STRENGTH TESTS AT EARLY AGES AND AT HIGH SETTING TEMPERATURES

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In some tropical countries, because of the favorable labor and weather conditions, concreting is frequently carried out 24 hours a day. This continual and high rate of placing of concrete requires a rapid control method for the estimation of potential strength. This paper presents a rapid control method by which compressive strength test results of concrete cubes 24 to 48 hours old will closely predict strengths at later ages. Test results of the cubes in which the setting temperatures are 113, 122, 131, 140, and 149 F (45, 50, 55, 60, and 65 C) are also presented. These setting temperatures considerably reduce the potential concrete strength. This reduction in strength is found to increase as the water-cement ratio and setting temperature increase.

•IN concreting operations, it is frequently advantageous or necessary to be able to predict the potential strength at any particular age or maturity almost immediately after the concrete has been placed. Normally, concrete cubes are tested at 7 and 28 days to determine whether the specified compressive strength at these two ages is met. However, where the placing of concrete has to be continuous and rapid and where large volumes are involved, this normal method of strength control is unsatisfactory because the test results are not available early enough to enable any unsatisfactory concrete to be removed easily or at low cost and to enable site adjustments of basic mix proportions to be effectively made if such changes are necessary.

RAPID CONTROL METHOD

To accommodate the needs precipitated by the continuous and rapid placing of concrete in large quantities, such as that which occurs in Malaysia, research programs on rapid control methods were undertaken. Ordman and Bondre (1) and King (2) carried out accelerated curing with oven heating and established an empirical relationship between the accelerated strength obtained by curing concrete cubes for 6 hours at a temperature slightly below 212 F (100 C) and the 28-day strength of the cubes normally cured in water. Akroyd (3) found that the ratio of the strength of cubes that were cured at 140 F (60 C) for 7 hours to the strength at 7 days of normal curing is the same as the ratio of the 7-day strength to that at 28 days of normal curing. King (4) reported that testing cubes after curing in water at 131 F (55 C) would enable the prediction of the 28-day strength with reasonable accuracy. He produced graphs relating these two strengths.

These investigators cured cubes at some fixed temperature and duration and related the strength of a single maturity to the 7 or 28-day strength.

Ever since it was realized that the strength of concrete increases as time or maturity increases, attempts have been made to express this relation in the form of an equation so that strength may be predicted without the need to perform long-term tests. It has been shown (5) that the relation between strength and age or maturity is hyperbolic, that is,

$$D/q = mD + C \quad (1)$$

where q is the compressive strength at age D or maturity M, and C and m are constants. If D/q is plotted against an abscissa of D, equation 1 becomes a straight line, the inverse slope (1/m) of which gives the maximum strength the concrete will attain with age.

Equation 1 will therefore enable the maximum strength that a concrete will finally attain and the strength at any specified age or maturity to be predicted from the test results obtained at an early age. This equation was, however, established with test results of specimens that were predominantly more than 3 days old. Therefore, it seems necessary to test the validity of equation 1 for the prediction of concrete strength with test results obtained at much earlier ages than 3 days and to determine what accuracy can be attained when the equation is used for predicting concrete strength by using the results at early maturities. It would, therefore, be necessary to start testing over a wide spectrum of maturities at as early a maturity as possible and to extend the tests to higher maturities. The lowest maturity will seem to be that at which the cubes have attained sufficient strength to withstand handling without physical damage so that reliable results can be produced. Under tropical conditions, this appears to be the age at which test cubes are normally demolded, that is, after an age of about 24 hours in an average ambient temperature of 86 F (30 C).

Cubes made from the same batch were tested at ages from 23 to 1,009 hours (about 42 days). Table 1 gives the results of set J, for which the mix was 1:2:4 by weight; the water-cement ratio was 0.45 (ordinary portland cement, river sand, and limestone were used); and the water curing temperature was 82.4 ± 33.8 F (28 ± 1 C). About forty-two 4-in. (10-cm) cubes were made from each batch, and the crushing strength given in Table 2 represents the mean strength of two test cubes.

In determining the linearity among the plots of D/q against an abscissa of D, the method of least squares is used. The closeness to 1 of the value of the product moment correlation coefficient confirms the high degree of linear association among the variates.

On the basis of the strengths at 23 and 29 hours, the predicted maximum strength of the concrete is 6,803 psi (46.9 MPa); on the basis of those at 23, 29, 36, and 47 hours, it is 7,194 psi (49.6 MPa). The mean value for the predicted maximum strength is 7,474 psi (51.5 MPa). The strength results at ages of within 48 hours, therefore, give a prediction that is reasonably close to that based on all 21 test results at ages from 23 to 1,009 hours.

For rapid-hardening cement, the test results at ages of up to 48 hours also give a close prediction of the maximum strength that will ultimately be attained. Table 2 gives the results of set P based on a rapid-hardening portland cement. The mix was 1:2:4 by weight; the water-cement ratio was 0.55 (rapid-hardening cement, river sand, and limestone were used); and the water curing temperature was 82.4 ± 33.8 F (28 ± 1 C).

On the basis of the test results at ages of 23, 29, 35, and 47 hours (Table 2), the following equation relating age D to crushing strength q is obtained:

$$D/q = 0.000153D + 0.000935 \qquad (2)$$

Using these four test results, that is, using equation 2 to predict the strength at, say, 695 hours, we have

$$695/q = 0.000153(695) + 0.000935 \qquad (3)$$

As a result, 6,479 psi (44.7 MPa) is the strength of the concrete when its age reaches 695 hours. This is a close prediction of the actual average crushing strength of 6,132 psi (42.3 MPa) when the cubes were tested at an age of 695 hours.

Equation 2 predicts a crushing strength of 6,497 psi (42.3 MPa) at 1,031 hours (about 42 days). The actual average crushing strength at this age was 6,584 psi (45.3 MPa).

This series of tests covered water-cement ratios of 0.45, 0.50, and 0.55. All the

Table 1. Compression test results for concrete test cubes made of ordinary portland cement.

Age (hours)	Average Crushing Strength (psi)	Correlation Coefficient	Constant	1/m (psi)
23	3,014			
29	3,409	1.0000	0.000147	6,803
36	3,658	0.9974	0.000171	5,848
47	4,309	0.9897	0.000139	7,194
53	4,340	0.9937	0.000147	6,803
71	5,132	0.9919	0.000131	7,634
78	5,035	0.9944	0.000136	7,353
95	5,712	0.9934	0.000127	7,874
106	5,663	0.9956	0.000129	7,752
132	5,589	0.9944	0.000138	7,246
144	5,519	0.9961	0.000138	7,246
156	6,321	0.9955	0.000134	7,463
167	6,349	0.9961	0.000132	7,576
193	6,633	0.9963	0.000129	7,752
239	6,643	0.9975	0.000129	7,752
336	6,765	0.9985	0.000132	7,576
432	6,927	0.9991	0.000133	7,519
504.6	7,203	0.9993	0.000131	7,634
672	7,870	0.9979	0.000125	8,000
840	7,980	0.9982	0.000121	8,265
1,009	7,777	0.9989	0.000122	8,197

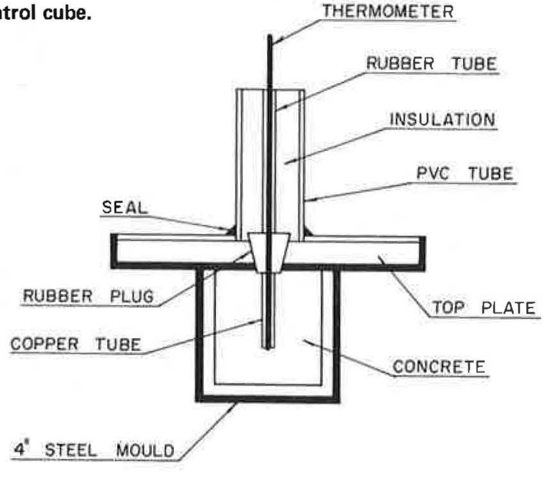
Note: Mean value of inverse of slope = 7,474 psi (51.5 MPa). 1 psi = 6.9 kPa.

Table 2. Compression test results for concrete test cubes made of rapid-hardening portland cement.

Age (hours)	Average Crushing Strength (psi)	Correlation Coefficient	Constant	1/m (psi)
23	5,240			
29	5,443	1.0000	0.000156	6,410
35	5,445	0.9990	0.000170	5,882
47	5,849	0.9978	0.000153	6,536
53	5,856	0.9989	0.000153	6,536
73	5,979	0.9996	0.000155	6,452
98	6,664	0.9961	0.000140	7,143
124	6,671	0.9980	0.000139	7,194
143	6,135	0.9958	0.000148	6,757
167	6,808	0.9962	0.000144	6,944
191	6,520	0.9973	0.000145	6,897
215	6,356	0.9976	0.000149	6,711
335	5,824	0.9952	0.000163	6,135
455	6,335	0.9973	0.000160	6,250
527	6,139	0.9983	0.000161	6,211
695	6,132	0.9991	0.000161	6,211
863	6,027	0.99932	0.000164	6,098
1,031	6,584	0.99845	0.000159	6,289

Note: 1 psi = 6.9 kPa.

Figure 1. Control cube.



test results produced similar levels of accuracy. From these tests, it could be concluded that test results obtained from cubes at ages of between 24 and 48 hours can produce close predictions of strength at higher ages. This, therefore, provides a rapid and reliable method of strength control.

HIGH SETTING TEMPERATURE

In tropical countries, like Malaysia, where aggregates, formwork, and reinforcing bars are frequently exposed to the sun, mixing, placing, and setting temperatures can be high. Often the supply situation of cement has been such that cement fresh from the cement works has to be used before it has the time to cool. Placing temperatures as high as 131 F (55 C) have occurred. It has been known that, although high curing temperatures would be beneficial because early strength is attained without subsequent adverse effects, placing and setting temperatures higher than 95 F (35 C) would reduce the maximum strength that the concrete would otherwise attain. [The reduction in strength when concrete is allowed to set at a temperature of 131 F (55 C) is also examined.] This reduction in strength is measured by comparing the test results of the cubes for which the setting temperature is 131 F (55 C) with those cubes from the same batch that are allowed to set at an average ambient temperature of 86 F (30 C) and that are then normally cured in water at 82.4 F (28 C).

Thirty-three 4-in. (10-cm) cubes were made from each batch; 11 for setting and curing at a temperature of 131 F (55 C), and the remaining 22 cubes were for normal curing in water at 82.4 ± 33.8 F (28 ± 1 C) after they had been set in the molds at an average ambient temperature of 86 F (30 C). The concrete was placed in the molds in two layers; each layer was vibrated for 1 min.

Setting Temperature of 131 F (55 C)

The 11 cubes of each batch were immediately leveled, and each mold was then covered with a watertight top plate. The molds were then placed in a tank into which water previously heated to a temperature of 131 F (55 C) was poured to completely submerge the molds. The warm water was maintained at 131 F (55 C), and the thermometers that were inserted into the center of two control cubes (Figure 1) were read periodically throughout the entire period of setting and curing. These cubes were tested at 3, 6, 9, 12, 15, 18, and 27 hours. Age was reckoned from the moment the warm water was introduced into the tank.

Normal Curing

The remaining 22 cubes from the same batch were covered with moist sacks for 24 hours in an average ambient temperature of 86 F (30 C). They were all demolded at an age of 24 hours and then cured in water maintained at a temperature of 82.4 ± 33.8 F (28 ± 1 C) until they were required for testing.

These cubes were tested at 1, 3, 7, 14, 28, 35, and 42 days. The test results of various sets are given in Table 3. All the mixes were 1:2:4 by weight. Batu Caves ¾-in. (19-mm) limestone, river sand, and a locally manufactured portland cement complying with the requirements of British Standard 12 were used.

Figure 2 shows D/q versus D for a set of cubes in which the setting temperature was 131 F (55 C). The values of the product moment correlation coefficient obtained from the test results of all the sets that were set in warm water are very close to 1. There is, therefore, a high degree of linear association between D/q and D. $1/m_a$ of the setting in warm water (Table 4) gives the inverse slopes, that is, the values of $1/m_a$ computed on the basis of the strength-age results obtained from the test cubes for ages from 3 to 27 hours. It is found that the values of $1/m_a$ decrease as the water-cement ratio increases.

Table 3. Results of cubes tested at 1, 3, 7, 14, 28, 35, and 42 days.

Water-Cement Ratio	Set No.	Warm-Water Temperature (C)	Water Temperature in Normal Curing (C)
0.40	3	55	28
0.45	2	55	28
0.50	1	45	28
0.50	1	50	28
0.50	5	55	28
0.50	1	60	28
0.50	1	65	28
0.60	3	55	28

Note: 1 C =(F - 32)/1.8

Figure 2. D/q and q versus D.

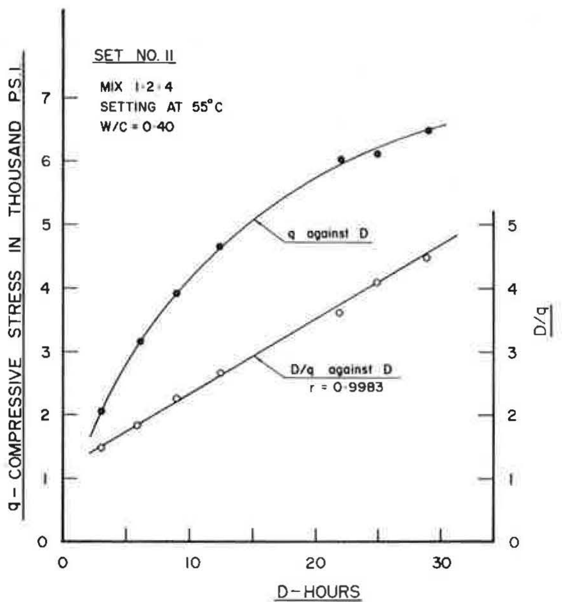


Table 4. Comparative values of $1/m_a$ and $1/m_n$.

Set No.	Water-Cement Ratio	Setting in Warm Water: Temperature (C)	Setting in Warm Water: $1/m_a$ (psi)	Setting in Ambient Temperature, 30 C, $1/m_n$ (psi)	Ratio of $1/m_a$ to $1/m_n$	Mean Ratio
4	0.40	55	9,259	9,709	0.95	
5	0.40	55	9,091	8,929	1.02	0.95
11	0.40	55	8,760	10,000	0.88	
16	0.45	55	7,107	9,015	0.79	0.80
17	0.45	55	8,053	9,902	0.81	
1	0.50	55	5,848	8,264	0.71	
2	0.50	55	4,785	6,494	0.74	
3	0.50	55	6,061	7,874	0.77	0.79
7	0.50	55	6,410	7,645	0.84	
8	0.50	55	5,714	6,525	0.88	
6	0.60	55	4,255	5,400	0.79	
14	0.60	55	4,320	6,121	0.71	0.73
15	0.60	55	4,135	5,724	0.72	
12	0.50	45	5,720	7,189	0.80	0.80
9	0.50	60	5,988	7,600	0.79	0.79
13	0.50	65	5,910	8,072	0.73	0.73

Note: 1 psi = 6.9 kPa. 1 C = (F -32)/1.8

The relation between D/q and D for the cubes that were normally cured in water at a temperature of 82.4 ± 33.8 F (28 ± 1 C) after setting at an average ambient temperature of 86 F (30 C) is also linear for all the water-cement ratios concerned.

Figure 3 shows the maximum stress computed from the inverse slope versus the water-cement ratio for the cubes that had set at ambient temperature and for those that had set in warm water. This relation between strength and cement-water ratio is approximately linear.

It is clear from Table 4 that, for every set of the test results, the value of 1/m for the cubes in which the setting was in warm water is lower than that obtained with the cubes of the same batch that had set at an average ambient temperature of 86 F (30 C). Let R be the ratio of $1/m_s$, the inverse slope of the plot of D/q against an abscissa of D obtained from the cubes in which the setting was in warm water, to $1/m_n$, the inverse slope obtained from the test results of those cubes that were normally cured. The values of R are less than 1 (Table 4), and this indicates that the higher setting temperature has considerable adverse effect on concrete strength. For example, a setting temperature of 131 F (55 C) reduces the maximum strength that the concrete will ultimately attain by 27 percent for the 1:2:4 mix with a water-cement ratio of 0.60. This is a significant reduction.

The test results show that the value of R decreases as water-cement ratio increases. The values of R are 0.95, 0.80, 0.79, and 0.73 for water-cement ratios of 0.40, 0.45, 0.50, and 0.60 respectively.

For a water-cement ratio of 0.50, the values of R are 0.80, 0.80, 0.79, and 0.73 for setting temperatures of 113, 131, 140, and 149 F (45, 55, 60, and 65 C) respectively. The maximum strength that the concrete will attain, therefore, decreases as setting temperature increases.

Development of Concrete Strength

The steepness of the strength-maturity curves at the beginning indicates very rapid initial growth of strength. This rate of growth in strength decreases as age or maturity increases until a finite value is ultimately reached. In equation 1, when q is differentiated with respect to D,

$$dq/dD = C/(mD + C)^2 \tag{4}$$

That is, the rate at which strength changes with age or maturity is equal to $C/(mD + C)^2$. When D is large, $dq/dD \to 0$; that is, after an appreciable time or maturity, the gain in strength with age becomes insignificant. The test results show that as much as 88 percent of the final concrete strength is attained at an age of 28 days for those cubes normally cured in water. This earlier attainment of final strength is typical of concrete placed under tropical conditions. The increases in strength with respect to age are, therefore, considerably less than those permitted in British Standard CP 114(1957) or in CP 110(1971).

When D is zero, that is, at the moment when the concrete begins to develop its strength,

$$dq/dD = 1/C \tag{5}$$

The value of 1/C is, therefore, the initial and also the maximum rate at which concrete develops its strength. This rate decreases as age or maturity increases. Table 5 gives the values of 1/C for the tests carried out. The value of 1/C for the cubes that had set at 131 F (55 C) is much higher than that for the cubes of the same batch that were allowed to set at an average ambient temperature of 86 F (30 C). The value of

Figure 3. Average predicted maximum compressive stress versus water-cement ratio.

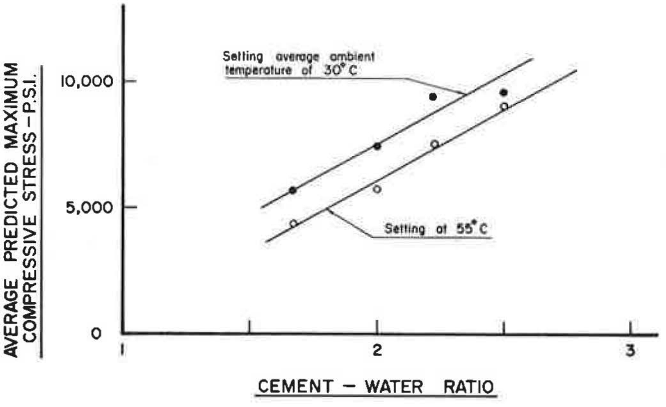


Table 5. Maximum rate of development of concrete strength.

Set No.	Water-Cement Ratio	Setting at 30 C: C x 10^{-4}	Average C x 10^{-4}	1/C	Setting at 55 C: C x 10^{-4}	Average C x 10^{-4}	1/C
4	0.40	6.43	5.01	199.6	1.07	1.14	877.2
5	0.40	3.91			1.17		
11	0.40	4.69					
16	0.45	5.70	5.69	175.7	0.84	1.22	819.6
17	0.45	5.67			1.59		
1	0.50	6.96	7.74	129.2	2.05	2.19	456.6
2	0.50	8.78			2.40		
3	0.50	7.92			1.98		
7	0.50	7.10			2.15		
8	0.50	7.94			2.35		
6	0.60	13.87	13.87	72.1	3.02	3.17	315.5
14	0.60	12.97			3.18		
15	0.60	14.78			3.31		

Note: 1 C = (F - 32)/1.8

1/C increases as the water-cement ratio for both the setting temperatures increases. The test results show that the higher the value of 1/C is, that is, the higher the initial rate of growth of strength is, the lower the maximum strength finally attained by the concrete will be.

CONCLUSIONS

This paper reports on a limited pilot study that is being extended to cover a larger range of water-cement ratios and setting temperatures and types of cement and aggregates. In particular, it will be expanded to determine whether there is in fact a critical setting temperature below which concrete strength will not be adversely affected. It seems necessary to extend the tests of the cubes that set at the high temperatures to higher maturities or ages than those reported in this paper to ascertain whether there is any possible recovery of concrete strength with time.

On the basis of the test results, the following conclusions have emerged:

1. The compressive test results obtained with cubes at ages between 24 and 48 hours can produce a close prediction of compressive strength at later ages.
2. Setting temperatures of 113 to 140 F (45 to 60 C) have significant adverse effects on concrete strength. The reduction in strength increases as the water-cement ratio increases.
3. The higher the initial rate of growth of concrete strength is, the lower the maximum strength finally attained by the concrete will be.
4. Under the higher ambient and water temperatures in the tropics, there is an earlier attainment of final concrete strength.

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