** Test cylinders were lost.
\+ Each value is the average of tests on two specimens, unless otherwise stated.
++ Strength estimated from 6x12-in. (15x30-cm) cylinders
*** For Mix Series 4 and 5, the values refer to cores taken from prisms.

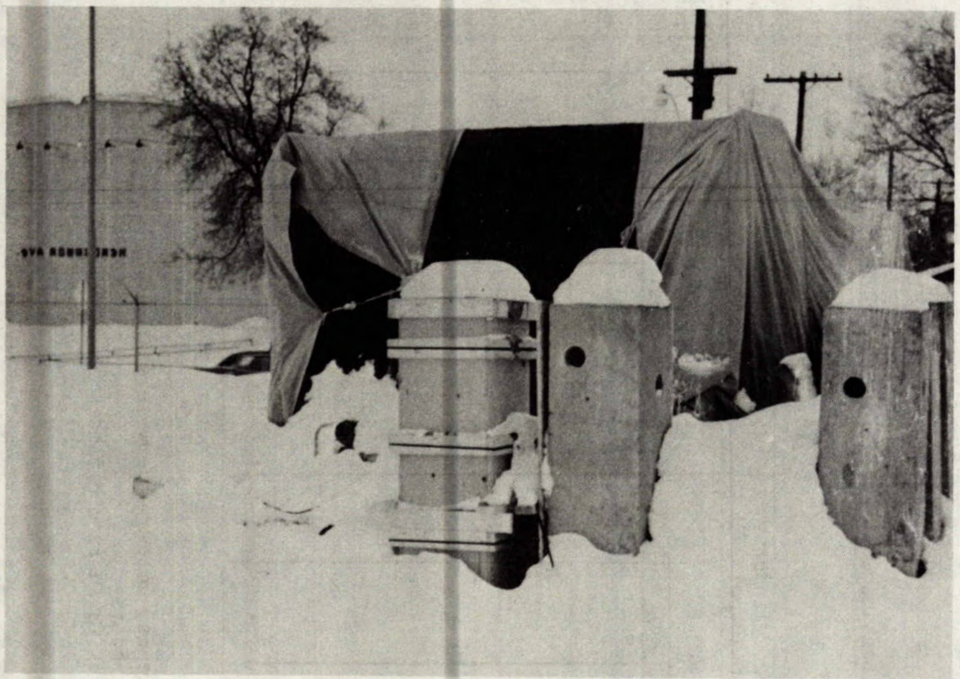

Figure 1. A view of the outdoor exposure station.

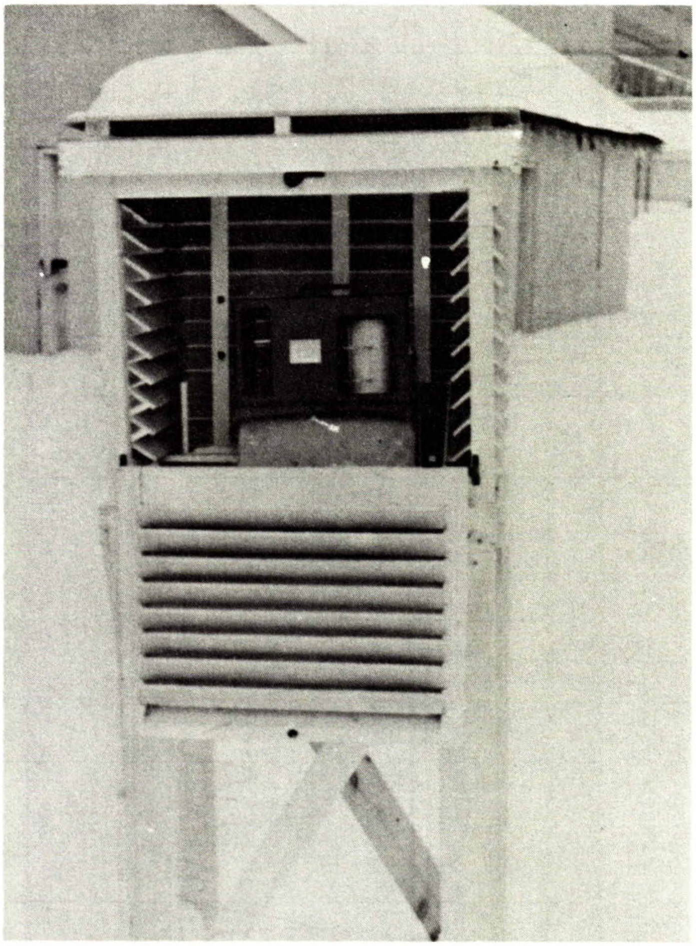

Figure 2. Hydro-thermal graph at the exposure station.

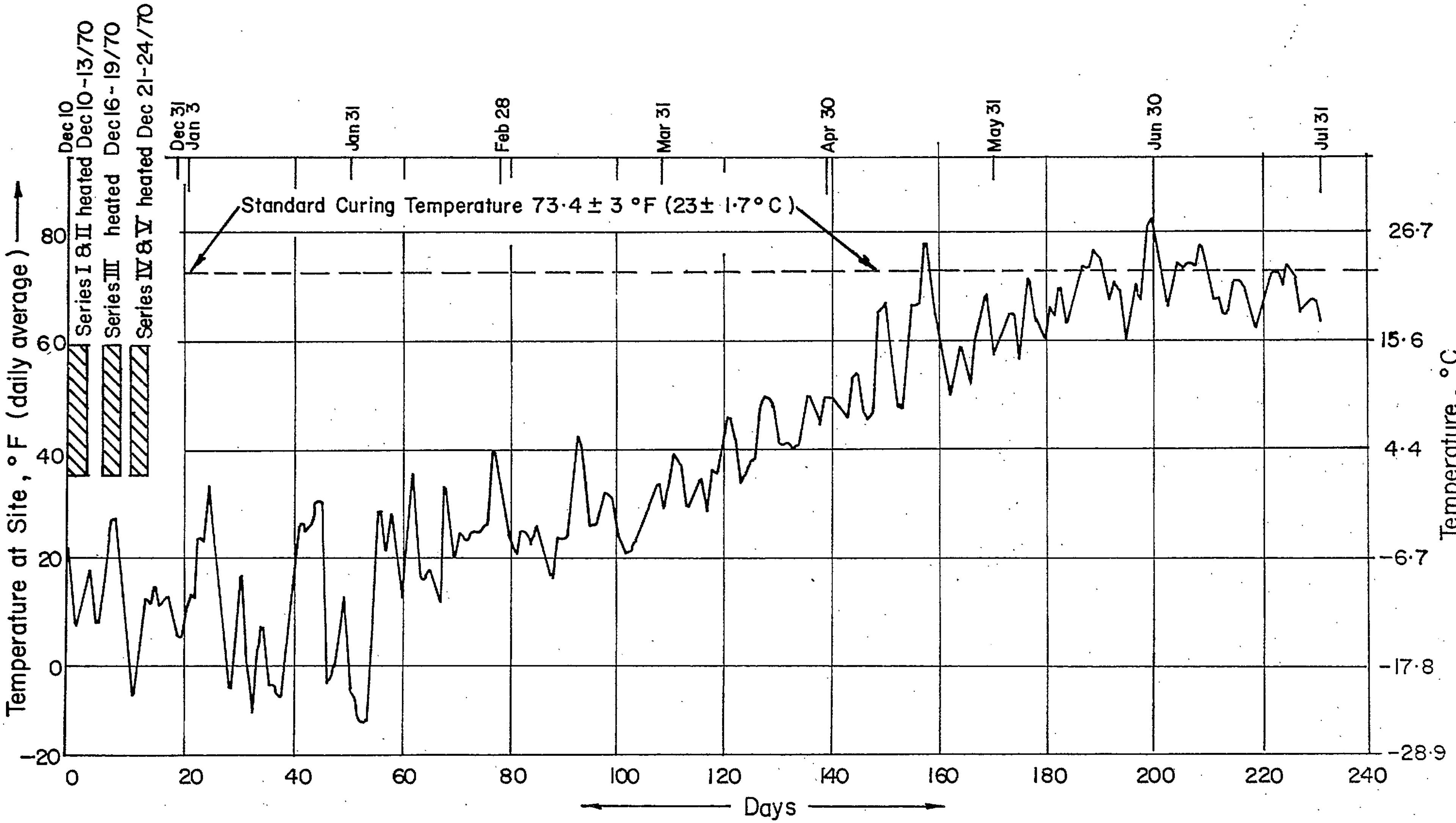

FIG. 3 - AVERAGE DAILY AIR TEMPERATURE AT THE EXPOSURE STATION.

FIG. 4 - A VIEW OF THE CORES BEING DRILLED FROM COLUMNS.

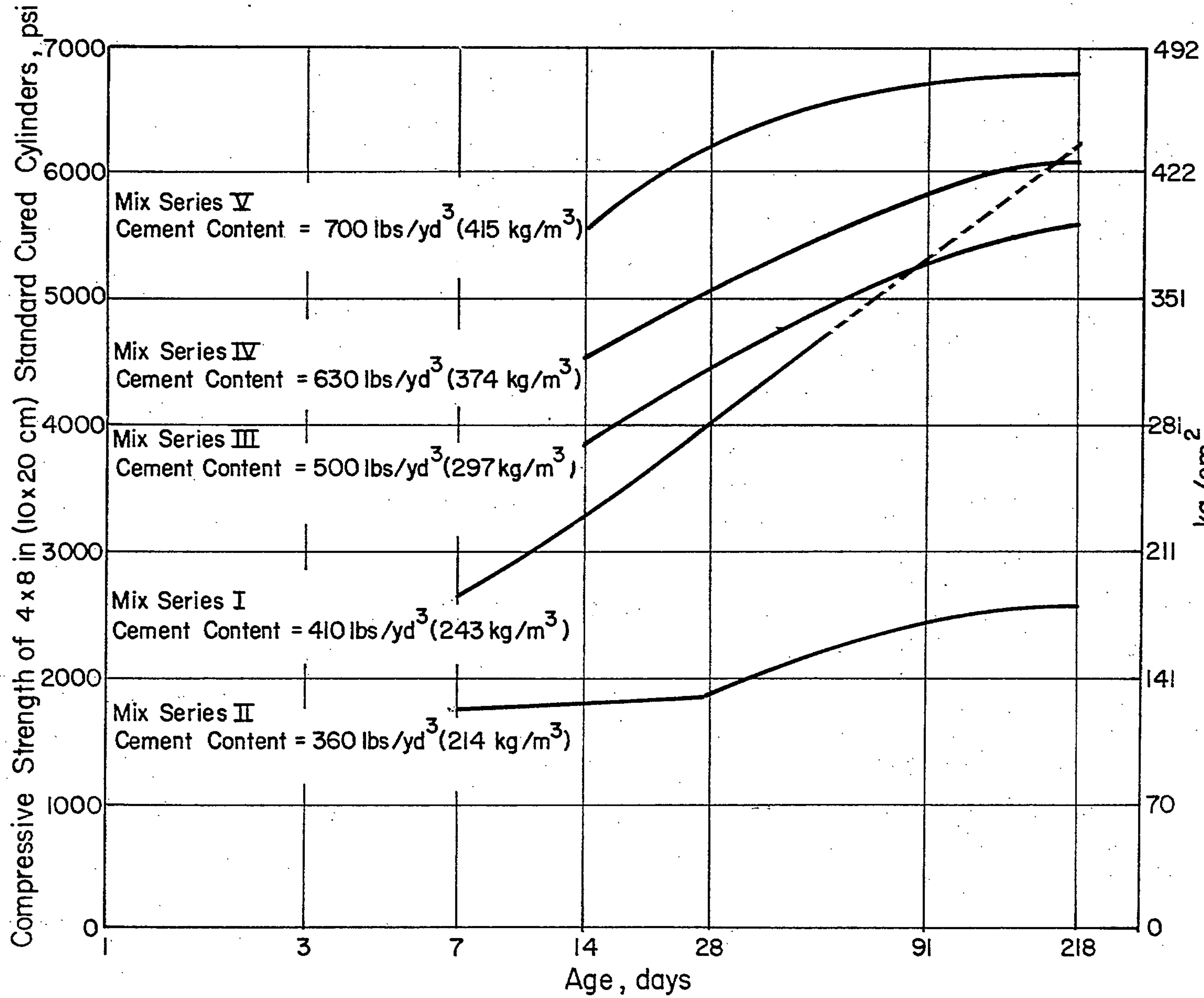

FIG. 5 - RELATIONSHIP BETWEEN AGE AND COMPRESSIVE STRENGTH OF STANDARD-CURED CYLINDERS

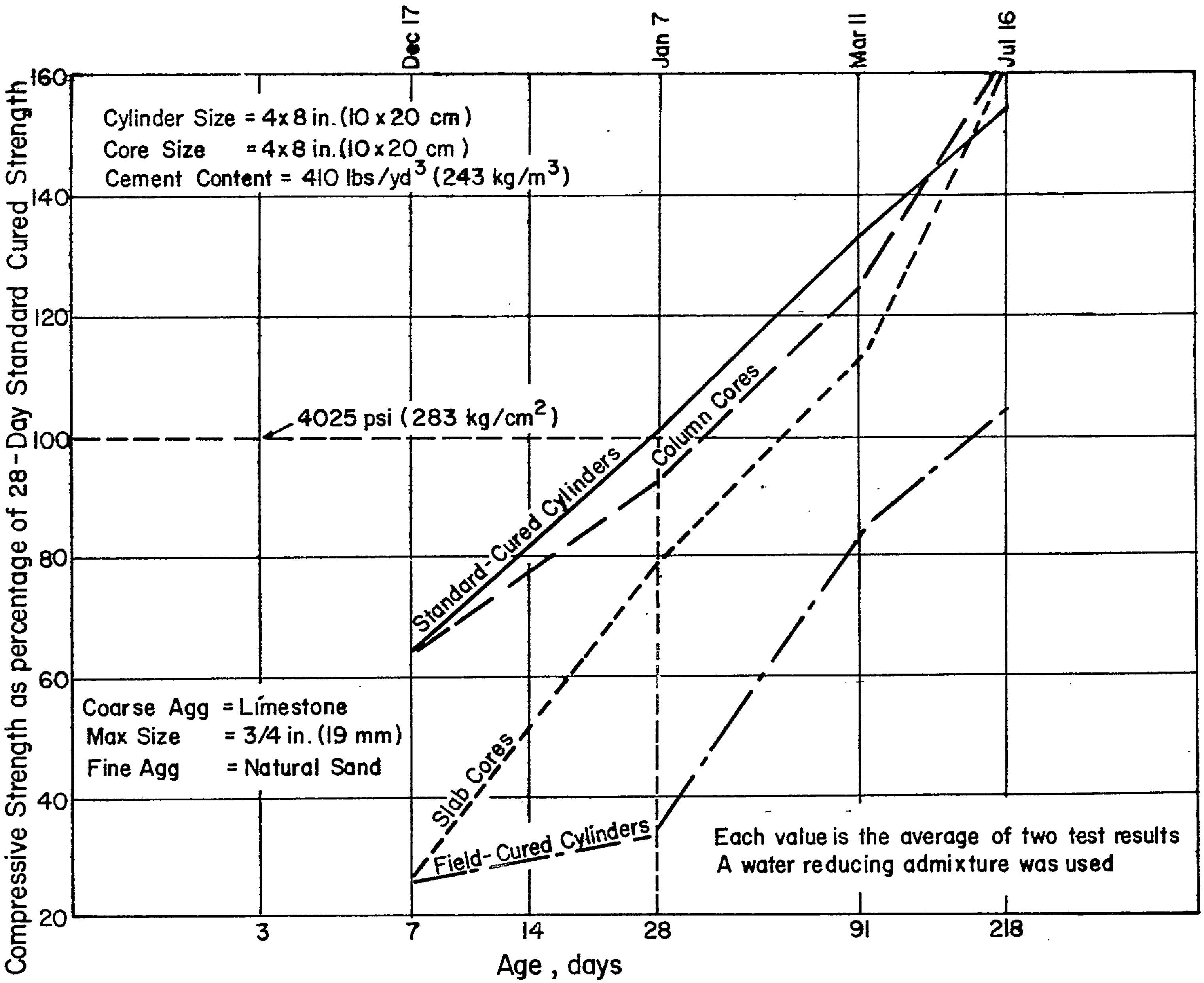

Fig. 6 - Relationship between age and compressive strength of both laboratory- and field-cured test specimens - Mix Series I

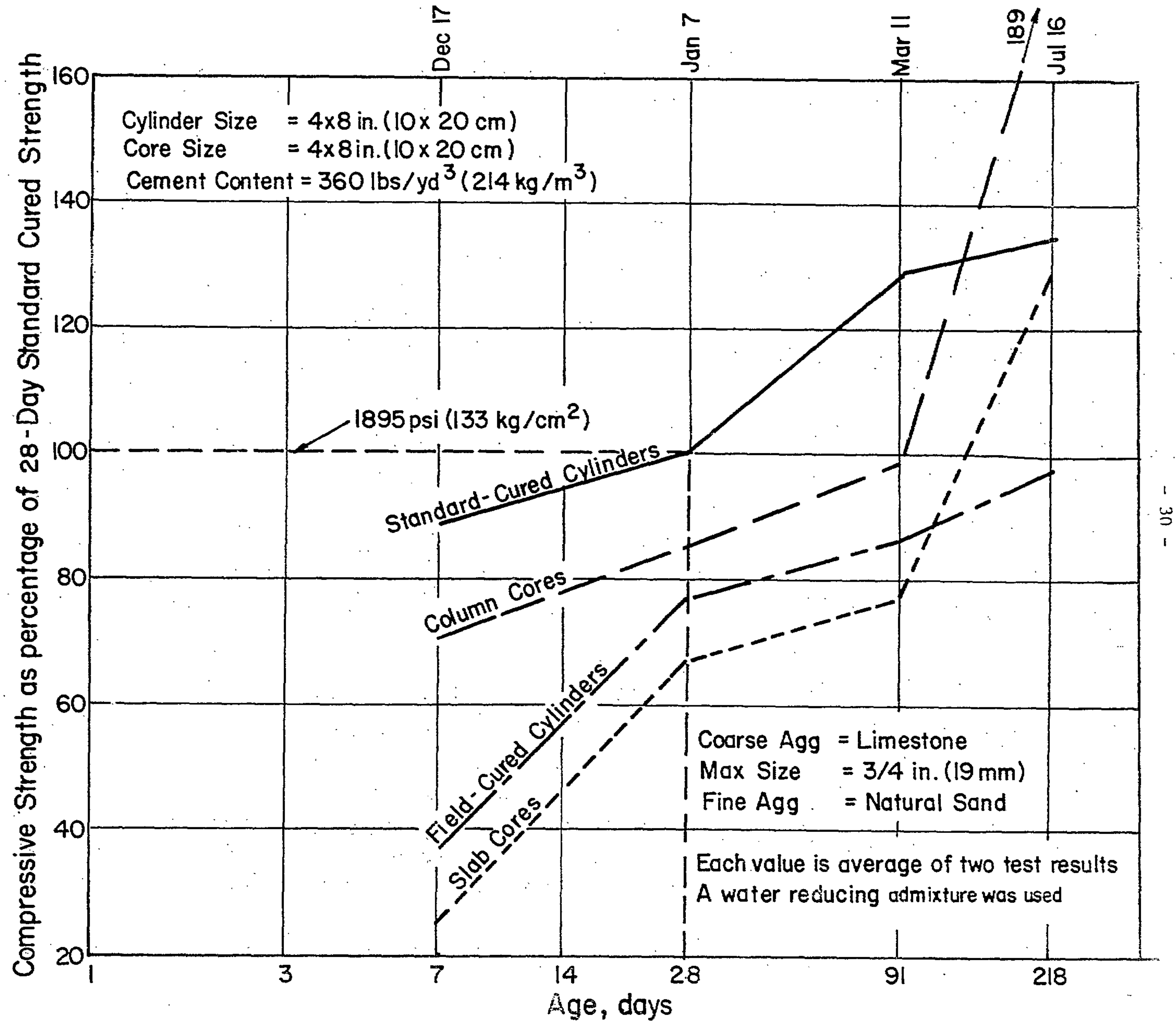

FIG. 7 - RELATIONSHIP BETWEEN AGE AND COMPRESSIVE STRENGTH OF BOTH LABORATORY- AND FIELD-CURED TEST SPECIMENS - MIX SERIES II

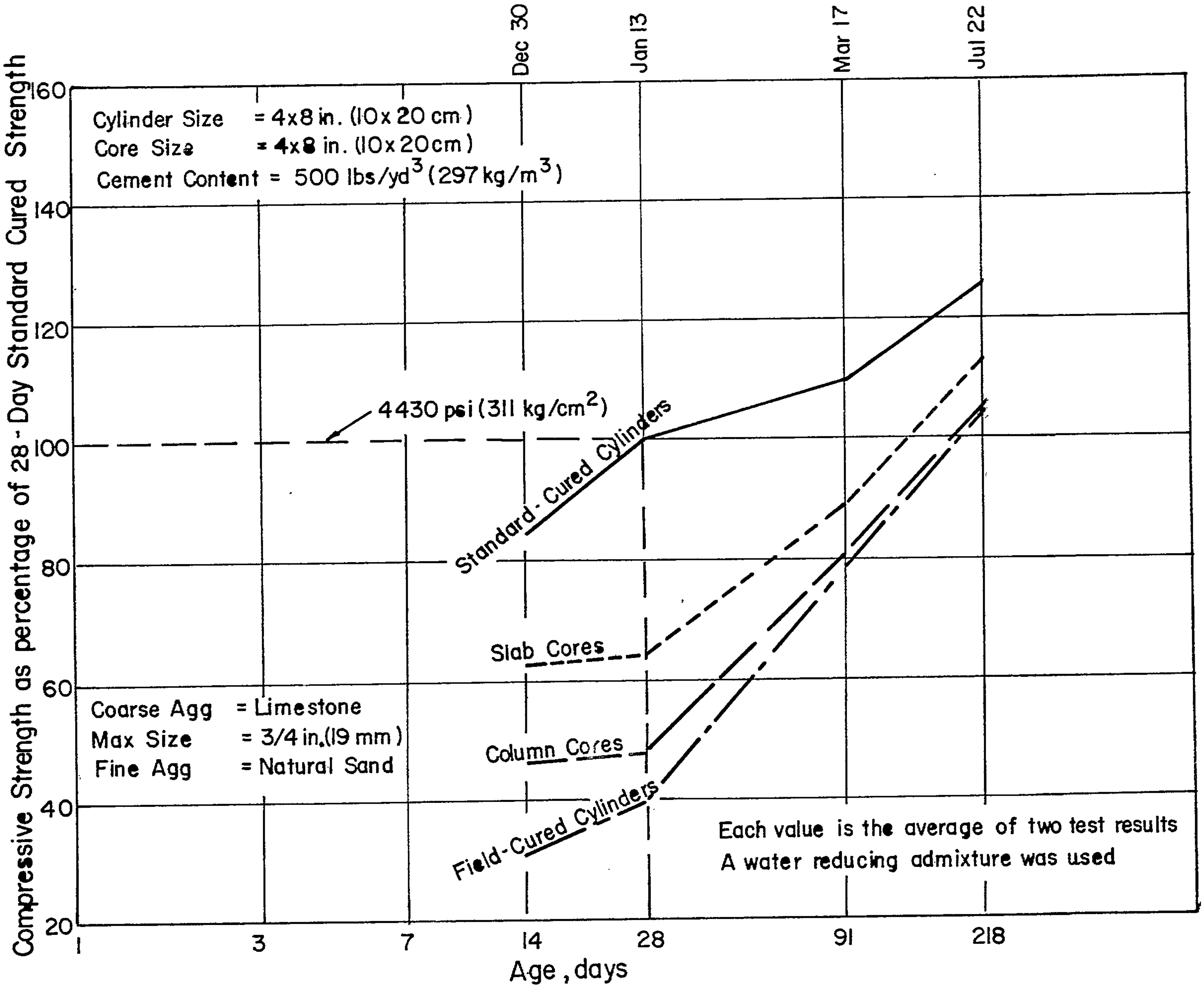

FIG. 8 - RELATIONSHIP BETWEEN AGE AND COMPRESSIVE STRENGTH OF BOTH LABORATORY- AND FIELD-CURED TEST SPECIMENS - MIX SERIES III

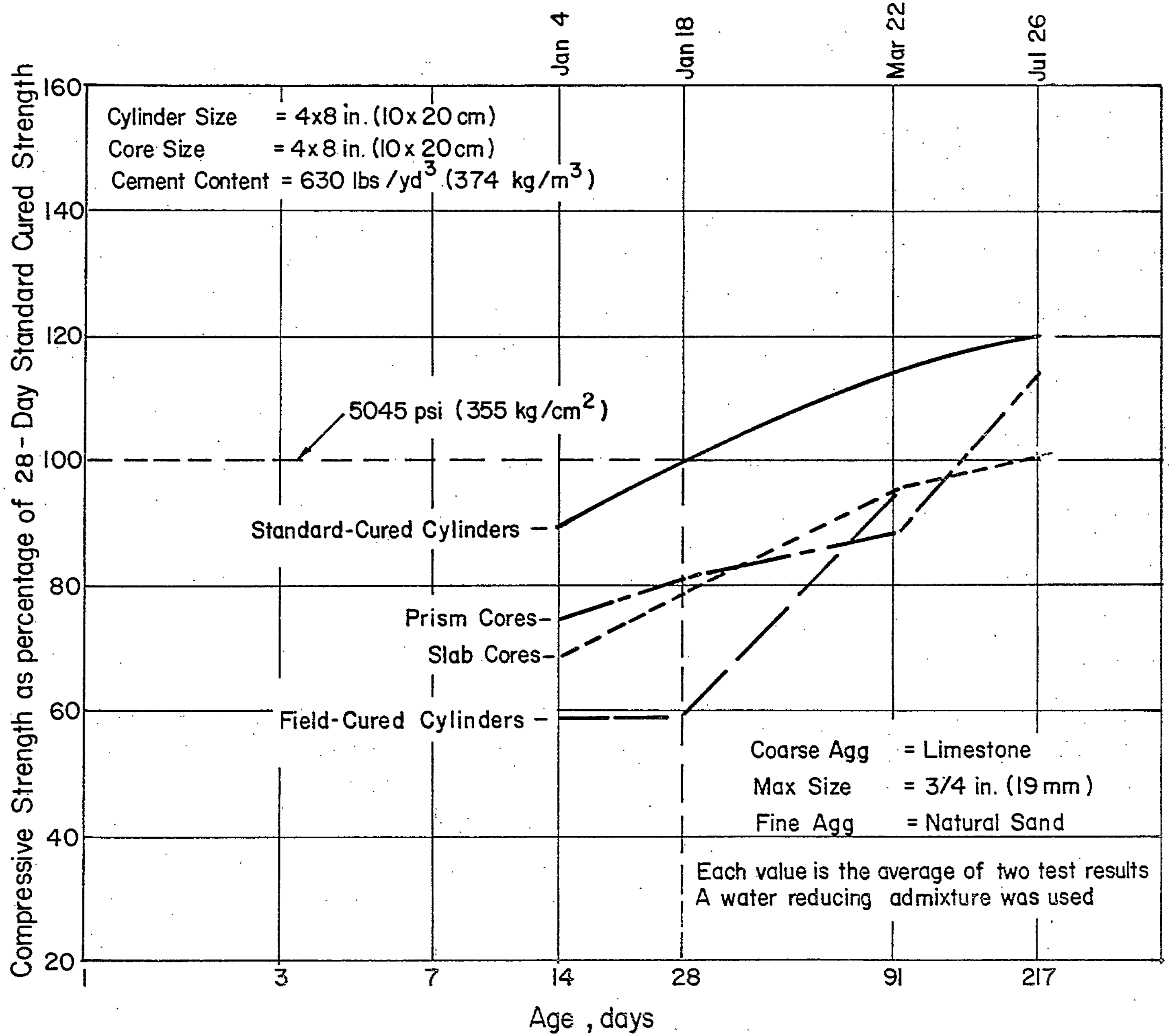

FIG. [illegible] RELATIONSHIP BETWEEN AGE AND COMPRESSIVE STRENGTH OF BOTH LABORATORY- AND FIELD-CURED TEST SPECIMENS - MIX SERIES IV

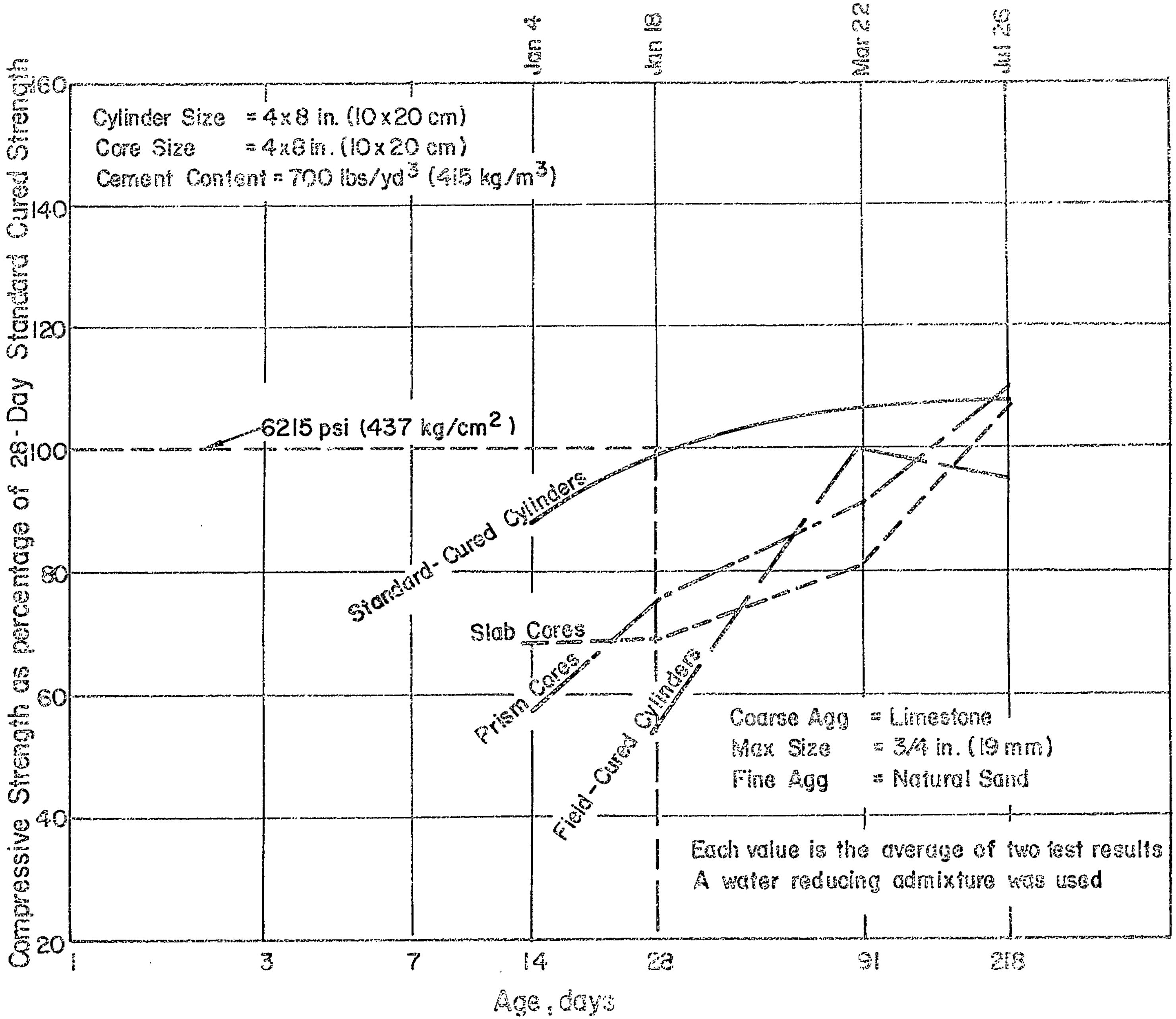

Fig. 10 - Relationship between age and compressive strength of both laboratory- and field-cured test specimens -- Mix Series V

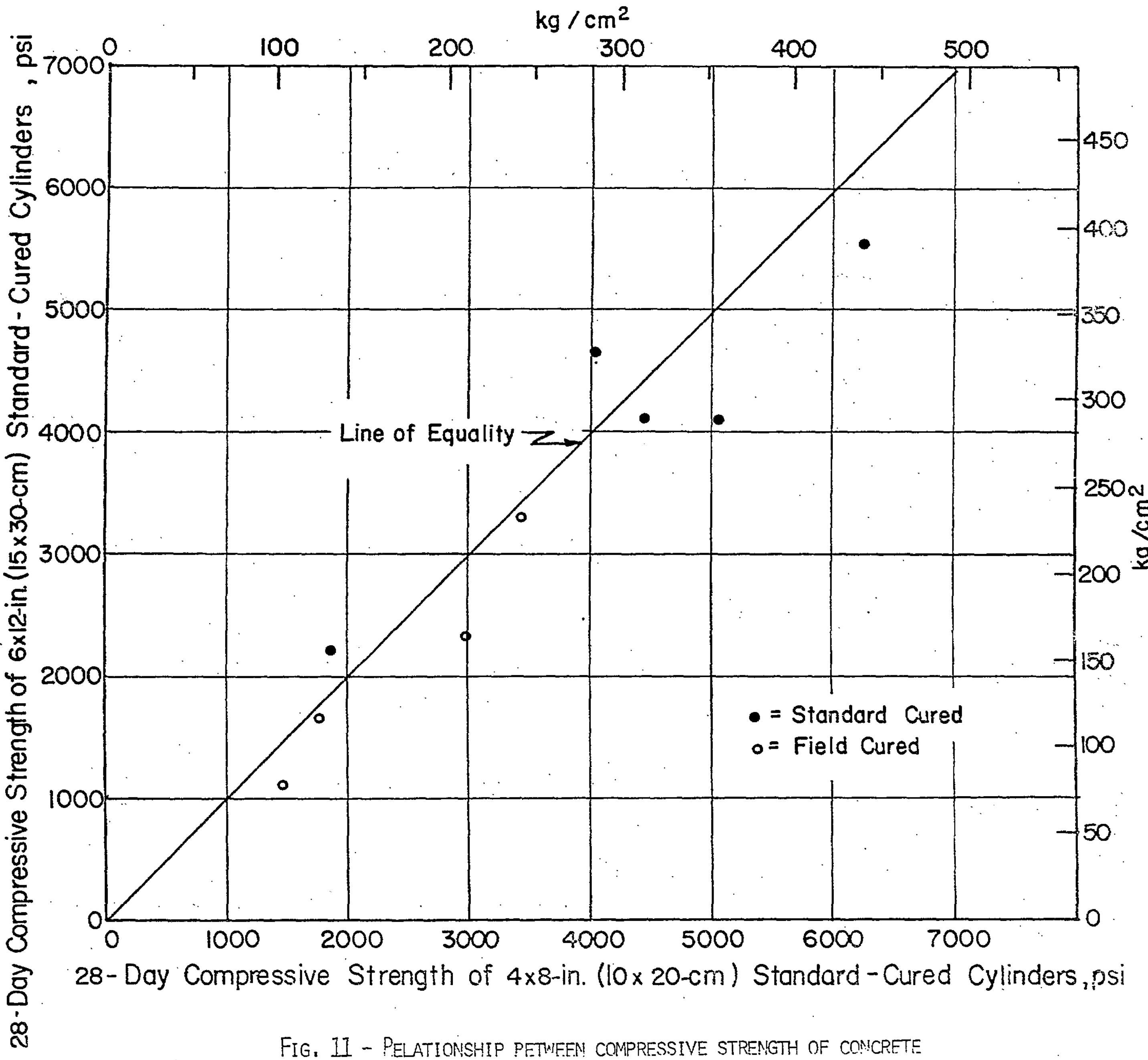

Fig. 11 - Relationship between compressive strength of concrete cylinders of different sizes.