CANADA

ACCELERATED TEST FOR DETERMINING THE 28-DAY COMPRESSIVE STRENGTH OF CONCRETE

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DEPARTMENT OF MINES AND TECHNICAL SURVEYS, OTTAWA

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ACCELERATED TEST FOR DETERMINING THE 28-DAY COMPRESSIVE STRENGTH OF CONCRETE

by

V. M. Malhotra*, N. G. Zoldners** and R. Lapinas***

ABSTRACT

This report presents the results of accelerated curing of concrete test cylinders using a boiling-water method. Briefly, the method consists of standard moist-curing of test specimens for 24 hours, followed by boiling for 3 1/2 hours and testing for compression one hour later.

In all, some 1512 test cylinders, 6 x 12 in., were prepared from concrete samples obtained from three different ready-mix plants (situated in the Montreal-Ottawa area) and a large number of laboratory mixes. The test cylinders were tested in compression at 28 1/2 hours, 7 days, and 28 days. The results were analysed and the advantages and limitations of the method are discussed.

The analysis of test data indicates that the relationship between the accelerated- and 28-day standard-cured strengths can be represented by a hyperbolic function of the type $Y = \frac{X}{AX + B}$ with an accuracy of $\pm$ 12 per cent. The established relationships appear to be independent of the cements, aggregates and admixtures used.

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A condensed version of this report was presented at the Research Session of the 17th Fall Convention, American Concrete Institute, Miami, Florida, on November 13, 1964.

Direction des mines

Rapport de recherches R 134

ESSAI ACCÉLÉRÉ POUR DÉTERMINER LA RÉSISTANCE À LA COMPRESSION DU BÉTON APRÈS DURCISSEMENT DE 28 JOURS

par

V.M. Malhotra*, N.G. Zoldners** et R. Lapinas***

RÉSUMÉ

Ce rapport présente les résultats de l'étude sur le durcissement accéléré des éprouvettes cylindriques de béton par la méthode de l'eau bouillante. En bref, la méthode consiste dans le durcissement habituel en milieu humide pendant 24 heures, suivi d'ébullition pendant trois heures et demie, et d'essai de compression une heure après.

Quelque 1512 éprouvettes cylindriques en tout, mesurant 6 pouces par 12, ont été préparées à partir d'échantillons provenant de trois usines différentes de béton préparé (usines situées dans la région Montréal-Ottawa) et d'un grand nombre de mélanges d'essai de laboratoire. Les éprouvettes cylindriques ont subi les essais de compression après durcissement de 28 heures et demie, de 7 jours et de 28 jours. On analyse les résultats et on expose les avantages et les limitations de la méthode dans le présent rapport.

L'analyse des données provenant des essais indique que la relation entre les résistances à la compression après durcissement accéléré et après durcissement normal de 28 jours peut être représentée par une fonction hyperbolique du type $Y = \frac{X}{AX + B}$ avec une marge d'erreur de $\pm$ 12 p. 100. La relation établie semble être indépendante des ciments, des agrégats et des additifs employés.

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Une version condensée de ce rapport a été présentée à la session de recherche de la 17e réunion d'automne de l'American Concrete Institute, tenue à Miami (Floride), le 13 novembre 1964.

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INTRODUCTION

The advent of prestressed concrete, the present-day rigid quality control specifications, and the much faster pace of current reinforced concrete construction have all strongly demonstrated the need for an accelerated test for the determination of compressive strength of concrete. For large projects of the magnitude of the Glen Canyon and Manicouagan-5 arch dams, where the rate of concrete placement can be as high as 300 to 400 cu yd per hour, it is most desirable to be able to predict, at the earliest moment after the concrete has been placed, the potential 28-day compressive strength of the concrete. Test cylinders cured in a standard manner (73.4 ± 3.0°F temperature and 100 per cent relative humidity), when tested under field conditions at ages of less than 7 days, do not give a reliable indication of the later age strength of concrete.

One of the earliest publications in this field was a study by Gerent (1) in 1927, in which acceleration of concrete strength was achieved by exposing the test specimens to a saturated steam bath at 80- to 100-lb pressure. The United States Bureau of Reclamation used an 8-hour accelerated strength test for field concrete control at Hoover dam in 1930 (2), but considered it unsatisfactory after giving it several years of trial. Since then, however, various other authorities have continued to use various modified forms of the test.

In recent years a considerable amount of work on accelerated strength testing of concrete has been carried out in Australia (3,4), England (5,6,7,8,9,10,11), Finland (12), Japan (13), and Poland (14). In North America, the Ontario Department of Highways (15) and the Canada Department of Mines and Technical Surveys (16,17,18) have been most active in the field.

The immediate need for such a test is reflected in the fact that in England a sub-committee of the Institution of Civil Engineers has initiated a cooperative test programme for the development of a satisfactory accelerated strength test. All the leading laboratories of the United Kingdom are participating in this research work. In Europe, the Réunion Internationale des Laboratories d'Essais et de Recherches sur les Matériaux et les Constructions (RILEM), Paris, France, is currently conducting a correspondence symposium on "Accelerated Hardening of Concrete With a View to Rapid Control Tests". The participants in this symposium include researchers from Europe, Japan, and North America. In 1963 the American Society for Testing and Materials established a sub-committee to look into the development of an accelerated strength test for concrete.

Several methods (19, 20) based upon the constituent analysis of freshly mixed concrete have been proposed for predicting the potential strength of hardened concrete. Recently, Malhotra (21) has proposed a statistical approach that uses the properties of fresh concrete, such as water/cement ratio, slump, air content, and unit weight, to predict within 24 hours the compressive strength at later ages. These methods, however, do not involve the testing of any hardened concrete specimens.

SCOPE OF RESEARCH

The purpose of this study was to look into the development of an accelerated strength test for hardened concrete in order to be able to predict the potential 28-day compressive strength of concrete in about 24 to 28 hours. Type I Portland cement from three different Canadian cement plants was used. Coarse aggregates consisted of crushed limestone and gravel, and the fine aggregate used was natural sand. The laboratory programme was supplemented by test results from three different construction jobs. Altogether, 132 concrete batches, comprising 1512 test cylinders (6 x 12 in.), were tested.

ACCELERATED TEST METHODS

Basic Requirements of an Accelerated Test

It is considered that any proposed accelerated strength test for concrete specimens should meet all or most of the following basic requirements:

1. The test equipment and procedure should be relatively simple; the equipment should be portable and capable of being installed at a construction site.

2. The test results should be reproducible in themselves and comparable to the results obtained elsewhere using similar equipment. Further, they should allow the potential 28-day compressive strength of concrete to be predicted with an acceptable degree of reliability.

3. The test results should be available within 24 to 28 hours after the concrete has been placed, and the completion of the test should require the minimum amount of overtime work.

4. The ratio of accelerated-cured to 28-day standard-cured strength should be as high as possible, and the results should be applicable to concrete mixes covering a wide strength range. It is desirable that the relationship between the accelerated and 28-day strengths should not be affected by the use of the usual admixtures.

Existing Test Methods

A literature survey revealed a number of different accelerated test methods that have been used by different organizations since 1927. The various forms of the test used by these agencies, together with other relevant data, are summarized in Table 1. Few of these methods meet the requirements stipulated in the foregoing paragraphs. The ones that seem to satisfy most of these requirements are those in which test specimens are moist-cured for 18 to 24 hours and are then heated for 3 to 4 hours at 176 to 212°F either in water or in an oven.

TEST METHOD UNDER INVESTIGATION

The salient features of the method selected for this investigation are:

(1) Prepare three 6 x 12 in. test cylinders in steel moulds, using standard moulding methods. The delay between mixing of concrete and preparation of test specimens should not exceed 30 minutes.

(2) Immediately after moulding, close all cylinder moulds with water-tight steel cover plates and place these in a moist-curing room or box maintained at 73.4 ± 3.0°F temperature and 100 per cent relative humidity. If the above moist-curing facilities are not available, cover the moulds with moist burlap, kept wet, for 24 hours.

(3) After 24 hours, remove the cylinders from the curing room and place them, complete with their moulds and covers, in boiling water. Keep the temperature of the water just below the boiling point (212°F) to avoid excessive evaporation.

(4) After 3 1/2 hours, remove the cylinders from the boiling water, strip the moulds, and allow the specimens to cool at room temperature for about 45 minutes.

TABLE 1

Accelerated Curing Methods Used in Different Countries

Stage of Test	Moore & Co., Engineers, San Francisco, U.S.A.	U.S. Bureau of Reclamation, Denver, U.S.A.	Port of London Authority, London, U.K.		Water Sewerage and Drainage Board, Sydney, Australia	Snowy Mountains Authority, Cooma, Australia	Constructional Services Limited, London, U.K.		Ossauskoski Hydro-Electric Plant, Finland	Ontario Department of Highways, Toronto, Canada
Year in which test was used or reported	1927	1933	1955	1956	1956	1957	1961	1961	1961	1963
Age of specimens when placed in heating medium	24 hours after moulding	1/2 hour after moulding	1/2 hour after moulding	18 to 24 hours after moulding	1 hour	1/2 hour	24 hours	1/2 hour	1 hour	20 min after the fresh concrete reaches initial set (approx. 6-hr after moulding)
Type and temperature of heating medium	saturated steam bath at 80 to 100-lb pressure	boiling water	oven at* 185 ± 5°F	oven at 185°F	boiling water	water at 165 to 170°F	boiling water	water at 167°F	water/ oven at 176°F	boiling water
Subsequent temperature control	maintained at 80 to 100-lb pressure	heat turned off when specimen is immersed; temperature depends on the efficiency of insulation and ambient conditions	maintained at 185 ± 5°F	maintained at 185 ± 5°F	heat turned off when specimen is immersed; temperature depends on the efficiency of insulation and ambient conditions	maintained at 165 to 170°F	maintained at boiling point	increased to boiling point and maintained at this temperature	maintained at 176°F	maintained at boiling temperature
Period, specimens kept in the heating medium, hours	12	6 1/2	6	4	21-21 1/2	21 1/2	3 1/2	7	20	16
Age of specimens at the end of heating period, hours	36	7	6 1/2	22 to 28	22-22 1/2	22	27 1/2	7 1/2	21	About 22 to 25
Age of specimen at the time of test, hours	37	8	7	22 1/2 to 28 1/2	24	24	28 1/2	8 1/2	24	About 23 to 26
Type of test specimen	6 x 12 in. cylinder	6 x 12 in. cylinder	6 in. cube	6 in. cube	6 x 12 in. cylinder	6 x 12 in. cylinder	6 in. cube	6 in. cube	6 x 12 in. cylinder or 6 in. cube	6 x 12 in. cylinder
Reference No.**	1	2	5, 7, 8, 9	8	3, 4	3, 17	11	11	12	15

*In the original method proposed by Professor King (5, 7) all work was carried out with oven at 200°F.

**See References on page 43.

(5) Weigh the test cylinders, cap them, and test in compression 15 minutes later.

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

The curing period of 24 hours and the boiling time of 3 1/2 hours (8, 11) were selected on a provisional basis. The effects of deviations of (a) moist-curing period, (b) boiling duration, (c) delay time between boiling and testing and (d) water temperature are discussed later.

EQUIPMENT

Simplicity was the keynote of the equipment used. For one series of tests, a semi-insulated 30-gallon steel drum with one 5000-watt, thermostatically controlled immersion heater was used (Figure 1). No more than three 6 x 12 in. cylinders were placed in the drum at one time. For the second series of tests, a 44-gallon steel drum with two 3000-watt, thermostatically controlled heaters was employed and six cylinders were placed in the drum for each test run. It is considered that, with properly insulated tanks, 1000- to 2000-watt heaters should be sufficient.

MATERIALS

Aggregates

Aggregates were used in graded sizes and are described below:

Fine aggregate. This consisted of natural sand from glacial-fluvial deposits.

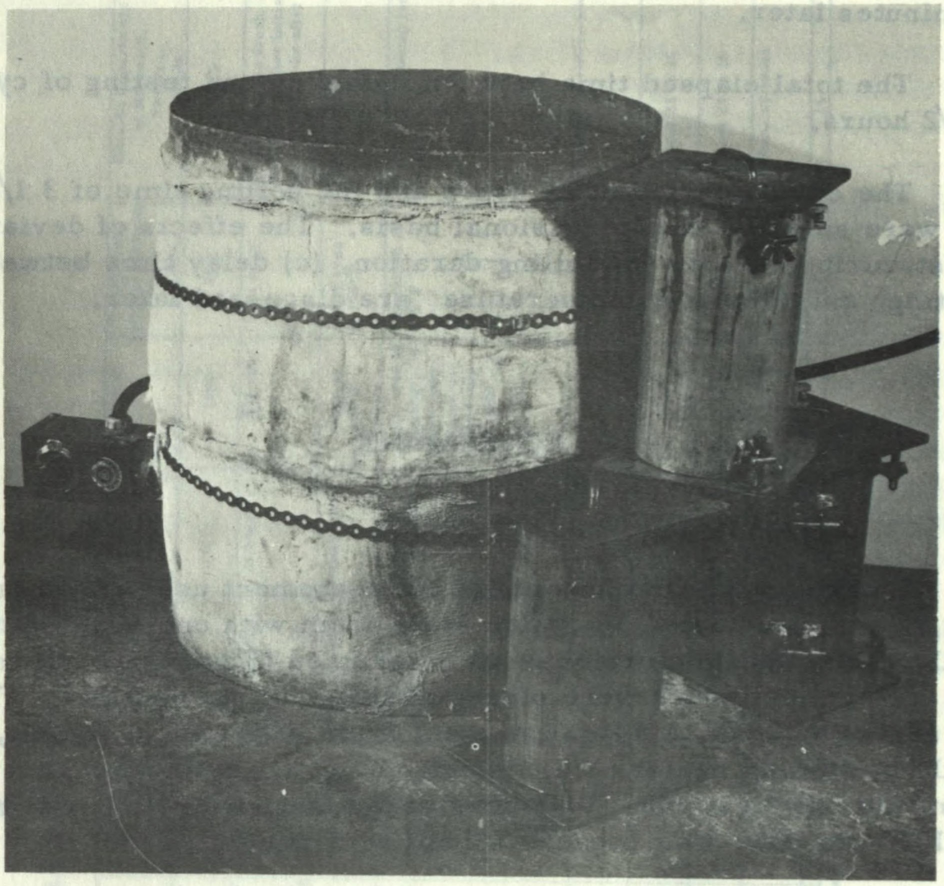

FIG 1. ACCELERATED BOILING WATER TANK

Note test cylinders, complete with moulds and cover plates, ready to be placed in the tank.

Coarse aggregate. Crushed gravel, a heterogeneous mixture of igneous rocks, was used for laboratory and Ottawa Pre-Mix* tests. Crushed limestone was used for both the Queensway** and the Mount Royal*** concretes. The limestone was a fine-grained, high-calcium variety, typical of the Trenton formation found in eastern Canada.

The gradings of the coarse and fine aggregates are given in Tables 2 and 3.

---

*Ottawa Pre-Mixed Concrete Limited, concrete mixing plant No. 8;
**McNamara Construction of Ontario, Queensway project in Ottawa; and
***Mount Royal Paving and Supplies Limited, Plant No. 4, Montreal. The three concretes will be referred to as Ottawa Pre-Mix, Queensway and Mount Royal, respectively.

TABLE 2

Grading of Aggregates

Sieve Sizes	Coarse Aggregates: Cumulative Percentage Retained — Ottawa Pre-Mix (gravel) 3/4 in.	Ottawa Pre-Mix (gravel) 3/8 in.	Queensway (crushed stone) 1 1/2 in.	Queensway (crushed stone) 3/4 in.	Mount Royal (crushed stone) 3/4 in.	Mount Royal (crushed stone) 1/2 in.	Mount Royal (crushed stone) 1/4 in.	Sieve Sizes	Fine Aggregates: Cumulative Percentage Retained — Ottawa Pre-Mix (natural sand)	Queensway (natural sand)	Mount Royal (natural sand)
1 1/2 in.			0					No. 4	0	1.3	12.1
1 in.			33.0		0			No. 8	12.0	4.6	21.6
3/4 in.	0		79.0	0	48	0		No. 16	35.2	19.7	34.6
1/2 in.	53.8	0	100.0	63.0	94	45	0	No. 30	61.4	49.1	56.6
3/8 in.	90.0	10.7		87.0	97	90	20	No. 50	83.6	82.1	80.9
No. 4	100.0	91.4		100.0	98	98	93	No. 100	93.7	95.9	95.9
Pan		100.0			100	100.0	100.0	Fineness Modulus	2.86	2.53	3.02

TABLE 3

Physical Properties of Aggregates

Physical Properties	Ottawa Pre-Mix C.A.*	Ottawa Pre-Mix F.A.**	Queensway C.A.	Queensway F.A.	Mount Royal C.A.	Mount Royal F.A.
Specific Gravity, bulk, SSD+	2.72	2.66	2.70	2.64	2.70	2.65
Absorption, per cent (by weight)	0.76	1.02	0.61	0.89	0.58	0.80

*C.A. = Coarse Aggregate; **F.A. = Fine Aggregate;
+SSD = Saturated Surface-Dry.

Cements

Normal Type I Portland cement from three different Canadian cement plants was used. The physical properties and chemical analyses of the cements are given in Table 4. The cements used for Queensway and Mount Royal concretes were of finer grind than that used for Ottawa Pre-Mix tests.

Admixtures

Air-entraining, water-reducing and accelerating agents were used in some of the concrete mixes. The various admixtures are briefly described below:

Air-entraining agents

These were of vinsol resin and petroleum refining by-product types commonly used in the Canadian construction industry and were obtained commercially.

Water-reducing and set-retarding agent

A well-known commercial brand of water-reducing admixture was used, either alone or in conjunction with an air-entraining agent.

Accelerating agent

Calcium chloride in amounts of 1 to 2 per cent by weight of cement was used as an accelerator in some of the test mixes, either alone or together with an air-entraining agent.

EFFECT OF DIFFERENT BOILING AND CURING CONDITIONS ON THE ACCELERATED METHOD UNDER INVESTIGATION

Before the chosen procedure was adopted, studies were carried out to determine the effect of the following variables on the accelerated strength:

(a) The duration of moist-curing
(b) The duration of boiling period
(c) The delay time between boiling and testing of cylinders
(d) The water temperature

TABLE 4

Physical Properties and Chemical Analyses of the Cements*

Description of Test		Unit	Ottawa Pre-Mix Cement	Queensway Cement	Mount Royal Cement
Physical Tests - General					
Time of Set**	(Initial	hr:min	3:10	1:35	2:10
	(Final	hr:min	5:45	3:20	4:10
Fineness - Blaine		cm^2/g	2900	3250	3250
Soundness - Autoclave Expansion		%	0.29	0.31	0.20
Physical Tests - Mortar Strength					
Tensile Strength	(3-day	psi	310	380	380
	(7-day	psi	390	415	460
	(28-day	psi	480	460	520
Compressive Strength	(3-day	psi	2330	3040	2840
	(7-day	psi	3490	3690	3640
	(28-day	psi	4630	4450	4910
Chemical Analysis					
Insoluble residue		%	0.38	0.16	0.30
Silicon dioxide	(SiO_2)	%	21.06	20.02	20.80
Aluminum oxide	(Al_2O_3)	%	5.34	6.01	5.45
Ferric oxide	(Fe_2O_3)	%	2.54	2.77	2.55
Calcium oxide	(CaO)	%	63.46	63.88	63.40
Magnesium oxide	(MgO)	%	2.97	1.85	3.00
Sulphur trioxide	(SO_3)	%	2.33	2.75	2.65
Loss on Ignition		%	1.19	1.35	0.73

* Test results and chemical analyses supplied by the cement manufacturing companies.
** Using Vicat apparatus.

A standard concrete mix was used for these exploratory studies. Details of the mix design and the properties of fresh concrete are given in Table 5.

TABLE 5

Design and Properties of Standard Concrete Mix

Type of cement	Normal Portland, Type I
Coarse aggregate	Natural gravel
Fine aggregate	Natural sand
Maximum aggregate size, in.	5/8
Water/cement ratio (by weight)	0.85
Aggregate/cement ratio (by weight)	8.2
Slump, in.	2.0
Air content, per cent	2.9
Unit weight, lb/cu ft	147.0
Admixtures	Nil

(a) The Effect of Duration of Moist-Curing

Sixteen 6 x 12 in. cylinders were made from two identical concrete mixes, and pairs of cylinders were placed in the boiling water after 18, 20, 22, 24, 25, 26 and 27 hours of moist-curing. Each pair was boiled for 3 1/2 hours and tested in compression one hour later. The test results, expressed as a percentage of the standard procedure (24 hours moist-curing and 3 1/2 hours boiling), show that the test cylinders after 22 and 25 hours of moist-curing have the same strength as those with 24 hours (Figure 2). For moist-curing periods other than these, there is a variation in the accelerated strength of up to 5.5 per cent.

(b) The Effect of Duration of Boiling Period

Eight 6 x 12 in. cylinders were made from a single mix and, after 24 hours of moist-curing, pairs were boiled for a period of 3, 3 1/2, 4 and 5 hours. The test results, expressed as a percentage of the standard procedure, indicate (Figure 3) that an increase in the boiling period from 3 1/2 to 5 hours increases the compressive strength by 4.5 per cent.

(c) The Effect of Delay Time Between Boiling and Testing of Cylinders

Eight 6 x 12 in. test cylinders cast from a single batch were moist-cured for 24 hours and boiled for 3 1/2 hours. After removal from the boiling water they were allowed to cool at room temperature. The cylinders, in pairs, were tested in compression at one-hour intervals. The test results (Figure 4) show that there was not much difference in

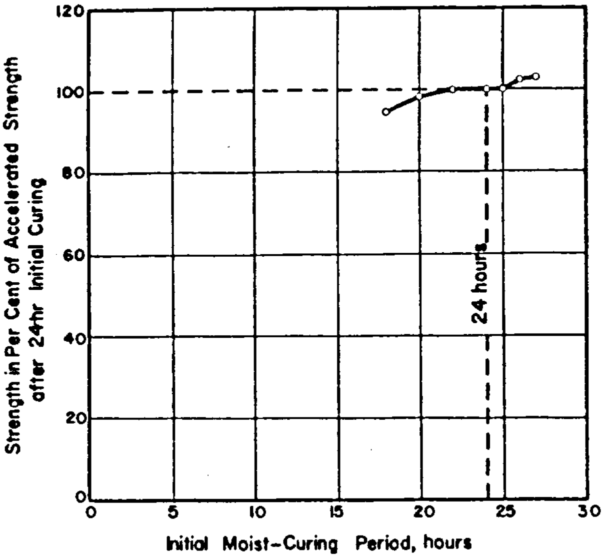

FIG.2. EFFECT OF MOIST-CURING TIME ON ACCELERATED STRENGTH

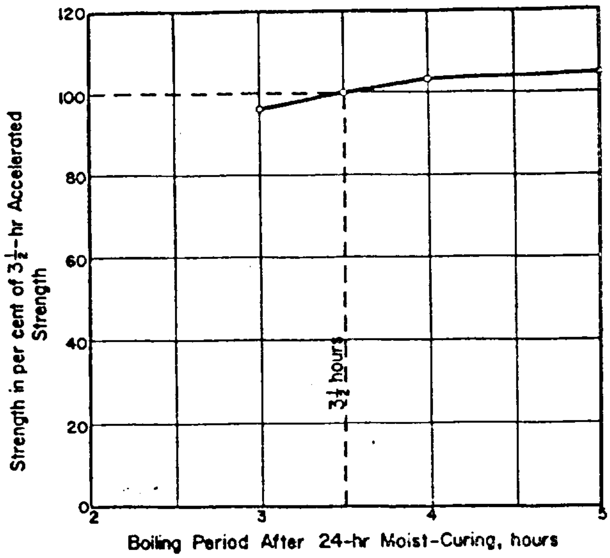

FIG.3. EFFECT OF BOILING DURATION ON ACCELERATED STRENGTH

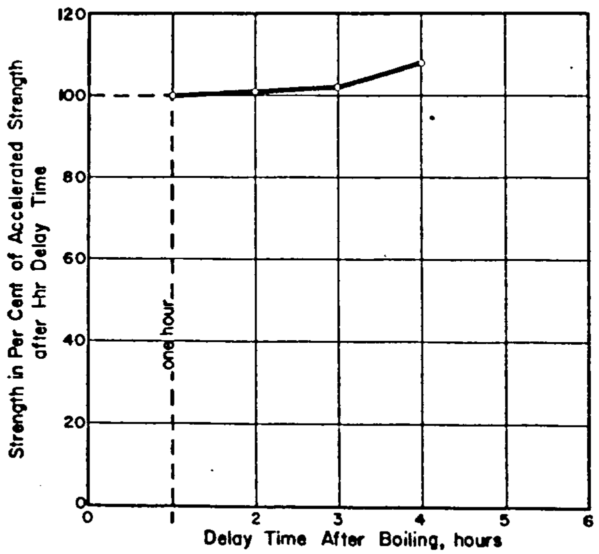

FIG.4. EFFECT OF DELAY TIME BETWEEN BOILING AND TESTING ON ACCELERATED STRENGTH

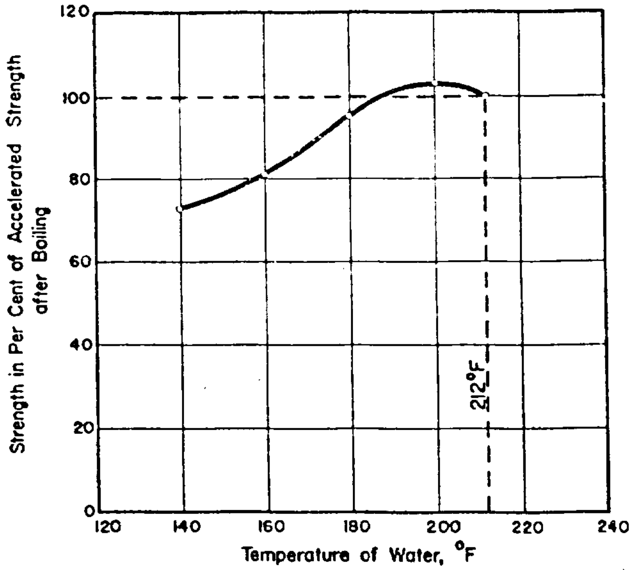

FIG.5. EFFECT OF WATER TEMPERATURE ON ACCELERATED STRENGTH

strength if the cylinders were tested at one or two hours after removal from the boiling water; however, there was an increase of 2 and 8 per cent with cooling periods of 3 and 4 hours.

(d) The Effect of Water Temperature

Five concrete mixes, with six 6 x 12 in. cylinders from each mix, were made to determine the effect of different water temperatures on the accelerated strength. All cylinders were moist-cured for 24 hours. For each temperature investigated, i.e., 140, 160, 180, 200 and 212°F, three cylinders were heated for 3 1/2 hours. The three companion cylinders from the same mix were boiled for 3 1/2 hours according to the provisional procedure. The test results (Figure 5) indicated that optimum strength was achieved at 200°F; compressive strength at this temperature was 3 per cent higher than that at 212°F. It is interesting to note that J.W.H. King (20) had conducted all his accelerated curing work at 200°F.

The above laboratory investigations indicated that the best accelerated curing cycle, as far as the ratio of the accelerated to 28-day strength was concerned, would be as follows:

Standard moist-curing	=	22 hours
Water temperature	=	200°F
Duration of heating	=	5 hours
Cooling period	=	4 hours
Total time	=	31 hours

Unfortunately, the gain in the ratio of the accelerated to 28-day strength would be offset by the overtime work requirements. From a practical viewpoint, at a construction site it is easier to maintain water at boiling point than at any other temperature. Further, if the above curing regime were adopted it would afford little opportunity to compare the results directly with those published elsewhere (11). After careful consideration it was concluded that there was no merit in introducing new variables merely for the sake of originality. Taking all these factors into account, it was decided to adopt the 28 1/2-hr accelerated curing cycle for all the subsequent work.

FIELD EXPERIMENTAL PROGRAMME

A total of 132 concrete test batches were sampled between June 1963 and July 1964, to provide 1512 test cylinders (6 x 12 in.). For Ottawa Pre-Mix and Mount Royal tests, concrete samples were collected from truck mixers before the trucks left the plants, and the test cylinders were moulded in the plant laboratories. In the case of Queensway tests, concrete samples were collected at the job site, brought to the laboratory, and remixed for three minutes before the cylinders were moulded.

Some additional mixes were prepared in the laboratory to cover the variables not encountered in the field concrete. These mixes have been incorporated with those of Ottawa Pre-Mix because the cement and aggregates used were identical to those of Ottawa Pre-Mix concrete. Basic mix data for various types of concrete are given in Table 6.

Characteristics of Fresh Concrete

Immediately after the samples were collected (for the Queensway project, after the concrete had been brought to the laboratory and remixed), the temperature, slump, unit weight, and air content were determined using ASTM standard procedures*. A brief summary of the test results is shown in Table 7.

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*ASTM Standard Methods of Tests for Slump of Portland Cement Concrete (C143-58); Air Content of Freshly Mixed Concrete by the Pressure Method (C231-60); Weight Per Cubic Foot (C138-44); 1961 Book of ASTM Standards, Part 4.

TABLE 6

Design Data of Field and Laboratory Concrete Mixes

	Ottawa Pre-Mix Concrete	Queensway Concrete	Mount Royal Concrete
Water/cement ratio (by weight)	0.38 to 0.99	0.70 ± .05	0.33 to 0.99
Aggregate/cement ratio (by weight)	3.06 to 9.20	5.56	3.24 to 11.8
Maximum aggregate size, in.	5/8	1 1/2	3/4

TABLE 7

Properties of Fresh Concrete

Type of Concrete	Temperature, deg F	Slump, in.	Unit Weight, lb/cu ft	Air, %
Ottawa Pre-Mix				
Plain concrete	62 to 78	1/4 to 3 3/4	140.0 to 154.8	1.0 to 3.2
Concrete with admixtures	64 to 72	3/4 to 5-1/2	135.6 to 150.8	1.2 to 8.4
Queensway				
Concrete with admixtures	Not recorded	1 to 2-3/4	148.8 to 155.6	2.2 to 5.0
Mount Royal				
Plain concrete	64 to 72	1 to 6	145.5 to 153.1	0.6 to 1.6
Concrete with admixtures	59 to 72	2-3/4 to 5-1/2	138.2 to 150.8	0.8 to 8.5

Test Specimens

Twelve 6 x 12 in. test cylinders were cast from each batch, except in the case of the mixes made in the laboratory, where the capacity of the mixer limited the number of test cylinders to 10. However, from all batches, three cylinders were tested after 28 1/2-hr accelerated and 28-day standard curing*. The details of the test cylinders cast from each type of concrete are given in Table 8.

TABLE 8

Number of Concrete Batches Tested and Test Cylinders Cast

Type of Concrete	Number of Concrete Batches Sampled	Number of 6 x 12 in. Cylinders
Ottawa Pre-Mix		
Plain concrete	37	390
Concrete with admixtures	14	150
Queensway		
Plain concrete	-	-
Concrete with admixtures	11	132
Mount Royal		
Plain concrete	47	564
Concrete with admixtures	23	276
Total	132	1 512

MOULDING AND CURING OF TEST CYLINDERS

Moulding

The test cylinders were prepared by filling 6 x 12 in. steel cylinder moulds in two approximately equal layers. Each layer was compacted with a 1-1/8 in. diameter internal vibrator by a single insertion of approximately 4 to 6 seconds. In compacting the second layer, the vibrator was allowed to penetrate approximately 1 in. into the first layer. The concrete surfaces were then levelled, using a steel trowel. Water-tight steel covers were placed on three of the moulds. All the moulds were

*At a 73.4 ± 3.0°F temperature and 100% relative humidity.

transferred immediately to a moist-curing room at a temperature of 73.4 ± 3.0°F and 100 per cent relative humidity. The delay between the mixing of concrete and the moulding of test specimens (for Queensway concrete, between remixing and moulding) was 15 to 20 minutes.

Curing and Testing

The accelerated-cured cylinders were tested at 28 1/2 hours according to the procedure outlined earlier. At the same time, three companion standard-cured cylinders were also tested in compression*.

The remaining cylinders were left in the moist-curing room for seven days, when their saturated surface-dry densities were determined. Three of the cylinders were then tested* and the remaining three were tested at 28-day age.

All cylinders were tested either in an Amsler testing machine of 600,000 lb capacity or in a 300,000-lb-capacity Riehle testing machine. Prior to testing, all cylinders were capped, either with a sulphur-flint mixture or a high early strength capping compound, depending on the strength level of the concrete.

COMPRESSIVE STRENGTH TEST RESULTS AND THEIR ANALYSIS

Test Results

A total of 528 test results (4 times the number of concrete batches) were available for analysis. Among these the accelerated strengths varied from 345 to 4695 psi. The corresponding 7-day and 28-day standard-cured strengths varied from 685 to 6255 and from 1125 to 7935 psi.

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* When only 10 cylinders were available from a batch, two each were tested after 28 1/2-hr and 7-day standard curing.

Analysis of Test Results

Method

The analyses have been confined to relationships between the accelerated- and standard-cured 7- and 28-day compressive strengths. In analysing the test results, hyperbolic curves of the type

$$Y = \frac{X}{AX + B},$$

where X = accelerated-cured strength, psi,
Y = 28-day standard-cured strength, psi, and
A and B = constants,

have been fitted to the accelerated strength versus 28-day standard-cured strength plots.

Summary

The plots of the accelerated to 7-day and accelerated to 28-day test results are shown in Figures 6 to 11 and 12 to 17. The equations of the hyperbolic curves of the above-mentioned form, which have been fitted to the plots of the accelerated versus 28-day strengths, are shown in Table 9. For the accelerated versus 7-day strengths the curves have been fitted by eye.

In order to evaluate the laboratory testing and casting techniques, the "within-batch coefficients of variation" of the test results at each testing age have been determined and are given in Table 10. Also included in this Table are the values for "within-batch variation" as recommended by the American Concrete Institute (22).

The reproducibilities of the accelerated-cured and the standard-cured strengths at various ages have been determined by calculating the between-batch coefficients of variation for these strengths (Table 11); care was taken to select only those results for which w/c ratios by weight and cement factor were constant.

The validity of the relationship $\frac{\text{Accelerated Strength}}{\text{7-day Strength}} = \frac{\text{7-day Strength}}{\text{28-day Strength}}$ has been checked in Figure 18, in which a plot of the accelerated versus 7-day strength is shown; also superimposed on the same figure is the curve for the 7-day to 28-day strength relationship.

In order to compare the results of this investigation with those of others, accelerated to 28-day strength relationships obtained by other investigators have been plotted in Figures 19 and 20 along with the curves established at the Mines Branch.

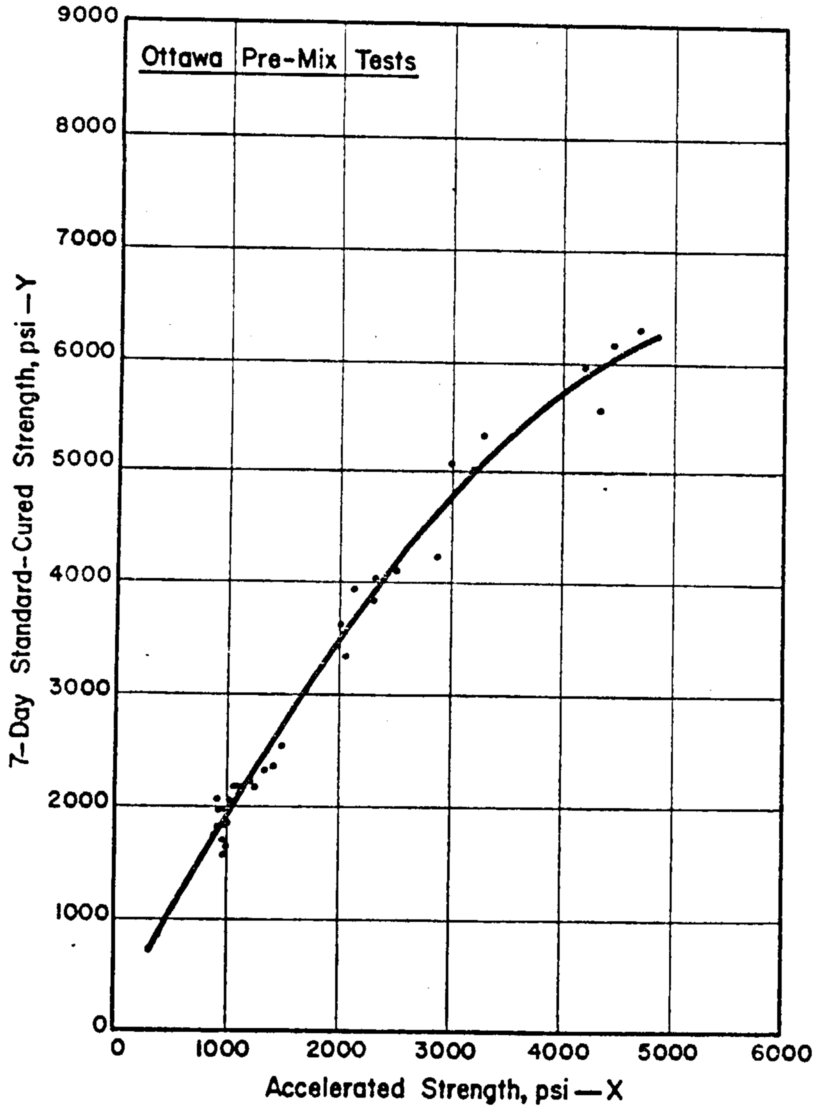

FIG.6. RELATIONSHIP OF ACCELERATED TO 7-DAY STRENGTH
Plain Concrete

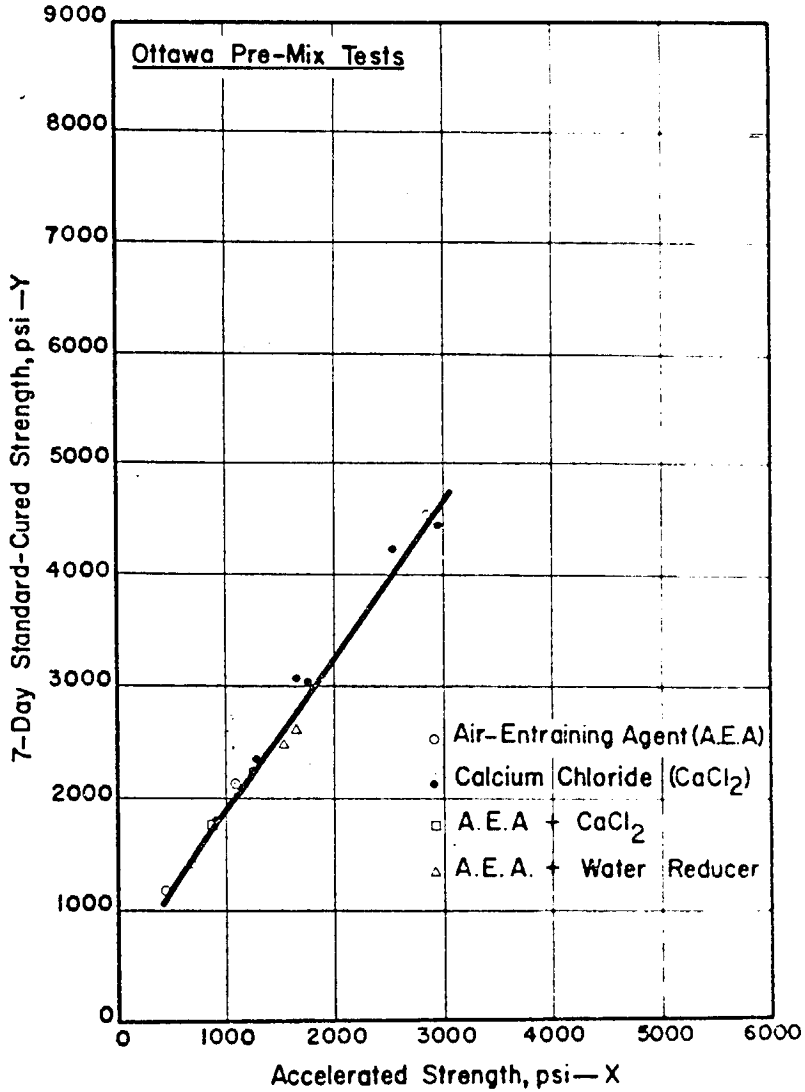

FIG.7. RELATIONSHIP OF ACCELERATED TO 7-DAY STRENGTH
Concrete Containing Different Admixtures

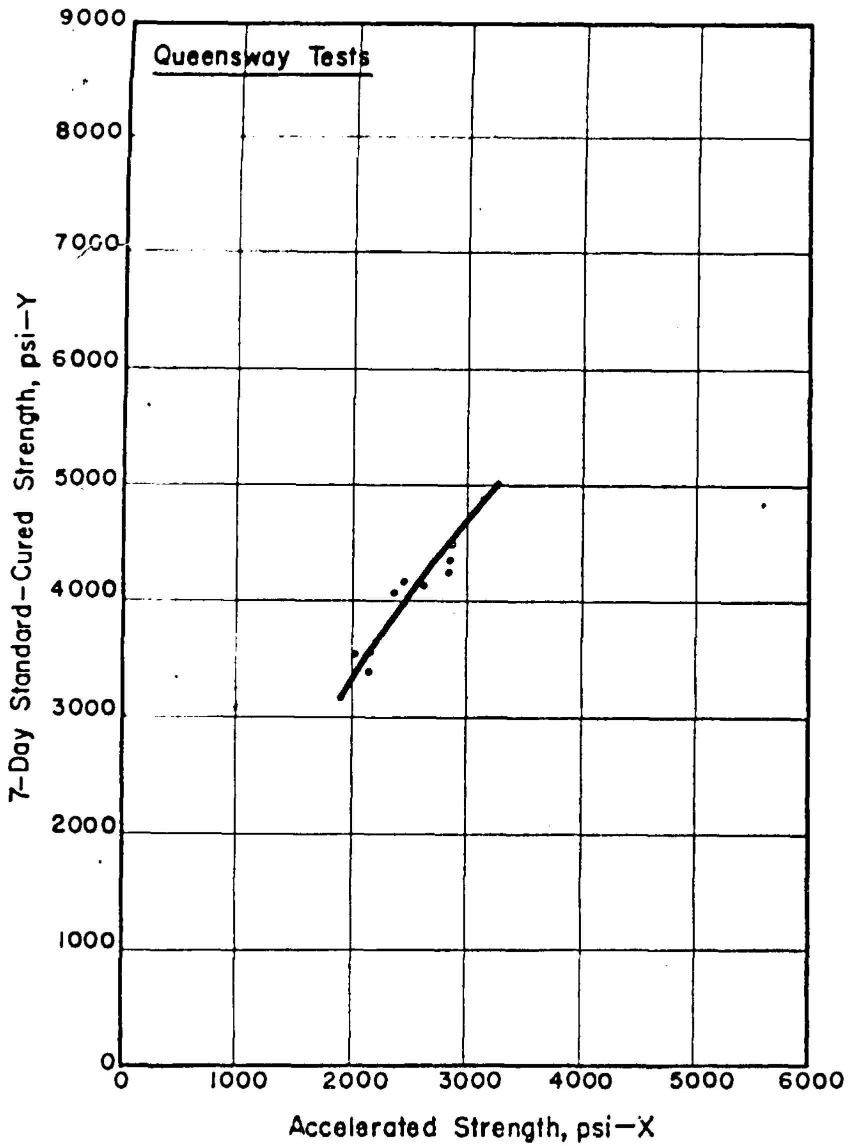

FIG.8. RELATIONSHIP OF ACCELERATED TO 7-DAY STRENGTH
Concrete Containing Air-Entraining And Set-Retarding Admixtures

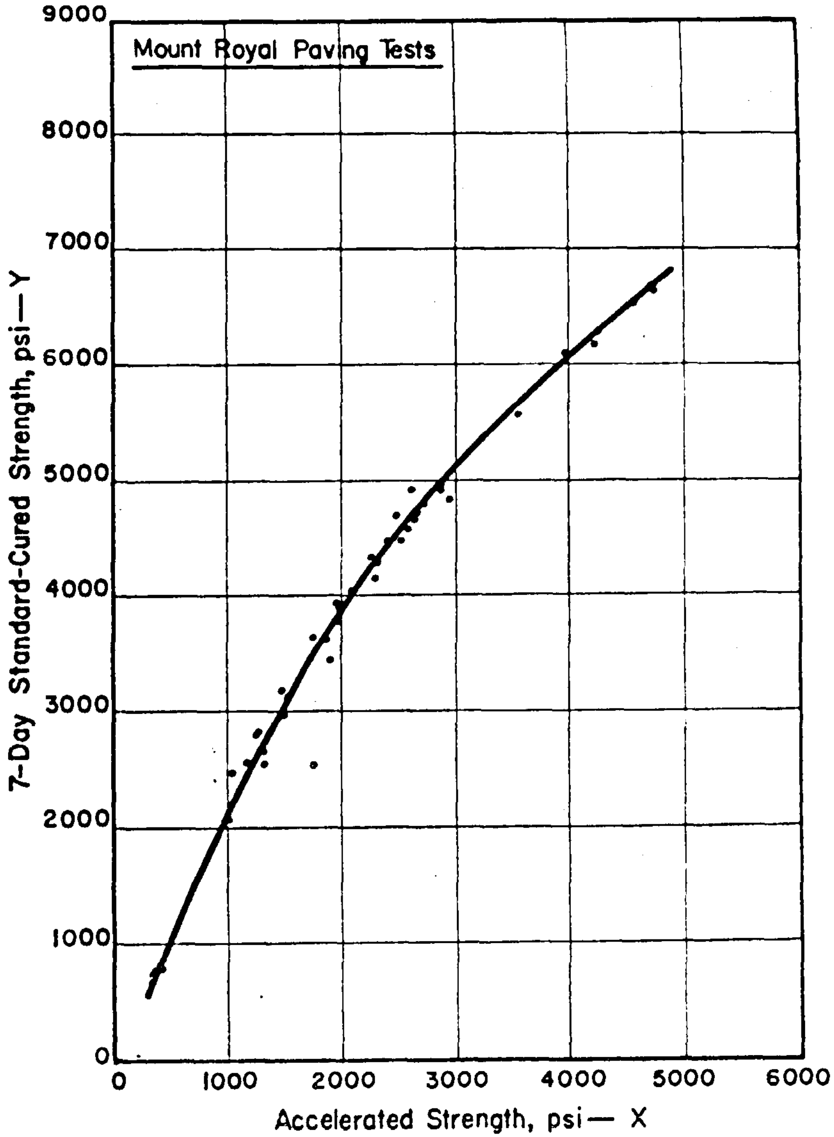

FIG.9. RELATIONSHIP OF ACCELERATED TO 7-DAY STRENGTH
Plain Concrete

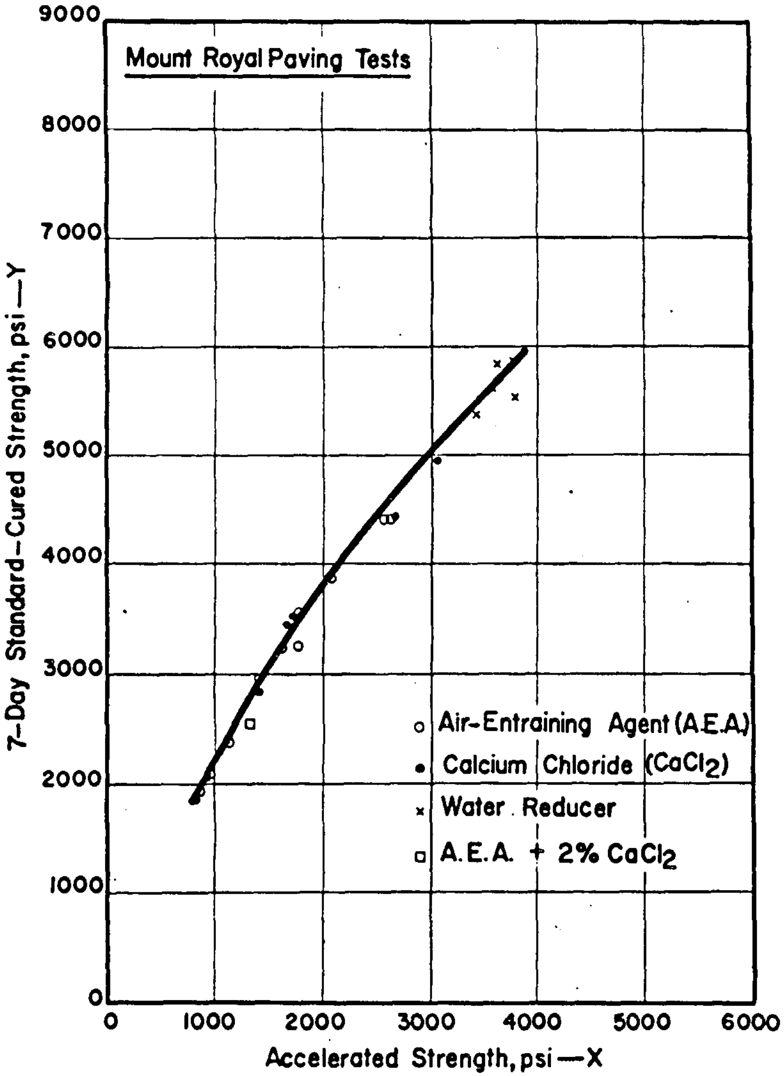

FIG.10. RELATIONSHIP OF ACCELERATED TO 7-DAY STRENGTH
Concrete Containing Different Admixtures

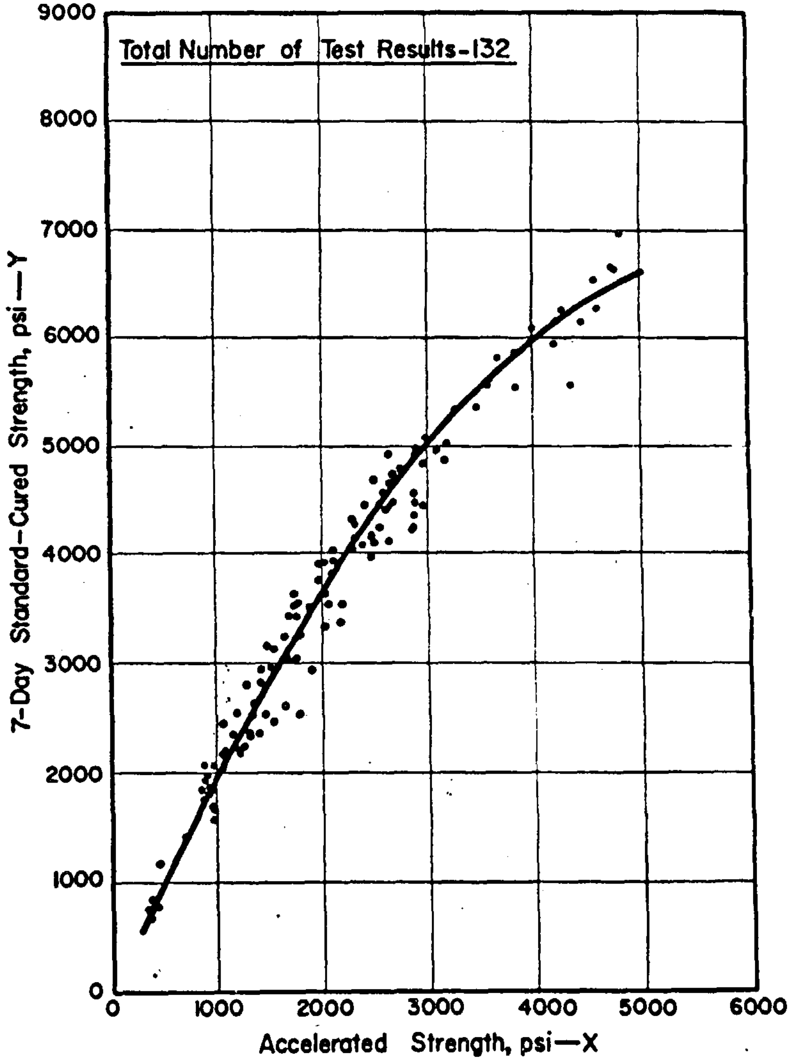

FIG.11. RELATIONSHIP OF ACCELERATED TO 7-DAY STRENGTH
Combined Data for All Types of Concrete

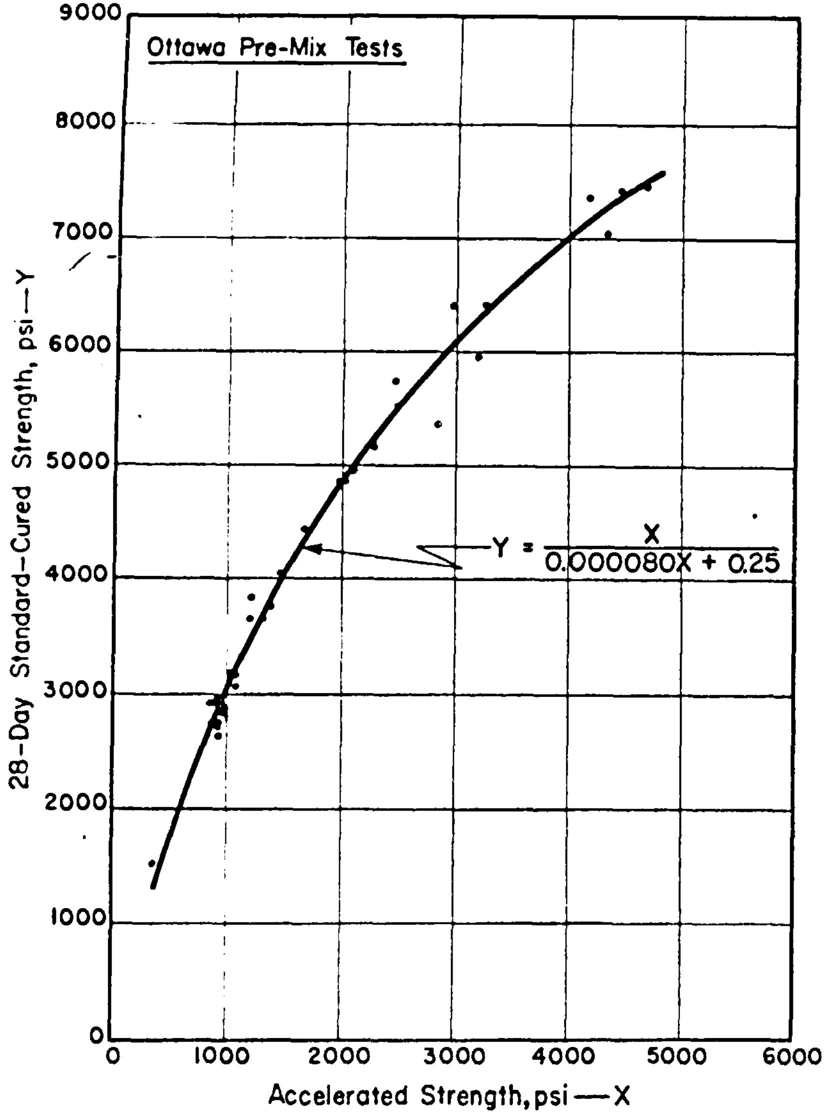

FIG.12. RELATIONSHIP OF ACCELERATED TO 28-DAY STRENGTH
Plain Concrete

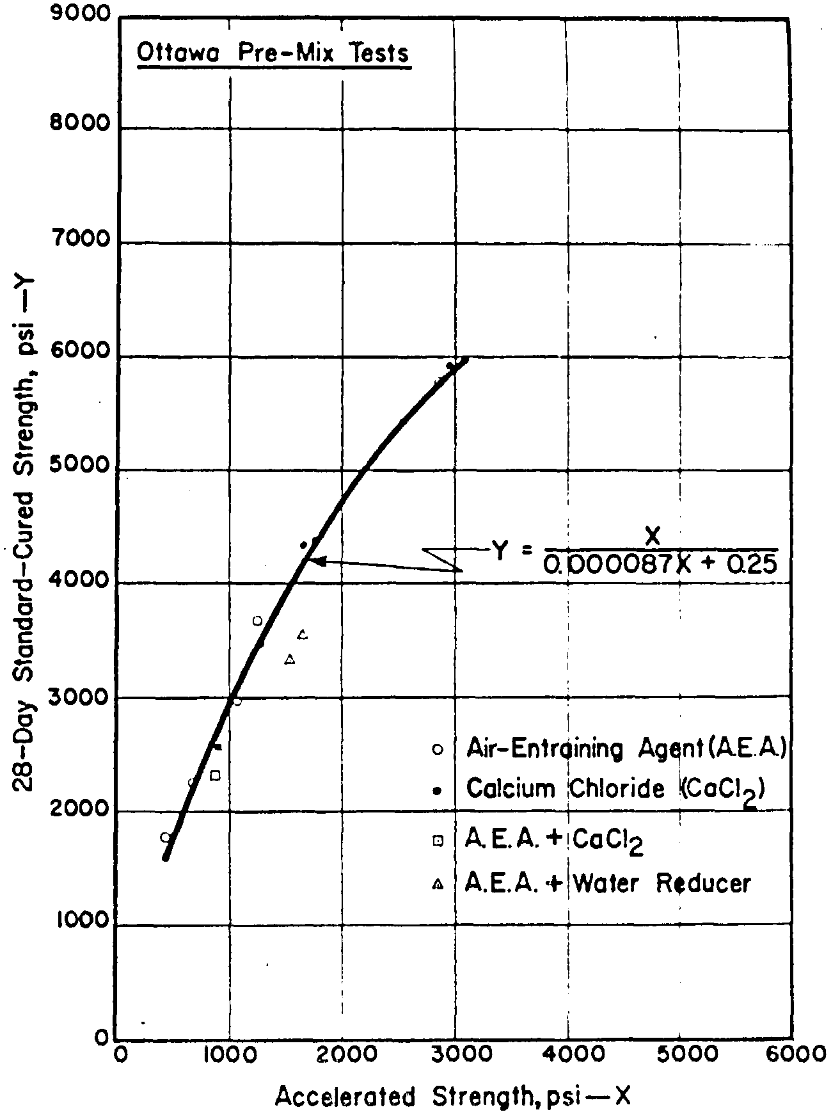

FIG.13. RELATIONSHIP OF ACCELERATED TO 28-DAY STRENGTH
Concrete Containing Different Admixtures

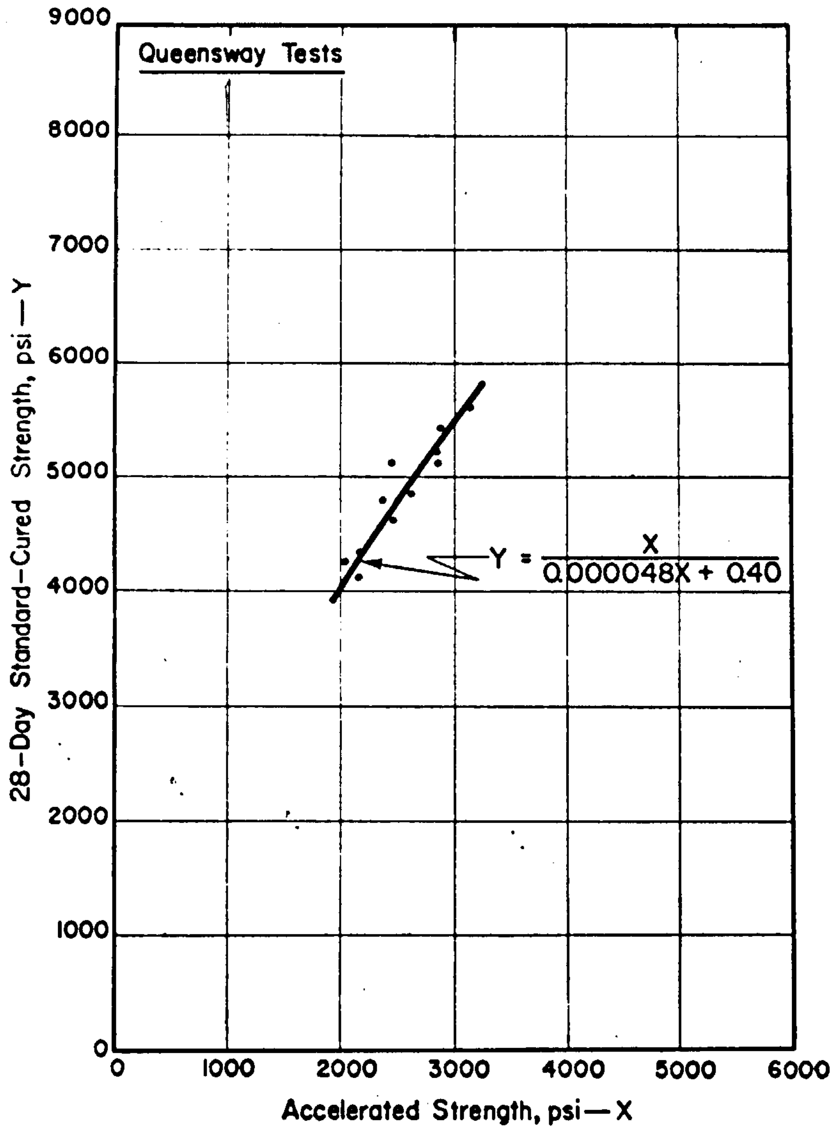

FIG.14. RELATIONSHIP OF ACCELERATED TO 28-DAY STRENGTH
Concrete Containing Air-Entraining And Set-Retarding Admixtures

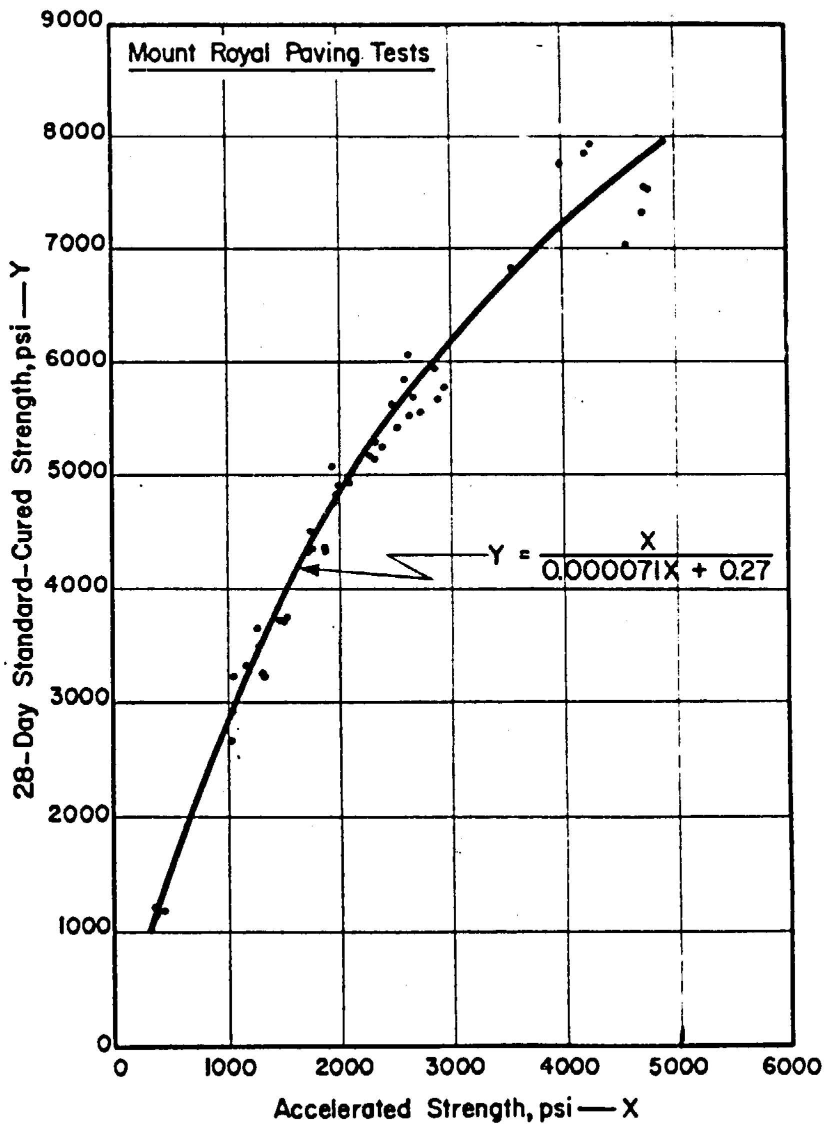

FIG.15. RELATIONSHIP OF ACCELERATED TO 28-DAY STRENGTH
Plain Concrete

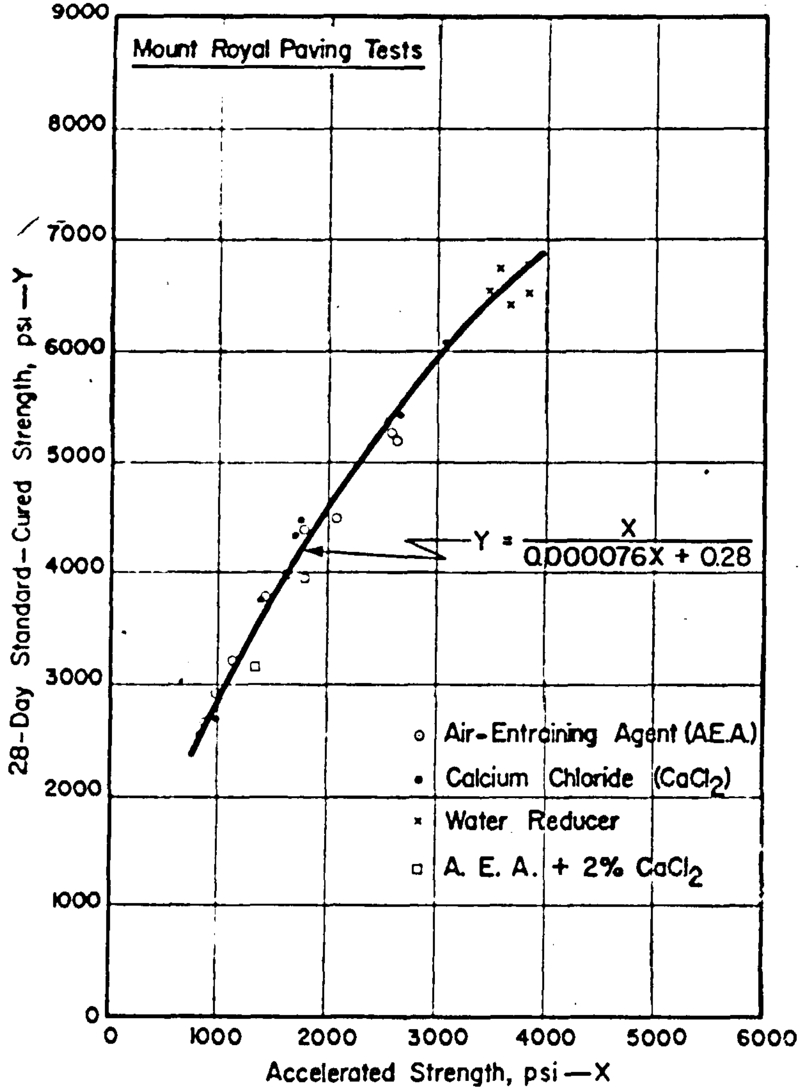

FIG.16. RELATIONSHIP OF ACCELERATED TO 28-DAY STRENGTH

Concrete Containing Different Admixtures

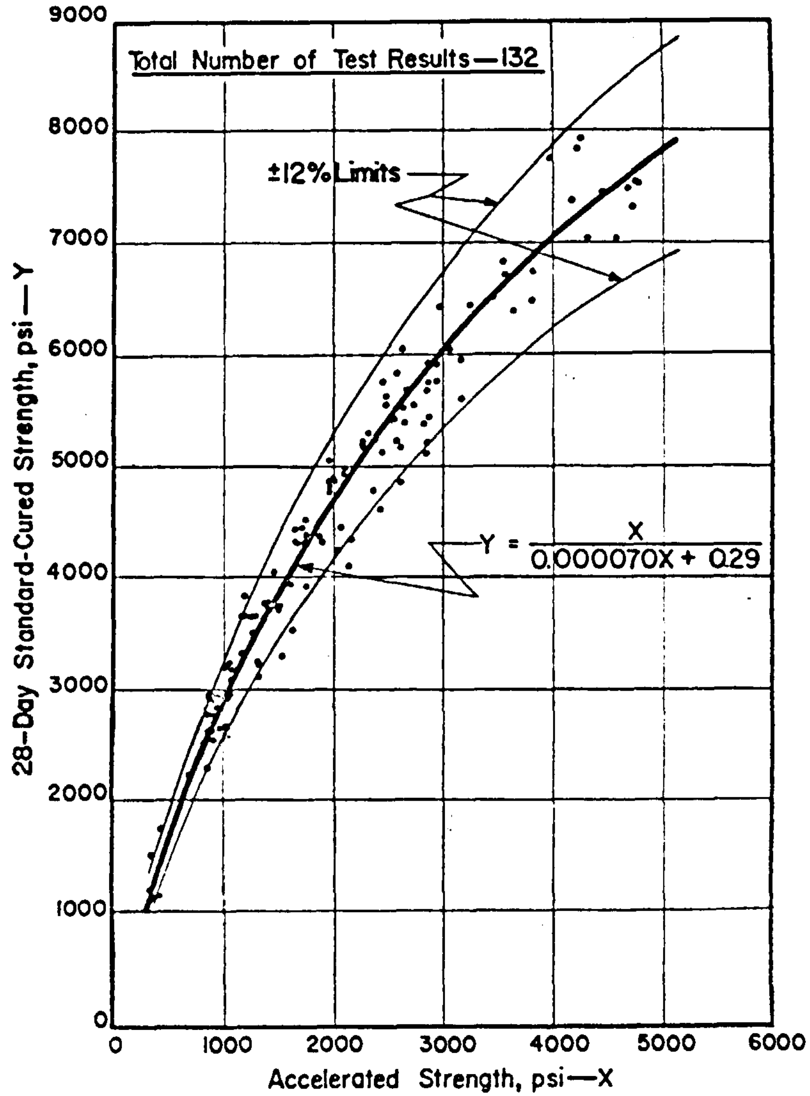

FIG.17. RELATIONSHIP OF ACCELERATED TO 28-DAY STRENGTH

Combined Data for All Types of Concrete

TABLE 9

Accelerated vs 28-Day Strength Relationships

Type of Concrete	Equation* $Y = \frac{X}{AX + B}$	Refer to Figure No.
Ottawa Pre-Mix		
Plain concrete	$Y = \frac{X}{0.000080x + 0.25}$	12
Concrete with admixtures	$Y = \frac{X}{0.000087x + 0.25}$	13
Queensway		
Plain concrete	-	-
Concrete with admixtures	$Y = \frac{X}{0.000048x + 0.40}$	14
Mount Royal		
Plain concrete	$Y = \frac{X}{0.000071x + 0.27}$	15
Concrete with admixtures	$Y = \frac{X}{0.000076x + 0.28}$	16
Combined data for all concretes	$Y = \frac{X}{0.000070x + 0.29}$	17

*X = Accelerated-cured strengths.
Y = 28-day standard-cured strengths.

TABLE 10

Within-Batch Coefficients of Variation

Type of Concrete	No. of Test Results	Coefficients of Variation			
		28 1/2-hr Standard	28 1/2-hr Accelerated	7-day	28-day
Ottawa Pre-Mix	20	2.2	2.0	2.4	2.2
	12	2.4	1.8	-	2.3
	16	1.4+	1.5	1.5+	2.0
Queensway++	11	3.8	3.3	3.7	3.3
Mount Royal	70	2.7	2.4	2.4	2.4
ACI recommended values for excellent laboratory control* = < 3.0					

+ Coefficients of variation are based upon the average of two 6 x 12 in. cylinders; all others are calculated from the mean of three cylinders.

++ Maximum aggregate size 1 1/2 in.; for Mount Royal = 3/4 in. and for Ottawa Pre-Mix = 5/8 in.

* Reference (22).

TABLE 11

Reproducibility of Test Results

	Standard Deviation and Coefficients of Variation*											
	Ottawa Pre-Mix				Queensway+				Mount Royal			
	28 1/2-hr Standard	28 1/2-hr Accelerated	7-day	28-day	28 1/2-hr Standard	28 1/2-hr Accelerated	7-day	28-day	28 1/2-hr Standard	28 1/2-hr Accelerated	7-day	28-day
No. of Tests	12	12	12	12	11	11	11	11	4	4	4	4
Mean Strength, psi	445	950	1975	2940	2215	2540	4070	4860	3835	4000	6020	7600
Standard Deviation, psi	29	72	150	142	337	358	445	491	365	324	310	506
Coefficient of Variation, per cent	6.6	7.6	7.6++	4.8	15.2	14.1	11.0	10.1	9.5	8.1	5.1	6.6

* All calculations are based upon the average of three 6 x 12 in. cylinders unless otherwise stated.

\+ Maximum aggregate size, 1 1/2 in.; for Mount Royal, 3/4 in.; for Ottawa Pre-Mix, 5/8 in.

++ Calculation based upon results of one test cylinder only.

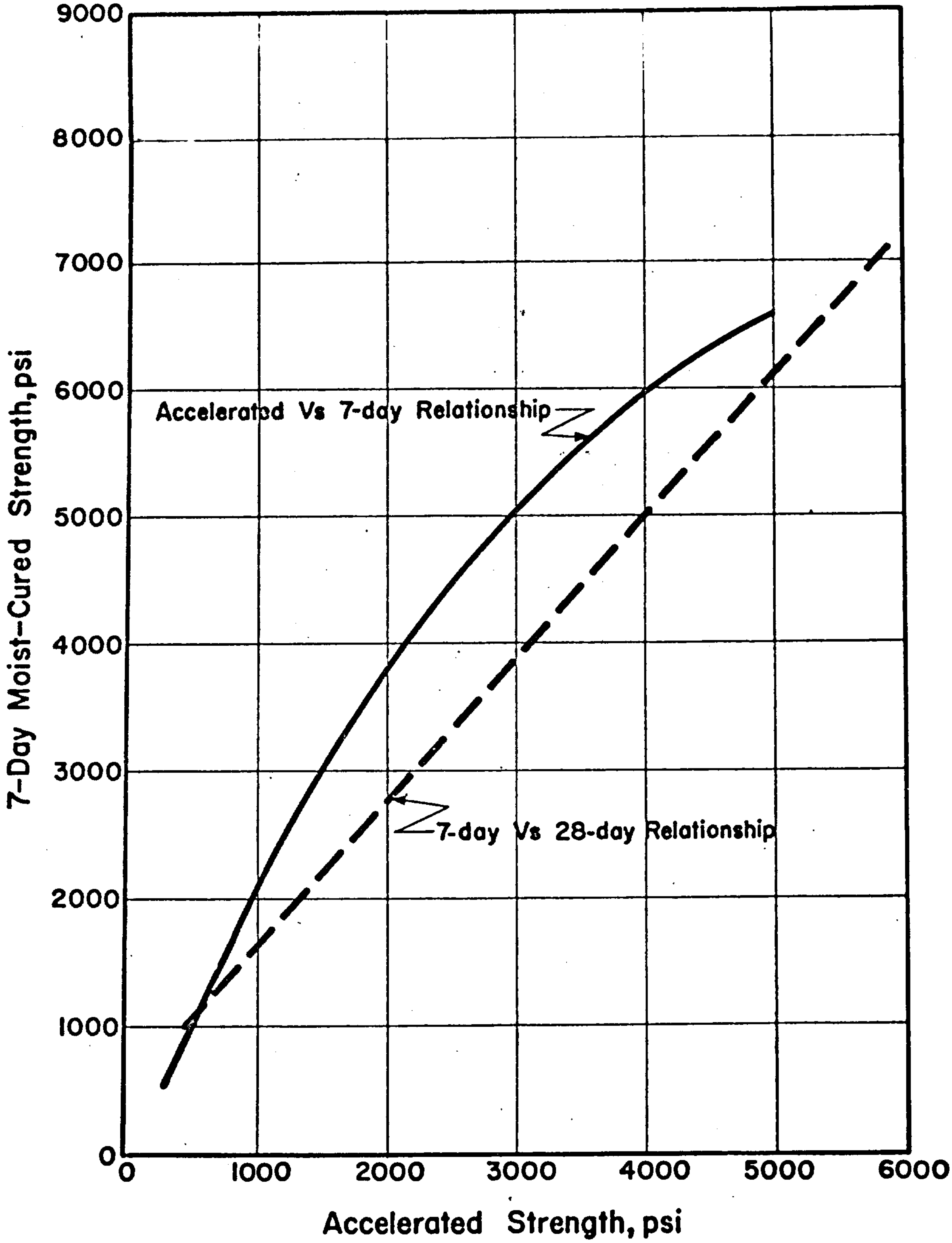

FIG.18. COMPARISON OF ACCELERATED VERSUS 7-DAY STRENGTH, AND 7-DAY VERSUS 28-DAY STRENGTH

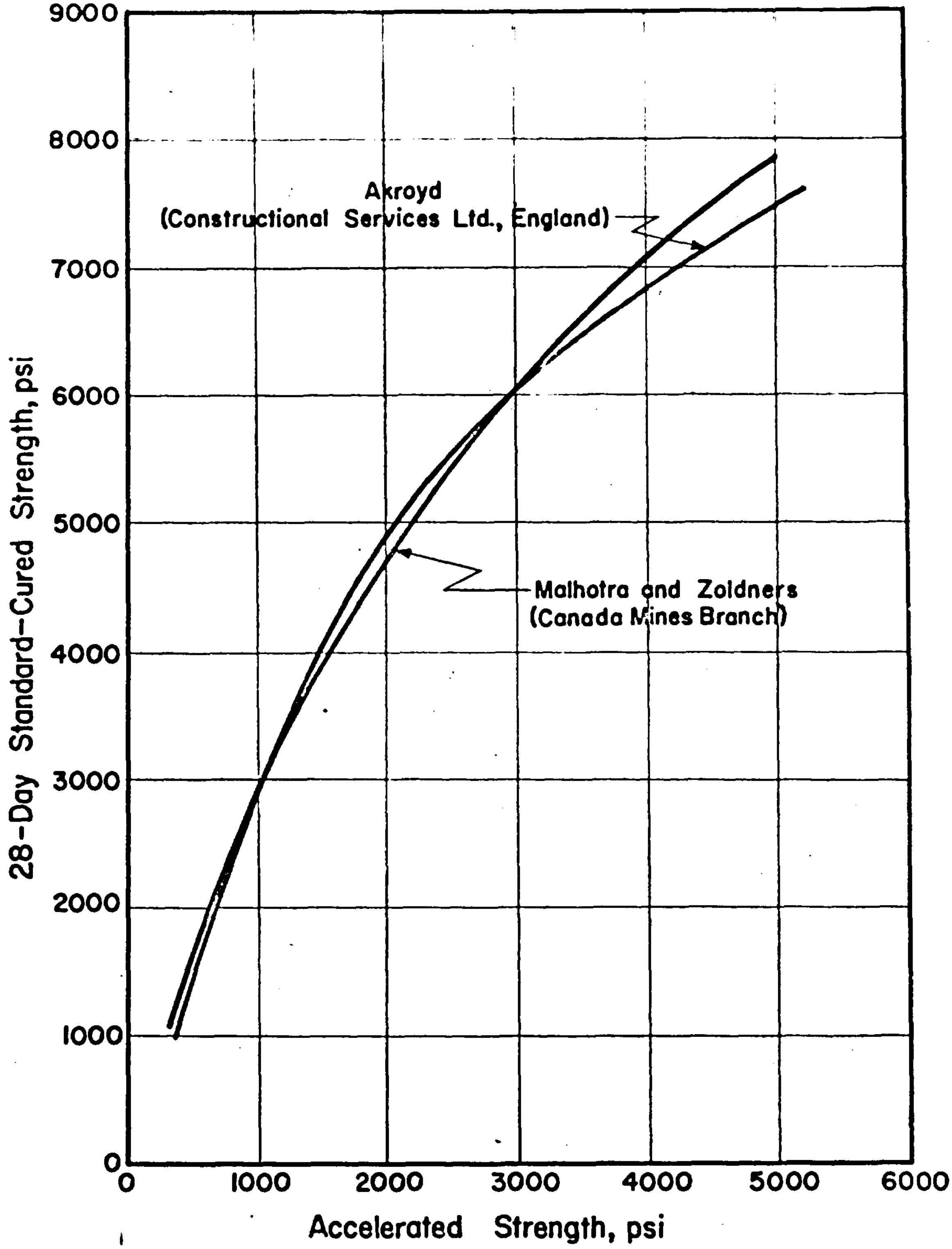

FIG.19. COMPARISON OF RESULTS OF DIFFERENT AUTHORS USING THE SAME CURING METHOD

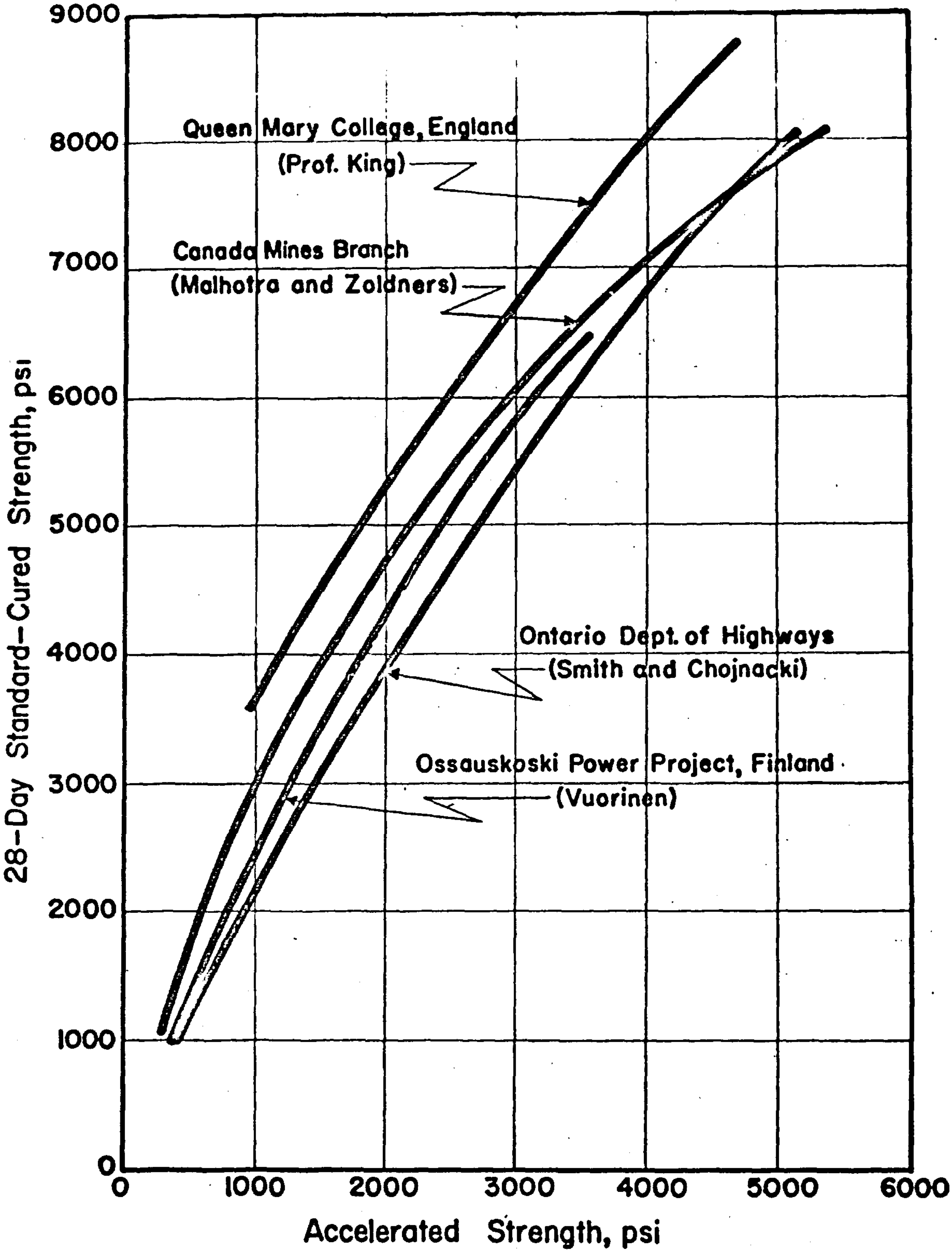

FIG.20. COMPARISON OF DIFFERENT ACCELERATED CURING METHODS

DISCUSSION OF TEST RESULTS AND ANALYSES

Accuracy of Prediction of 28-Day Compressive Strength

The plot of the combined data for accelerated versus 28-day strength tests (Figure 17) shows that the accelerated strength test can be used to estimate the standard 28-day strength of concrete with an accuracy of $\pm$ 12 per cent. The reliability of prediction would improve if separate correlation graphs were established for different cements and admixtures; however, the above degree of accuracy is considered satisfactory for routine quality control work. The accelerated strengths can also be used to predict the 7-day compressive strength with an acceptable degree of reliability.

Effect of Accelerated Curing on Compressive Strength

The strength gain of the accelerated-cured cylinders, as compared with the companion 28 1/2-hr standard cured cylinders, varies from 38.3 to 224.0, 4.2 to 32.5, and 0 to 238.0 per cent for Ottawa Pre-Mix, Queensway and Mount Royal concretes, respectively. The variation in strength gain is probably due to the different strength characteristics of the cements: the 7-day strength of Ottawa Pre-Mix concrete averaged about 70 per cent of its 28-day strength, whereas the 7-day strengths of Queensway and Mount Royal concretes averaged about 80 and 85 per cent respectively. Limited investigations carried out with a modified low heat Type II cement tend to confirm this, as the strength gain of the accelerated-cured cylinders amounted to about 250 to 300 per cent (23). It was also noticed that the lean mixes had shown much higher gain in strength than the corresponding rich mixes.

However, the most important aspect of the test is not the relative gain in the strength of accelerated-cured cylinders but the nature of the relationship between the accelerated-cured and 28-day standard-cured strengths. Figure 17 shows that, irrespective of the cements, aggregates and admixtures used, a hyperbolic curve of the type

$$Y = \frac{X}{AX + B} \quad ^{*}$$

can be used to represent the relationship between the accelerated-cured and the 28-day standard-cured strengths; the ratio of the accelerated to 28-day

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*X = Accelerated-cured strength, psi.
Y = 28-day standard-cured strength, psi.
A and B = constants.

strength decreases with increasing water/cement ratio. The relationship between the accelerated and 7-day strengths for the combined data is also curvilinear (Figure 11), though there are deviations from this for some concretes (Figure 7).

Effect of Concrete Constituents on Accelerated Strength

Cement

The established relationships between the accelerated-cured and 28-day standard-cured strengths (Table 9) are true only for Type I Portland cements. Experimental studies have indicated that changing the type of cement, i.e., the use of modified low heat Type II cement, would change the relationship between the accelerated- and standard-cured strengths.

Aggregates

Inasmuch as only two types of coarse aggregates and three different natural sands have been used, an estimate of the effects of different aggregates on the accelerated strength is not possible. For normal purposes, i.e., in the strength range 2000 to 4000 psi, the effect of aggregates can be neglected; at higher strength levels a separate relationship for each type of aggregate may be necessary (11).

Admixtures

The admixtures employed--i.e., air-entraining agents, water reducers, and accelerators--do not significantly affect the general relationship between the accelerated and 28-day standard strengths. Furthermore, when two admixtures have been used simultaneously, e.g., an air-entraining agent and a water reducer, the established relationships still hold good. It is interesting to note that similar results have been reported by other research workers (15). Since a limited number of admixtures have been investigated and the number of test results per admixture is small, no generalized conclusions can be drawn.

Ratio of Accelerated to 28-Day Strength

The ratio of accelerated to 28-day strength, expressed as a percentage, varies from 23.8 at low strength level to 64.8 per cent at high strength level (Figure 17). The ratio at the low strength level is not as high as reported by others using somewhat more complicated curing procedures (15). It is considered that this ratio could be increased by using the same method but a different curing and boiling cycle. Unfortunately, the increase in the accelerated strength is offset by longer curing cycle requirements and the need for overtime work. However, when we take into account the simplicity of both method and equipment, together with the convenience of fitting this test into a normal working day, the lower value of the above ratio becomes relatively insignificant. Further, it must be stressed that the lower value of the accelerated to 28-day strength ratio is of little consequence as long as it does not affect the reliability of prediction of the 28-day compressive strength of concrete.

Ratio of Accelerated to 7-Day Strength

It has been claimed by Akroyd (11) that, for the method under study, the accelerated-cured strength bears the same relation to the 7-day standard-cured strength as does the 7-day to the 28-day standard-cured strength. Figure 18 shows a curve for the accelerated versus 7-day test results for the combined results of this investigation. Superimposed upon Figure 18 is the corresponding curve for the 7-day versus 28-day standard cured strengths. It is readily seen that the two curves are different; thus, the above claimed relationship does not hold good.

Reproducibility of Accelerated Test

The coefficients of variation of the accelerated strengths are 2.8, 4.0 and 1.5 per cent higher than the corresponding values for the 28-day standard-cured strengths for Ottawa Pre-Mix, Queensway and Mount Royal concretes (Table 11). Perhaps this indicates that the reproducibility of the accelerated strength may not be as good as that of the corresponding 28-day strength. However, additonal data are under study to confirm this, since a very limited number of test results were available that satisfied the requirements of the above analysis.

Scatter of Test Results of High-Strength Concrete

A wide scatter in test results beyond an accelerated strength of 3000 psi has been reported by several investigators (11, 15, 16). The plot of combined data for all types of concrete (Figure 17) does not show any increased scatter at higher strengths; however, additional test data are under analysis to confirm this.

Number of Cylinders per Test and Reliability of Prediction

At each testing age, the results of three 6 x 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 considerably reduced. Cornwell (3) 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.

Limitation of Test Data

Since the experimental programme in the field was conducted in conjunction with two ready-mix plants and a highway paving contractor, the availability of a particular type of test sample depended on the requirements for that kind of concrete in the field; for example, in Queensway tests, only concrete containing admixtures was available. Because of these considerations the test programme was not designed statistically; however, a sufficient number of test mixes covering different variables have been sampled for the results to be valid for practical purposes.

GENERAL COMMENTS

Comparison of These Results with Those of Other Investigators

The accelerated curing method under study is identical to that used by Akroyd (11). For purposes of comparison, the relationship between accelerated strength versus 28-day standard-cured strength, established in this investigation (Figure 17), and that published by Akroyd (11) have been plotted in Figure 19. The two curves are almost identical; perhaps this is due to the fact that the strength development characteristics of some of the cements used by Akroyd are similar to those of the cement used for Ottawa Pre-Mix concrete. The implications of the curves of Figure 19 become more obvious when it is noted that Akroyd carried out his work in England on concrete without admixtures, using different aggregates, cements, and types of specimens.

Apart from the work of the above-mentioned author, the results of this investigation cannot be compared directly with those of J. W. H. King and others because the accelerated curing procedures used by the latter are essentially different. Professor King, who was the first to initiate the accelerated curing research work in England, used an oven-curing technique with a 7-hour curing cycle (5,7,9,10). Thompson (20) developed a 24-hour, hot-water (95°F) curing method by finding the temperature which gave about the same strength as King's oven-curing method. Smith and Chojnacki (15) used the boiling-water method with about a 24-hour curing cycle but have complicated the procedure by introducing a new variable, i.e., the time at which the test specimens are placed in the boiling water is determined by the setting time of the concrete. Vuorinen (12) and Malhotra (17) have used the hot-water curing (165°F) method with a 24-hour curing cycle on large construction jobs. Then there are others who have used somewhat similar accelerated curing methods (13,14). As a matter of interest, Figure 20 shows the results of the present investigation and some of the other results mentioned above.

Organizations in Canada Using the Boiling Method in the Field

At the suggestion of the Mines Branch, the above method is being studied by the Concrete Laboratory Inc., Montreal, with a view to adopting it as one of the control tests at the Manicouagan-2 Project of the Quebec Hydro-Electric Commission.

At present the Control and Research Laboratory of the City of Montreal is carrying out extensive field tests with a view to adopting this method as a control test on its concrete paving jobs.

CONCLUSIONS

From the analyses of the test data the following conclusions may be drawn:

1. The boiling method investigated in this report appears to be a satisfactory means of accelerating the strength development of concrete for predicting 28-day compressive strength at 28 1/2 hours.

2. The relationship between the accelerated-cured and 28-day standard-cured strength can be represented by a hyperbolic curve of the type

$$Y = \frac{X}{AX + B}.$$

This relation is considered to be independent of the cement brands, aggregates, and admixtures used.

3. The established relationships (Table 9) are true only for Type I cement; the use of low heat modified Type II or any other type of cement would require establishment of new correlations between accelerated and 28-day strengths.

4. The 28-day standard-cured strength can be predicted from the accelerated strength with an accuracy of about $\pm$ 12 per cent. This accuracy is considered satisfactory for routine quality control work; however, the reliability of prediction will improve if allowance is made for the effects of different cement brands, aggregates, and admixtures.

ACKNOWLEDGEMENTS

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Mr. L. Franceschini, President, Mount Royal Paving and Supplies Limited, Montreal,
Mr. L.W. Franceschini, General Manager, Ottawa Pre-Mixed Concrete Limited, Ottawa.

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REFERENCES

1. M.S. Gerend, "Steam-Cured Cylinders Give 28-Day Concrete Strength in 48 Hours", Engineering News Record, Vol. 98, No. 7, pp. 282-283 (February 17, 1927).

2. D.G. Patch, "An 8-hour Accelerated Strength Test for Field Concrete Control", Journal of the American Concrete Institute, Proceedings, Vol. 4-5, pp. 318-324 (March-April 1933).

3. J.S. Cornwell, "The Reliability of 24-hr Compressive Strength of Accelerated-Cured Concrete as a Basis for Predicting the Strength of Standard-Cured Concrete Aged 28 and 90 Days", Construction Materials Report No. S.M. 53, The Snowy Mountains Hydro-Electric Authority, Australia (1956).

4. T.B. Nicol, "Warragamba Dam", The Institution of Civil Engineers, Proceedings, Vol. 27, p. 529 (March 1964).

5. J. W. H. King, "Concrete Quality Control", Chartered Civil Engineer, November 1955, pp. 46-48.

6. T. N. W. Akroyd and R. G. Smith-Gander, "Accelerated Curing of Concrete Test Cubes", Engineering (London), Vol. 181, pp. 153-155 (1956).

7. J. W. H. King, "Further Notes on the Accelerated Test for Concrete", Chartered Civil Engineer, May 1957, pp. 15-19.

8. N. N. B. Ordman and N. B. Bondre, "Accelerated Curing Tests on Concrete", Engineering (London), Vol. 185, p. 243 (1958).

9. J. W. H. King, "Accelerated Testing of Concrete", Proceedings, Fiftieth Anniversary Conference, Institute of Structural Engineers, pp. 376-381 and 386-387 (October 1958).

10. J. W. H. King, "Accelerated Test for the Strength of Concrete", Journal of Applied Chemistry (June 1960), pp. 256-262.

11. T. N. W. Akroyd, "The Accelerated Curing of Concrete Test Cubes", The Institution of Civil Engineers, Proceedings, Vol. 19, pp. 1-22 (1961).

12. J. Vuorinen, "Some Notes on the Use of Accelerated Curing of Test Specimens for Concrete Quality Control", paper submitted to the RILEM Correspondence Symposium on "Accelerated Hardening of Concrete With a View to Rapid Control Tests", Paris, France (1964-65).

13. H. Yokomichi and M. Hayashi, "Influence of High Temperature Curing in Early Ages on Strength of Concrete", paper submitted to the RILEM Correspondence Symposium on "Accelerated Hardening of Concrete With a View to Rapid Control Tests", Paris, France (1964-65).

14. W. Jarocki, "The Rapid Control of Concrete Strength on the Basis of Specimens Cured in Hot Water", paper submitted to the RILEM Correspondence Symposium on "Accelerated Hardening of Concrete With a View to Rapid Control Tests", Paris, France (1964-65).

15. P. Smith and B. Chojnacki, "Accelerated Strength Testing of Concrete Cylinders", American Society for Testing and Materials, Proceedings, Vol. 63, pp. 1079-1101 (1963).

16. Discussion by V. M. Malhotra of Reference 15: American Society for Testing and Materials, Proceedings, Vol. 63, pp. 1101-1104 (1963).

17. V. M. Malhotra, "Analyses of Accelerated 24-hr Concrete Strengths from Field Tests", Canada Dept. of Mines and Tech. Surveys, Mines Branch Internal Report MPI 64-8, Feb. 1964, submitted to the RILEM Correspondence Symposium on "Accelerated Hardening of Concrete With a View to Rapid Control Tests", Paris, France (1964-65).

18. V. M. Malhotra and N. G. Zoldners, "Accelerated Strength Testing of Concrete, Using the Modified Boiling Method", paper submitted to the RILEM Correspondence Symposium on "Accelerated Hardening of Concrete With a View to Rapid Control Tests", Paris, France (1964-65).

19. William R. Lorman, "Verifying the Quality of Freshly Mixed Concrete", American Society for Testing and Materials, Proceedings, Vol. 62, pp. 949-957 (1962).

20. Discussion by J. W. H. King et al. of Reference 11: The Institution of Civil Engineers, Proceedings, Vol. 21, p. 680 (March 1962).

21. V. M. Malhotra, "Predicting Compressive Strength from Properties of Fresh Concrete", ASTM Materials Research and Standards, Vol. 3, No. 6, pp. 483-485 (June 1963).

22. ACI Committee 214, "Recommended Practice for Evaluation of Compression Test Results of Field Concrete", American Concrete Institute Journal, Vol. 29, No. 1 (July 1957).

23. Personal communication from Mr. J. Chartrand, Concrete Laboratory Inc., Montreal (March 1964).

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