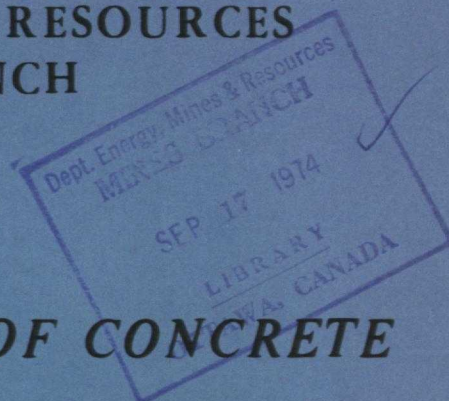




DEPARTMENT OF
ENERGY, MINES AND RESOURCES
MINES BRANCH
OTTAWA



*RAPID ESTIMATION OF CONCRETE
STRENGTHS POTENTIAL FOR HYDRO-QUEBEC
DAMS WITH SPECIAL REFERENCE TO
MODIFIED BOILING METHOD*

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RAPID ESTIMATION OF CONCRETE STRENGTH POTENTIAL FOR HYDRO-QUEBEC DAMS WITH SPECIAL REFERENCE TO MODIFIED BOILING METHOD (*)

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CANADA

INTRODUCTION

For large concrete dams and other massive concrete structures, the design criterion of the quality of concrete is generally a 91-day or a 1-year compressive strength of test cylinders/cubes that are cast, cured and tested under controlled laboratory conditions. In order to make sure that concrete-in-place will meet the 91-day or 1-year strength requirements, test specimens, cast and tested at 3, 7 and 28 days, provide early indications of the potential strength of the concrete. New design concepts and a steadily increased speed of construction, by which 300 to 400 cu yd (229 to 306 cu m) of concrete can be placed in one hour, demand that potential strength of concrete be known at the earliest possible time after the concrete has been placed. The results of strength tests made prior to 7 days on cylin-

(*) *Evaluation rapide de la résistance du béton des barrages d'Hydro-Québec par la méthode d'ébullition modifiée.*

ders/cubes, cured in a standard moist-room curing environment ⁽¹⁾, usually show a wide dispersion; some means of accelerating the strength development of concrete must be found. An earlier strength determination of concrete with satisfactory reliability would allow the field concrete engineer to make necessary changes in the design of concrete mixes sooner, thus maintaining quality of concrete.

A number of accelerated-strength test methods have been developed and used in several countries to control the quality of concrete during the construction of large dams [1-5]. This paper refers to two such methods which have been tried by the Quebec Hydro-Electric Commission (Hydro-Quebec) and describes in detail the modified boiling method which was adopted by the Commission as a control test during the construction of a 270-ft (82.3-m) high concrete gravity dam at Outardes-3.

ACCELERATED CURING METHODS USED BY HYDRO-QUEBEC

Hydro-Quebec has used the following two accelerated curing methods during the construction of the Manicouagan-Outardes hydro-electric complex.

- 1) The 48-hour hot-water method,
- 2) The modified boiling method.

THE 48-HOUR HOT-WATER METHOD.

In this method, which was used initially on an experimental basis during the construction of the 703-ft (214.3-m) high concrete, multiple - arch Manicouagan - 5 dam, the test procedure was as follows [6]:

The 8 × 16-in. (20 × 40-cm) test cylinders were cured in the laboratory at ambient temperature and humidity for 10 hr, followed by heating in water at 170 °F (77 °C) for 38 hr, and the compressive strength was measured *immediately* afterwards. The total elapsed time between moulding and testing of cylinders was 48 hr.

Figure 1 shows the relationship between compressive strengths at 48 hr after hot-water curing and those at 91 days after standard moist-curing. This relationship is based upon the testing of several hundred 8 × 16-in. (20 × 40-cm) test cylinders [6].

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

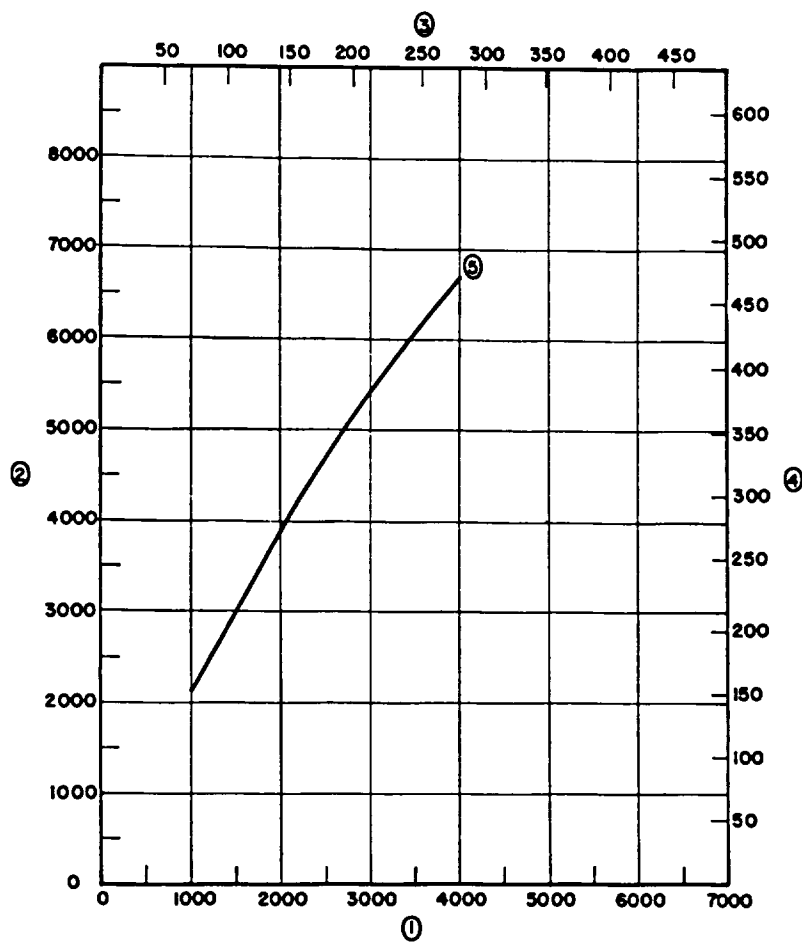


Fig. 1

Relationship of accelerated to 91-day strength — hot-water method,
Manicouagan-5 project.

- | | |
|-----------------------------------------------------------------|---------------------------------------|
| (1) Accelerated strength, lb/in. ² - X. | (4) 91-day standard-cured strength, |
| (2) 91-day standard-cured strength, | kg/cm ² - Y ₁ . |
| lb/in. ² - Y. | (5) Regression line. |
| (3) Accelerated strength, kg/cm ² - X ₁ . | |

*Rapport de la résistance accélérée à résistance normale de 91 jours —
méthode eau chaude, projet Manicouagan 5.*

- | | |
|-----------------------------------------------------------------|-----------------------------------------------|
| (1) Résistance accélérée, lb/po ² - X. | (4) Résistance après 91 jours de cure |
| (2) Résistance après cure humide de | humide, kg/cm ² - Y ₁ . |
| 91 jours, lb/po ² - Y; | (5) Ligne de régression. |
| (3) Résistance accélérée, kg/cm ² - X ₁ . | |

In 1967, after two years of experimentation this test method was approved by the Hydro-Quebec as a routine test for controlling the quality of concrete for Manicouagan-5 dam.

THE MODIFIED BOILING METHOD.

This method, *in its present form*, was developed by the Canadian Mines Branch in Ottawa [7]. Briefly, the method consists of curing 6 × 12-in. (15 × 30-cm) test cylinders under standard moist curing

environment for 24 hr, followed by boiling in water for 3-1/2 hr and measuring compressive strength one hr later. Recently this method was selected by ASTM ⁽²⁾ as one of the three most promising methods for an international cooperative testing programme [8, 9, 10].

Initial investigations carried out at the Canadian Mines Branch indicated that the modified boiling method could be satisfactorily used for predicting the potential strength of concrete at later ages [7]. As a result of this work, Laboratoire de Béton Inc., Montreal, a testing and inspection company, which had been retained by Hydro-Quebec to provide the quality control services for Manicouagan-2 concrete dam and allied structures, installed an accelerated curing tank at its field laboratory. Unfortunately when the accelerated strength-testing programme was started in 1964, the dam construction was already nearing completion, and therefore, only a limited number of test results could be obtained. The analysis of these rather limited test data did confirm the findings of the Mines Branch as to the usefulness of the accelerated strength test [11].

In 1964, Hydro-Quebec commenced the construction of a concrete gravity dam at Outardes-3. The 6-in. (15-cm) aggregate concrete for the interior of the dam was to have a strength of 1750 psi (1230 kg/cm²) at 1 year. For routine control of quality of concrete, Hydro-Quebec selected the modified boiling method for the job. Before this test was finally adopted as the control test, further investigations were carried out both in the field laboratory ⁽³⁾ at Outardes-3 and at the Mines Branch [12] to obtain additional information on :

a) Compressive strength of 6 × 12-in. (15 × 30-cm) test cylinders after 23 hr of standard moist-curing to see if test cylinders could be handled at low strengths without damage.

b) Percentage gain in compressive strength of 6 × 12-in. (15 × 30-cm) test cylinders after accelerated curing, to justify the use of this test.

USE OF THE MODIFIED BOILING METHOD AT THE OUTARDES-3 PROJECT

DETAILS OF THE TEST METHOD.

The salient features of the modified boiling method are as follows [7] :

(i) Three 6 × 12-in. (15 × 30-cm) test cylinders are prepared

⁽²⁾ The American Society for Testing and Materials, Philadelphia, Pa, U.S.A.

⁽³⁾ Laboratoire d'Inspection et d'Essais Inc.

in steel moulds, using standard moulding methods. The delay between the mixing of concrete and preparation of test specimens should not exceed 30 min.

(ii) Immediately after moulding, all moulds are tightly closed with steel cover plates and placed in a moist-curing room or a water-filled tank maintained at 73.4 ± 3 °F (23 ± 1.7 °C) temperature and 100 per cent relative humidity. If suitable moist-curing facilities are not available, the moulds should be covered with moist burlap and kept wet for 24 hr.

(iii) At the end of this curing period, the cylinders are removed from the curing room and placed, *complete with their moulds and covers*, in boiling water. The temperature of the water should be kept just below the boiling point, 212 °F (100 °C), to avoid excessive evaporation.

(iv) After 3-1/2 hr of boiling, the cylinders are removed from the boiling water, the moulds are stripped, and the specimens are allowed to cool for 45 min. By the end of this cooling period the cylinders reach a temperature of about 135 °F (57 °C).

(v) The test cylinders are weighed, capped and tested in compression, 15 min later.

The total elapsed time between moulding and testing of cylinders is 28-1/2 hr.

MATERIALS USED.

Crushed granitic gneiss was used as the coarse aggregate; the fine aggregate consisted of a blend of two natural sands. The overall gradings of fine and coarse aggregates used in the design of concrete mixes are given in Tables 1 and 2. These grading were modified at times to suit job conditions.

TABLE 1
Grading of Fine Aggregate

Sieve Size		Individual Percentage Retained, by weight
No.	mm	
4	4,76	11-13
8	2,38	25-27
16	1,19	30-32
30	0,596	16-20
50	0,297	10-12
100	0,149	2-4
Pan		1-2

TABLE 2
Grading of Coarse Aggregate

Size of Aggregate		Per cent (by weight)
in.	mm	
3/16 to 3/8	4,76 - 9,5	9
3/8 to 3/4	9,50 - 19,0	17
3/4 to 1 1/2	19,0 - 38,0	23
1 1/2 to 3	38,0 - 76,0	25
3 to 6	76,0 - 152,0	26

Low-heat portland cement obtained from 2 different sources was used. Special features of this cement are its low heat of hydration and its limit of 5 per cent on the maximum content of tricalcium aluminate (C_3A). The average physical and chemical properties of this cement together with the calculated compound composition are given in Table 3.

Apart from a commercially obtained air-entraining agent, no chemical admixtures were used in the concrete mixes.

MIX DESIGN DATA.

The water/cement ratio (by weight) of the mixes varied from 0.55 to 0.66, and the cement content varied from 330 to 230 lb/cu yd (196 to 137 kg/cu m). The proportion of fine aggregate ranged from about 24 to 27 per cent of the total aggregate by weight, for concrete made with 6-in. (152-cm) maximum size aggregate.

PROPERTIES OF FRESH CONCRETE.

The properties of fresh concrete, i. e. temperature, slump, unit weight and air content, are given in Table 4.

MOULDING AND CURING OF TEST SPECIMENS.

The test cylinders were cast in a laboratory adjacent to the concrete batch plant. The concrete was brought in from the batch plant in a small bucket and discharged on to a 1 1/2-in. (38-mm) vibrating screen for wet-screening. The wet-screened concrete was remixed by hand before using it for casting test specimens.

The 6 × 12-in. (15 × 30-cm) cylinders were prepared according

TABLE 3

*Physical Properties, Chemical Analyses and Calculated Compound Composition of Low-Heat Portland Cements **

Description of Test	Source	
	A	B
<i>Physical Tests (General)</i>		
Time of Set (Vicat needle)		
Initial, hr:min	2 : 30	4 . 10
Final, hr:min	4 : 30	5 . 25
Specific Surface (Air Permeability Method), cm ² /g	3300	3250
Soundness (Autoclave), %	0 . 09	0 . 1
Heat of hydration at 7 days, cal	62	62
<i>Physical Tests – Mortar Strength</i>		
Compressive Strength, 2-in. (5-cm) cube, lb/in ² . (kg/cm ²).		
3-day	1885 (132)	1900 (134)
7-day	2625 (184)	2650 (186)
28-day	4660 (327)	4660 (328)
90-day	6035 (424)	6535 (459)
<i>Chemical Analyses</i>		
Insoluble Residue, %	0 . 24	0 . 19
Silicon Dioxide, %	23 . 0	22 . 0
Aluminum Oxide, %	4 . 4	4 . 2
Ferric Oxide, %	4 . 4	4 . 0
Calcium Oxide (total)	61 . 3	62 . 5
Magnesium Oxide, %	2 . 7	3 . 3
Sulphur Trioxide, %	2 . 2	2 . 0
Loss on Igniton, %	0 . 8	0 . 9
Free Lime	0 . 3	0 . 3
<i>Calculated Compound Composition</i>		
Tricalcium Silicate C ₃ S , %	31 . 3	46 . 4
Dicalcium Silicate C ₂ S, %	42 . 3	28 . 1
Tricalcium Aluminate C ₃ A , %	4 . 2	4 . 4
Tetracalcium Alumino Ferrite C ₄ AF, %	13 . 4	12 . 2

* Test data supplied by a commercial testing laboratory and cement manufacturers.

TABLE 4
Properties of Fresh Concrete

Type ⁺ of Concrete	W/C ⁺⁺	Temperature* °F (°C)			Slump*, in. (cm)			Unit Weight*, lbs/cu ft (kg/cu m)			Air Content, %		
		Max.	Min.	Average	Max.	Min.	Average**	Max.	Min.	Average	Max.	Min.	Average
SE	0.66	63 (17)	48 (9)	54 (12)	2.0 (5.1)	0.25 (0.6)	1.0 (2.5)	160.6 (2573)	154.1 (2468)	157.5 (2523)	4.7	2.5	3.4
SE	0.65	69 (21)	59 (15)	63 (17)	2.0 (5.1)	0.25 (0.6)	0.75 (1.9)	164.0 (2627)	153.0 (2451)	157.2 (2520)	4.8	2.0	3.7
AL	0.58	68 (20)	52 (11)	62 (16)	2.5 (6.4)	0.25 (0.6)	1.0 (2.5)	160.0 (2563)	152.0 (2435)	154.8 (2480)	5.8	2.2	4.1
AL	0.65	65 (18)	57 (14)	62 (16)	2.5 (6.4)	0.25 (0.6)	1.5 (3.8)	155.0 (2483)	152.0 (2435)	153.7 (2462)	5.4	3.5	4.2
NT	0.55	67 (19)	54 (12)	62 (16)	3.5 (8.9)	0.25 (0.6)	1.5 (3.8)	163.0 (2611)	153.0 (2451)	157.0 (2515)	4.7	2.5	3.6

* Figures in brackets are the equivalent values in metric units.

** Rounded off to the nearest 1/4-in.

+ SE = Mass concrete, 6-in. maximum size aggregate.

+ AL = Downstream-face concrete, 3-in. maximum size aggregate.

+ NT = Upstream-face concrete, 6-in. maximum size aggregate.

** Water/cement ratio (by weight).

to the CSA ⁽⁴⁾ Standard A23.12. The moulds were filled in two approximately equal layers. Each of the two layers was compacted with a 3/4-in. (19-mm) diameter internal vibrator, inserted three times. Immediately afterwards, water-tight cover plates were placed on top of the moulds, and the moulds were removed to a room maintained at $70 \pm 2^\circ\text{F}$ ($21 \pm 1^\circ\text{C}$) and placed in water troughs held at the same temperature as the room.

After 23 1/2 hr of curing, the test cylinders still in their moulds were transported to the main field laboratory where, 1/2 hr later, three specimens from each batch were subjected to accelerated curing and the remaining three cylinders from the same batch were cured in water for 91 days, the water being maintained at $70 \pm 2^\circ\text{F}$ ($21 \pm 1^\circ\text{C}$).

TESTING OF SPECIMENS.

All testing was carried out in the main field laboratory in a 400,000 -lb (180,000 -kg) Forney 2-range machine. All specimens were capped before testing using a proprietary capping compound.

COMPRESSIVE STRENGTH TEST RESULTS.

A total of 244 test results were available for analyses, which were confined to the relationships between the test results of accelerated-cured and 91-day moist cured cylinders. The compressive strength of the test cylinders, after accelerated curing, varied from 280 to 1760 lb/in.² (20 to 124 kg/cm²) and the corresponding strength values of the cylinders after moist curing for 91 days ranged from 1820 to 6550 lb/in.² (128 to 460 kg/cm²).

ANALYSES OF TEST RESULTS.

Method.

Standard statistical methods were used to determine the line of best fit for predicting 91-day compressive strengths from accelerated 28 1/2-hr strengths. The estimate of the accuracy of prediction is expressed within ± 15 per cent.

Before the analyses were carried out, statistical considerations together with professional experience were used to eliminate three test results which probably had been influenced by certain undesirable

(4) Canadian Standards Association, Toronto, Canada.

and assignable factors. In the analyses, no allowance was made for the changes in the composition of cement, for errors of individual inspectors, and for changes in the gradings of aggregates.

Summary.

The number of test results analysed and the correlation coefficients for the various types of concretes are shown in Table 5. The regression equations are given in Table 6; also included in this Table is the standard deviation of the regression lines.

The plots of the test results, together with lines for best fit and for the limits ± 15 per cent are shown in Figures 2 to 6. The relationships between the 28 1/2-hr strengths after accelerated curing and 91-day strengths after moist curing for the various types of concretes are shown in Figure 7 to bring out the effects of water/cement ratio.

In order to compare the reproducibility of the strengths after accelerated and moist curing for 91 days, coefficients of variation have been calculated for the two strengths (Table 7).

To evaluate the laboratory testing and casting techniques, the within-batch coefficients of variation for the strengths of test cylinders after accelerated and 91-day moist curing have been determined. This analysis is shown in Table 8; also shown for comparison is the maximum value for within-batch variation recommended by the ACI ⁽⁵⁾ [13].

DISCUSSION OF TEST RESULTS

ELIMINATION OF ERRATIC TEST RESULTS.

Professional experience and statistical evidence were used to screen the test data. The number of test results thus omitted from the analyses was only 3, i.e. about 1 per cent of the total number of results considered. The test results that were omitted had rather high values for 91-day compressive strengths.

EFFECT OF CEMENT TYPE.

The relationships (Table 6) between compressive strengths of the test cylinders after accelerated and moist curing are true only

(5) American Concrete Institute, Detroit, Michigan, U.S.A.

TABLE 5
Number of Test Results Analyzed and Correlation Coefficients

Type of Concrete	W/C*	No. of Test Results	No. of Test Results Considered Unsatisfactory	No. of Test Results Analyzed	Correlation Coefficient	Required Value of "r" for Correlation to be Significant at 1 % Level	Refer to Figure No.
SE	0.66	22	none	22	0.729	0.537	1
SE	0.65	110	none	110	0.899	0.254	2
AL	0.58	25	1	24	0.660	0.511	3
AL	0.65	10	none	10	0.909	0.765	4
NT	0.55	77	2	75	0.930	0.296	5
	Total	244	3	241	0.950	0.254	6

* Water/cement ratio by weight.

TABLE 6
Results of Regression Analysis

Type of Concrete	W/C*	Regression Equation		Standard Deviation about the Regression Line		Refer to Figure No.
		$Y = A + BX$ lb/in. ²	$Y_1 = A_1 + B_1 X_1$ kg/cm ²	lb/in. ²	kg/cm ²	
SE	0.66	$Y = 1647 + 2.86X$	$Y_1 = 115.8 + 2.86X_1$	440	30.9	1
SE	0.65	$Y = 761 + 3.72X$	$Y_1 = 53.5 + 3.72X_1$	254	17.9	2
AL	0.58	$Y = 2513 + 2.03X$	$Y_1 = 176.7 + 2.03X_1$	376	26.4	3
AL	0.65	$Y = 797 + 3.59X$	$Y_1 = 56.0 + 3.59X_1$	210	14.8	4
NT	0.55	$Y = 2256 + 2.52X$	$Y_1 = 158.6 + 2.52X_1$	289	20.3	5
Combined Data for all Concretes		$Y = 1.42X + 0.78$ lb/in. ²	$Y_1 = 11.85X + 0.78$ kg/cm ²	358	25.2	6

* Water/cement ratio by weight.

X = Compressive strength after accelerated curing, lb/in.²

Y = Compressive strength after 91-day moist-curing, lb/in.²

A₁, B₁ = Constants.

X₁ = Compressive strength after accelerated curing, kg/cm².

Y₁ = Compressive strength after 91-day moist-curing, kg/cm².

A, B, = Constants.

TABLE 7
Statistical Summary of Test Data

Type of Concrete	W/C*	Number of Test Results**	Average Strength				Standard Deviation				Coefficient of Variation	
			Accelerated-cured		91-day moist-cured		Accelerated-cured		91-day moist-cured		Accelerated-cured	91-day moist-cured
			lb/in. ²	kg/cm ²	lb/in. ²	kg/cm ²	lb/in. ²	kg/cm ²	lb/in. ²	kg/cm ²	per cent	per cent
SE	0.66	16	605	42	3480	245	168	11.8	556	39.2	27.9	16.0
SE	0.65	(a) 85	500	35	2615	184	111	7.8	503	35.4	22.2	19.2
		(b) 25	680	48	3320	233	144	10.1	495	34.8	21.2	14.9
AL	0.58	24	830	58	4195	295	162	11.4	500	35.2	19.5	11.9
AL	0.65	10	875	61	4145	291	127	8.9	501	35.2	14.5	12.1
NT	0.55	(a) 33	920	65	4600	323	187	13.1	632	44.4	20.3	13.7
		(b) 42	1340	94	5610	404	209	14.7	578	40.6	15.6	10.3

* Water/cement ratio by weight.

** Data for concrete types SE (w/c = 0.65) and NT (w/c = 0.55) has been divided into two groups each to eliminate the effect of different brands of cements used.

TABLE 8
Within-Batch Coefficients of Variation

Type of Concrete	W/C*	Number of Test Results	Coefficients of Variation,** per cent	
			Accelerated cured	91-day moist cured
SE	0.66	22	3.9	3.1
SE	0.65	110	2.9	3.4
AL	0.58	24	3.5	2.4
AL	0.65	10	3.1	2.6
NT	0.55	75	3.4	3.1
ACI recommended values for excellent field control = less than 3.0 per cent				

* Water/cement ratio by weight.

** Coefficients of variation are based upon the results of three 6 × 12-in. (15 × 30-cm) cylinders.

for low-heat portland cement. The laboratory and field studies have indicated that changing the type of cement would change the relationships between the two strengths under discussion [11].

EFFECT OF WATER/CEMENT RATIO.

Figure 8 shows that at low strength levels, for equal strengths of accelerated-cured test cylinders, the ratio of the strength of accelerated cured to 91-day moist cured test cylinders is lower for concretes with lower water/cement ratios than for concretes with higher water/cement ratios: for example, for 600 psi (42 kg/cm²) strength of accelerated cured test cylinders, the above ratios are 0.20 and 0.16 for water/cement ratios of 0.66 and 0.55 respectively. Figure 8 therefore raises the possibility of a significant difference between the regression equations for different types of concrete investigated. The significance of the apparent variations of water-cement ratio has not been statistically analyzed. If this difference is statistically significant, the regression equation for the combined data, Figure 7, is not independent of the water/cement ratio.

REPRODUCIBILITY OF THE RESULTS OF THE ACCELERATED STRENGTH TEST.

The coefficients of variation of the compressive strength of test cylinders after accelerated curing are higher than the coefficients of

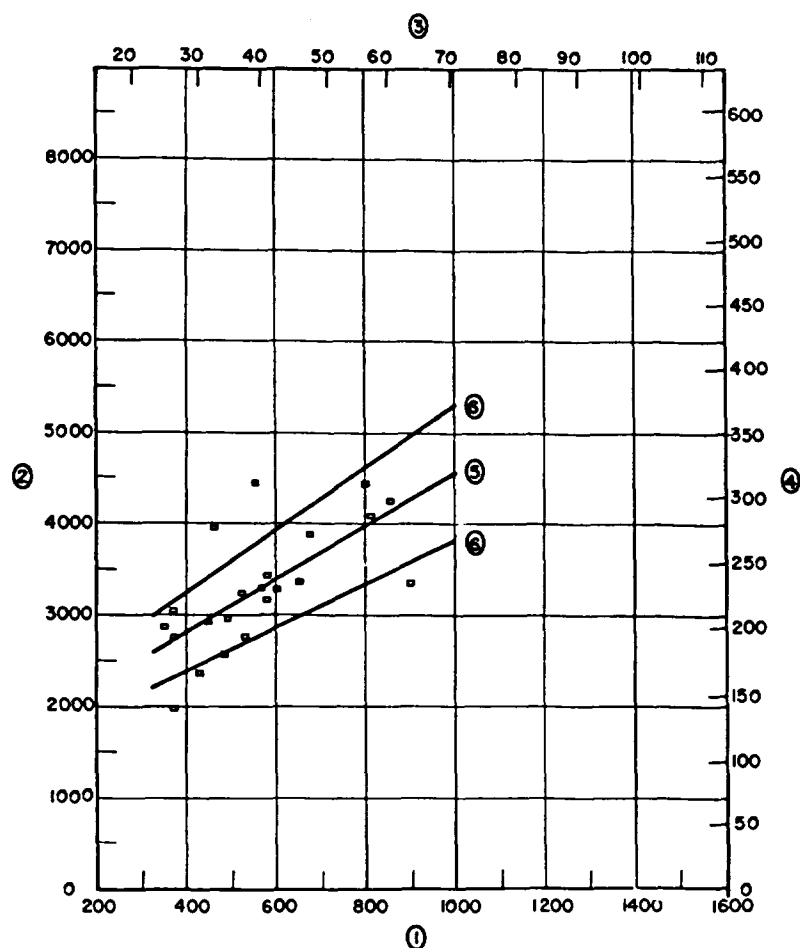


Fig. 2

Relationship of accelerated to 91-day strength — modified boiling method.
Water/cement ratio = 0.66.

- (1) Accelerated strength, lb/in.² - X.
- (2) 91-day standard-cured strength, lb/in.² - Y.
- (3) Accelerated strength, kg/cm² - X₁.
- (4) 91-day standard-cured strength, kg/cm² - Y₁.
- (5) Regression line.
- (6) ± 15 per cent limits.

Additional information :

Number of test results = 22.
Correlation coefficient = 0.729.
Equation of regression line,
 $Y = 1647 + 2.86 X$ lb/in.²;
 $Y_1 = 115.8 + 2.86 X_1$ kg/cm².
Standard deviation = 440 lb/in.²,
30.9 kg/cm².

*Rapport de la résistance accélérée à résistance normale de 91 jours —
méthode d'ébullition modifiée. Rapport eau/ciment = 0.66.*

- (1) Résistance accélérée, lb/po² - X.
- (2) Résistance après 91 jours de cure humide, lb/po² - Y.
- (3) Résistance accélérée, kg/cm² - X₁.
- (4) Résistance après 91 jours de cure humide, kg/cm² - Y₁.
- (5) Ligne de régression.
- (6) Limites de ± 15 pour cent.

Information supplémentaire :

Nombre de résultats d'essais = 22.
Coefficient de corrélation = 0.729.
Equation de la ligne de régression,
 $Y = 1647 + 2.86 X$ lb/po²;
 $Y_1 = 115.8 + 2.86 X_1$ kg/cm².
Ecart type = 440 lb/po²;
30.9 kg/cm².

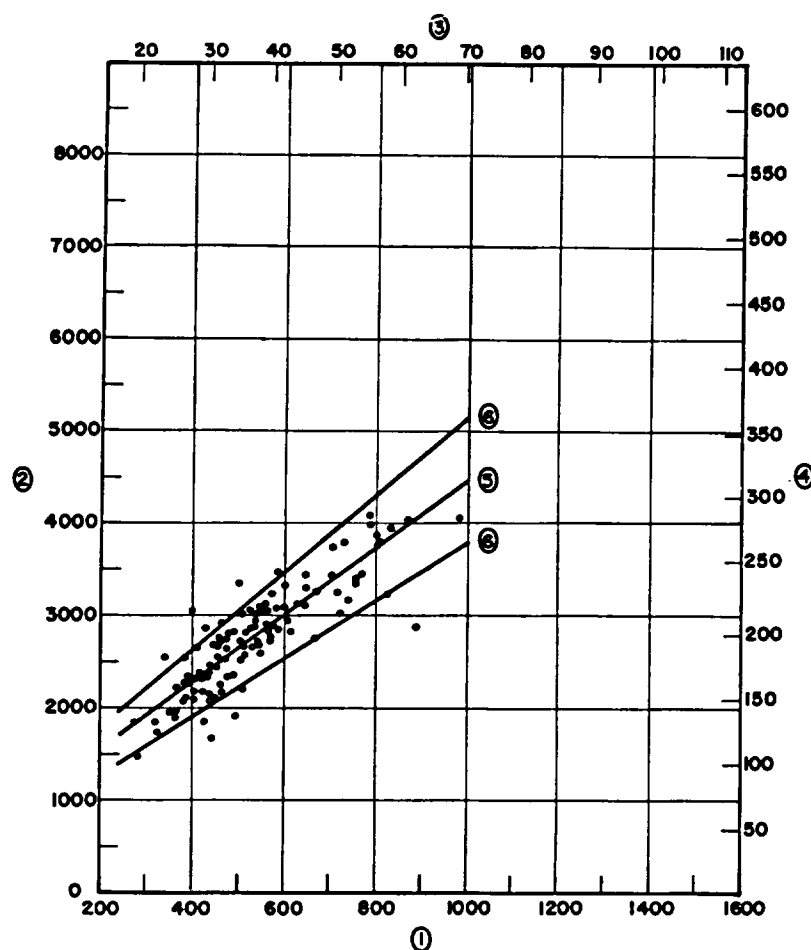


Fig. 3

Relationship of accelerated to 91-day strength — modified boiling method.
Water/cement ratio = 0.65.

- (1) Accelerated strength, lb/in.² - X.
- (2) 91-day standard-cured strength, lb/in.² - Y.
- (3) Accelerated strength, kg/cm² - X₁.
- (4) 91-day standard-cured strength, kg/cm² - Y₁.
- (5) Regression line.
- (6) ± 15 per cent limits.

Additional information :

Number of test results = 110.

Correlation coefficient = 0.899.

Equation of regression line,

$$Y = 761 + 3.72 X \text{ lb/in.}^2;$$

$$Y_1 = 53.5 + 3.72 X_1 \text{ kg/cm}^2.$$

Standard deviation = 254 lb/in.²;

17.9 kg/cm².

*Rapport de la résistance accélérée à résistance normale de 91 jours —
méthode d'ébullition modifiée. Rapport eau/ciment = 0.65.*

- (1) Résistance accélérée, lb/po² - X.
- (2) Résistance à 91 jours de cure humide, lb/po² - Y.
- (3) Résistance accélérée, kg/cm² - X₁.
- (4) Résistance à 91 jours de cure humide, kg/cm² - Y₁.
- (5) Ligne de régression.
- (6) Limites de ± 15 pour cent.

Information supplémentaire :

Nombre de résultats d'essai = 110.

Coefficient de corrélation = 0.899.

Equation de la ligne de régression,

$$Y = 761 + 3.72 X \text{ lb/po}^2;$$

$$Y_1 = 53.5 + 3.72 X_1 \text{ kg/cm}^2.$$

Ecart type = 254 lb/po²;

17.9 kg/cm².

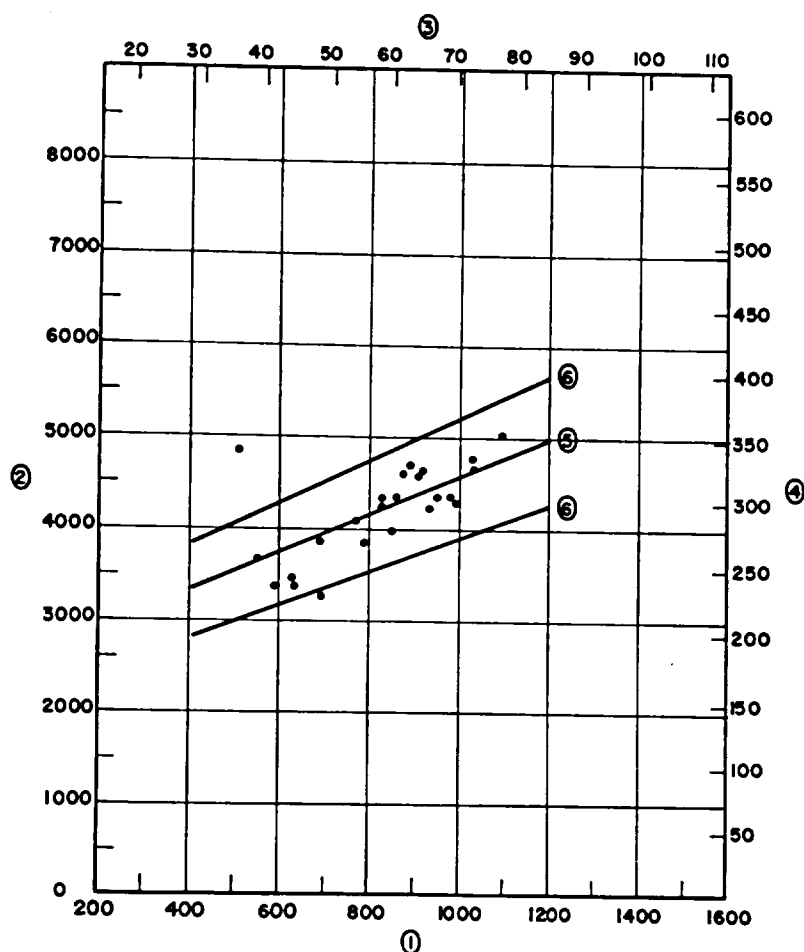


Fig. 4

Relationship of accelerated to 91-day strength — modified boiling method.
Water/cement ratio = 0.58.

- (1) Accelerated strength, lb/in.² - X.
- (2) 91-day standard-cured strength, lb/in.² - Y.
- (3) Accelerated strength, kg/cm² - X₁.
- (4) 91-day standard-cured strength, kg/cm² - Y₁.
- (5) Regression line.
- (6) ± 15 per cent limits.

Additional information :

Number of test results = 24.
Correlation coefficient = 0.660.
Equation of regression line,
 $Y = 2513 + 2.03 X$ lb/in.²;
 $Y_1 = 176.7 + 2.03 X_1$ kg/cm².
Standard deviation = 376 lb/in.²;
26.4 kg/cm².

*Rapport de la résistance accélérée à résistance normale de 91 jours —
méthode d'ébullition modifiée. Rapport eau/ciment = 0.58.*

- (1) Résistance accélérée, lb/po² - X.
- (2) Résistance à 91 jours de cure humide, lb/po² - Y.
- (3) Résistance accélérée, kg/cm² - X₁.
- (4) Résistance à 91 jours de cure humide, kg/cm² - Y₁.
- (5) Ligne de régression.
- (6) Limites de ± 15 pour cent.

Information supplémentaire :

Nombre de résultats d'essai = 24.
Coefficient de corrélation = 0.660.
Equation de la ligne de régression,
 $Y = 2513 + 2.03 X$ lb/po²;
 $Y_1 = 176.7 + 2.03 X_1$ kg/cm².
Ecart type = 376 lb/po²;
26.4 kg/cm².

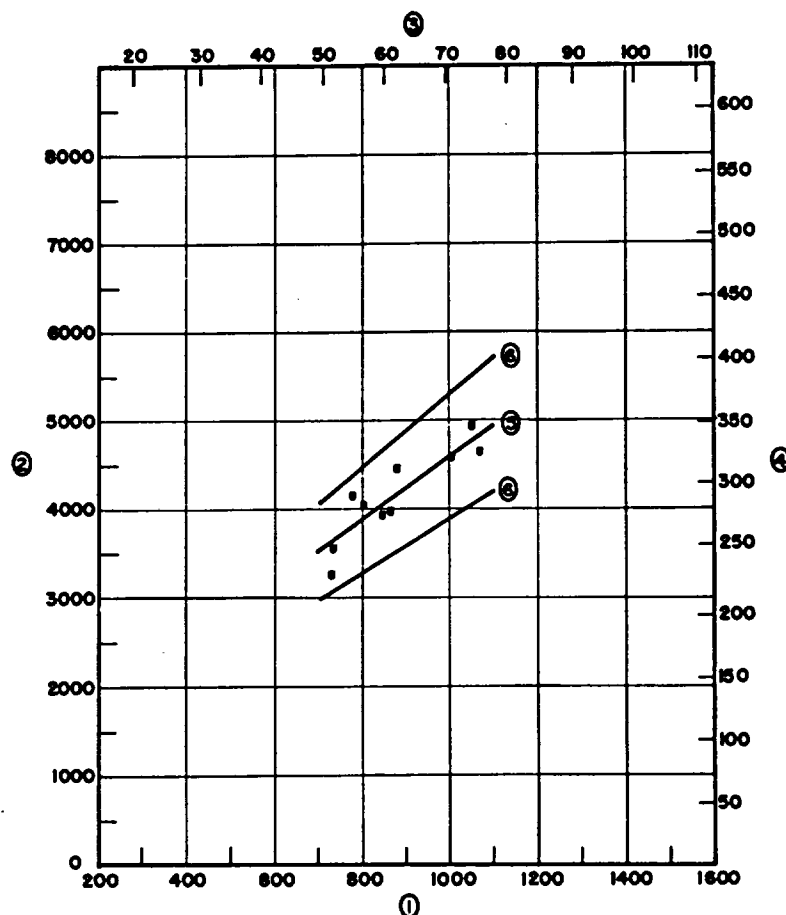


Fig. 5

Relationship of accelerated to 91-day strength — modified boiling method.
Water/cement ratio = 0.65.

- (1) Accelerated strength, lb/in.² - X.
- (2) 91-day standard-cured strength, lb/in.² - Y.
- (3) Accelerated strength, kg/cm² - X₁.
- (4) 91-day standard-cured strength, kg/cm² - Y₁.
- (5) Regression line.
- (6) ± 15 per cent limits.

Additional information :

Number of test results = 10.

Correlation coefficient = 0.909.

Equation of regression line,

$$Y = 797 + 3.59 X \text{ lb/in.}^2;$$

$$Y_1 = 56.0 + 3.59 X_1 \text{ kg/cm}^2.$$

Standard deviation = 210 lb/in.²;

14.8 kg/cm².

Rapport de la résistance accélérée à résistance normale de 91 jours — méthode d'ébullition modifiée. Rapport eau/ciment = 0.65.

- (1) Résistance accélérée, lb/po² - X.
- (2) Résistance à 91 jours de cure humide, lb/po² - Y.
- (3) Résistance accélérée, kg/cm² - X₁.
- (4) Résistance à 91 jours de cure humide, kg/cm² - Y₁.
- (5) Ligne de régression.
- (6) Limites de ± 15 pour cent.

Information supplémentaire :

Nombre de résultats d'essai = 10.

Coefficient de corrélation = 0.909.

Equation de la ligne de régression,

$$Y = 797 + 3.59 X \text{ lb/po}^2;$$

$$Y_1 = 56.0 + 3.59 X_1 \text{ kg/cm}^2.$$

Ecart type = 210 lb/po²;

14.8 kg/cm².

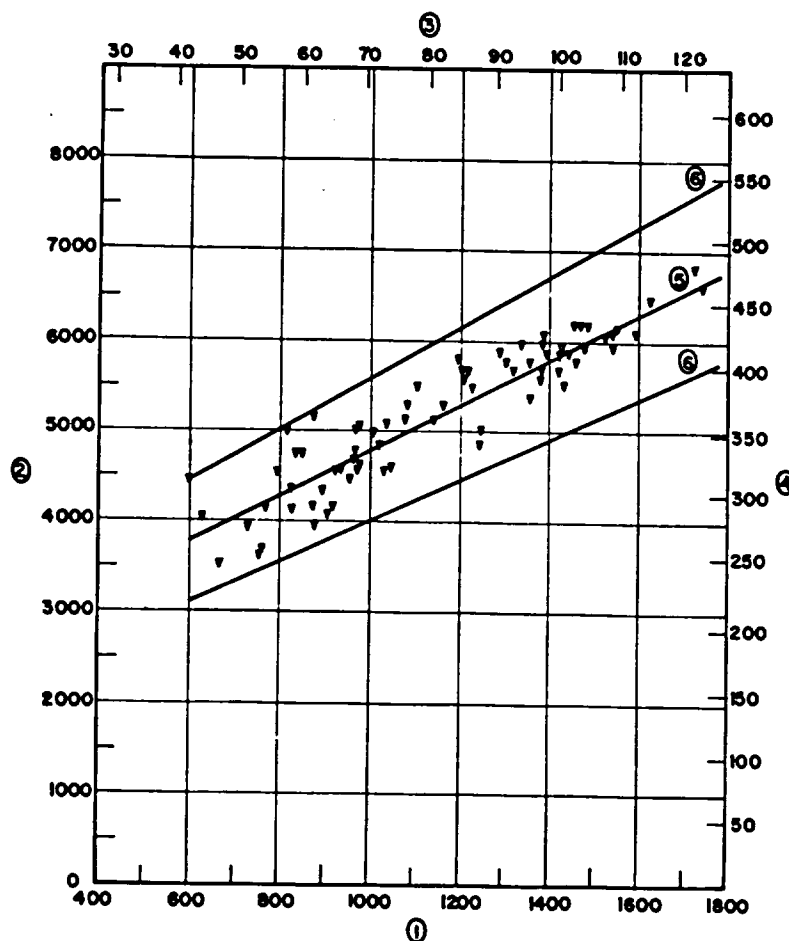


Fig. 6

Relationship of accelerated to 91-day strength — modified boiling method.
Water/cement ratio = 0.55.

- (1) Accelerated strength, lb/in.² - X.
- (2) 91-day standard-cured strength, lb/in.² - Y.
- (3) Accelerated strength, kg/cm² - X₁.
- (4) 91-day standard-cured strength, kg/cm² - Y₁.
- (5) Regression line.
- (6) ± 15 per cent limits.

Additional information :

Number of test results = 75.

Correlation coefficient = 0.930.

Equation of regression line,

$$Y = 2256 + 2.52 X \text{ lb/in.}^2;$$

$$Y_1 = 158.6 + 2.52 X_1 \text{ kg/cm}^2.$$

Standard deviation = 289 lb/in.²;
20.3 kg/cm².

*Rapport de la résistance accélérée à résistance normale de 91 jours —
méthode d'ébullition modifiée. Rapport eau/ciment = 0.55.*

- (1) Résistance accélérée, lb/po² - X.
- (2) Résistance à 91 jours de cure humide, lb/po² - Y.
- (3) Résistance accélérée, kg/cm² - X₁.
- (4) Résistance à 91 jours de cure humide, kg/cm² - Y₁.
- (5) Ligne de régression.
- (6) Limites de ± 15 pour cent.

Information supplémentaire :

Nombre de résultats d'essai = 75.

Coefficient de corrélation = 0.930.

Equation de la ligne de régression,

$$Y = 2256 + 2.52 X \text{ lb/po}^2;$$

$$Y_1 = 158.6 + 2.52 X_1 \text{ kg/cm}^2.$$

Ecart type = 289 lb/po²;
20.3 kg/cm².

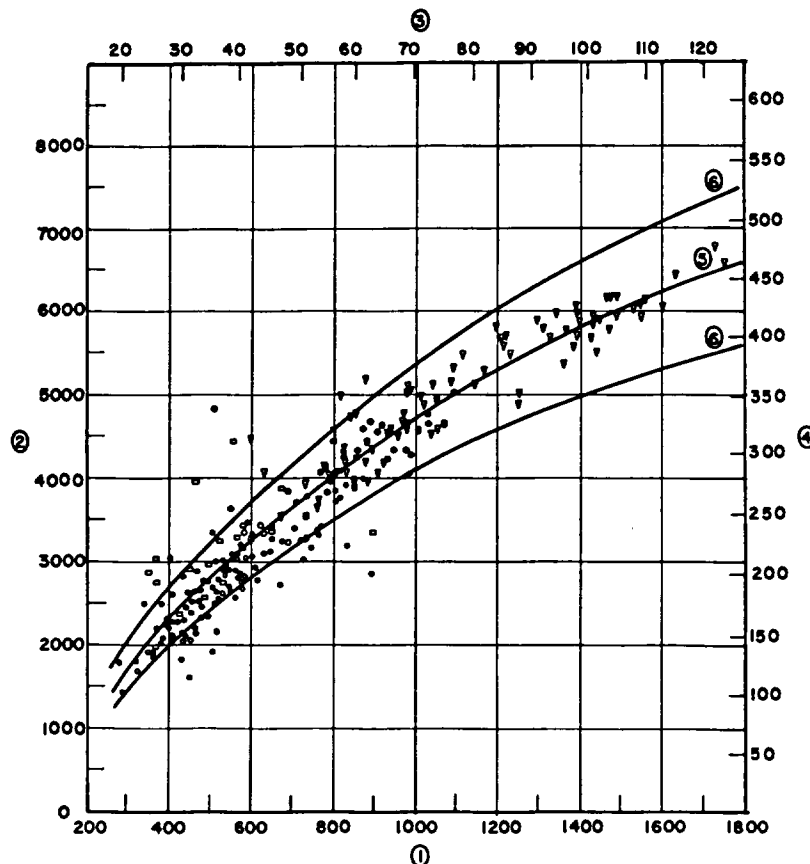


Fig. 7

Relationship of accelerated to 91-day strength — modified boiling method.
Combined data for all water/cement ratios.

- (1) Accelerated strength, lb/in.² - X.
- (2) 91-day standard-cured strength, lb/in.² - Y.
- (3) Accelerated strength, kg/cm² - X₁.
- (4) 91-day standard-cured strength, kg/cm² - Y₁.
- (5) Regression line.
- (6) ± 15 per cent limits.

Additional information :

Number of test results = 241.

Correlation coefficient = 0.950.

Equation of regression line,

$$Y = 21.42 X^{0.78} \text{ lb/in.}^2;$$

$$Y_1 = 11.85 X^{0.78} \text{ kg/cm}^2.$$

Standard deviation = 358 lb/in.²;
25.2 kg/cm².

*Rapport de la résistance accélérée à résistance normale de 91 jours —
méthode d'ébullition modifiée. Ensemble des données de tous les rapports
eau/ciment.*

- (1) Résistance accélérée, lb/po² - X.
- (2) Résistance à 91 jours de cure humide, lb/po² - Y.
- (3) Résistance accélérée, kg/cm² - X₁.
- (4) Résistance à 91 jours de cure humide, kg/cm² - Y₁.
- (5) Ligne de régression.
- (6) Limites de ± 15 pour cent.

Information supplémentaire :

Nombre de résultats d'essai = 241.

Coefficient de corrélation = 0.950.

Equation de la ligne de régression,

$$Y = 21.42 X^{0.78} \text{ lb/po}^2;$$

$$Y_1 = 11.85 X^{0.78} \text{ kg/cm}^2.$$

Ecart type = 358 lb/po²;

25.2 kg/cm².

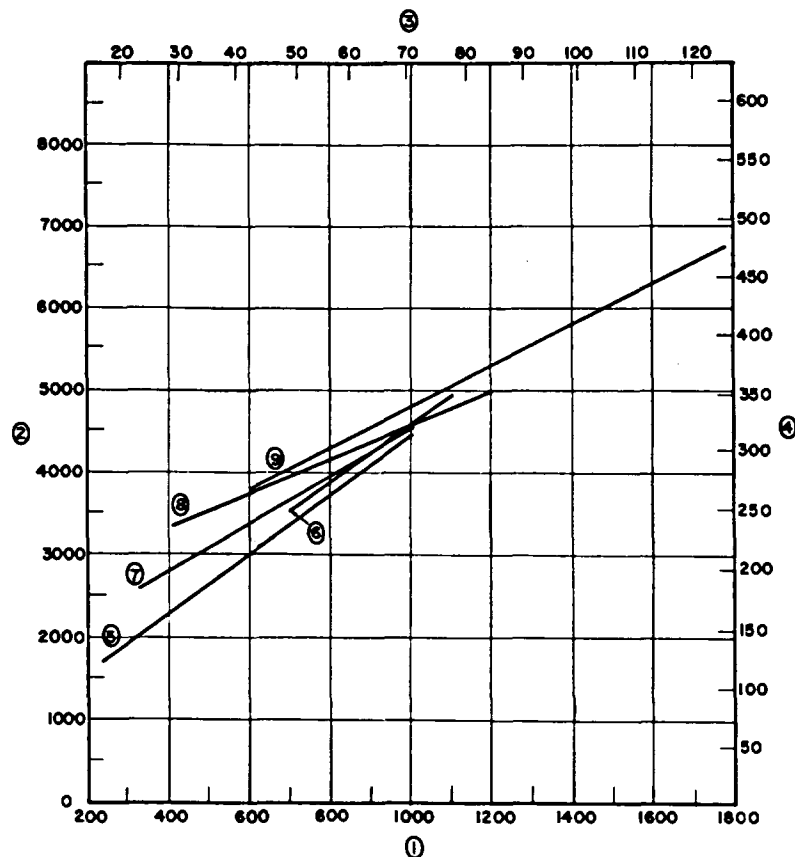


Fig. 8

Relationship of accelerated to 91-day strength — modified boiling method.
Comparison between concretes of different water/cement ratios.

- | | |
|---------------------------------------------------------------------------|----------------------------------------------------|
| (1) Accelerated strength, lb/in. ² - X. | (6) Regression line for water/cement ratio = 0.65. |
| (2) 91-day standard-cured strength, lb/in. ² - Y. | (7) Regression line for water/cement ratio = 0.58. |
| (3) Accelerated strength, kg/cm ² - X ₁ . | (8) Regression line for water/cement ratio = 0.65. |
| (4) 91-day standard-cured strength, kg/cm ² - Y ₁ . | (9) Regression line for water/cement ratio = 0.55. |
| (5) Regression line for water/cement ratio = 0.66. | |

Rapport de la résistance accélérée à résistance normale de 91 jours — méthode d'ébullition modifiée. Comparaison entre bétons de divers rapports eau/ciment.

- | | |
|---------------------------------------------------------------------------------|---------------------------------------------------------|
| (1) Résistance accélérée, lb/po ² - X. | (6) Ligne de régression pour rapport eau/ciment = 0.65. |
| (2) Résistance à 91 jours de cure humide, lb/po ² - Y. | (7) Ligne de régression pour rapport eau/ciment = 0.58. |
| (3) Résistance accélérée, kg/cm ² - X ₁ . | (8) Ligne de régression pour rapport eau/ciment = 0.65. |
| (4) Résistance à 91 jours de cure humide, kg/cm ² - Y ₁ . | (9) Ligne de régression pour rapport eau/ciment = 0.55. |
| (5) Ligne de régression pour rapport eau/ciment = 0.66. | |

variation of the compressive strength test cylinders after 91-day moist curing. Therefore the compressive strength results in the accelerated test may not be reproduced with the same degree of accuracy as the corresponding 91-day strength test results. This, to some extent, is to be expected, because of the rather slow strength development charac-

teristics of the low-heat, portland cement. It is, however, emphasized that the reproducibility of accelerated strength test results though poor as compared to the 91-day moist-cured strength test results, is superior to that obtained with strength test results after 3 or 7 days moist curing [14].

ACCURACY OF PREDICTION.

The plot of the combined data for accelerated versus 91-day strength test results (Figure 7) shows that the accelerated strength test can be used to estimate the compressive strength of test cylinders after 91-day moist curing with an accuracy of ± 15 per cent. The reliability of prediction improves if separate correlation graphs are used for each type of concrete (Figures 2-6); however, the above degree of accuracy is considered satisfactory for routine control of quality of concrete on large dams.

NUMBER OF CYLINDERS PER TEST AND RELIABILITY OF PREDICTION.

At each testing age the results of three 6×12 -in. cylinders have been averaged to give one test result. It is emphasized that, with the reduction in the number of cylinders comprising a test sample to two or one, the accuracy of 28-day strength prediction would be somewhat reduced. Cornwell [2] has reported a reduction from ± 12 per cent to ± 20 per cent when the number of test cylinders is reduced from three to one per test.

CONCLUSIONS

The modified boiling method reported in this paper appears to be a satisfactory means of earlier strength determination of concrete, and its use for routine control of quality of concrete during the construction of large dams is recommended. The compressive strength of test cylinders after 91-day moist curing can be estimated from the strength of accelerated cured test cylinders with an accuracy of about ± 15 per cent, and this degree of accuracy is considered adequate.

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SUMMARY

This paper outlines the accelerated curing methods used by the Quebec Hydro-Electric Commission, for estimating the 91-day strength of concrete. This is followed by a detailed statistical analysis of the field test data obtained on Outardes -3 project of the Commission using the modified boiling method. Briefly, this method consists of initial standard moist-curing of test specimens for 24 hours, followed by boiling for 3 1/2 hours and measuring compressive strength 1 hour later.

The analysis of the field data, which consist of several hundred test results, indicates that the modified boiling method is an acceptable means for potential strength determination of concrete, and its use during the construction of large concrete dams is recommended.

RÉSUMÉ

Ce rapport expose les méthodes de cure accélérée utilisées par la Commission hydroélectrique de Québec pour évaluer la résistance d'un béton de 91 jours. Il présente ensuite une analyse statistique des données d'essai en laboratoire tirées du projet Outardes 3 de la Commission en utilisant la méthode d'ébullition modifiée. En résumé, cette méthode consiste en une conservation classique initiale de 24 heures des échantillons qui sont soumis ensuite à une ébullition de 3 heures 1/2 avant de mesurer leur résistance à la compression une heure plus tard.

L'analyse des données qui résultent de plusieurs centaines d'essais indique que la méthode d'ébullition est un moyen acceptable d'obtenir la détermination préliminaire de la résistance du béton et conduit à recommander l'utilisation de cette méthode au cours de la construction des grands barrages en béton.