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STRENGTH DEVELOPMENT OF NON-REINFORCED CONCRETE SLABS EXPOSED TO OTTAWA TEMPERATURE EXTREMES

by

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MINERAL PROCESSING DIVISION

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SUMMARY OF RESULTS

Concrete slabs cured for three days at 73 ± 5°F (22.8 ± 2.8°C) and 50 per cent relative humidity and then immediately exposed to freezing temperatures continued to gain strength. Four by eight-inch (102 x 203-mm) cores drilled from the slabs at 28 days reached a strength of 66.7 per cent of the 28-day compressive strength of standard-cured test cylinders; at 116 days a value of 81.2 per cent was reached. Comparatively, at 116 days, standard-cured cylinders reached a value of 111.1 per cent of the compressive strength at 28 days.

If the 3-day compressive strength of 4 x 8-in. (102 x 203-mm) cylinders, the age at which the slabs were exposed to freezing temperatures, is taken as 100 per cent, then the compressive strength of 4 x 8-in. (102 x 203-mm) standard-cured cylinders at 28- and 116-days were 159.7 and 177.4 per cent respectively; the corresponding values for the drilled cores at 3-, 28-, and 120 days were 86.8, 106.5 and 129.7 per cent respectively.

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INTRODUCTION

Since December 1970, investigations have been in progress at the Mines Branch to develop fully the relationship of the strength of standard-cured cylinders to the strength of concrete in structures cured under exposed winter conditions.

Two previous investigations[1,2] were conducted by the Mines Branch in co-operation with the Department of Civil Engineering, University of Ottawa. In these studies, a number of concrete slabs, columns, and cylinders were cast at outdoor exposure sites. After initial curing for three days at $50^{o} \pm 10^{o}$F ($10^{o} \pm 6^{o}$C), achieved by using gas heaters, specimens were exposed to the prevailing weather conditions for a period of one year. At various ages cylinders, and cores drilled from the slabs and columns were tested for compressive strength, and the results were compared with those obtained from companion cylinders cured under standard conditions of temperature and humidity.

The current investigation was undertaken to develop some data on the strength development of concrete at low temperatures after initial curing at 73 ± 5^{o}F (22.8 ± 2.8^{o}C) instead of 50 ± 10^{o}F (10 ± 6^{o}C).

SCOPE

In this investigation, six 24 x 24 x 8-in. (610 x 610 x 203-mm) slabs, twelve 6 x 12-in. (152 x 305-mm) cylinders, and twelve 4 x 8-in. (102 x 203-mm) cylinders were cast from a concrete mix with a nominal water/cement ratio of 0.57 and cement content of 500 lb/cu yd (296 kg/cu m). All specimens were cast in the Mines Branch laboratory. Two thermocouples were installed in each of the slabs, one at the centre and the other 1-in. (25.4-mm) way from one of the edges.

All specimens were cured at 73 ± 5°F (22.8 ± 2.8°C) and 50 per cent relative humidity for 3 days. Following this, the test cylinders were standard-cured* and the slabs were exposed to the elements. Cores were taken from the slabs at 3, 14, 28, 59, 93, and 116 days. The cores and the standard-cured cylinders were tested in compression to determine their relative strength development.

PREPARATION AND CURING OF TEST SPECIMENS

The investigation was started in December, 1970, and terminated about 4 months later. A cubic yard (0.76 m^3) of concrete was obtained from a local ready-mixed concrete supplier. The slabs were cast in plywood moulds and compacted by an internal vibrator. All cylindrical specimens were compacted by hand rodding; the 6 x 12-in. (152 x 305-mm) cylinders were compacted in three equal layers and the 4 x 8-in. (102 x 203-mm) cylinders were compacted in two equal layers, using standard methods. To ensure uniformity, the same operator carried out the hand rodding of the specimens. Immediately after casting, all test specimens were covered with wet burlap kept wet for the next three days. The temperature in the laboratory where the test specimens were cast was 73 ± 5°F (22.8 ± 2.8°C) and the estimated relative humidity was 50 per cent.

Before the test specimens were cast, 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 (CSA Type 10**) used for the concrete mix are given in Table 1. The mix design data, supplied by the ready-mixed concrete supplier, and the properties of the fresh concrete are shown in Table 2.

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* Temperature 73.4 ± 3°F (23 ± 1.7°C) and 100 per cent relative humidity.
** ASTM Type 1.

AIR TEMPERATURE AT EXPOSURE SITE

The six slabs were exposed to outdoor ambient temperatures after 3 days of curing at 73 ± 5°F (22.8 ± 2.8°C). The exposure site was a 20 ft (6.1 m) wide-open space between two laboratories of the Mines Branch (Figure 1). During the winter, it was ensured that the specimens were not buried under snow though this could not be avoided during weekends. The thermocouple wires from the slabs were led to a recorder located in the nearby basement and an hourly record of the concrete temperature was kept for the first few days.

It was noted that the temperature of the concrete slabs reached almost the ambient temperature within 24 hours and remained close to this temperature for the duration of the test. The record of the temperature from the field was compared with the hourly dry-bulb temperatures recorded by the D.O.T. Meteorological Office, International Airport, Uplands, Ottawa. No significant difference was found between these two temperatures although the Mines Branch laboratories are located near downtown Ottawa and the airport is about 10 miles south. Due to frequent breakdowns in the laboratory recording equipment during this investigation, the average air temperatures obtained at the airport station have been plotted in Figure 2.

No measurements of relative humidity were taken during this investigation, but it is known that relative humidity in the Ottawa area during December to April fluctuates between 60 and 75 per cent.

TESTING OF CONCRETE SPECIMENS

The 6 x 12-in. (152 x 305-mm) and 4 x 8-in. (102 x 203-mm) standard-cured cylinders were tested in pairs at 3, 14, 28, 59, 93, and 116 days. At each of these ages, two 4 x 8-in. (102 x 203-mm) cores were drilled from the slabs. Immediately afterwards, 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 machine of 600,000 lbs (271,800 kg) capacity. 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. (102 x 203 mm), giving a length:diameter ratio of 2, so that no correction factors were needed for core strengths.

At the age of 59, 93, and 116 days, the densities of the moist-cured cylinders and the cores were determined.

PRESENTATION OF TEST RESULTS

The test results are summarized in Tables 3 to 6. The relationships between age and compressive strength for the moist-cured cylinders and for the cores are given in Figure 3. The relationship between age and compressive strength as a percentage of the 28-day strength of 4 x 8-in. (102 x 203-mm) cylinders, is shown in Figure 4.

In order to avoid size effects in the analysis, the strength of 4 x 8-in. (102 x 203-mm) cylinders was selected for comparison with the strength of drilled cores.

To determine the reproducibility of the test results, within-batch standard deviations and coefficients of variation have been computed for the test data (Table 7).

STRENGTH DEVELOPMENT WITH AGE

The relationships between age and compressive strength of standard-cured cylinders and of drilled cores are shown in Figure 2. The standard-cured cylinders and the cores show continuous gain in strength with age. The 4 x 8-in. (102 x 203-mm) cylinders show the highest strength at all ages followed, in turn, by the 6 x 12-in. (152 x 305-mm) cylinders and the cores.

The 4 x 8-in. (102 x 203-mm) cylinders reached a strength of 4655 psi (32.1 MN/m^2) at 28 days* and at 116 days they reached a value of 111.1 per cent of the standard strength. At 28 days, the cores reached a strength of 66.7 per cent of the standard strength, and at 116 days the corresponding value was 81.2 per cent. In the two investigations referred to earlier[1,2] the 120-day strength of cores drilled from slabs were of the order of 68 and 85 per cent. The current investigation was terminated at 116 days. It is believed that, if this investigation had been continued over the summer months, the cores would have followed a pattern of strength gain somewhat similar to that noted in the earlier investigations.

If the three day compressive strength of 4 x 8-in. (102 x 203-mm) cylinders, the age at which the cylinders were removed from the laboratory and exposed to the outdoor ambient temperature, is taken as 100 per cent, then the compressive strength of 4 x 8-in. cylinders at 28- and 116 days reached a value of 159.7 and 177.4 per cent; the corresponding values for the cores at 3, 28, and 116 days are 86.8, 106.5, and 129.7 per cent respectively.

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

DENSITIES OF TEST CYLINDERS AND CORES

The densities of the test cylinders and the drilled cores at various ages are given in Table 6. The densities of 4 x 8-in. (102 x 203-mm) cylinders and cores varied from 146.93 to 147.60 lb/ft^3 (2354 to 2365 kg/m^3), but those of the cores varied from 145.50 to 148.80 lb/ft^3 (2331 to 2384 kg/m^3). The cylinders had been compacted by hand rodding, whereas the slabs had been compacted by an internal vibrator. The relationship between age and density of the concrete cylinders is shown in Figure 5.

REPRODUCIBILITY OF TEST RESULTS

The within-batch standard deviations and coefficients of variation of the test results at various ages are shown in Table 7. The analyses indicate that at 28 days the cores had poorer reproducibility with a coefficient of variation of 3.6 per cent; the corresponding value for 4 x 8-in. (102 x 203 mm) standard-cured cylinders was 2.3. The same relationship applied at all other ages except 3 and 93 days, when the reverse was true. These results are generally in line with those reported earlier[1,2].

RELATIONSHIP BETWEEN THE STRENGTHS OF DIFFERENT-SIZED CYLINDERS

In this investigation, compressive strengths of 4 x 8-in. (102 x 203-mm) drilled cores have been compared with those of standard-cured cylinders of the same size. However, 6 x 12-in. (152 x 305-mm) cylinders were also cast and tested (Table 3). The strength of 6 x 12-in. cylinders was lower than the strength of 4 x 8-in. cylinders, the difference being 310 psi (2.13 MN/m^2) at 3 days and 955 psi (6.57 MN/m^2) at 28 days.

STRENGTH DEVELOPMENT AND MATURITY CONCEPT

An attempt has been made to determine if an increase in compressive strength of concrete during winter months can be explained in terms of maturity concept[3]. Maturity calculations indicate that at low temperatures the maturity rule considerably underestimates the potential strength of concrete. It is believed that the following modified equation may explain the strength development of concrete at low temperatures.

$$\text{Maturity, } ^{o}F \times \text{hours} = \sum \alpha_t (t + 35)$$

α_t = duration of curing in hours

t = temperature in ^{o}F

Using the above modified equation, maturity values have been calculated (Table 8) and a plot of maturity versus strength is shown in Figure 6.

CONCLUDING REMARKS

Non-reinforced concrete slabs cured for three days at 73 ± 5^{o}F (22.8 ± 2.8^{o}C) and 50 per cent relative humidity and then immediately exposed to below freezing temperatures continue to gain strength. After about four months of exposure at these low temperatures, the compressive strength of 4 x 8-in. (102 x 203-mm) cores drilled from the slabs have a strength of 81.2 per cent of the 28-day compressive strength of 4 x 8-in. standard-cured cylinders,

REFERENCES

1. V. M. Malhotra and Carl Berwanger, "Effect of Below-Freezing Temperatures on Strength Development of Concrete", Mines Branch Investigation Report IR 71-71, Department of Energy, Mines and Resources, Ottawa, November 1971, 34 pp.

2. V. M. Malhotra and Carl Berwanger, "Strength Development of Concrete Exposed to Ottawa Temperature Extremes", Mines Branch Investigation Report IR 73-46, Department of Energy, Mines and Resources, Ottawa, June 1973, 30 pp.

3. V. M. Malhotra, "Maturity Concept and the Estimation of Concrete Strength - A Review", Mines Branch Information Circular IC 277, Department of Energy, Mines and Resources, Ottawa, November 1971, 43 pp.

VMM/am

TABLE 1

Physical Properties and Chemical Analysis of the Cement*

Description of Test	
Physical Tests, General	
Time of Set (Vicat Needle): Initial	3 hr 00 min
Final	5 hr 00 min
Fineness: No. 200 (Passing)	96.7 per cent
Soundness - Autoclave	0.21 per cent
Physical Tests - Mortar Strength	
Compressive Strength of 2-in. (50.8 mm) Cubes	
3-day	2520 psi (17.31 MN/m^2)
7-day	3740 psi (25.79 MN/m^2)
28-day	5000 psi (34.40 MN/m^2)
Chemical Analysis	
Insoluble Residue	0.13 per cent
Silicon Dioxide (SiO_2)..................	20.80 per cent
Aluminum Oxide (Al_2O_3)	5.90 per cent
Iron Oxide (Fe_2O_3)	2.70 per cent
Calcium Oxide (CaO) Total	64.10 per cent
Magnesium Oxide (MgO)	2.90 per cent
Sulphur Trioxide (SO_3)	2.40 per cent
Loss on Ignition	0.46 per cent
Others	0.61 per cent

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

TABLE 2

Mix Proportions and Properties of Fresh Concrete

Mix Proportions				Properties of Fresh Concrete						
Nominal* Water/Cement Ratio	Cement Content		Aggregate*/Cement Ratio	Temperature		Slump		Unit Weight		Air Content, %
	lb/cu yd	(kg/cu m)		°F	°C	in.	mm	lb/ft^3	kg/m^3	
0.57	500	(296)	6.57	60	15.6	3	76	144.4	2313	5.6

*All ratios are by weight.

TABLE 3

Summary of Results of Compressive Strength of Cylinders and Cores

Age, days	Standard-cured Cylinders 6x12-in. (152x305-mm)		Standard-cured Cylinders 4x8-in. (102x203-mm)		Cores "as received" 4x8-in. (102x203-mm)	
	psi	MN/m^2	psi	MN/m^2	psi	MN/m^2
3	2615	18.03	2925	20.17	2530	17.45
14	3415	23.55	4220	29.10	3215	22.17
28	3700	25.52	4655	32.10	3105	21.41
59	3915	27.00	5195	35.83	3515	24.24
93	4330	29.86	5060	34.90	3365	23.21
116	4605	31.76	5170	35.65	3780	26.07

TABLE 4

Summary of Results of Compressive Strength as a Percentage of 3-day Strength of Standard -cured Cylinders

Age, days	Standard-cured Cylinders*	Cores "as received"*
3	2925 (100 %)	2530 (86.8%)
14	4225 (144.9%)	3215 (110.3%)
28	4655 (159.7%)	3105 (106.5%)
59	5195 (178.2%)	3515 (120.6%)
93	5060 (173.6%)	3365 (115.4%)
116	5170 (177.4%)	3780 (129.7%)

* Cylinder and core size: 4 x 8 in. (102 x 203 mm)

TABLE 5

Summary of Results of Compressive Strength as A Percentage of 28-day Strength of Standard-cured Cylinders

Age, days	Standard-cured Cylinders*	Cores "as received"*
3	2925 (62.8%)	2530 (54.4%)
14	4225 (90.8%)	3215 (69.1%)
28	4655 (100 %)	3105 (66.7%)
59	5195 (111.6%)	3515 (75.5%)
93	5060 (108.7%)	3365 (72.3%)
116	5170 (111.1%)	3780 (81.2%)

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

TABLE 6

Densities of Cylinders and Cores

Age, days	Standard-cured Cylinders				Cores	
	6x12 in. (152x302 mm)		4x8 in. (102x203 mm)		4x8 in. (102x203 mm)	
	lb/ft^3	kg/m^3	lb/ft^3	kg/m^3	lb/ft^3	kg/m^3
59	146.88	2353	146.93	2354	145.50	2331
93	146.72	2351	147.00	2355	148.80	2384
116	146.60	2349	147.60	2365	146.75	2351

TABLE 7

Within-Batch Variations in Strength Test Results at Various Ages

Age, days	Specimen Type	Compressive Strength		S.D.,		C.V., %
		psi	MN/m^2	psi	MN/m^2	
3	6x12-in. (203x305-mm) cylinders	2615	18.03	17.7	0.122	0.68
	4x8-in. (102x203-mm) cylinders	2925	20.17	84.9	0.586	2.90
	4x8-in cores	2530	17.45	16.7	0.115	0.66
14	6x12-in. cylinders	3415	23.55	176.8	1.219	5.18
	4x8-in. cylinders	4220	29.10	42.4	0.292	1.00
	4x8-in. cores	3215	22.17	162.6	1.121	5.00
28	6x12-in. cylinders	3700	25.52	67.2	0.463	1.82
	4x8-in. cylinders	4655	32.10	106.1	0.732	2.28
	4x8-in. cores	3105	21.41	113.4	0.782	3.64
59	6x12-in. cylinders	3915	27.00	42.4	0.292	1.08
	4x8-in. cylinders	5195	35.83	49.5	0.341	0.95
	4x8-in. cores	3515	24.24	63.6	0.439	1.81
93	6x12-in. cylinders	4330	29.86	99.0	0.683	2.29
	4x8-in. cylinders	5060	34.90	56.6	0.390	1.12
	4x8-in. cores	3365	23.21	28.3	0.195	0.84
116	6x12-in. cylinders	4605	31.76	14.9	0.103	0.32
	4x8-in. cylinders	5170	35.65	84.2	0.581	1.64
	4x8-in. cores	3780	26.07	78.5	0.541	2.08

S.D. = Standard Deviation; C.V. = Coefficient of Variation.

TABLE 8

Maturity and Compressive Strength of Concrete at Various Ages

Time Internal, days	Mean Temperature during indicated time intervals		Maturity, °F x hours	Compressive Strength of 4x8-in. (102x203-mm) Cylinders	
	°F	°C		psi	MN/m^2
0 - 3	75	23.9	4,608*	2530	17.45
4 - 14	12.4	-10.9	16,940**	3215	22.17
15 - 28	8.5	-13.0	31,609**	3105	21.4
29 - 59	6.7	-14.0	63,510**	3515	24.24
60 - 93	17.2	- 8.2	99,194**	3365	23.21
94 - 116	23.7	- 4.6	125,659**	3780	26.07

* Maturity calculated using the equation: $\sum \alpha_t$ (64-11)

** Maturity calculated using the equation: $\sum \alpha_t$ (64+35)

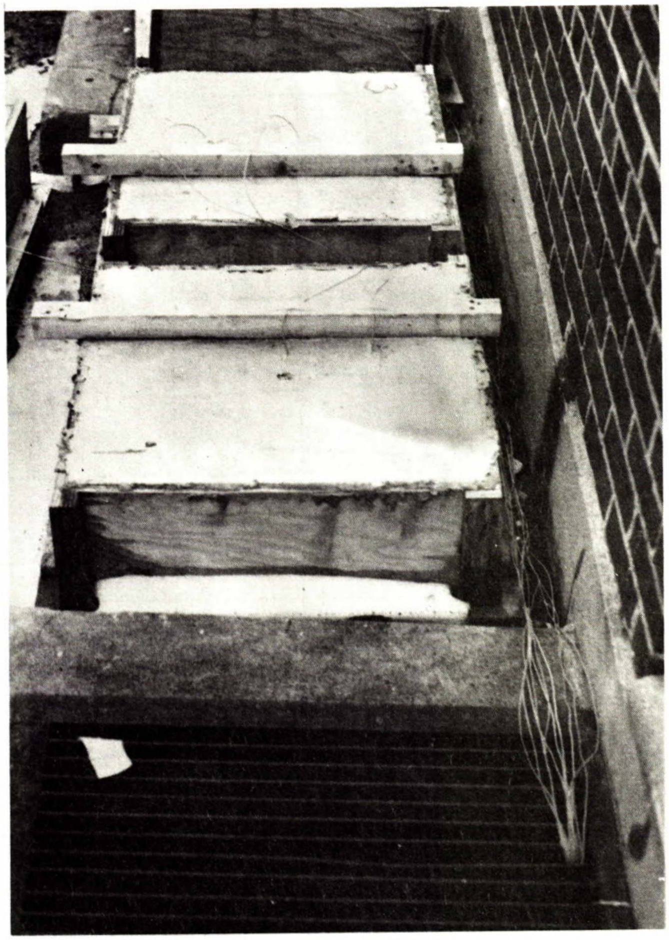

Figure 1 - A view of the outdoor exposure site.

Note: Thermocouple wires from two of the slabs can be seen being taken to the recorder.

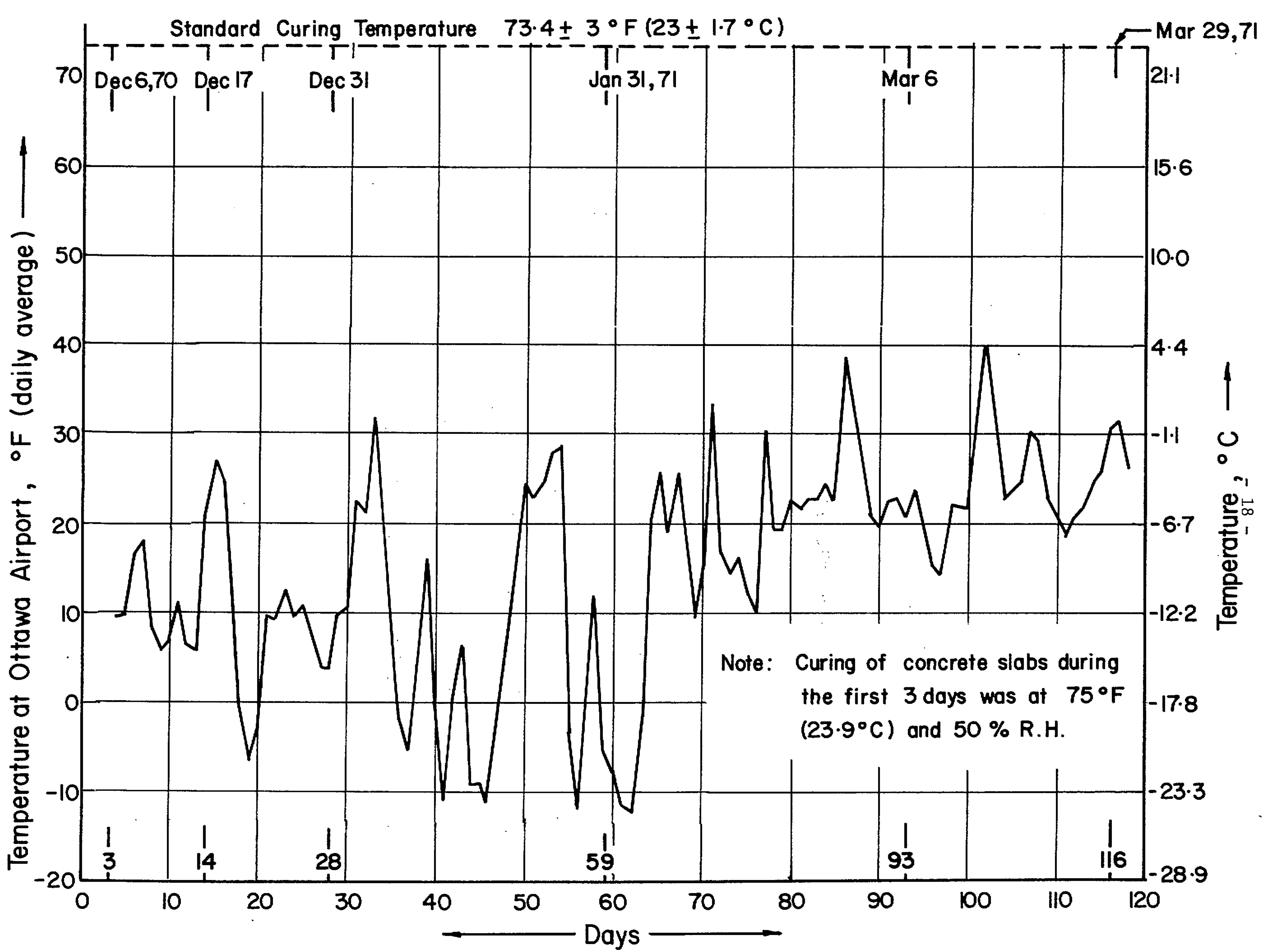

Figure 2 - Average daily air temperatures

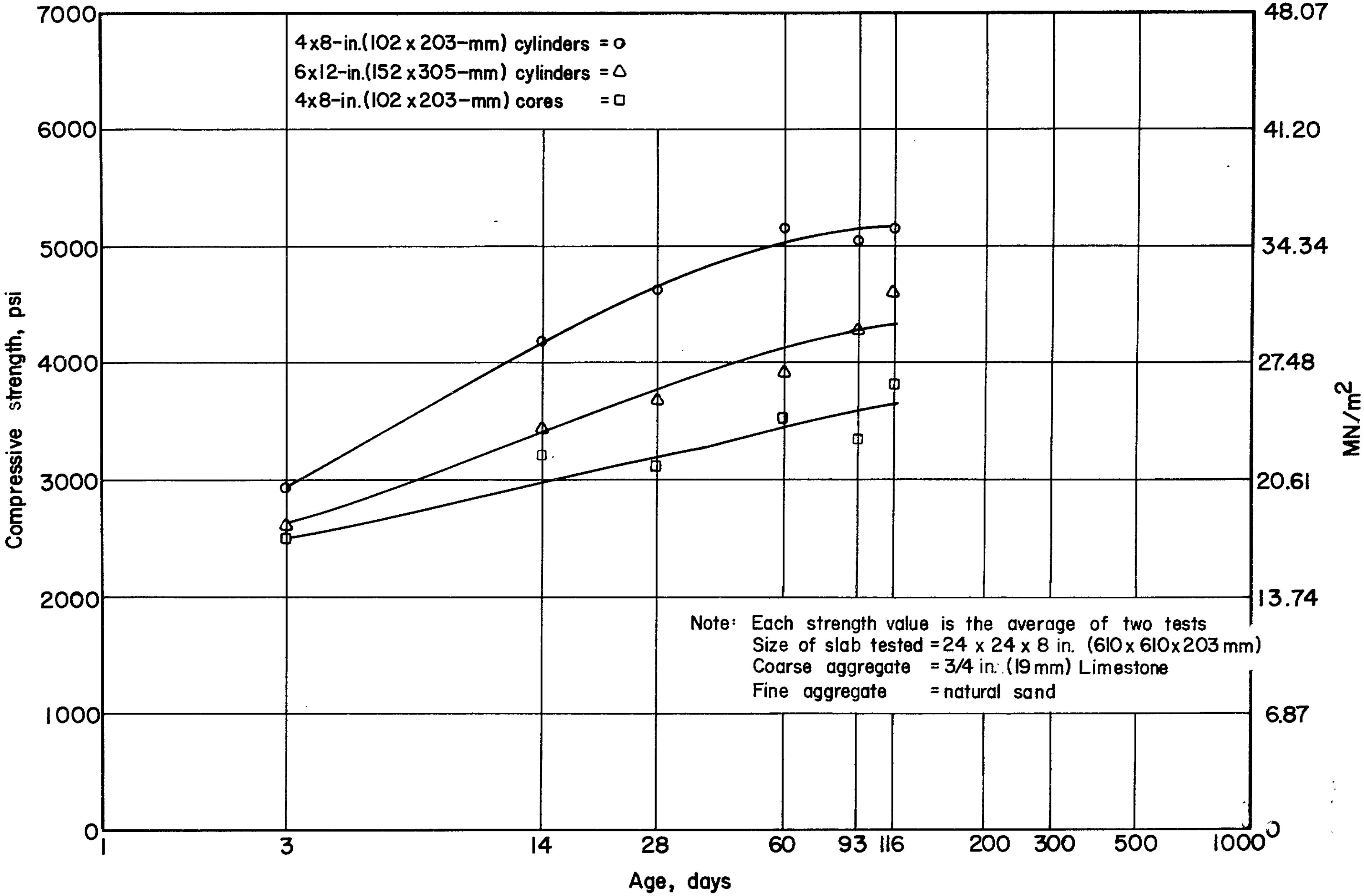

Figure 3 - Relationship between age and compressive strength of cylinders and cores.

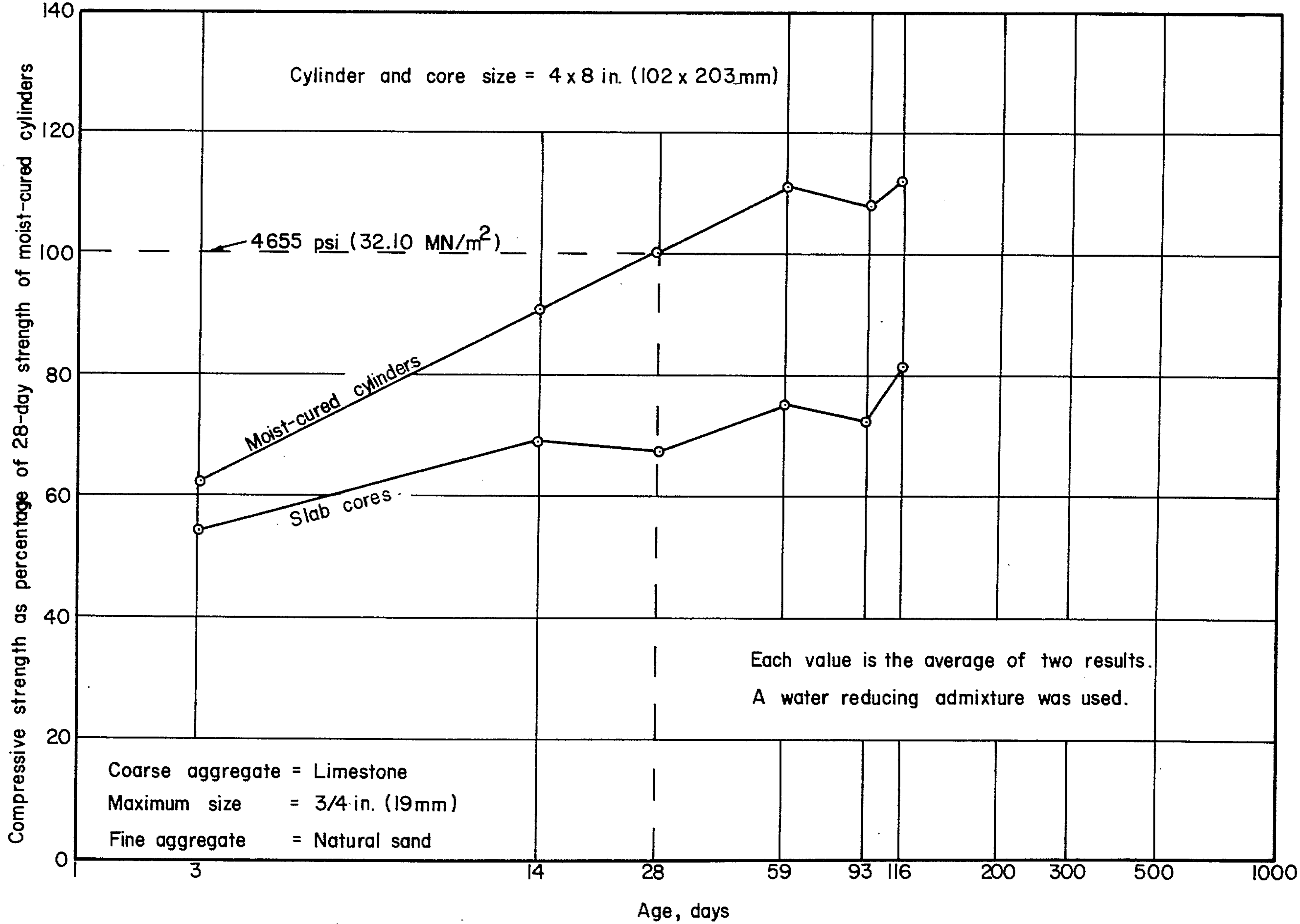

Figure 4 - Relationship between age and compressive strength as percentage of 28-day standard-cured cylinders.

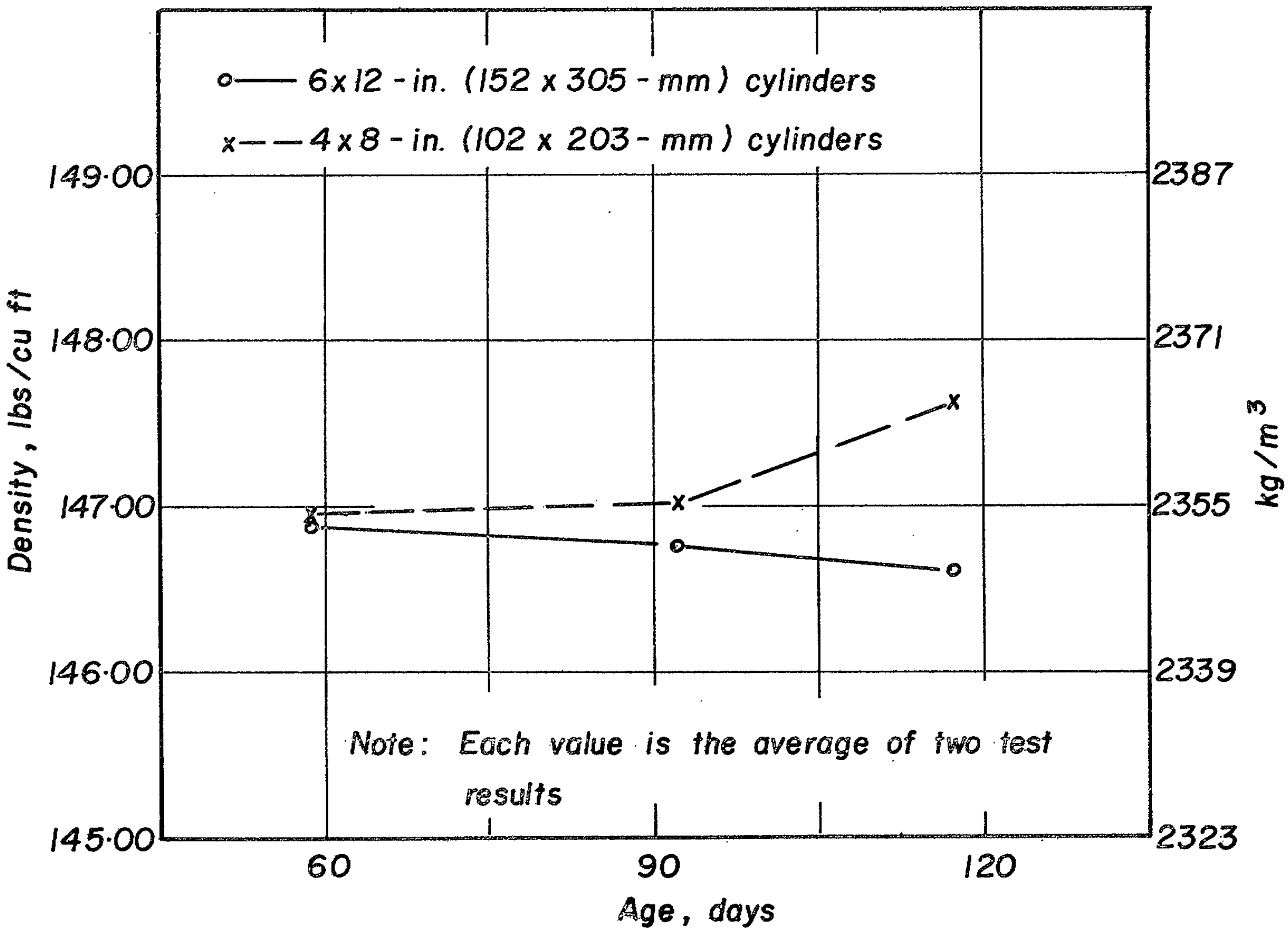

Figure 5 - Relationship between age and density of cylinders.

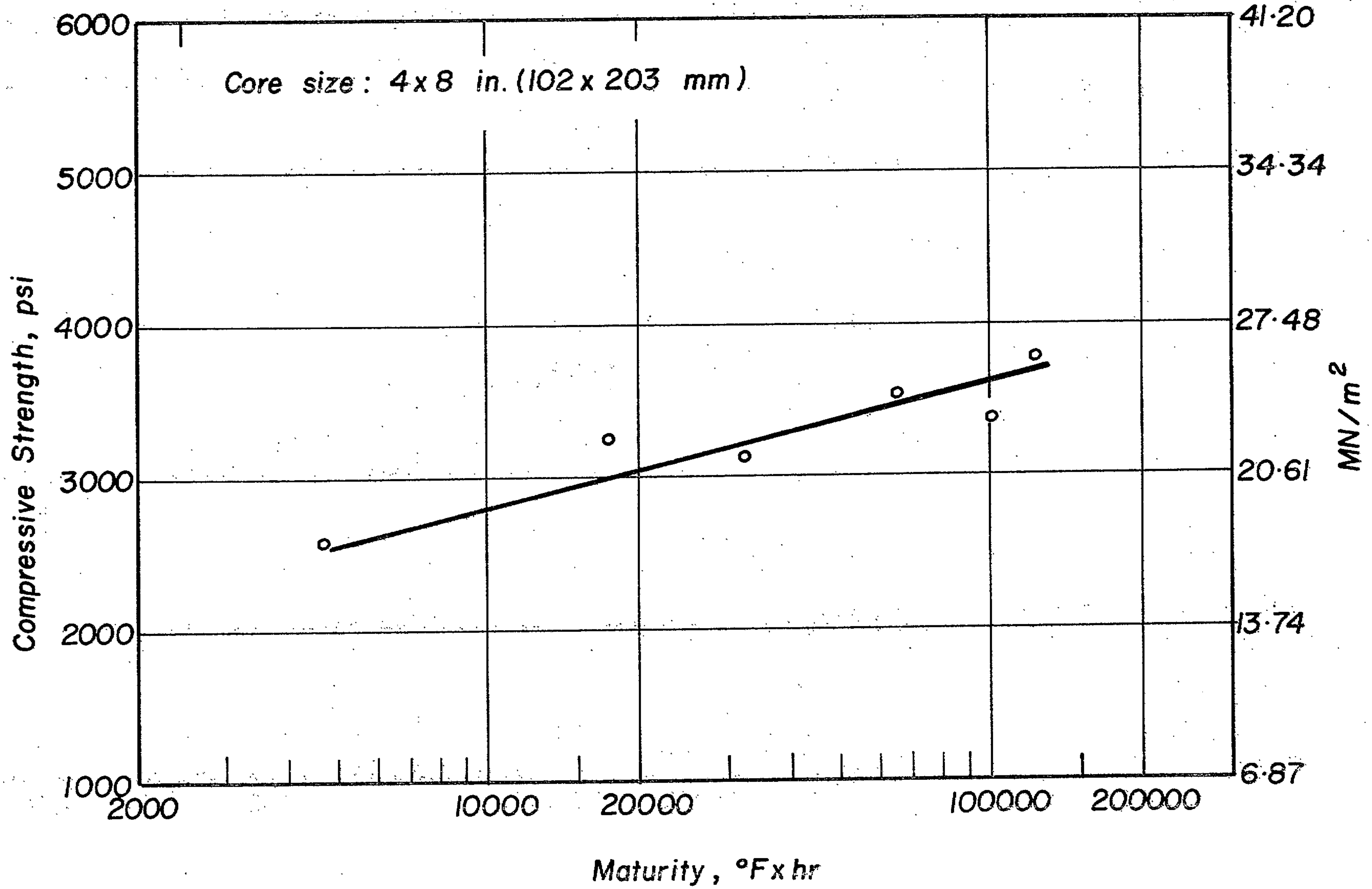

Figure 6 - Relationship between maturity and compressive strength of concrete.