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The effectiveness of a number of special techniques in increasing the compressive strength of high strength concrete.

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THE EFFECTIVENESS OF A NUMBER OF SPECIAL TECHNIQUES IN INCREASING THE COMPRESSIVE STRENGTH OF HIGH STRENGTH CONCRETE

A THESIS

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ABSTRACT

Three special techniques and three admixtures were employed in a research programme, designed to produce high compressive strength concretes. The three special techniques were high speed slurry mixing, seeding and revibration. The three admixtures were fly ash, lignosulphonic type water-reducing agent and hydroxylated carboxylic type water-reducing agent. High-speed slurry mixing, revibration and water-reducing agents appear to hold the most promise for increasing the compressive strength of high strength concrete.

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Chapter I

INTRODUCTION

For the majority of jobs in which concrete is the building material, the specified minimum compressive strengths at 28 days will normally be in the range of 2000 to 5000 psi. Rarely will strengths higher than 5000 psi be specified. However, the subject of the use of concrete of a strength very much in access of the commonly accepted standards of to-day is not one of merely speculative interest, but of an immediate practical importance. In a common concrete structure, the low working stresses are a safeguard against possible defects in the choice of materials and in making, placing and curing concrete. Certainly it involves a great waste which could be eliminated in highly stressed concrete structures by the use of high-strength concrete.

In arch construction, concrete fulfils most completely its function of carrying load by compression of the structural members. Towles[38] in 1932 discussed the advantage of the use of "high-strength concrete". His analysis was based on the"assumption that it would be possible to manufacture satisfactory concrete of a 28-day strength of 7000 psi". He further assumed that "the extreme fibre stress in compression is limited to 37.5 per cent .....or 2600 psi ..... and concentric compression to 25 per cent or 1750 psi". He considered, for simplicity, "arches of open spandrel construction in which the load is carried vertically at equal intervals to the arch ring or rib". He stated: "It will be found that the following ratios of weights will hold approximately for arches with solid ribs of the same type and proportions with equal load per foot of length imposed upon the arch rings (exclusive of the dead load of the arch rings themselves), and for ordinary ratios of rise to span (say from 1/5 to 1/8)". Comparing concrete of strength f_{cc} = 750 psi as given in most then - current codes with concrete of a strength of 1750 psi, he found:

Span, ft	W_{750}/W_{1750}
50	2.5 ±
100	2.7 ±
150	2.7 to 3.1
200	2.8 to 3.6
250	3.0 to 4.0

This comparison, he noted, revealed that "for the same proportions in the arch ring and for the same loading per foot imposed on the arch rib, it would be possible with 1750-lb concrete to construct a span with the same weight per foot in the arch rib which would be 2 1/3 times as long as with 750-lb ....concrete". He added "..... in the future when we have surmounted the practical difficulties of producing high-strength concretes, we may expect arch spans of unprecedented length". He concluded: ".....from the standpoint of cost, there would be marked advantages in the use of high-strength concretes, particularly for designs involving multiple arch spans, for single long span crossings, and for arches in which it is desired to keep the ratio of rise to span at a minimum".

Parme[26], of the Portland Cement Association, has pointed out that beneficially utilizing concrete of unusually high compressive strength in reinforced concrete construction is not possible unless one has steel which could be subjected to proportionately higher working stresses. Using higher-strength concrete with balanced reinforcement will reduce the volume of the concrete but increase the amount of steel. While advantage cannot economically be taken of very high-strength concrete in ordinary reinforced concrete construction using normal-strength reinforcing steel, Mather[26], has indicated that the situation is quite different in shell structures below the ground. Such structures derive their advantages from soil-structure interaction as a result of which the loading is distributed advantageously and the dynamic strength of the soil is utilized in resisting the effects of dynamic loading. In order for the soil strength to be economically utilized and to mobilize the dynamic energy of distortion of the soil, the shell must be flexible. Even the thinnest reinforced concrete arches fail in compression at high over-pressures long before critical buckling stresses are revealed. The lowest possible section modulus is conducive to maximum flexibility. Hence, partially or wholly underground reinforced concrete arches designed to withstand dynamic loading should be as thin as possible; such design makes appropriate the use of materials of the highest available strength.

High-strength concrete should also be useful in prestressed concrete work because of its lower creep and, therefore, less relaxation of stress in the prestressing wires. In recent years the Department of Highways of Ontario has been using concretes having strengths in excess of 6000 psi for some of their precast prestressed bridge girders.

And, finally, it should be mentioned that better resistance to weathering action and more satisfactory appearance are obvious advantages of high-strength concrete that for some applications can be very important.

From the foregoing, it can be seen that there are many situations in which high-strength concrete could be used to advantage. At the present time there is considerable knowledge as to the factors affecting the potential compressive strength of concrete. These are discussed in the next chapter. In Chapter III, special techniques for increasing the compressive strength of concrete are discussed. The purpose of the experimental programme is to investigate the effectiveness of a number of special techniques in increasing the compressive strength of high-strength concrete.

Chapter II

FACTORS AFFECTING POTENTIAL COMPRESSIVE STRENGTH OF CONCRETE

This literature survey is concerned primarily with the more fundamental factors that affect what the potential strength of a concrete mixture can be. These factors depend on the inherent properties of the materials used in the mixture, on the proportions in which they are combined, and the manner in which they interact. The factors affecting potential compressive strength of concrete will be considered in the following order:

a) The water-cement ratio

b) Compaction

c) Properties of the aggregate

d) Characteristics of the cementing medium

e) Curing

f) Testing

a) <u>THE WATER-CEMENT RATIO</u>

The cementing medium in concrete is produced by the chemical reaction between portland cement and water. The inherent strength of this medium is primarily a function of the ratio of the amounts of these two components, normally known as Abrams' water-cement-ratio law which states "with given concrete materials and conditions of test, the quantity of mixing water used per bag of cement determines the strength of the concrete, so long as the mix is of a workable plasticity". The water-cement ratio of the cement paste is considered the most important single factor affecting the compressive strength of concrete. Both Kleiger[22] and Collins[9] agreed that optimum high strength can be obtained at that water-cement ratio which is as low as possible and still permits full compaction.

Powers[32] stated: "We have no adequate theory about the strength of cement gel .... However, it is unlikely that physical forces account for all the strength....We assume....that inter-particle chemical bonds exist that cannot be severed by the spreading pressure of water. Accordingly, we assume that strength is derived from inter-particle physical forces and chemical bonds, the chemical bonds affecting a relatively small part of the cross-sectional area. A given cement gel should be expected to have a characteristic strength, but the strength of the structure built of it, that is, the paste as a whole, should depend on the amount of gel in the space available to it ... The amount of space available to gel is equal to the sum of the volume of water-filled space originally present plus the space made vacant by the hydration of cement". It is known that if the water-cement ratio is less than 0.38, complete hydration is not possible as the volume available is insufficient to accommodate all the products of hydration. It, therefore, follows that in the high-strength ranges, the higher the strength desired, the lower the proportion of cement that can become hydrated.

It should also be noted that at low water-cement ratios a problem of workability will be encountered. Mixes in the high-strength range, that is with water-cement ratios lower than approximately 0.33, are much too stiff to be properly compacted by ordinary methods and it is here that special techniques must be employed. Abrams[33] obtained strengths of the order of 40,000 psi using mixes of neat portland cement with a water-cement ratio of 0.08, but clearly considerable pressure was applied in moulding the specimens.

Lecznar and Barnoff[24] reported on pre-compressed cement-water pastes "In summary, the magnitude of moulding pressure and the length of curing time greatly affect the compressive strength of pre-compressed cement-water pastes, while varying the water-cement ratio produces practically an insignificant change in the compressive strength". It would appear doubtful from the foregoing that the water-cement ratio strength law holds for concretes in the high-strength ranges.

b) COMPACTION

The strength of concrete is controlled primarily by the water-cement ratio, provided the concrete is fully compacted.

Actually it may be more accurate to say that strength is related to the voids-cement ratio, the voids being the sum of the volumes of water and air in the concrete, the volume of air being an index of the efficiency of compaction. Any technique is suitable provided full compaction can be attained. If full compaction is attained, the water-cement ratio will then be as good a criterion of strength as voids-cement ratio, since the amount of entrapped air voids would be small and exert little influence on the magnitude of the voids-cement ratio.

Klieger[22] pointed out that the restriction limiting use of the water-cement ratio law to "plastic", "workable" mixtures properly should be interpreted to mean to "fully compacted mixtures with a minimum of entrapped air voids". Thus, as the water-cement ratio is progressively reduced for a mixture by decreasing the amount of water used, the concrete will become progressively less workable and progressively greater effort will be required to achieve full compaction.

Davies[24] studied the effects of compaction of concrete by vibration and concluded that: "The effectiveness of vibration depends mainly on its acceleration, and not on the individual values of its frequency and amplitude; but, very small amplitudes of the order of 0.002 inches, are comparatively ineffective. There is little to choose between vertical linear and horizontal circular vibration; vertical circular vibration is definitely better than either. The effectiveness of vibration increases with its acceleration, probably up to at least 20 g; but above about 12 g the increase is slow".

The Joint Committee of the Institutions of Structural and Civil Engineers[14] emphasized the importance of compaction in the attainment of the compressive strength for which the constituents and proportions of a mix were selected. The report points out that with a properly proportioned concrete mixture "extended vibration will be wasteful of effort but not harmful to the concrete". If, on extended vibration, segregation of the concrete mixture occurs, this indicates that the mixture is not properly proportioned.

According to Sawyer and Lee[37] the possibility of over-vibrating is not critical insofar as the compressive strength of concrete is concerned, so that, an extension of the vibration time beyond that necessary to obtain satisfactory compaction or over-vibration is not harmful with dry mixes or those in which the mortar content was low.

Similar results were confirmed by the work of the Research Committee of the Institutions of Civil and Structural Engineers[15]. At a water-cement ratio of 0.4 and frequencies of 1500 to 5000 vibrations per minute, the strength increases appreciably with the time of vibration up to about 3 minutes and thereafter the increase is only small. For a frequency of 8,000 vibrations per minute, however, the strength still increases appreciably with time of vibration even after 12 minutes.

At a water-cement ratio of 0.50 the rate of increase of strength with time of vibration is small after 15 seconds with frequencies of 1,500 to 5,000 vibrations per minute and after 30 seconds with frequencies of 8,000 vibrations per minute.

The Research Committee showed that for short periods of vibration the greater strengths are obtained with small frequencies especially at the lower water-cement ratios but that the higher frequency of 8,000 vibrations per minute gave greater strenths at the lower water-cement ratios when vibration was prolonged to twelve minutes.

c) PROPERTIES OF THE AGGREGATE

Properties of both the fine and coarse aggregates can have a bearing on the potential compressive strength of concrete, which can be indirect or direct. For example, the gradation of both the fine and coarse aggregates and the proportions in which they are combined can affect the water requirement for a given workability and cement content and thereby indirectly affect the resultant compressive strength. Similarly, surface texture and shape of both fine and coarse aggregates can affect the water requirement for a given workability and cement content and thereby indirectly affect the resultant compressive strength. However, the type of aggregate used in a concrete mix can also exert a direct influence on the compressive strength. Bond characteristics, for example, can have an influence on strength. Kaplan[43] reported that the use of different types of coarse aggregate in a given concrete mixture (constant w/c ratio) resulted in a 29 per cent variation in compressive strength. It has also been reported that for water-cement ratios below 0.4, the use of crushed aggregate has given strengths up to 38 per cent higher than when gravel is used[23], (again at constant w/c ratio). Collins[10] stated that for concretes having strengths of 7,000 psi or more the aggregate plays an important role and sets a limit on the strength attainable. This limit, he says, generally lies in the range from 12,000 to 15,000 psi. Jones[16] seems to agree with this when he states that the aggregate should have a crushing strength at least equal to that of the hardened cement paste.

The fine aggregate plays an important role in the concrete in that it combines with the cement paste to form a mortar and fill in the voids between the particles of coarse aggregate. It was reported by Smith[35] et al that the use of coarse sand (finemess modulus of approximately 3.00) in high compressive strength concrete was desirable. Kennedy[18] developed this point further and pointed out that there is a general tendency for strength to decrease with decreasing fineness modulus.

The maximum size of coarse aggregate is another factor that many authorities claim affects the compressive strength of concrete. Although concrete containing large aggregate requires less water and cement than concrete containing smaller maximum size aggregate (for a given water-cement ratio) such a concrete generally has a lower compressive strength than concrete with smaller maximum size aggregate. Walker and Bloom[36] reported test results to support this and concluded that "the size of coarse aggregate exerts an influence on concrete strength independently of the water-cement ratio. For example, for a given water ratio, strength becomes less as maximum size of coarse aggregate is increased". Smith et al[35] would seem to agree with this when they state that the use of crushed limestone aggregate, graded to a maximum size of one-half inch will aid in producing high compressive strength concrete. A possible explanation for higher compressive strengths with smaller maximum size aggregate is that a large rock has relatively much less surface area to be gripped by the mortar. There is then a strong possibility that initial compressive failure within the mass of the concrete is a failure in bond between the mortar and aggregate which exerts a direct influence on the compressive strength. Before leaving the subject of influence of maximum size of aggregate on compressive strength, it should be noted that there is not unanimity on this issue.

Kleiger[22] claims that the maximum size of any given aggregate affects strength only indirectly as it influences water requirement for a given consistency.

Although the aggregate-cement ratio has been proven to be a secondary factor in the compressive strength of concrete, it has been found that for a constant water-cement ratio, a leaner mix leads to higher strengths[13].

d) CHARACTERISTICS OF THE CEMENTING MEDIUM

Several types of Portland cement are available commercially to meet the varying needs of the building industry. In performance, the three most important types (Normal, High-Early Strength and Low Heat) differ mainly in their rates of strength development. As the type names would suggest,the High-Early type develops strength more rapidly than Normal Portland whereas, the Low Heat type develops strength more slowly. It is interesting to note that at the age of three months, the strengths exhibited by these three types will be approximately equal. However, the ultimate strength of the Low Heat type will generally be higher than that of Normal Portland, whereas, the ultimate strength of High-Early cement will be somewhat lower than for Normal Portland.

The different strength performances of the different types of cement is achieved primarily by controlling the chemical composition and fineness of grinding. Of the four main compounds in hydrated Portland cement, the silicates C_3S and C_2S are primarily responsible for the strength development. A convenient approximate rule assumes that C_3S contributes most of the strength development during the first four weeks and C_2S influences the gain in strength from four weeks onwards[42]. At the age of about one year, the two compounds, weight for weight, contribute approximately equally to the ultimate strength[12]. Neat C_3S and neat C_2S have been found to have a strength of the order of 10,000 psi at the age of 18 months but at the age of 7 days C_2S had no strength while the strength of C_3S was about 6,000 psi [29].

The influence of the other major compounds (C_3A and C_4AF) on the strength development of cement has been less clearly established[12]. C_3A contributes to the strength of the cement paste at one to three days, and possibly longer, but causes retrogression at an advanced age particularly in cements with a high C_3A (or $C_3A + C_4AF$) content. Powers[31], in reporting compressive strength values for five cements of differing composition, said his data indicated that cement gels low in C_3A are stronger than those higher in C_3A. Thus, the role of C_3A is still controversial. The role of C_4AF in the development of strength of cement is also debatable but it certainly makes no appreciable positive contribution[12].

The faster strength development of High-Early Portland is achieved primarily by having a higher C_3S content and finer grinding of the cement clinker. The slower strength development of the Low Heat Portland cements is achieved primarily by having a lower content of the more rapidly hydrating compounds C_3S and C_3A.

The effects of the minor compounds on the strength of cement paste have not been thoroughly investigated as these compounds are not thought to be of importance as far as strength is concerned. Recent tests on the influence of alkaliis have shown that the increase in strength beyond the age of 28 days is strongly affected by the alkali content. Tuthill[39], found that increased alkali content of five cements tested reduced the compressive strengths for both non-air and air-entrained concretes.

It should be pointed out that during the past 55 years or so an increase in the average computed C_3S content and an increase in fineness have both contributed to higher concrete strengths at all ages.

e) CURING

Curing is one of the most important factors affecting the performance of concrete. Concrete of normal consistency contains more water than is necessary for proper curing so that if excessive loss of water by evaporation or self-dessication is prevented during the early hardening period, the concrete will continue to gain strength for a considerable time. Adequate curing of concrete is essential in order to develop to a high degree the desirable properties of concrete. Curing promotes the hydration of cement and controls the temperature and moisture movement from and into the concrete.

Curing with water has been long recognized as the most satisfactory method. Among other methods commonly employed are ponding or covering with wet earth or straw, low pressure and high pressure steam curing, the use of surface coatings of sodium silicate and asphaltic materials and water proof paper.

Kleiger[22] reported that for low water-cement ratio concretes, it is more necessary to supply additional water during curing than is the case with higher water-cement ratio concretes. For concrete of 0.29 water-cement ratio, the strength of specimens made with saturated aggregates and cured by ponding water on top of the specimen was 850 psi to 1,000 psi greater at 28 days than that of comparable specimens made with dry aggregates and cured under damp burlap. Kleiger[13] also noted that although early strength is increased by elevated temperatures of mixing and curing, later strengths are reduced by such temperatures.

According to Smith et al[35], continuous moist-curing of the concrete for atleast 28 days is necessary to develop compressive strength in excess of 10,000 psi at 90 days.

Price[34] showed that at the 80 days age, concrete specimens that had been continuously moist-cured showed higher compressive strength than any whose curing had been interrupted. However, in tests of specimens at the 90 days age, he found higher strengths for specimens moist-cured to 28 days and thereafter stored in laboratory air.

f) TESTING FACTORS

The most common of all tests on hardened concrete is the compression test. When performing strength tests, attention must be paid to testing factors such as specimen size and shape, rate of load applications, influence of moisture condition and capping compounds.

(i) Specimen Size

Neville[28] pointed out that the strength of a brittle material can be defined as the critical state of stress at which fracture occurs. He noted that the actual stress at fracture is considerably lower than the theoretical strength estimated from molecular cohesion and calculated from surface energy. He suggested that the Griffith theory relating to cracks and flaws which lead to high stress concentrations and local fracturing while the average stress is low, can be invoked not only to account for the low actual strength of such materials, but also for the observed effects of specimen size on indicated strength of concrete. He suggested that as specimen size increases, the probability of the presence of a critical flaw of critical location and orientation likewise increases. In review of data on flexural strength, he found "convincing proof" that the effect of specimen size was as follows: as the area of the bottom surface of the beam subjected to critical stress increases, the probability of a critical flaw being present increases; hence, the lower average strength and the lower the coefficient of variation.

(ii) Specimen Shape and Proportions

In North American, references to the compressive strength of concrete are assumed to refer to results of tests made on moulded cylinders having a height equal to twice the diameter, generally 6 inches in diameter and 12 inches in height. When the ratio of length to diameter is less than two for cylindrical specimens such as drilled cores, ASTM designation C 42[2] provides that the calculated compressive strength be reduced by a correction factor taken from the following tabulation or obtained by interpolation from those given:

Ratio of Length To Diameter	Strength Correction Factor
1.75	0.98
1.50	0.96
1.25	0.94
1.10	0.90
1.00	0.85

The validity of this approach and of the use of these values has been questioned, and it has been noted[19] that the magnitude of the correction will depend on age, strength, mixture constituents and proportions, and moisture content.

Kesler[20] carried out studies on the effect of the length to diameter ratio on the apparent compressive strength of concretes and concluded, as follows: (1) As the l/d ratio decreases, greater corrections must be made to approximate the strength of the standard cylinders (2) The lower strength concretes require greater corrections than do the higher strength concretes (3) The age of the specimen has little effect on the correction factors.

Price[34] concluded that the strength of a 36 inch diameter cylinder is only 82% that of a 6 inch diameter cylinder. This difference is believed due to the possible faster strength gain of the smaller diameter cylinders. This may also serve as another instance in which Griffith's hypothesis may be applied since the larger the specimen then the greater the possibility of a critical flaw being present.

The alternate procedure given by ASTM[2] for compressive strength determination, using "modified cubes" (portions of beams brokern in flexure), does not provide for a correction factor to relate results of such tests to those that might have been expected had the specimens been cylinders of 1/d = 2. Information on this question was reviewed by Mather[25] who found that no specific correction could be recommended since the appropriate factor appeared to vary from at least 0.85 to 1.00 depending on the strength level of the concrete and other factors.

Kesler[21] reported results of over 1400 tests of concrete made with the same aggregates and tested as beams in flexure and as modified cubes and cylinders in compression at different mixture proportions and ages. He concluded that the cylinder strength was about 80% of the modified cube strength for low-strength concrete, but about the same as the modified cube strength for high-strength concrete.

Nowadays there is a tendency to use cylinders rather than cubes for research purposes as cylinders are less affected by end restraints and they give more uniform strength results. Also, the stress distribution on horizontal planes in a cylinder is more uniform than on that of a square cross-section.

(iii) Moisture Control of Specimens

The moisture content of a specimen at the time of testing has a definite bearing on the compressive strength. An air-dried specimen can exhibit 20 to 40 percent higher strength than that of corresponding concrete tested in a saturated condition. The higher the temperature of the specimen at the time of testing, the lower is the indicated strength.

(iv) Rate of Loading

The rate of loading has a marked influence on the compressive strength. The lower the rate at which stress increases, the lower the recorded strength. At low stress rates there is an increase in strain with time due to creep, thereby, causing the specimen to fail at a much lower stress than it would have at higher loading rates. For test results to be comparable, the rate of stress application must be standarized. Although there may be a big difference in compressive strengths with the different loading rates within the range of customary testing procedure, the loading effect is not large and this makes it very important to follow standard testing specifications.

(v) Capping Compounds

Price[34] said that the indicated strength of concrete capped with soft or rubbery material can be as much as 50% lower than companion cylinders capped with a hard, strong material.

(vi) Specimen Moulds

Burmeister[20] reported that concrete compression test cylinders made in paper moulds showed lower strengths than do those made in steel moulds. The reduction in strength is apparently due to cracks and mechanical injuries to the outer shell of concrete of the cylinder caused by movement of paper stock during the first 24 hours of curing.

Summary of Pertinent Findings

The production of high-compressive-strength concrete will normally require the use of lower water-cement ratios than are generally used in construction. Concrete proportioned using such lower-than-average water-cement ratios will be "drier", "harsher", "less workable" and "less plastic" than mixtures generally used. Consequently, the mixing, placing and compaction procedures employed will generally need to be modified from those customarily used.

It is obvious that low water-cement ratios must be used but at this present time it is unknown whether the water-cement ratio law holds for strengths above some given level or whether high-strength concrete may involve relations other than simple extrapolations based on normal-strength concrete.

There is a strong need for full compaction when working in the low water-cement ranges. If compaction is to be achieved by vibration, it is important that the vibration be prolonged enough to produce maximum compaction. It is considered desirable to run unit weight determination on the hardened concrete, as these will provide a good indication of compaction achieved.

Aggregates, for the production of high-strength concrete, must themselves be strong. Aside from this, probably the most important factors are (a) that crushed aggregates produce higher strength concretes than gravel aggregates, and, (b) that in general, the lower the maximum size of aggregate, the higher the compressive strength of the resulting concrete.

The three most common types of Portland cement (Normal, High-Early and Low Heat) can, in general, all be used to produce high-strength concrete. Variations in chemical composition do, however, affect the levels of strength that can be achieved.

Curing procedures can affect significantly the maximum strength obtainable; continuous moist curing within specified temperature limits until time of testing is recommended to produce high strength concrete.

Testing procedures can also affect significantly the indicated strength levels achieved by a given concrete mix and it is vital, therefore, to standardize testing procedures. Unless all the factors entering into its production and testing are controlled, no standard of compressive strength can be assumed or guaranteed for concrete of any particular proportions made with any aggregate.

Chapter III

SPECIAL TECHNIQUES FOR INCREASING THE COMPRESSIVE STRENGTH OF CONCRETE

In the foregoing Chapter, the main fundamental factors affecting the potential compressive strength of conrete were reviewed and a summary was provided of the presently known principles that must be applied to produce high-compressive-strength concrete. The reviewed data have suggested that once the high-strength area is reached a barrier at the upper limits of strength of Portland cement concretes will be encountered. Whether or not this barrier can be exceeded by the application of certain special techniques or the use of special admixtures is the subject of this thesis. But first, it is desirable to review the limited work already carried out to evaluate the effectiveness of these special techniques and admixtures in increasing the compressive strength of concrete. These will be considered in the following order:

a) Seeding

b) Revibration

c) High Speed Slurry Mixing

d) Use of Materials as a Partial Replacement for Portland Cement

e) Water-Reducing Agents

a) Seeding

The "seeding" of concrete with a small percentage of finely ground, fully hydrated Portland cement is a technique that is claimed to produce higher compressive strengths, although relatively little information is available on this subject. An abstract from a Russian[5] article described the preparation of two types of crystalline "seeding" material. "Crystallization seeding material 'A' is prepared by stirring a cement in a large amount (1:20) of water for 15 days or more, followed by filtration and drying at 90-100°. Another is made by hydrating cement for 28 days, without sand, with the amount of water corresponding to normal consistency. It is stored under water but before use it is dried and ground to a specific surface of 3000 sq. cm/g. With additions of 2% "A", the one-day crushing strength of a Portland cement was not increased; with 10%, it rose from 384 to 654 psi. On the other hand, the 3 month strength with 2% "A" rose from 1878 to 2660 psi and with 10% only 2347 psi. Analogous results were obtained with other similar additives". The information in the abstract was very limited and no mention was made of the water-cement ratios employed.

An abstract of an Hungarian paper[7] also summarizes some work done on this subject. They claimed that best results were obtained by adding the seeding material in a quantity of

2 per cent by weight of cement. An increase in strength of 10 to 30 per cent was observed by the second and seventh days respectfully. The seeding material, when used together with $CaCl_2$ or,with $CaCl_2$ and bentonite, was claimed to increase the strength by 40 to 45 per cent when 2 days old. No mention is made of water-cement ratios employed in the tests.

The Lehigh Portland[27] cement company also carried out some limited work on this subject after reviewing the abstract of the Russian article. Although specific results of their studies are not available, they reported that the results were not encouraging. They prepared their seeding material by first hydrating cement for one month using an amount of water corresponding to normal consistency. These specimens were then air dried for one month after which they were pulverized to the minus 20 micron size. The material was then oven-dried and ground to a Wagner fineness of 1840 sq. cm/g.

b) Revibration

By revibration is meant the disturbance of the hardening process or the early hydration process of concrete. Some investigators claim that revibration has been found to be beneficial rather than detrimental, provided that the concrete is again brought back to a plastic condition[8].

Both the test age at which revibrated specimens give the greatest strength increase and the optimum time for revibration after the initial casting are topics of much controversy. Tests[40] were made to determine the effect on 28-day strength of revibration at intervals of 1 to 4 hours after placing. Maximum strength increase resulting from revibration varied from 8.5 per cent to 17.1 per cent and averaged 14 per cent for the mixes with water-cement ratios ranging from 0.61 to 0.75. Maximum strength increase of the mixes with water-cement ratios ranging from 0.5 to 0.63 varied from 6.9 per cent to 16.7 per cent and averaged 13.7 per cent. All maximum strength gains were obtained when revibration was carried out to 2 hours after placing. Sawyer and Lee[37] also studied the effects of delayed revibration on concrete, with and without air entrainment. The concrete was revibrated after delays ranging from 45 min. to 6 hr. The greatest increase in compressive strength of revibrated concrete was at 7 days for the specimens without air entrainment. This increase was approximately 36 per cent and occurred when revibration was carried out after a 4 hour delay. The corresponding increases for the 28 and 90 day specimens were 24 per cent and 15 per cent, respectfully. The increase in strength of the air-entrained specimens was approximately half of the non-air-entrained at each test age with the maximum increase in strength occurring when revibration was carried out about 3 hours after casting. The water-cement ratios used in the non-air-entrained mixes varied from 0.70 to 0.77 and in the air-entrained mixes varied from 0.59 to 0.68. Sawyer and Lee[37] mentioned in the same paper, without giving any water-cement ratios, that Bastian[4] reported increases in compressive strength for cube specimens of 38% at 2 days, 27% at 3 days, 12% at 5 days and 10% at 28 days. The time of revibration was 4 hours after casting in all instances.

To date, two theories have been advanced by Sawyer and Lee[37] to account for the increased compressive strengths produced by revibration. In the first theory, it is believed that the mortar and concrete would be more densely consolidated, therby permitting more advantageous use of the hydration products. The second theory contends that the vibratory disturbances in some way would accelerate and extend the production and consequently increase the amount of the strengthening hydrates at ages up to 90 days.

There is not, however, complete agreement as to the beneficial effects of revibration without presenting any experimental data, the Research Committee of the Institutions of Civil and Structural Engineers[15] was quoted[30] as showing that concrete revibrated for 3 minutes after being allowed to remain undisturbed for various periods up to 17 hours from the initial vibration was affected little with respect to strength, irrespective of the water-cement ratio.

c) High Speed Slurry Mixing

The high speed slurry mixing process involves the advance preparation of a cement-water mixture which is then blended with aggregate to produce concrete. Higher compressive strengths thus obtained are presumably attributable to more efficient hydration of the cement resulting from the more intimate contact between cement particles and water achieved in the vigorous blending of cement paste.

Bloem[6] conducted tests on mortars using a water-cement ratio of 0.6 and on concretes using an average water-cement ratio of 0.76. In the mortar tests, mixtures of constant water-cement ratio were made by (a) hand mixing of the water and cement prior to adding the sand, (b) slow-speed mechanical mixing of the cement paste, and (c) high-speed mixing of the cement-water paste. For all three methods, elapsed times for the various stages of mixing were the same, as was the procedure for blending the sand with the cement paste. Mechanical mixing of the cement-water slurry at slow speed produced no change in the properties of the mortars from those obtained by hand-mixing. Mixing of the cement-water slurry at a very high speed using a blender similar to a milk shake mixer (10,000 rpm) produced an average increase of 13% in compressive strength for the three test ages of 3, 7 and 28 days.

In the concrete tests there was a significant increase in compressive strength for the high-speed mixing, averaging 10% greater than that obtained by hand mixing. The strength advantage was essentially constant in terms of pounds per square inch at the three test ages of 3, 7 and 28 days, with the result that the percentage difference decreased from 13 to 6% as the strength level increased.

d) Use of Materials as a Partial Replacement for Portland Cement.

The general term pozzolan applies to silaceous materials, which in themselves possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Examples of such materials which can be used in amounts ranging from 10 to 50 per cent of the weight of the cement are: fly ash, volcanic ash, heat-treated diatomaceous earths, and either heat-treated or raw shales or clays. The effect of pozzolans upon the strength of portland-pozzolan concrete varies markedly with the particular pozzolan used. Depending on the pozzolan used, portland cement replacements of as high as 30% can sometimes be made and still achieve equivalent ultimate strengths to plain mixes. It is claimed that the use of small percentage replacements (say 10%) can result in higher strengths of mortar and concrete than those for plain mixes.

Fly ash is today one of the most commonly used pozzolanic materials. Fly ash is a finely divided residue resulting from the combustion of pulverized coal as used in many modern steam-generating stations.

Smith[35] et al using water-cement ratios of 0.29 to 0.37 showed that at least 10% by weight, of the portland cement used in high-compressive-strength concrete, can be replaced by pozzolans such as fly ash or calcined shale. The strength increase was 16% over the non-pozzolanic mixes at 90 days.

Two portland cement clinkers (1 low, 1 high in free CaO, , CaO. Al_2O_3, and K_2O) were blended with three fly ashes (2 containing spherical viterous particles, 1 containing fine, irregular crystals of high porosity) in various proportions. Compressive strength tests were among several made on the mixes at equal consistencies and at equal water-cement ratios. Strengths changed little for equal water-cement ratio mixes up to 20% of the two viterous ashes, with 300 day strengths slightly greater than that of the original cement; with up to 40% ash, the strength after a few years should be greater than for the cement. At equal consistencies, the 20 and 30% ash blends were often stronger than the cement alone, because the water requirement could be reduced. No strength differences were observed between mixes blended by grinding the mixture and those ground separate before blending[41].

e) Water Reducing Agents

Water-reducing admixtures are materials generally consisting of certain organic compounds or mixtures which, when added to portland cement concrete, markedly increase the fluidity of the concrete. When such admixtures are used to produce concrete of slumps equal to those of plain or air-entrained concretes of the same design, a significant reduction in the water-cement ratio can be made. Thus, in accordance with Abrams' finding, concrete of greater strength should result.

The materials that are currently sold commercially as "water-reducing agents" for concrete include lignosulfonic acids and their salts, modifications or derivatives of lignosulfonic acids and their salts, hydroxylated carboxylic acids and their salts, and modifications or derivatives of hydroxylated carboxylic acids and their salts.

The principal component of the water-reducing admixtures considered in the classifications above are surface active agents; That is, substances which because of their chemical configuration are concentrated at the interface between two immiscible phases and alter the physiochemical forces acting at this interface. Interfacial tension is always present at the interface between any two completely immiscible phases. Dispersion may be facilitated by a reduction in the interfacial tension of the system. As the term water-reducing implies, the primary function of this type of admixture is to reduce the water requirement of a concrete mix while maintaining the desired plasticity and workability.

The concrete division of the U.S. Army Engineer Waterways Experiment Station[17] carried out an intensive investigation to develop information on the performance in pastes, mortars and concrete of several proprietary water-reducing admixtures. Water was added to the pastes and mortars as required to produce a normal consistency. The water-cement ratios for concrete mixes ranged from 0.39 to 0.30. Thirteen chemical admixtures were tested and two portland cements were used (Type I manufactured in Mississippi and a Type II manufactured in Alabama). The fine aggregate was a natural siliceous sand from Mississippi and a crushed limestone from Tennessee; the coarse aggregates were a crushed traprock from Connecticut and a crushed limestone from Tennessee.

The test results indicated the following: for the pastes, seven of the admixtures permitted a 10% or greater reduction in the amount of mixing water required to produce a paste of normal consistency as compared with the amount required when no admixture was used.

For the mortars, eight of the admixtures permitted a 5% or greater reduction in the amount of mixing water required to produce a mortar having a flow in the specified range (100 to 115 %). Of the fifteen mortar mixtures prepared, five exceeded the strength of the control mixture by more than 20% and two exceeded the control mixture by less than 20%. All seven mixtures and water-reducers permitted a 5% or greater reduction in the mixing water. In the concrete tests only five water-reducing admixtures were tested in fifteen mixtures. It was found that all but three of the mixtures produced a reduction in the water-cement ratio, the reduction varying from 0.05 to 0.40 gal. of water per bag of cement. Six of the fifteen mixtures had lower compressive strengths at two days than the control mixture; however, two of the six were within 8% of the control. Three of the mixtures had lower compressive strengths than the control at 28 days but the difference in strength was not over 9% in any case,. All other mixes averaged an increase in compressive strength of 11% over the control mix.

Smith[35] et al working with water-cement ratios from 0.29 to 0.40 in the production of high-compressive strength concrete concluded that water-reducing admixtures are definitely beneficial. Their results showed that the 7, 28 and 90 days compressive strengths were 11, 21 and 19% respectively greater than the control mixes.

Laboratory investigations carried out at the University of California Engineering Materials Laboratory[3] on concretes employed three lignin type and one organic acid type water reducer and four different California portland cements. The effects of the two main types of water reducers on the cement composition and compressive strength was evaluated. Based on the results of the tests, the following concluding statements were made: (1) "The effect of a water reducer on compressive strength of a concrete cannot be explained by only the reduction in water-cement ratio. The brand of cement through its chemical effectiveness has a large influence on the effectiveness of a given water reducer. (2) Water reducers seem to improve more the compressive strengths of concretes containing cements of low alkali content than of concretes containing cements of high alkali content. (3) If a water reducer exhibits poor performance with a given cement, it may be expected that other water reducers also will show similarly poor performance. (4) Generally, the largest percentage improvement in the compressive strength of a concrete through the use of a water reducer is obtained at an early age, and this percentage decreases with time. (5) Water reducers used in amounts appropriate to the composition of a given cement will usually allow a reduction in cement content of 5 to 15 per cent without loss in compressive strength".

In many cases reviewed during this literature study, the increase in compressive strength afforded by the water reducer was reported to be greater than would be expected simply from the amount of water reduction produced.

SUMMARY

Three special techniques - seeding, revibration and high-speed slurry mixing - have been investigated to a limited extent, as a means of increasing the compressive strength of concrete of low or medium strength levels, i.e. at w/c ratios above 0.4. Claims of strength increases have been made for all these techniques, although there is not unanimity on their effectiveness or on the percentage strength increases to be expected. Furthermore, it appears that none of these techniques has been investigated on high-strength concrete mixes, i.e. at w/c ratios below 0.4.

Fly ash and other pozzolanic materials have often been used to replace 20 to 30% of the Portland cement in concrete mixes when it is desired to limit the rate of early heat generation in the concrete (and so control temperature rise) without adversely affecting the ultimate strengths obtained. Recently, it has been indicated that by replacing a small percentage of the Portland cement with fly ash, a significant increase in compressive strength can be obtained.

Water-reducing agents, by lowering the water requirement for a given consistency, are known to produce increased compressive strengths. Some authorities claim that the increased compressive strength afforded by the water reducing agents is greater than would be expected from the amount of water reduction produced.

TABLE I

SUMMARY OF EXPERIMENTAL PROGRAMME

Nominal w/c Ratio	Reference Mix	High Speed Slurry Mix	Fly Ash Mix	Seeding Mix	Water * Reducer (Ligno Sul) Mix	Water* Reducer (Car. Hydrox.) Mix	Revibration Mix
0.31	Normal P.C. (Canada)	Normal P.C. (Canada)	Normal P.C. (Canada)	→	→	→	→
0.35	Normal P.C. (Canada)	→	→	→	→	→	→
0.39	Normal P.C. (Canada)	→	→	→	→	→	→
0.35	Normal P.C. (St. Mary's)	→	→	→	→		→
0.35	High Early P.C. (Canada)	→	→	→	→		→

* 0.31, 0.35 and 0.39 w/c ratios were reduced to 0.29, 0.32 and 0.36 respectively in order that the consistencies were the same as the reference mixes.

Chapter IV

EXPERIMENTAL PROGRAMME

The main purpose of this experimental programme was to evaluate the relative effectiveness of the three special techniques ("seeding", revibration, and high speed slurry mixing) and the two admixture types (fly ash and water-reducing agents) in increasing the compressive strength of high-strength concretes, i.e. concretes having w/c ratios below 0.4. A secondary purpose of the programme was to determine if Abrams water-cement ratio law holds for concretes in the high strength range, i.e. at water-cement ratios below 0.4. An outline of the experimental programme is given in Table I, and is discussed in the following paragraphs.

Mix Proportions: No coarse aggregates were used in this programme. In all mixes, cement and fine aggregate were combined in the proportion of 1:2.50, by weight. Water was gauged to produce the desired water-cement ratios, except that in the mixes containing water-reducing agents, the water content was gauged to produce the same consistency as the reference mixes. The water reducing agents were used in dosages recommended by the manufacturers.

In the fly ash mixes, ten percent (by weight) of the cement was replaced by fly ash; and in the "seeding" mixes, three percent (by weight of cement) of the seeding material was added to each mix.

Water-cement ratios: In preliminary experimental work it was found that mixes having water-cement ratios below 0.31 were too stiff to compact by any ordinary methods. This then represented a lower limit of water-cement ratios to be used in the programme because it was desired to deal with mixes of such consistency that could be placed without resorting to extreme methods of compaction. Since one of the purposes of the programme was to determine if Abrams water-cement ratio law holds for concretes in the high strength range, it was desirable to include some mixes at other water-cement ratios. Therefore, with one cement, mixes were made up at water-cement ratios of 0.31, 0.35 and 0.39. With the other two cements, water-cement ratios of 0.35 only were included.

Materials (a) Cement: Two normal Portland cements (one each from Canada Cement Co. and St. Mary's Cement Co.) and one High-Early Portland cement (Canada Cement Co.) were included in the programme. The choice of the two normal Portland cements used in the programme was based on their different chemical compositions, especially the C_2S and C_3S contents. The brand choice of High-Early cement was purely arbitrary but it was considered desirable to include one High-Early product in the programme. Chemical and physical analyses of all cements used are given in Table 3, Appendix A.

(b) Sand: The sand used was a well-graded concrete sand from the West pit at Paris, Ontario, which meets ASTM specification C33-64. Initially, it was intended to use pure silica sand, but it was found impossible to get a well-graded one and the silica sand we had was found to produce excessive amounts of entrained air and this is an unsatisfactory situation, to say the least, when one is trying to produce high strengths. Properties of the sand used in the programme are given in Table 4, Appendix A.

(c) Fly Ash: The fly ash used in this programme was obtained from the Detroit Edison Company and the source was the Trenton Channel Power Plant. The physical and chemical properties of the ash are given in Table 5, Appendix A.

(d) Water-Reducers: Two water-reducing agents were included in the programme (1) a lignosulphonic acid admixture produced by Sika Chemical Company and (2) a hydroxylated carboxylic acid admixture produced by the Master Builders Company. These represent the two main types of water-reducing admixtures on the market.

(e) "Seeding" Material: Normal Portland Cement (Canada brand) was used for preparation of the seeding material. A paste was prepared using this cement and water at a water ratio of normal consistency from which a number of cubes were moulded and cured under water for thirty-five days. After curing, the cubes were air-dried for two weeks and then ground up to a fineness of 3561 cm^2/gm. The grinding operation was done in a small ball mill charged with steel shot.

Chapter V

EXPERIMENTAL PROCEDURES

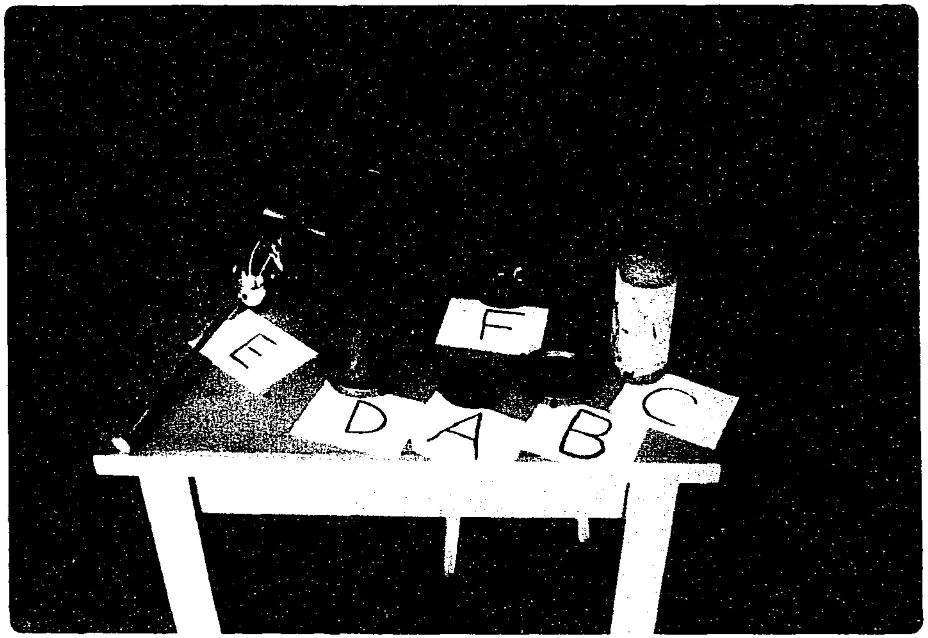
The following section describes in detail the mixing, preparation of moulds and compacting procedures along with the tests performed both on the fresh mortar and hardened mortar cylinders.

(a) Mixing Procedures

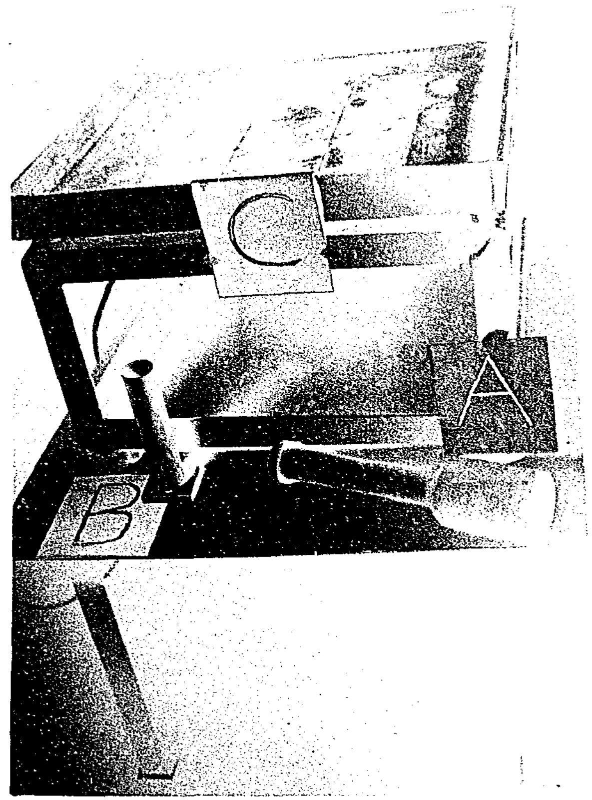
All mixes were prepared using a Blakeslee mixer (2/3 cu. ft. capacity, bench model with speeds of 102, 180 and 354 rpm). The cement was added to the water in the mixing bowl and then the sand was added to the cement paste. There were, however, the following exceptions. The water reducers were added to the water. The "seeding" material and fly ash were blended with the dry cement before being combined with the mixing water. The mixing operations were in accordance with ASTM Specification C305-59T except that in the high speed slurry mixing technique the water and cement were mixed by the high speed mixer before the sand was added. The procedure thereafter was the same as for the rest of the batches.

(b) Workability

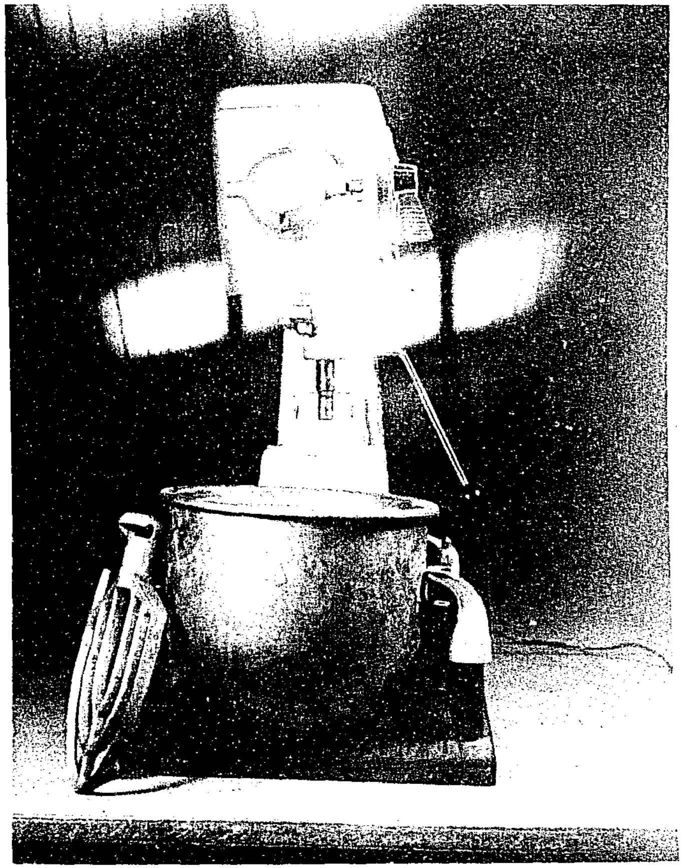
The workability of each batch was measured using a flow table. The test was conducted according to ASTM Specification C124-39.



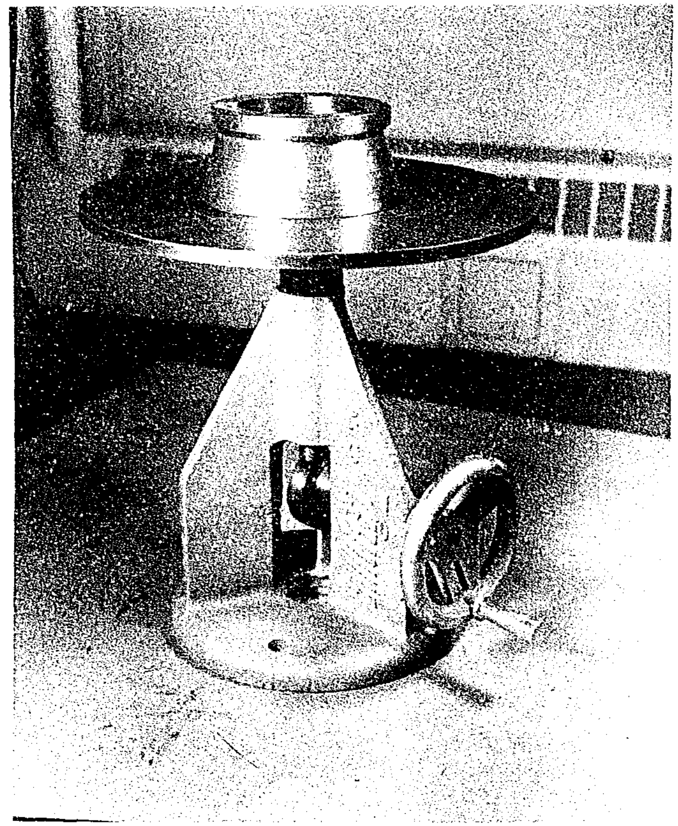
PHOTOGRAPH I. SHOWING A-RUBBER GASKET B-MOULD BASE
C-HARDENED SPECIMEN D-ASSEMBLED MOULD
E-HIGH SPEED SLURRY MIXER F-STEEL MOULD



PHOTOGRAPH 2. SHOWING A-WOODEN TAMPING MALLET B - BRASS AIR METER C - VIBRATING TABLE



PHOTOGRAPH 3. SHOWING BENCH MIXER, BOWL AND TABLE



PHOTOGRAPH 4. SHOWING FLOW TABLE

(c) Air Content

Since it is desirable to keep entrapped or entrained air to a minimum when trying to obtain high compressive strength, air content determinations were made on every batch. Any batches yielding more than 2% air were discarded. Air content measurements were made by a gravimetric method using a cylindrical brass cylinder 6 inches long and 1 5/16 inches in diameter. The calibration of the container was done with water at laboratory temperature (72 F ± 2 F).

(d) Moulding And Compaction

Four 3" x 6" cylinders were moulded from each batch with one cylinder per test age used in the experiment (7,28 days, 3 months and 1 year). The moulds were placed at each corner of the VIBCO table vibrator (model U.S. 450, 115 volts, 2.8 amp. 10,000 V.P.M.) and were not removed at any time during the filling and tamping operations. The mortar was placed in five layers in the cylinders. A clockwise movement was followed during the moulding. After each layer was placed the mortar was tamped with a wooden mallet five times. The filling operation took approximately ten minutes and after each mould was filled, it was left vibrating for an additional nine minutes. The time and tamping procedure used in the experiment were pre-determined and found to give the best results when working with such stiff mixes. The specimens were left in the moulds for a twenty-four hour period . During that time, they were covered with wet burlap bags. After the specimens were removed from the steel moulds, they were labelled and then allowed to soak for an hour in water at laboratory temperature. After this procedure, the specimens were placed in the curing chamber until testing time.

(e) Revibration

The specimens that were revibrated were done so for nine minutes, three hours, after they had been moulded. All the revibrated specimens were initially vibrated in the same manner as the other specimens.

(f) High Speed Slurry Mixing

In this technique the cement and water were mixed for twelve minutes using a high speed mixer. The high mixer (Hamilton Beach 10,000 RPM) used was a modified milk shake mixer. The shaft was 11 inches long and the paddle was 1 inch in diameter.

(g) Compressive Strength

In order to keep a close check on the uniformity of our test specimens, immediately upon their removal from the curing chamber, unit weight determinations were made on each specimen. The specimens were allowed to dry in the air for thirty minutes before being tested. In between the removal of the specimens from the curing chamber and testimg time, the specimens were capped with high-compressive-strength (10,000 psi) sulphur compound. Curing of the specimens was done in accordance with ASTM Specification C31-62T. Testing of the specimens was carried out using a 300,000 lb capacity hydraulic testing machine. Testing procedures were in accordance with ASTM Specification C31-62T.

CHAPTER VI

DISCUSSION OF RESULTS

The results of the tests are presented in Tables 2, 3, and 4 and are plotted in Graphs 1 to 16. The tables of results include mean values, standard deviations, coefficients of variation, per cent higher or lower than standard and indicate whether or not differences are statistically significant. Each point on the graphs showing the reference mixes for the 7 and 28 day tests using Canada Normal cement represents the average of six tests. The reference mixes for the 7 and 28 day tests using St. Mary's Normal cement and Canada High Early cement represents the average of five tests. The other points in the remaining plots represent the average of four tests, the only exception being the cases where a test was discarded for warrantable reasons.

The water-cement ratio-strength relationships for all mixes are presented in Graphs 1 to 6. It can be seen that in the range of water-cement ratios used in this programme (0.31 to o.39) there does not appear to be an inverse relationship between strength and water-cement ratio as stated in Abrams' law. In fact, for the most part, it can be seen that there was little difference in the strengths obtained at the three different w/c ratios. When working

TABLE 2

SUMMARY OF 7 DAY EXPERIMENTAL RESULTS

Cement Type and w/c Ratio	Analysis	Reference	Slurry Mixing	Fly Ash	Seeding	Water Reducer Ligno. Sul.	Water Reducer Car. Hydrox.	Revibration
Canada Normal .31	Mean psi	7069	7333	5474	7852	7791	7808	6717
	Standard Deviation psi	1523	440	335	1508	822	1084	606
	Coefficient of Variation %	21.5	6	6.1	19.2	10.6	13.9	9.02
	% Higher or Lower than Ref.		+3.7	-22.6	+11.1	+10.2	+10.5	-5.0
	Statistically Significant		NO	NO	NO	NO	NO	NO
Canada Normal .35	Mean	6244	8125	6320	7483	5476	7835	6400
	Standard Deviation	953	261	356	498	777	833	270
	Coefficient of Variation	15.3	3.2	5.6	6.7	14.2	10.6	4.2
	Higher or Lower than Ref.		+30.1	+1.2	+19.8	-12.3	+25.5	+2.5
	Statistically Significant		+YES	NO	+YES	NO	+YES	NO
Canada Normal .39	Mean	6708	7967	5388	7104	8997	8107	6532
	Standard Deviation	977	361	723	541	301	116	472
	Coefficient of Variation	14.6	4.5	13.4	7.6	3.4	1.43	7.2
	Higher or Lower than Ref.		+18.8	-19.7	+5.9	+34.1	+20.9	-2.6
	Statistically Significant		+ YES	NO	NO	+ YES	+ YES	NO

TABLE 2 (continued)

Cement Type and w/c Ratio	Analysis	Reference	Slurry Mixing	Fly Ash	Seeding	Water Reducer Ligno. Sul.	Water Reducer Car.Hydrox.	Revibration
St. Mary's Normal .35	Mean	6197	6400	6016	4762	7077		4974
	Standard Deviation	920	1015	388	918	259		433
	Coefficient of Variation	14.8	15.9	6.5	19.3	3.7		8.7
	Higher or Lower than Ref.		+3.3	-2.9	-23.2	+14.2		-19.7
	Statistically Significant		NO	NO	NO	NO		- YES
Canada High Early .35	Mean	7606	5599	7615	8380	8328		6690
	Standard Deviation	1130	410	540	697	723		1220
	Coefficient of Variation	14.9	7.3	7.1	8.32	8.7		18.2
	Higher or Lower than Ref.		-26.4	+0.1	+10.2	+9.5		-12.0
	Statistically Significant		- YES	NO	NO	NO		NO

TABLE 3

SUMMARY OF 28 DAY EXPERIMENTAL RESULTS

Cement Type and w/c Ratio	Analysis	Reference	Slurry Mixing	Fly Ash	Seeding	Water Reducer Ligno. Sul.	Water Reducer Car. Hydrox.	Revibration
Canada Normal .31	Mean psi	8574	10282	10009	8917	9780	8354	10722
	Standard Deviation psi	2282	525	225	1023	438	1029	544
	Coefficient of Variation %	26.6	5.1	2.3	11.5	4.5	12.3	5.1
	% Higher or Lower than Ref.		+19.9	+16.7	+4.0	+14.1	-2.6	+25.1
	Statistically Significant		NO	NO	NO	NO	NO	NO
Canada Normal .35	Mean	8304	10608	9798	8460	10405	9129	10009
	Standard Deviation	2052	389	507	509	649	666	449
	Coefficient of Variation	24.7	3.7	5.2	6.0	6.2	7.3	4.5
	Higher or Lower than Ref.		+27.7	18.0	+1.9	+25.3	+9.9	+20.5
	Statistically Significant		NO	NO	NO	NO	NO	NO
Canada Normal .39	Mean	8527	8953	9656	8750	11620	9991	8970
	Standard Deviation	1530	574	504	213	916	446	615
	Coefficient of Variation	17.9	6.4	5.2	2.4	10.9	4.5	6.9
	Higher or Lower than Ref.		+5.0	+13.2	+2.6	-1.4	+17.2	+5.2
	Statistically Significant		NO	NO	NO	NO	NO	NO

TABLE 3 (continued)

Cement Type and w/c Ratio	Analysis	Reference	Slurry Mixing	Fly Ash	Seeding	Water Reducer Ligno. Sul.	Water Reducer Car.Hydrox.	Revibration
St. Mary's Normal .35	Mean	8535	8283	9067	7482	10088		7755
	Standard Deviation	1328	301	467	309	308		513
	Coefficient of Variation	15.6	3.6	5.2	4.1	3.1		6.6
	Higher or Lower than Ref.		-3.0	+6.2	+12.3	+18.1		-9.1
	Statistically Significant		NO	NO	NO	NO		NO
Canada High Early .35	Mean	10370	10819	10704	10203	12923		11242
	Standard Deviation	1713	472	579	674	371		256
	Coefficient of Variation	16.5	4.4	5.4	6.6	2.9		2.3
	Higher or Lower than Ref.		+4.3	+3.2	-1.6	24.6		+8.4
	Statistically Significant		NO	NO	NO	+ YES		NO

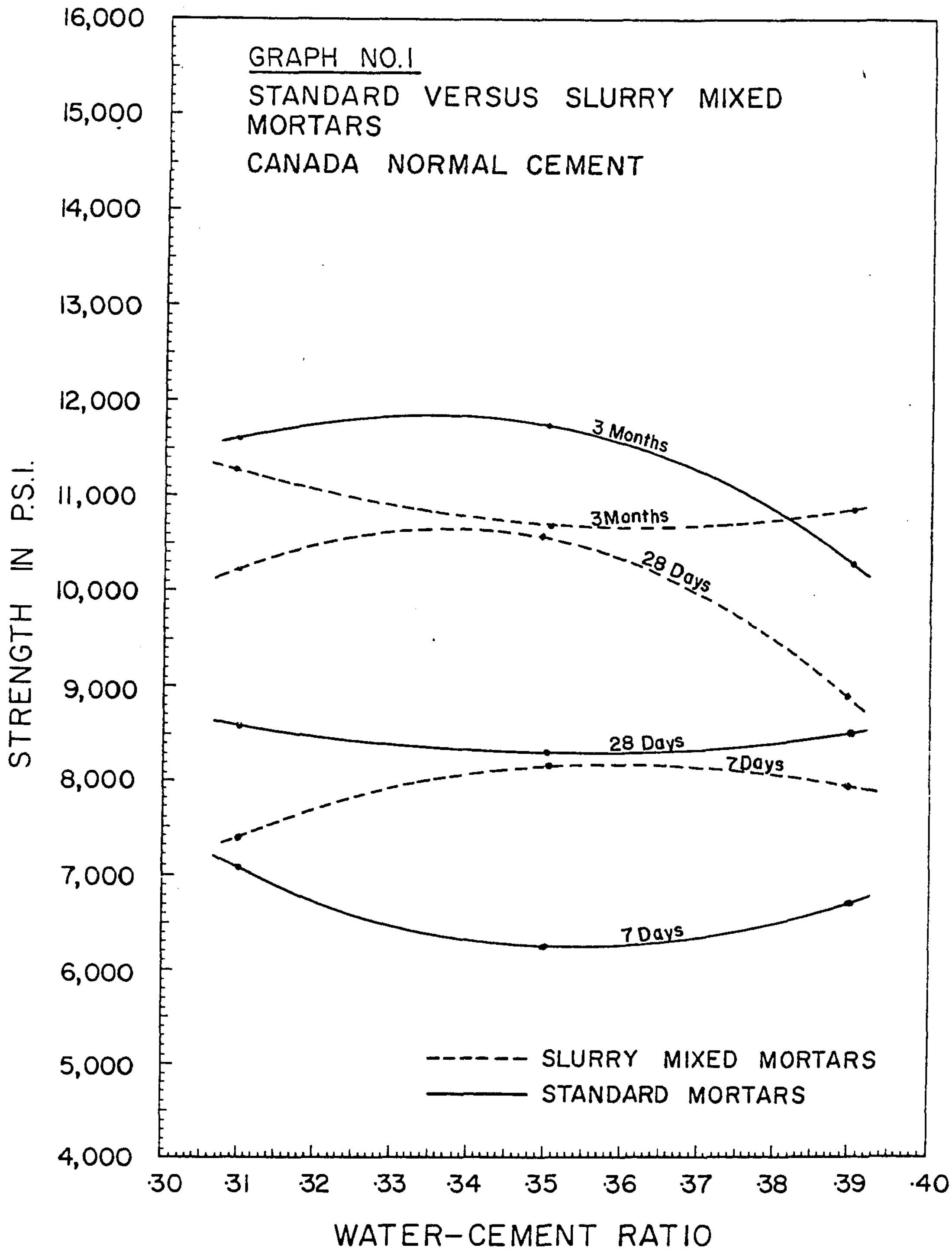
TABLE 4

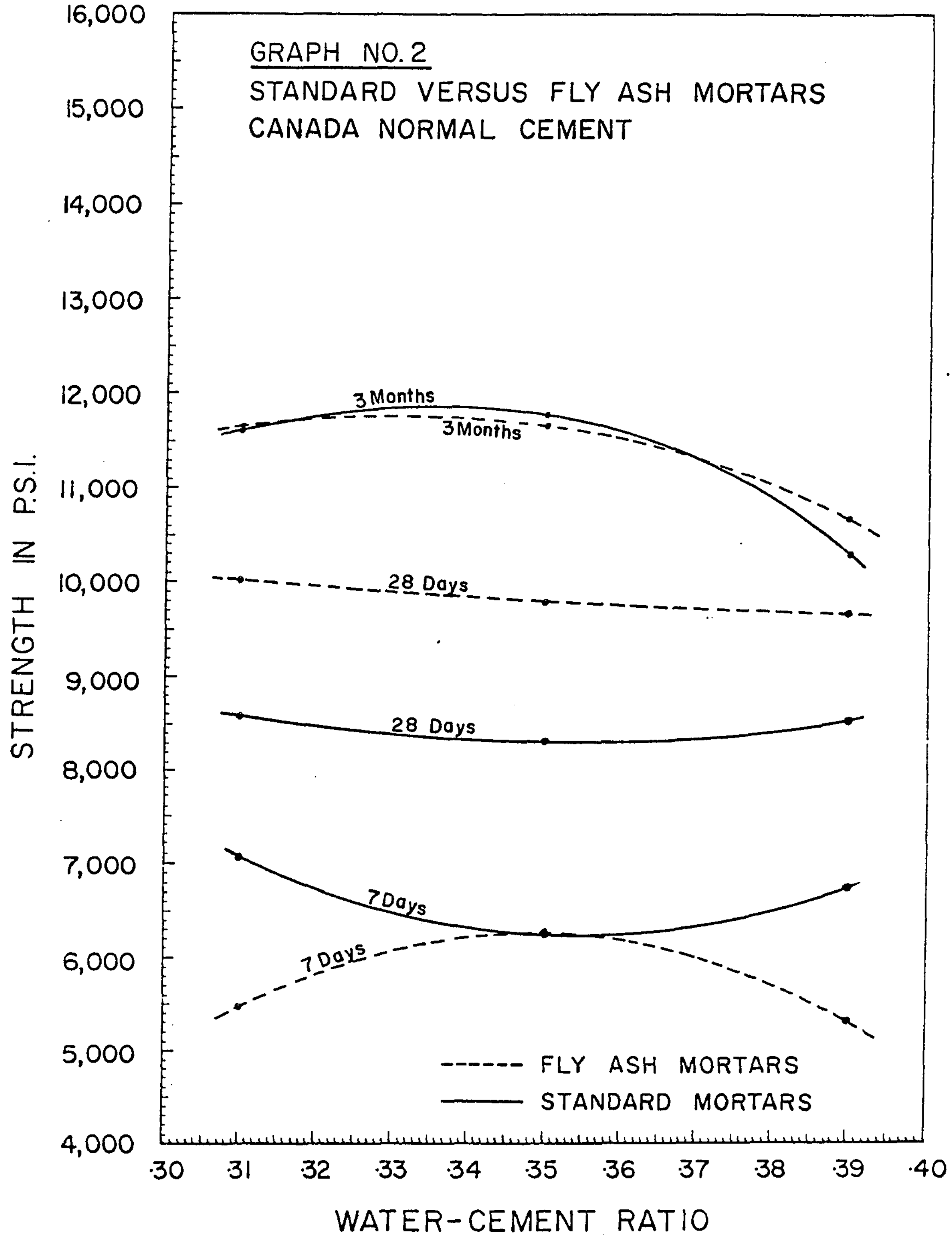
SUMMARY OF 3 MONTH EXPERIMENTAL RESULTS

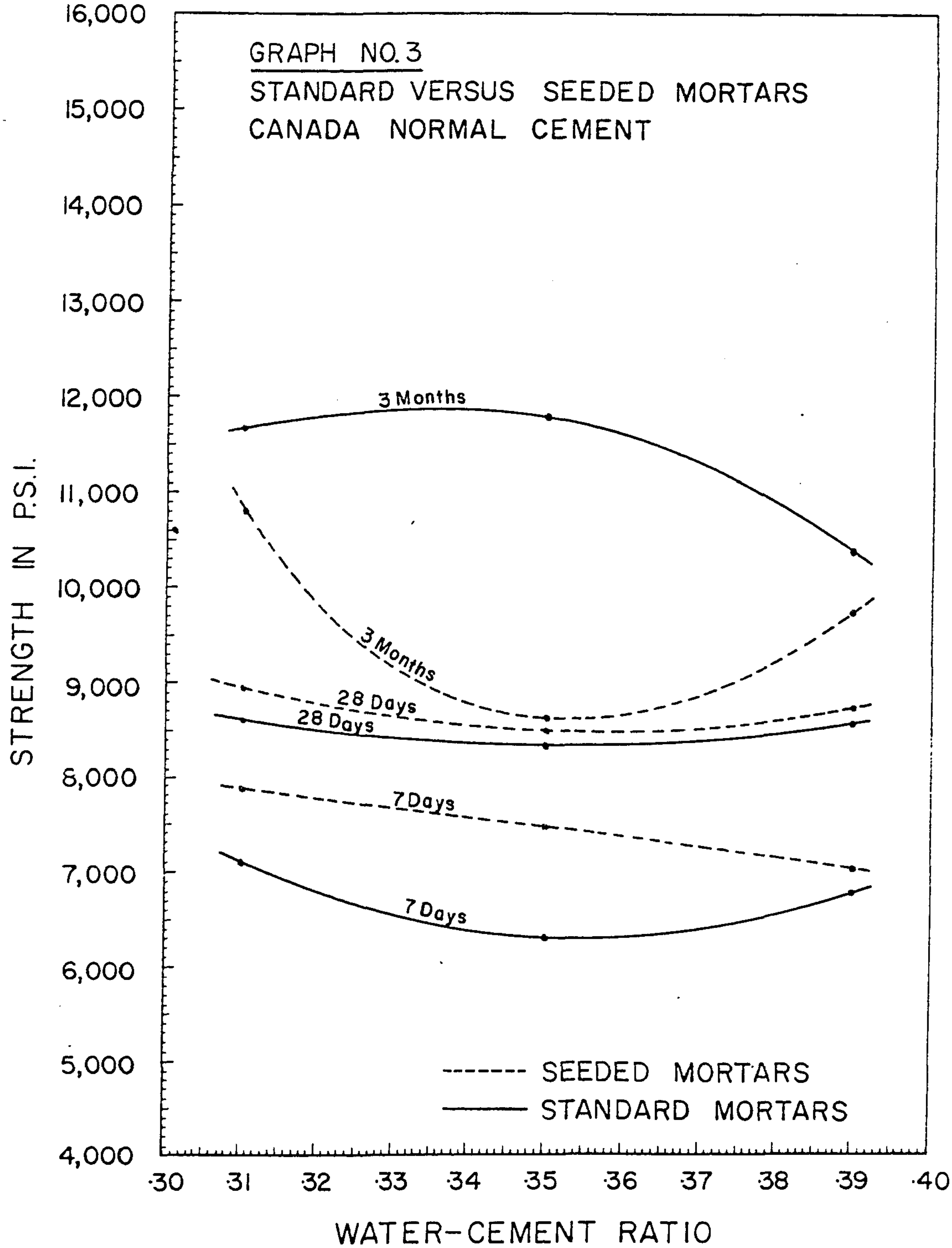
Cement Type and w/c Ratio	Analysis	Reference	Slurry Mixing	Fly Ash	Seeding	Water Reducer :igno. Sul.	Water Reducer Car. Hydrox.	Revibration
Canada Normal .31	Mean psi	11611	11268	11646	10810	10512	9726	12412
	Standard Deviation psi	714	566	587	413	788	785	194
	Coefficient of Variation %	6.1	5.0	5.0	3.8	7.5	6.8	1.6
	% Higher or Lower than Ref.		-3.0	-0.1	-6.9	-9.5	-16.2	+6.9
	Statistically Significant		NO	NO	NO	- YES	- YES	NO
Canada Normal .35	Mean	11734	10651	11690	8600	11523	9550	11523
	Standard Deviation	636	978	701	890	675	1440	711
	Coefficient of Variation	5.4	9.2	6.0	10.3	5.9	12.3	6.2
	Higher or Lower than Ref.		-9.2	-0.4	-26.7	-1.8	-18.6	-1.8
	Statistically Significant		NO	NO	- YES	NO	- YES	NO
Canada Normal .39	Mean	10326	10845	10775	9709	11620	10775	11080
	Standard Deviation	440	217	718	323	399	292	264
	Coefficient of Variation	4.3	2.0	6.7	3.3	3.4	2.7	2.4
	Higher or Lower than Ref.		+5.0	+4.3	-6.0	+12.5	+4.3	+7.3
	Statistically Significant		NO	NO	- YES	+ YES	NO	+ YES

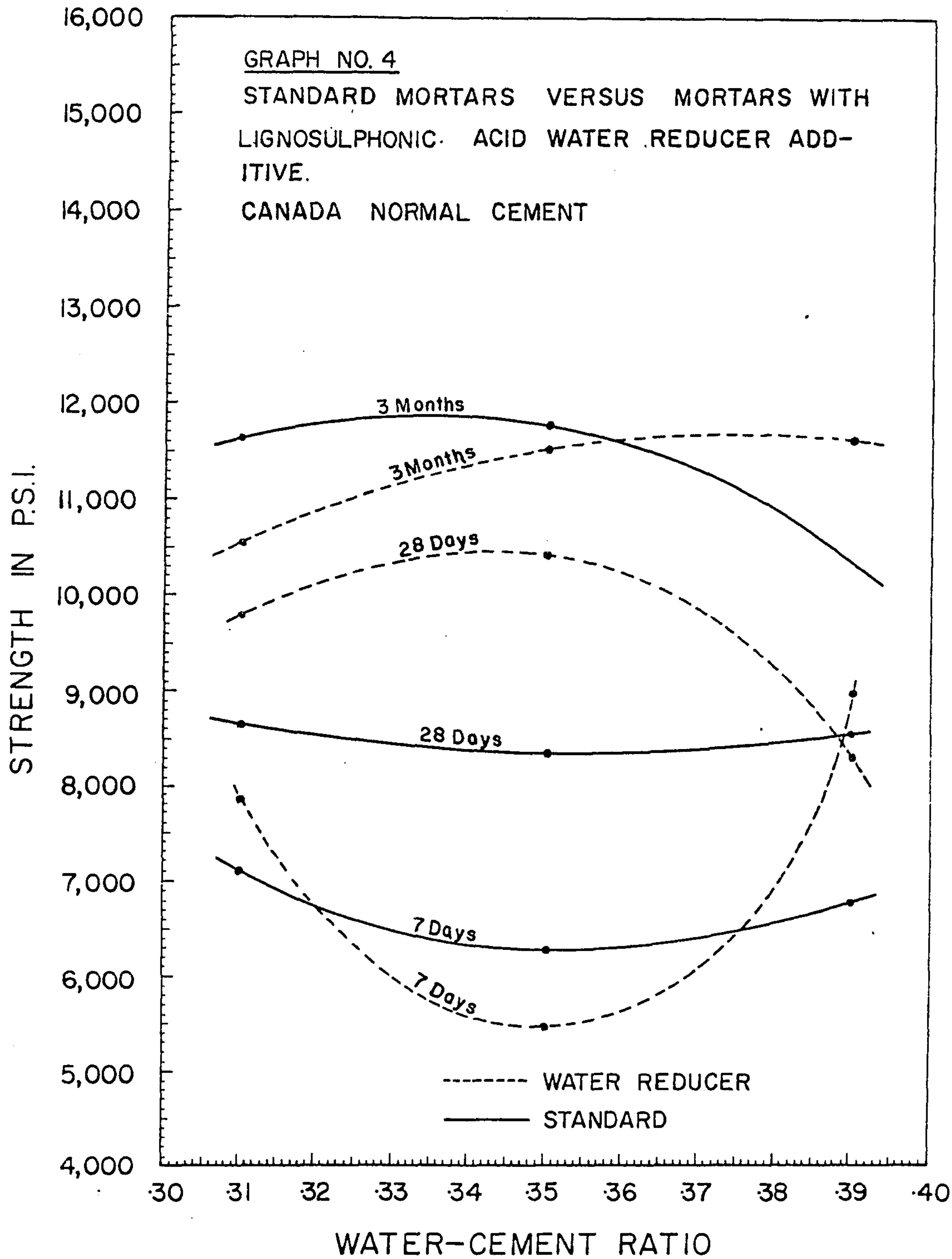
TABLE 4 (continued)

Cement Type and w/c Ratio	Analysis	Reference	Slurry Mixing	Fly Ash	Seeding	Water Reducer Ligno. Sul.	Water Reducer Car. Hydrox.	Revibration
St. Mary's Normal .35	Mean	10731	9023	9859	8741	11004		8829
	Standard Deviation	220	527	1180	451	797		987
	Coefficient of Variation	2.1	5.8	12.0	5.2	7.2		11.2
	Higher or Lower than Ref.		-15.9	-8.1	-18.5	+2.5		-21.5
	Statistically Significant		- YES	NO	- YES	NO		- YES
Canada High Early .35	Mean	11910	11294	11637	11356	14119		11963
	Standard Deviation	611	1739	978	332	375		476
	Coefficient of Variation	5.1	15.4	8.4	2.9	2.7		4.0
	Higher or Lower than Ref.		-5.2	-2.3	-4.7	+18.5		+0.4
	Statistically Significant		NO	NO	NO	+ YES		NO

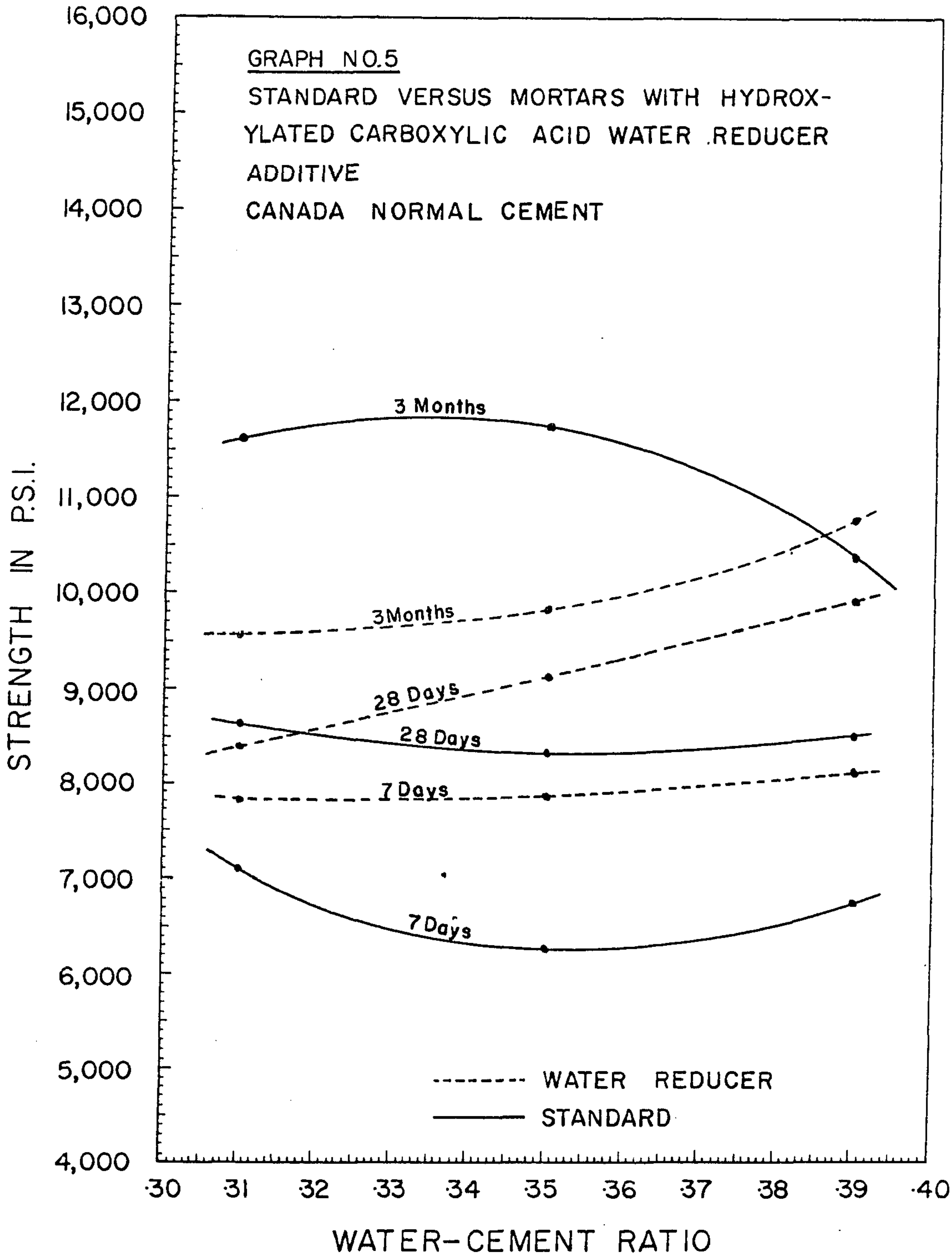

GRAPH NO.I
STANDARD VERSUS SLURRY MIXED MORTARS
CANADA NORMAL CEMENT
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
STRENGTH IN P.S.I.
3 Months
3Months
28 Days
28 Days
7Days
7 Days
SLURRY MIXED MORTARS
STANDARD MORTARS
·30
·31
·32
·33
·34
·35
·36
·37
·38
·39
·40
WATER–CEMENT RATIO

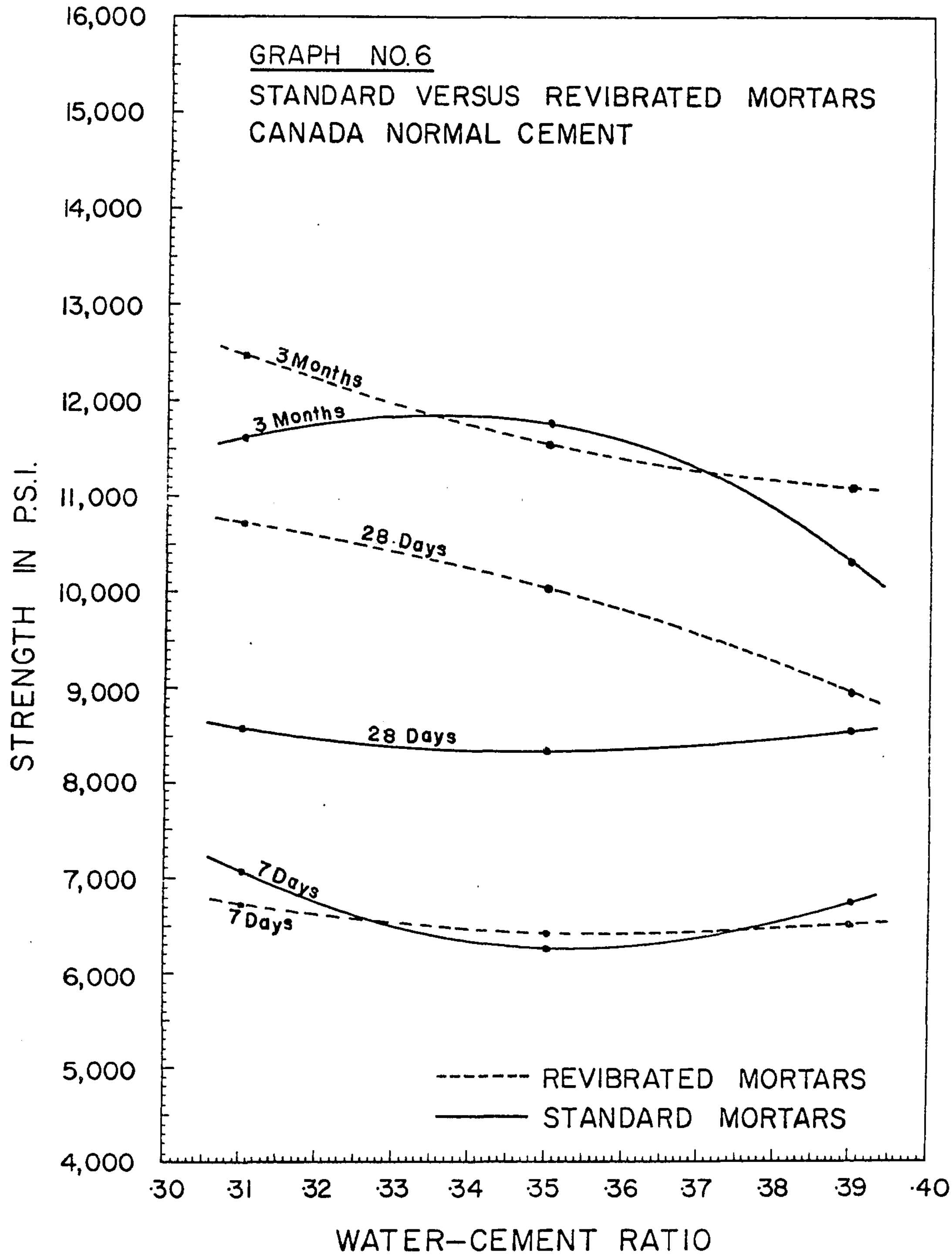

GRAPH NO. 2
STANDARD VERSUS FLY ASH MORTARS
CANADA NORMAL CEMENT
3 Months
3 Months
28 Days
28 Days
7 Days
7 Days
FLY ASH MORTARS
STANDARD MORTARS
STRENGTH IN P.S.I.
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
·30
·31
·32
·33
·34
·35
·36
·37
·38
·39
·40
WATER-CEMENT RATIO


GRAPH NO. 3
STANDARD VERSUS SEEDED MORTARS
CANADA NORMAL CEMENT
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
STRENGTH IN P.S.I.
3 Months
3 Months
28 Days
28 Days
7 Days
7 Days
SEEDED MORTARS
STANDARD MORTARS
·30
·31
·32
·33
·34
·35
·36
·37
·38
·39
·40
WATER-CEMENT RATIO


GRAPH NO. 4
STANDARD MORTARS VERSUS MORTARS WITH LIGNOSULPHONIC ACID WATER REDUCER ADDITIVE.
CANADA NORMAL CEMENT
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
STRENGTH IN P.S.I.
3 Months
3 Months
28 Days
28 Days
7 Days
7 Days
WATER REDUCER
STANDARD
·30
·31
·32
·33
·34
·35
·36
·37
·38
·39
·40
WATER-CEMENT RATIO

S U R P R I S E !


GRAPH NO.5
STANDARD VERSUS MORTARS WITH HYDROXYLATED CARBOXYLIC ACID WATER REDUCER ADDITIVE
CANADA NORMAL CEMENT
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
STRENGTH IN P.S.I.
3 Months
3Months
28 Days
28 Days
7 Days
7 Days
WATER REDUCER
STANDARD
·30
·31
·32
·33
·34
·35
·36
·37
·38
·39
·40
WATER-CEMENT RATIO



GRAPH NO.6
STANDARD VERSUS REVIBRATED MORTARS
CANADA NORMAL CEMENT
STRENGTH IN P.S.I.
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3 Months
3 Months
28 Days
28 Days
7 Days
7 Days
REVIBRATED MORTARS
STANDARD MORTARS
·30
·31
·32
·33
·34
·35
·36
·37
·38
·39
·40
WATER–CEMENT RATIO

in low water-cement ratio ranges the problem of compaction is encountered and it would seem that the strength attainable will depend on the degree of compaction that it is possible to achieve.

In graphs 7 to 16 are presented the age-strength relationships for all mixes investigated; graphs 7 to 11 deal with the mixes containing admixtures, while graphs 12 to 16 deal with special techniques. The effectiveness of the various admixtures and special techniques in producing high-strength concrete will be discussed individually in the following paragraphs.

(a) Fly Ash

From Graph 7, it is seen that the 7-day strength of the fly ash mix at a water-cement ratio of 0.31 was 22.6% lower than the reference mix, 16.7% higher at the 28-day test age and almost equal to the reference mix strength at 3 months at the 0.35 water-cement ratio. Graph 8 shows that the 7-day and 3-month strengths were almost equal to the reference mix at those ages but the fly ash mix was 18.0% higher than the reference mix at 28 days. At 0.39 water-cement ratio, Graph 9 shows that the fly ash mix was 19.7% lower at the 7-day test age, 13.2% higher at 28 days and 4.3% higher than the reference mix at 3 months. However, none of the foregoing differences in strengths were found to be statistically significant. Similarly, Graphs 10 and 11 show that the fly ash mixes of Canada High Early cement and St. Mary's Normal cement produced higher strengths (6.2% and 3.2% respectively) than the reference mixes at 28 days but in both cases the fly ash mixes produced lower strength values at the 3 month test age. Again, none of the strength diferences were found to be statistically significant. When dealing with pozzolans it is to be expected that slow strength development characteristics will be exhibited at early ages. Hence it is not unexpected to find lower strength values for the 7-day tests even though the percentage of fly ash used was only 10 percent. However, one would certainly not expect a lower strength for the fly ash mixes at the age of 3 months.

(b) Lignosulphonic Water-Reducer

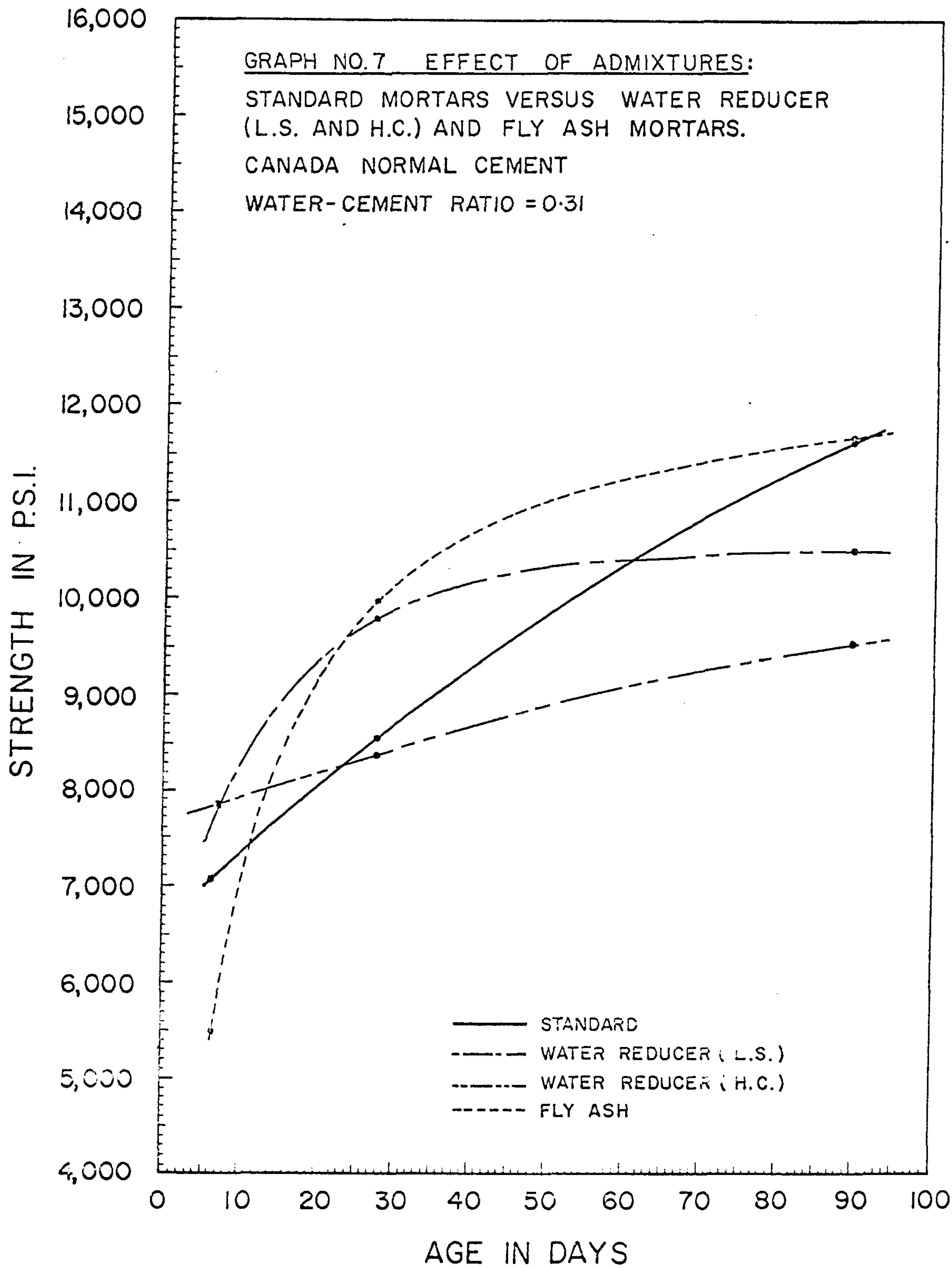
Although the lignosulphonic type of water-reducer permitted an 8% reduction in the mixing water (for the same consistency as the reference mix), there was not necessarily a strength increase at all test ages. For example, in the Canada Normal cement mix at 0.31 water-cement ratio (Graph 7), the 7 and 28 day strengths were 10.2 and 14.1 % higher respectively than the reference mix. But, at 3 months, the water-reducer mix gave a strength of 9.5% lower than the reference mix. In the 0.35 w/c ratio Canada Normal cement mix (Graph 8), both the 7-day and the 3 month strengths of the water-reducer mix were below the reference standard but the 28-day strength of the water-reducer mix was some 25% higher than the reference mix.

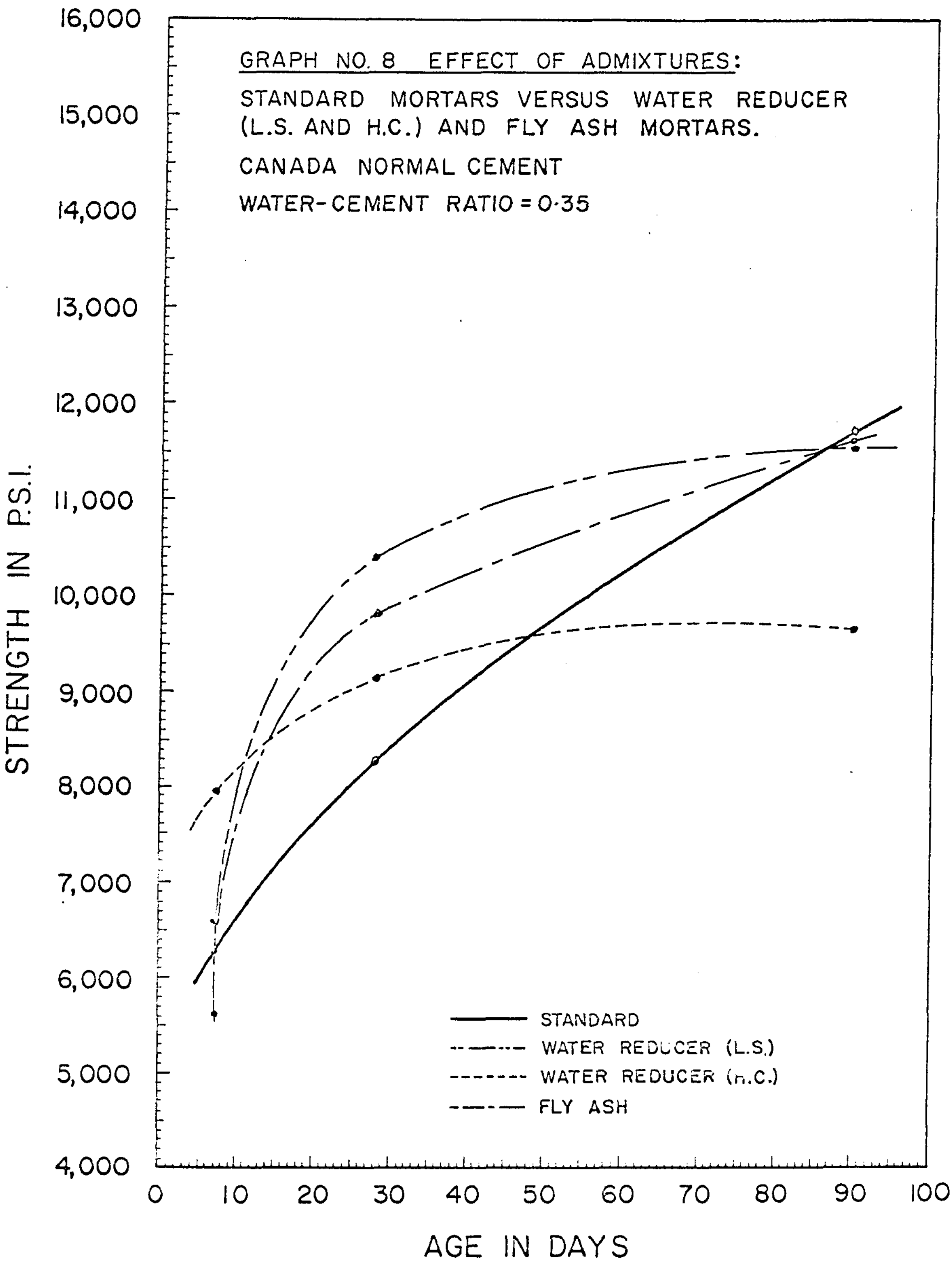
In the 0.39 w/c ratio, Canada cement mix and in the two other mixes (High Early cement and St. Mary's Normal) mixes containing the lignin water-reducer showed higher strengths at all ages (Graphs 9, 10, 11), although in many cases the strength increases were not statistically significant.

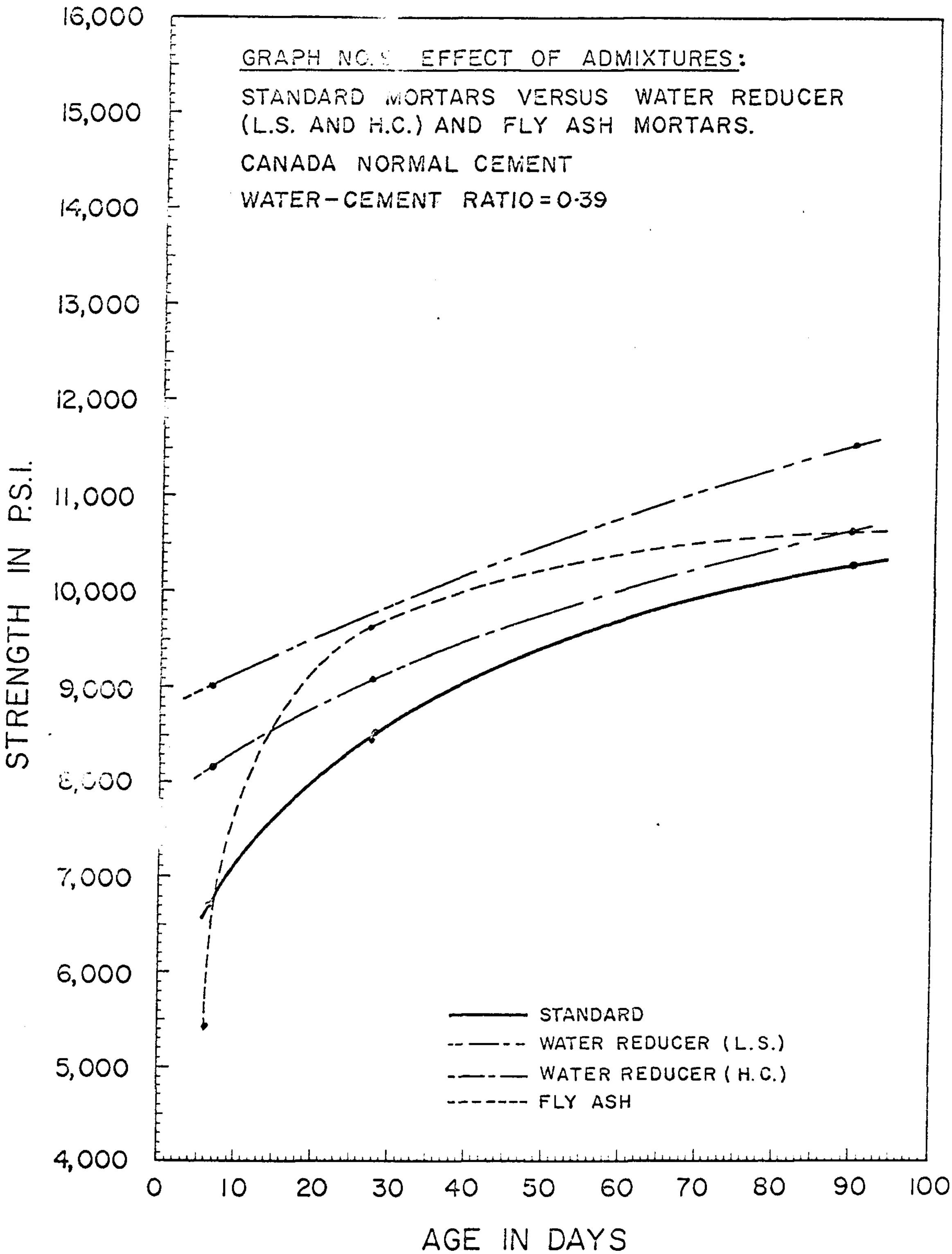
In all cases it can be seen (Graphs 7 to 11) that the highest strength increases were produced at the 28-day age, with either minor increases or indeed decreased strengths exhibited at the other ages relative to the standard mixes.

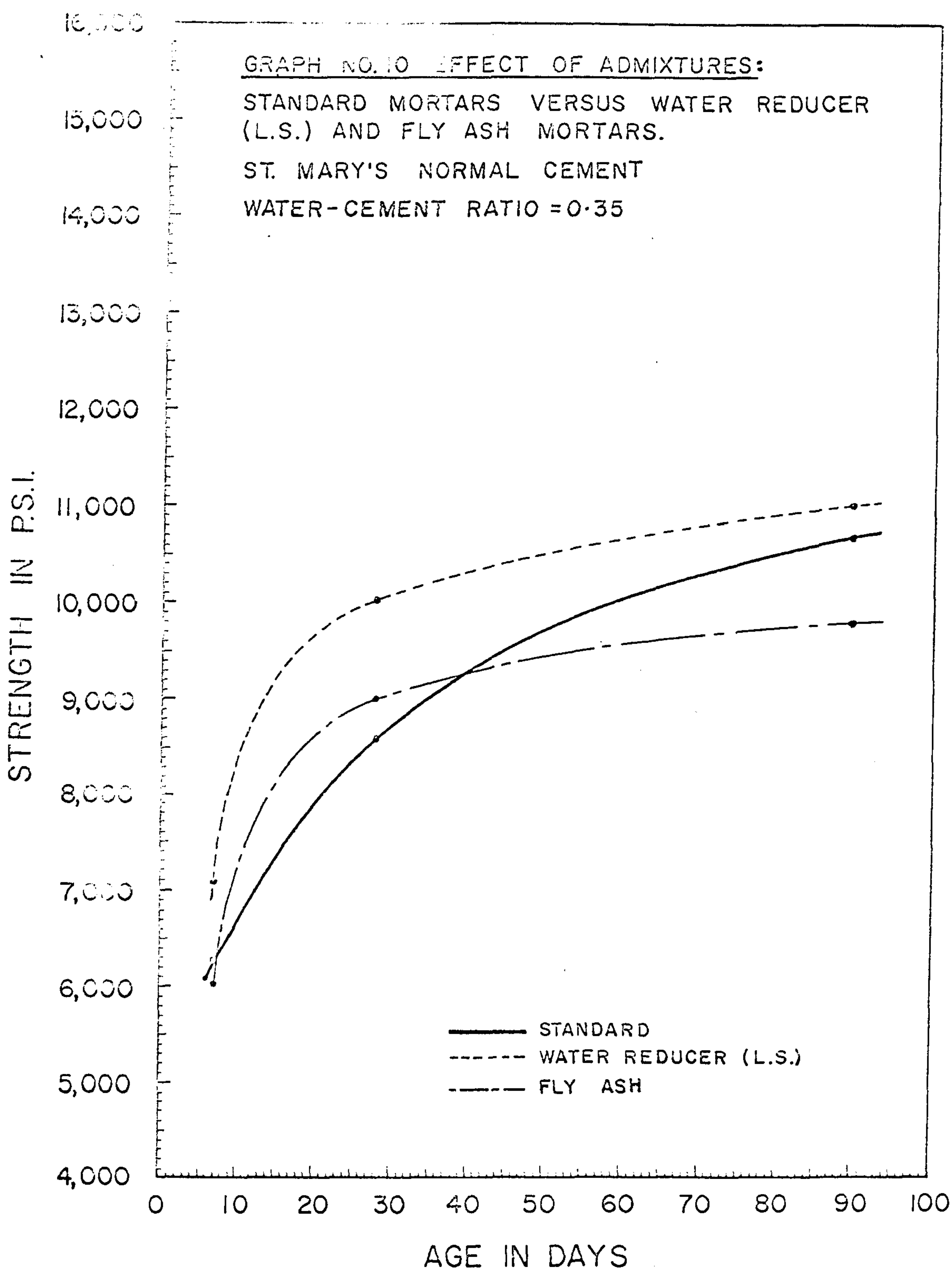
(c) Hydroxylated Carbonylic Water-Reducer

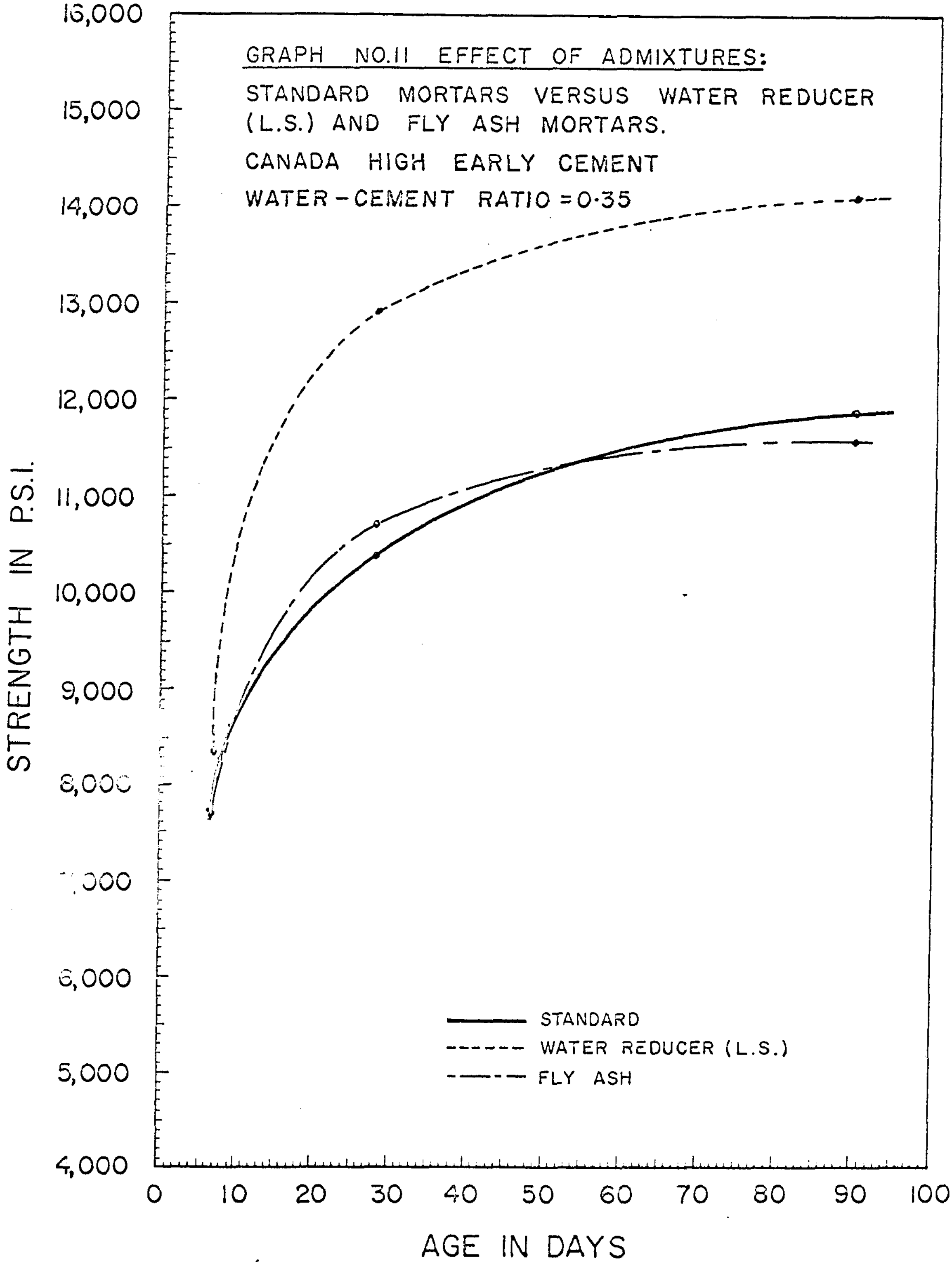
The hydroxylated carbonylic type water-reducer was tested in three mixes (w/c= o.31, 0.35 and 0.39) using Canada Normal Portland cement. (Graphs 7, 8 and 9). A rather interesting pattern is discernible in the test results. At the highest w/c ratio (0.39) this water-reducer produced average strength increases of 20.9, 17.2 and 4.3% respectively, at ages of 7, 28 and 91 days; at the intermediate w/c ratio (0.35) the strength changes produced were +25.5, +9.9 and -18.6% respectively at the 7, 28 and 91 day ages, while at the lowest w/c ratio (0.31) the strength changes produced were +10.5, -2.6 and -16.2%, respectively at ages 7, 28 and 91 days. It can thus be seen that the higher strength increases were produced at the


GRAPH NO. 7 EFFECT OF ADMIXTURES:
STANDARD MORTARS VERSUS WATER REDUCER (L.S. AND H.C.) AND FLY ASH MORTARS.
CANADA NORMAL CEMENT
WATER-CEMENT RATIO = 0·31
STANDARD
WATER REDUCER (L.S.)
WATER REDUCER (H.C.)
FLY ASH
STRENGTH IN P.S.I.
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
0
10
20
30
40
50
60
70
80
90
100
AGE IN DAYS


GRAPH NO. 8 EFFECT OF ADMIXTURES:
STANDARD MORTARS VERSUS WATER REDUCER (L.S. AND H.C.) AND FLY ASH MORTARS.
CANADA NORMAL CEMENT
WATER-CEMENT RATIO = 0·35
STRENGTH IN P.S.I.
AGE IN DAYS
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
0
10
20
30
40
50
60
70
80
90
100
STANDARD
WATER REDUCER (L.S.)
WATER REDUCER (H.C.)
FLY ASH


GRAPH NO. EFFECT OF ADMIXTURES:
STANDARD MORTARS VERSUS WATER REDUCER (L.S. AND H.C.) AND FLY ASH MORTARS.
CANADA NORMAL CEMENT
WATER-CEMENT RATIO = 0·39
STANDARD
WATER REDUCER (L.S.)
WATER REDUCER (H.C.)
FLY ASH
STRENGTH IN P.S.I.
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
0
10
20
30
40
50
60
70
80
90
100
AGE IN DAYS


GRAPH NO. 10 EFFECT OF ADMIXTURES:
STANDARD MORTARS VERSUS WATER REDUCER (L.S.) AND FLY ASH MORTARS.
ST. MARY'S NORMAL CEMENT
WATER-CEMENT RATIO = 0·35
STRENGTH IN P.S.I.
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
0
10
20
30
40
50
60
70
80
90
100
AGE IN DAYS
STANDARD
WATER REDUCER (L.S.)
FLY ASH


GRAPH NO.11 EFFECT OF ADMIXTURES:
STANDARD MORTARS VERSUS WATER REDUCER (L.S.) AND FLY ASH MORTARS.
CANADA HIGH EARLY CEMENT
WATER-CEMENT RATIO = 0·35
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
STRENGTH IN P.S.I.
0
10
20
30
40
50
60
70
80
90
100
AGE IN DAYS
STANDARD
WATER REDUCER (L.S.)
FLY ASH

higher water-cement ratios and the earlier ages. Or conversely, as the w/c ratio was lowered and the age of test increased, the effectiveness of the water-reducer in increasing strength is reduced and indeed eventually produces an adverse effect.

(d) Revibration

Revibration was found to produce fairly high increases (from 5 to 25%) in the 28-day strengths of all but one of the five mixes investigated (Graphs 12 to 16). The highest increases (25 and 20%)were produced in the low w/c ratio (0.31 and 0.35) mixes of Canada Normal cement.

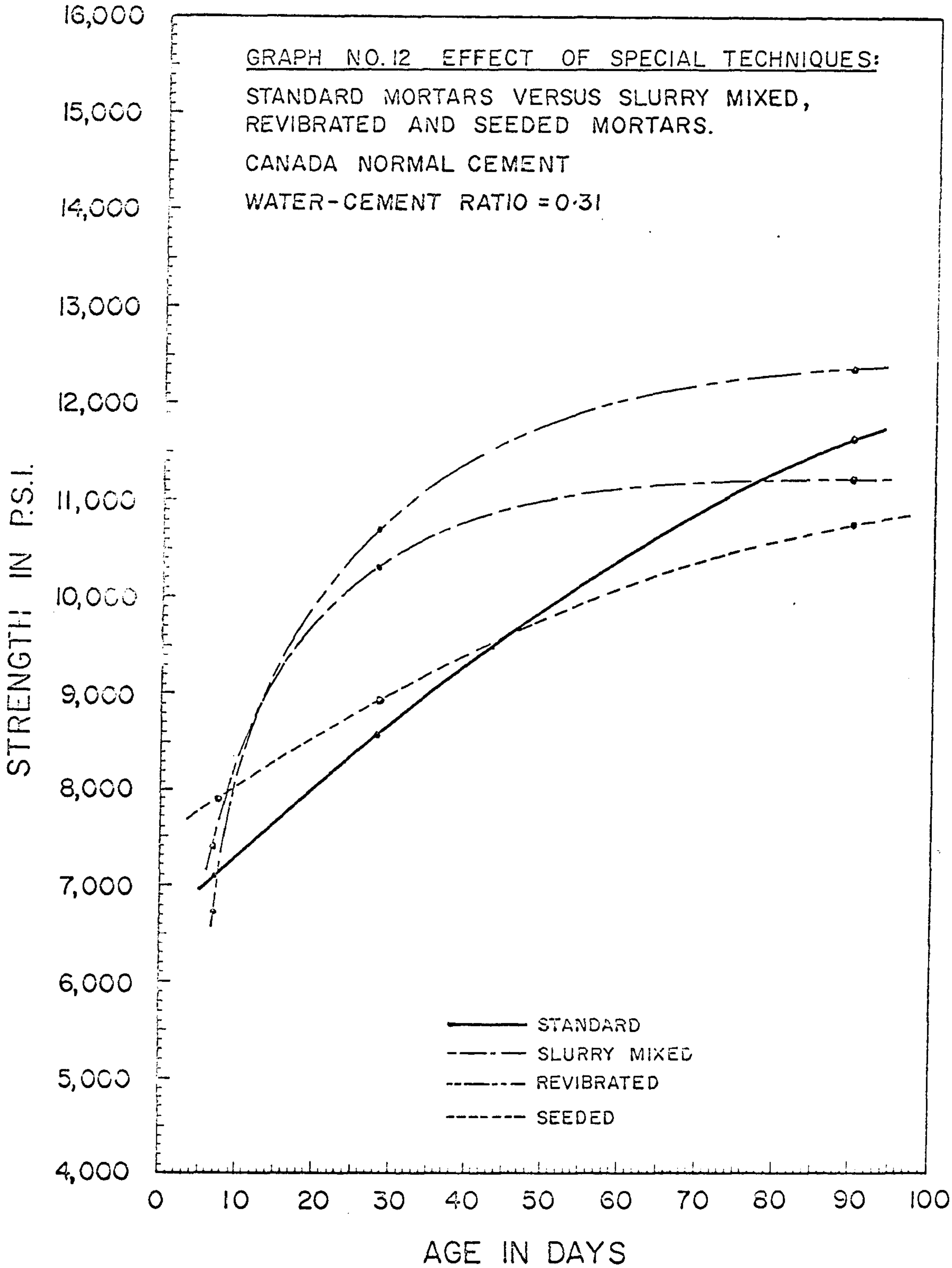
The effect of revibration on both the 7-day and 3-month strengths were found to be much less, on the average, than at the 28-day age but it should be pointed out that virtually none of the strength increases indicated for revibration were found to be statistically significant.

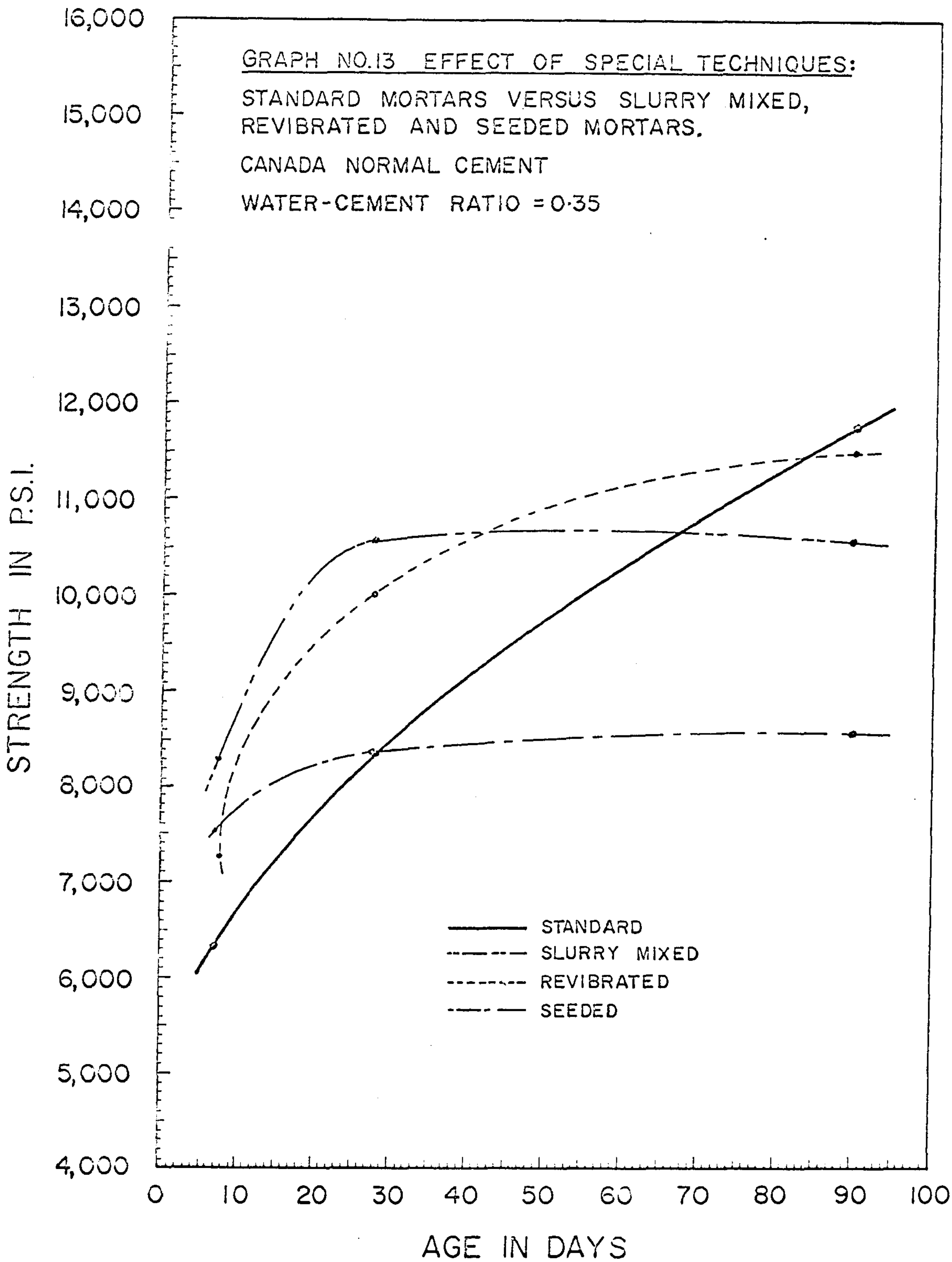
(e) High Speed Slurry Mixing

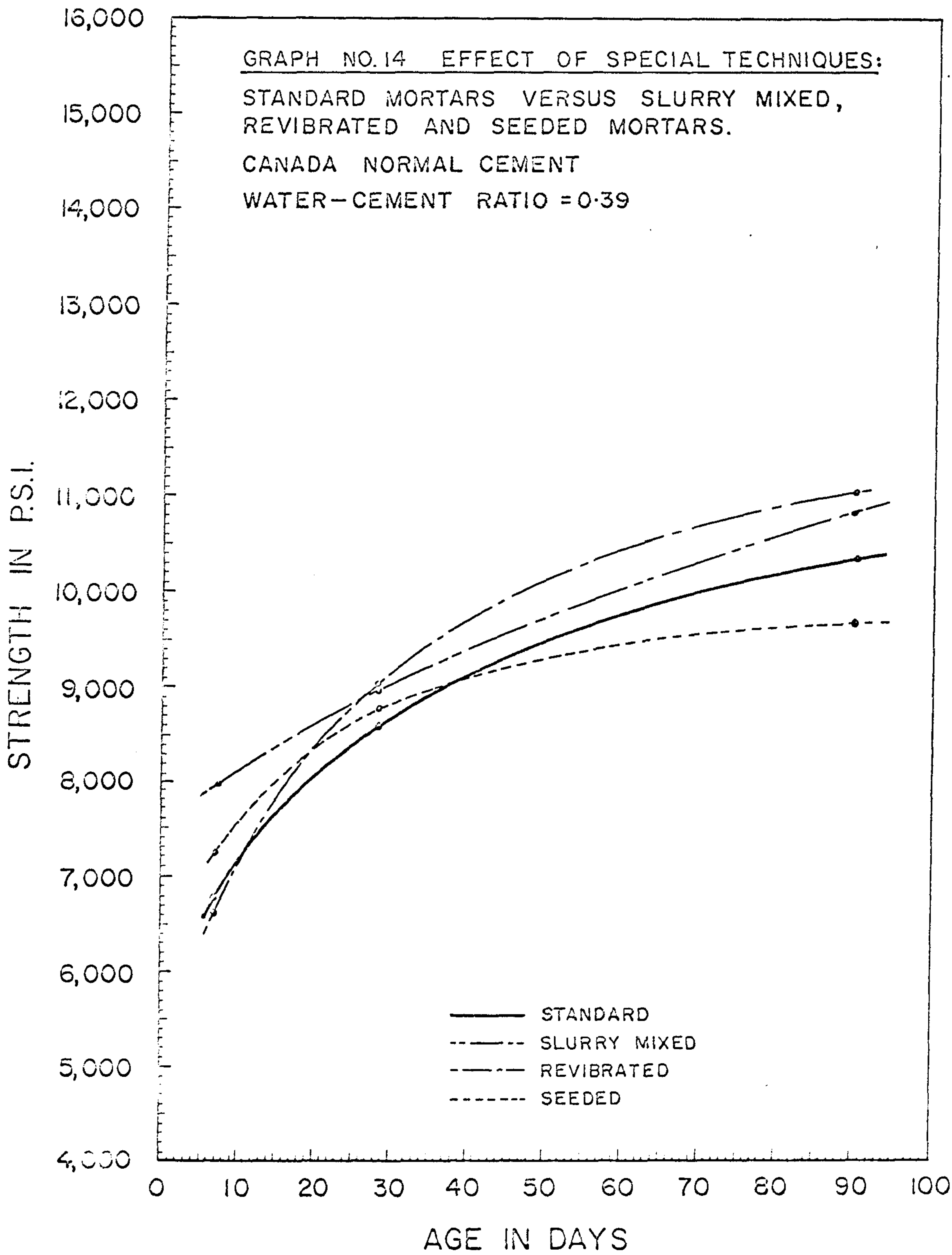
It can be noted (Tables 2, 3, 4 and Graphs 12 to 16) that in all but one of the five mixes investigated, high-speed slurry mixing produced increases in the 7-day strengths and two of these increases (+30% and +18%) were found to be statistically significant. Twenty- eight day strength increases ranging from 4.3% to 28% were also indicated for high speed slurry mixing. but at the age of 3 months all but one of the slurry mixes showed strength decreases compared with the standard mixes.

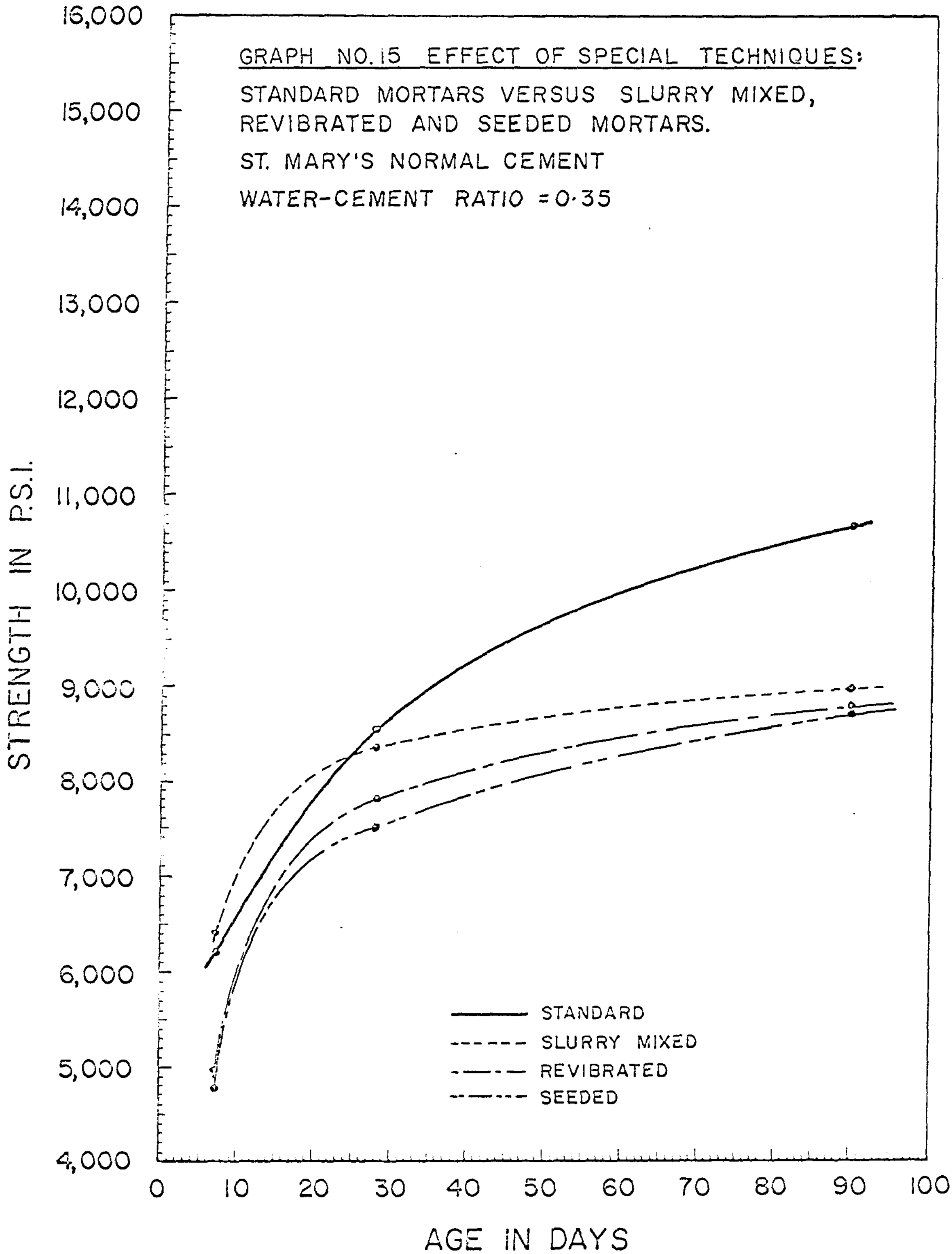
(f) Seeding

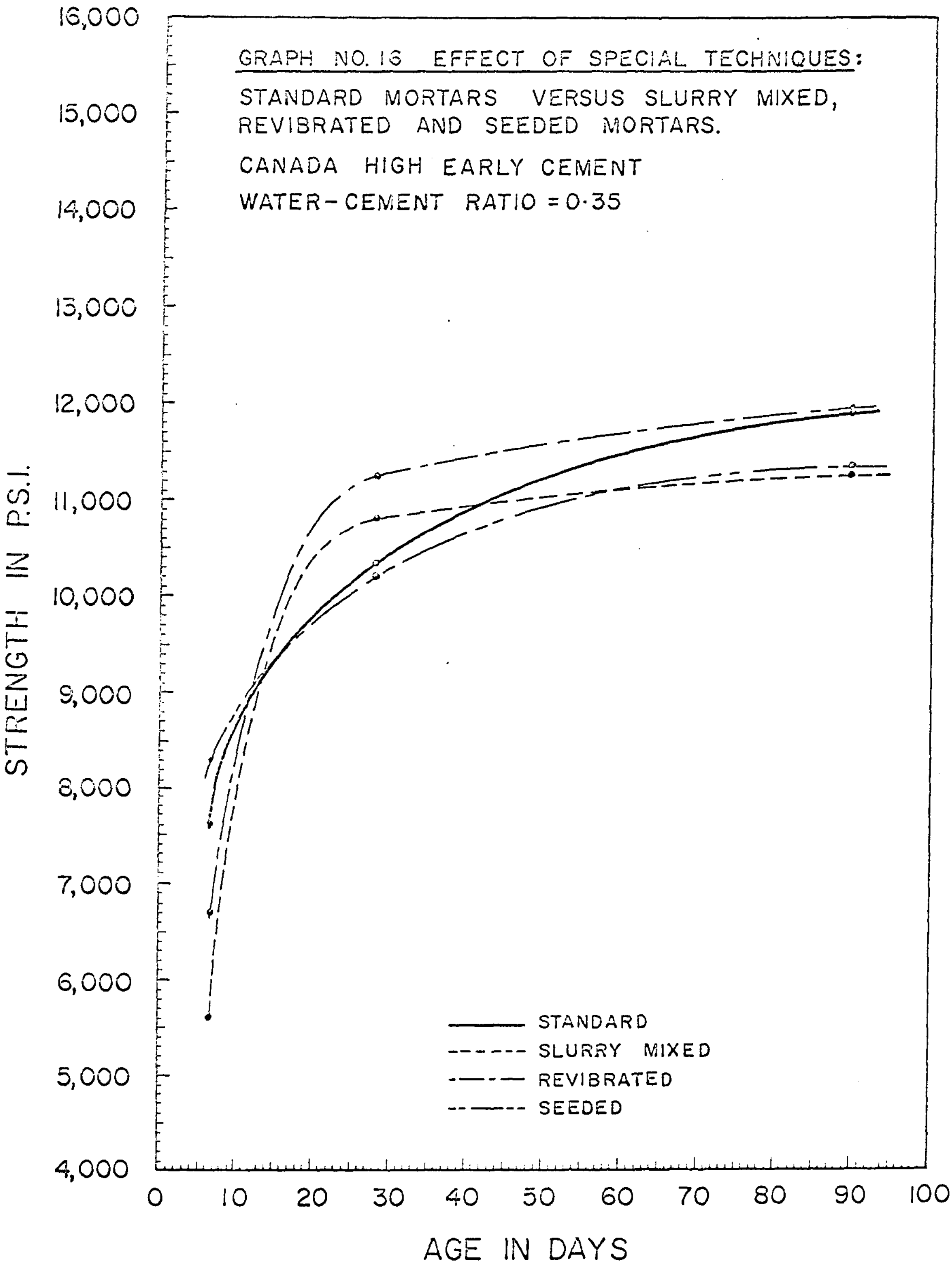
Four of the five mixes investigated showed strength increases at the 7 and 28 day ages ranging from 1.9 to 19.8%, (See Graphs 12 to 16), but only one of these increases (19.8% for the 7-day strength of 0.35 w/c Canada Normal cement mix) was indicated to be statistically significant. All of the five mixes investigated showed strength decreases for the 3 month specimens ranging from 4.7% to 26.7%. The strength decreases for three of the mixes were indicated to be statistically significant.


GRAPH NO. 12 EFFECT OF SPECIAL TECHNIQUES:
STANDARD MORTARS VERSUS SLURRY MIXED, REVIBRATED AND SEEDED MORTARS.
CANADA NORMAL CEMENT
WATER-CEMENT RATIO = 0·31
STRENGTH IN P.S.I.
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
0
10
20
30
40
50
60
70
80
90
100
AGE IN DAYS
STANDARD
SLURRY MIXED
REVIBRATED
SEEDED


GRAPH NO.13 EFFECT OF SPECIAL TECHNIQUES:
STANDARD MORTARS VERSUS SLURRY MIXED, REVIBRATED AND SEEDED MORTARS.
CANADA NORMAL CEMENT
WATER-CEMENT RATIO = 0·35
STRENGTH IN P.S.I.
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
0
10
20
30
40
50
60
70
80
90
100
AGE IN DAYS
STANDARD
SLURRY MIXED
REVIBRATED
SEEDED


GRAPH NO. 14 EFFECT OF SPECIAL TECHNIQUES:
STANDARD MORTARS VERSUS SLURRY MIXED, REVIBRATED AND SEEDED MORTARS.
CANADA NORMAL CEMENT
WATER-CEMENT RATIO = 0·39
STRENGTH IN P.S.I.
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
0
10
20
30
40
50
60
70
80
90
100
AGE IN DAYS
STANDARD
SLURRY MIXED
REVIBRATED
SEEDED


GRAPH NO. 15 EFFECT OF SPECIAL TECHNIQUES:
STANDARD MORTARS VERSUS SLURRY MIXED, REVIBRATED AND SEEDED MORTARS.
ST. MARY'S NORMAL CEMENT
WATER-CEMENT RATIO = 0·35
STRENGTH IN P.S.I.
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
0
10
20
30
40
50
60
70
80
90
100
AGE IN DAYS
STANDARD
SLURRY MIXED
REVIBRATED
SEEDED


GRAPH NO. 16 EFFECT OF SPECIAL TECHNIQUES:
STANDARD MORTARS VERSUS SLURRY MIXED, REVIBRATED AND SEEDED MORTARS.
CANADA HIGH EARLY CEMENT
WATER-CEMENT RATIO = 0·35
STRENGTH IN P.S.I.
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
0
10
20
30
40
50
60
70
80
90
100
AGE IN DAYS
STANDARD
SLURRY MIXED
REVIBRATED
SEEDED

CHAPTER VII

CONCLUSIONS

This experimental programme was designed to explore, in a preliminary fashion, the relative effectiveness of a number of admixtures and special techniques in producing high compressive strength concretes. Although much work remains to be done in this field it is felt that the following conclusions are warranted on the basis of the results obtained in this programme.

1. Abrams water-cement ratio-strength law does not appear to be valid for water-cement ratios below 0.39. It would seem that for w/c ratios below 0.39 strength is more a function of degree of compaction attained than of the w/c ratio of the mix.

2. A ten percent replacement of cement with fly ash appears to produce higher 28 day strengths in low w/c ratio mixes but the test results are not too conclusive.

3. Water-reducting agents can effectively lower the water requirement of low water-cement ratio mixes. Their greatest beneficial effect on strength appears to be in the early ages and at the higher w/c ratios.

4. Revibration appears to be most effective in the low w/c ratio mixes and at the 28-day test age, but the results for this technique were rather inconclusive.

5. High-speed slurry mixing produced significant (20 x 30%) strength increases at the 7-day age and somewhat higher strengths at 28 days but at 3 months the effect appeared negligible.

6. Seeding does not appear too promising as a technique for increasing compressive strengths of concrete. Some small increases were indicated for the 7-day age, but it appeared to produce significant decreases in strength at 3 months.

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APPENDIX A

APPENDIX A

TABLE I

PHYSICAL TEST RESULTS FOR CANADA
HIGH EARLY PORTLAND CEMENT

Physical Tests

Blaine Fineness	
Fineness, sq cm/g	4025
Time of Set, Gillmore Needle	
Initial, hr., :min.	1:35
Final, hr., :min.	3:15
Compressive Strength, psi	
1 day	3022
7 day	4631
14 day	4963
28 day	6725

APPENDIX A

TABLE I

CHEMICAL AND PHYSICAL TEST RESULTS OF ST. MARY'S NORMAL PORTLAND CEMENT

Chemical Analysis	
C_3S	48 %
C_2S	25 %
C_3A	9.9 %
C_4AF	9.0 %
Physical Tests	
Blaine Fineness	
Fineness, sq cm/g	3622
Soundness	
Autoclave Expansion, percent	.09
Time of Set, Gillmore Needle	
Initial, hr.,: min.	1:52
Final, hr.,: min.	3:55
Compressive Strength, psi	
1 day	1428
7 day	3088
14 day	3553
28 day	4556
Normal Consistency, %	23.5

APPENDIX A

TABLE I

CHEMICAL AND PHYSICAL TEST RESULTS FOR CANADA NORMAL PORTLAND CEMENT

Chemical Analysis

C_3S	58 %
C_2S	18 %
C_3A	7.3 %
C_4AF	8 %

Physical Tests

Blaine Fineness	
Fineness, sq cm / g	3697
Soundness	
Autoclave Expansion, percent	0.07
Time of Set, Gillmore Needle	
Initial, hr., : min.	2:05
Final, hr., : min.	4:12
Compressive Strength, psi	
1 day	1404
7 day	3200
14 day	2835
28 day	3775
Normal Consistency, %	25.0

APPENDIX A

TABLE 2

COMPOSITION OF PARTS SAND

Sieve Sizes Per Cent Retained	No. 4	No. 8 12.5	No. 14 15.4	No. 28 26.1	No. 48 30.6	No. 100 10.5	Pass No. 100 4.9	Total No. 8 to - No. 100	Quality Phys.	Chem.
	Amount of Particles in Per Cent by Count in Various Sieve Sizes									
Dolomite	36.5	54.7	55.0	28.0	18.3	16.3	25.4	31.1		
Dolomite, pitted	3.6	3.7						.5		
Dolomite, calcitic (or with coating)	25.0	7.1	5.7	10.0	4.9			5.8		
Limestone	3.6	.3	1.7	2.7	2.7	12.7		3.2		
Limestone, dolomitic (shaly?)	3.6	2.0	7.0	12.7	6.7			6.7		
Marl, aphanitic	12.4	5.3	4.3	5.7	6.3	.3		4.8		
" , brittle		.7	1.0	.3	1.0			.7	Fair	Delet.
" , friable	.9	.3	.7	1.0				.6	Poor	Delet.
Shaly, calcareous sandstone, brownish		13.0	6.7	5.0	5.7	1.5		5.9		
" " distinctly limonitic	2.7	1.7	2.3	1.0	1.0	1.2		1.3		Delet.
Ironstone	2.7	1.0	1.0	2.3	1.0	.3		1.3		Delet.
Sandstone		1.3	1.7	.3	.7	.3		.7		
, brittle		.3						X	Fair	
Recent sandstone		.7	1.0	.7	.7			.6		
Chert T.S. 1247	.9	1.0	.3	1.0	.3	.3		.5		
Aplite T.S. 1247		2.0	2.7	5.0	6.0	4.1		4.2		
Granite	4.5	2.0	2.3	4.0	2.0	3.3		2.6		
,brittle		.3	.3					.1	Fair	
Gneiss		.7	1.3	.3				.4		
Diabase	.9	.7		.3	.3			.3		
Hornfels T.S. 1247		.3	1.3	1.3				.6		

Appendix A

TABLE 2

QUALITY OF PARTS SAND

Fractions	No. 8 to No. 100 Per Cent	No. 4 Per Cent
Physical Quality		
Good particles	97.7	99.1
Fair particles	.8	
Poor particles	1.5	.9
	100.0	100.0
Chemical Quality		
Innocuous particles	96.1	93.7
Deleterious (?) particles	2.0	2.7
Deleterious particles	1.9	3.6
	100.0	100.0
Harmful particles	4.8	6.3

Poor particles: Soft marl and micaceous minerals (mica, chlorite)

Deleterious particles: Soft marl and ironstones

Particles suspected of being deleterious: Brittle marl and limonitic calcareous sandstone, rich in limonite.

APPENDIX A

TABLE 2

PARTICLE SHAPE AND SURFACE OF PARTS SAND (in per cent)

	Retained on Sieve Sizes						Pass	TOTAL
	No. 4	No. 8	No. 14	No. 28	No. 48	No. 100	No. 100	No. 8 to No. 100
Shape of Particles								
Angular, subangular								
Cubic particles	67	83	89	89	88	78	90	87
Flat particles	8	8	2	1	2	6	5	3
Oblong particles		X	X	X		1	X	X
Rounded, subrounded								
Cubic particles	25	9	9	10	10	15	5	10
	100	100	100	100	100	100	100	100

X = Amounts less than one per cent

The surface of the particles was mainly crystalline, on limestones and on feldspar it was smooth, on the few sandstones, clastic.

Appendix A

TABLE 3

Physical Properties and Chemical Components of Fly Ash from Trenton Channel Power Plant

Physical Properties

1.	Specific gravity	2.15
2.*	Specific surface, sq cm per g	3080
3.*	Mean particle diameter, microns	9.1
4.**	Density (loose), lb per cu ft	49.70
5.	Percent retained on No. 325 Sieve (wet sieving)	20.1
6.	Percent retained on No. 4) Sieve (dry sieving)	0.09
7.	Percent passing No. 200 Sieve (dry sieving)	85.9
8.***	Microparticle size analysis, percent finer than:	
	20 microns	58
	10 microns	38
	5 microns	22
9.	Moisture, percent	0.07
10.	Loss on ignition, percent	4.0
11.	pH	8.6

Chemical Components, percent of dry weight

A. Spectrographic analysis

1.	SiO_2	52.5
2.	Fe_2O_3	8.0
3.	Al_2O_3	28.0
4.	CaO	1.2
5.	MgO	1.2
6.	TiO_2	1.4
7.	Na_2O	0.7
8.	K_2O	2.1

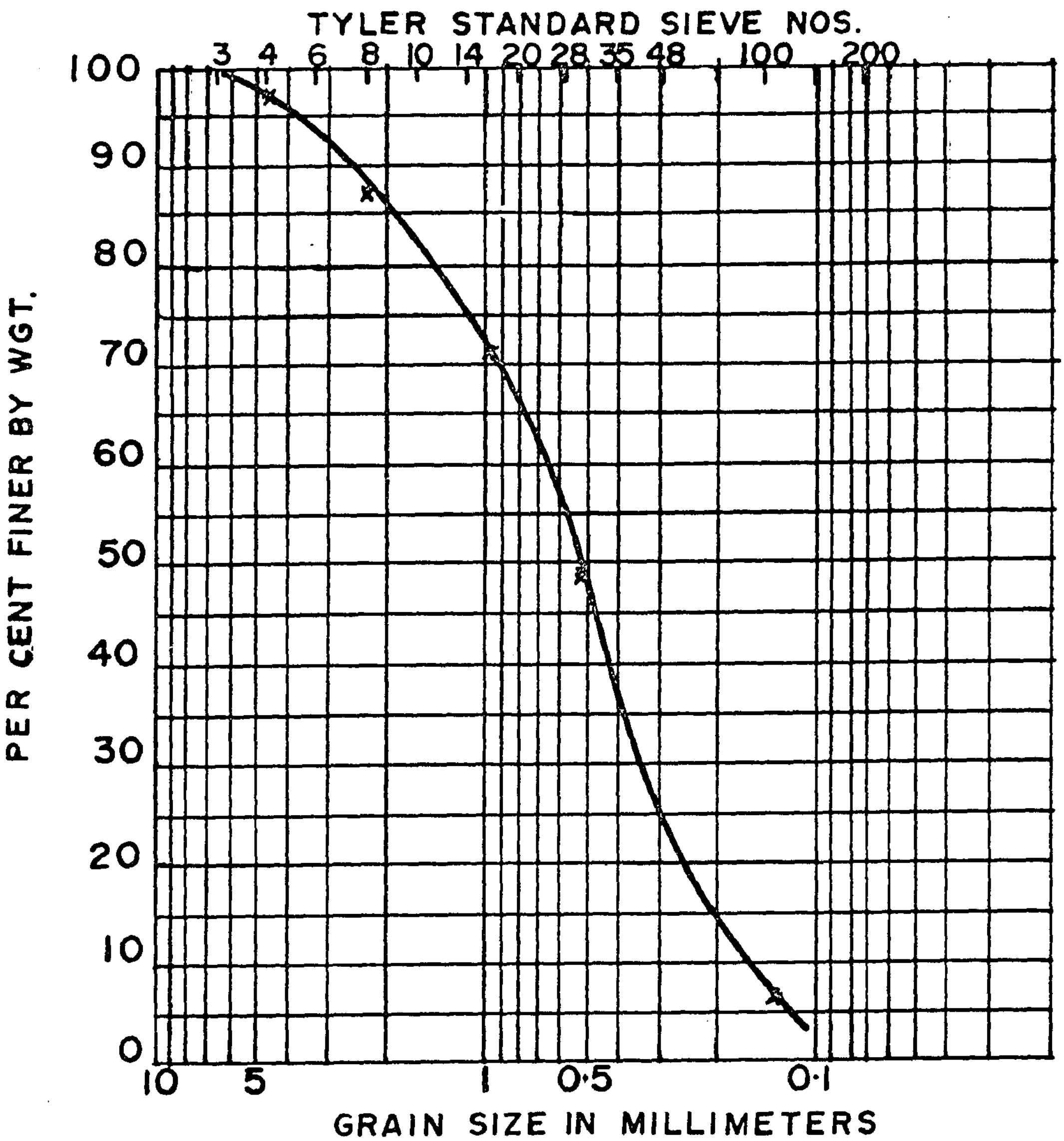
B. Chemical analysis

1.	SiO_2	50.4
2.	Fe_2O_3	8.4
3.	Al_2O_3	31.4
4.	Carbon	3.44
5.	SO_3	0.44

* Blain Air-permeability Apparatus
** Scott Volumeter
*** Bahco Microparticle Classifier.

APPENDIX A

Figure 1



GRAIN SIZE DISTRIBUTION
FOR
PARIS SAND

APPENDIX B

APPENDIX B

Test Data Showing the Effect of High Speed Slurry Mixing

Cement Brand	Water - Cement Ratio	Batch Number	Standard Comp Strength psi 7 day	28 day	3 mo.	High Speed Slurry Mixing Comp.Strength psi 7 day	28 day	3 mo.
Canada Normal	.31	1	4282	5211	12535	7113	10845	11479
		2	6796	6338	11725	7113	9577	10563
		3	7148	10493	11338	7993	10387	11901
		4	7359	10775	10845	7113	10317	11127
		5	8275	9085				
		6	8556	9542				
Canada Normal	.35	1	6268	5669	12183	7782	10141	11127
		2	5775	8028	10880	8063	10563	9225
		3	6901	10493	11620	8310	10634	11408
		4	5282	10352	12254	8345	11092	10845
		5	7817	9085				
		6	5423	6197				
Canada Normal	.39	1	6162	7570	9683	7641	9155	11092
		2	5951	6127	10528	7676	8873	10880
		3	6549	8239	10669	8204	8979	10563
		4	5775	10317	10423	8345	8803	10845
		5	8169	9577				
		6	7641	9331				
St.Mary's Normal	.35	1	6761	7042	10951	6127	8239	8944
		2	4577	7394	10493	7465	8592	8627
		3	6408	9930	10880	7218	8415	9789
		4	6761	9789	10599	4789	7887	8732
		5	6479	8521				
Canada High Early	.35	1	7183	11268	12430	5245	10317	12817
		2	7711	10739	12254	5352	11303	12711
		3	6655	7993	11901	5634	10528	9366
		4	6972	11479	11056	6162	11127	10282
		5	9507					

APPENDIX B

Test Data Showing the Effect on Fly Ash

Cement Brand	Water - Cement Ratio	Batch Number	Standard Comp Strength psi 7 day	28 day	3 mo.	Fly Ash Comp Strength psi 7 day	28 day	3 mo.
Canada Normal	.31	1	4282	5211	12535	5810	9859	12430
		2	6796	6338	11725	5458	10035	11761
		3	7148	10493	11338	5141	9824	11162
		4	7359	10775	10845		10317	11646
		5	8275	9085				
		6	8556	9542				
Canada Normal	.35	1	6268	5669	12183	6725	10423	11408
		2	5775	8028	10880	6549	9718	10880
		3	6901	10493	11620	5986	9859	12535
		4	5282	10352	12254	6061	9190	11937
		5	7817	9085				
		6	5423	6197				
Canada Normal	.39	1	6162	7570	9683	4437	9437	10775
		2	5951	6127	10528	5458	9049	9789
		3	6549	8239	10669	5458	10035	11056
		4	5775	10317	10423	6197	10106	11479
		5	8169	9577				
		6	7641	9331				
St.Mary's Normal	.35	1	6761	7042	10951	6423	8556	10563
		2	4577	7394	10493	6268	9648	10493
		3	6408	9930	10880	5739	9190	10282
		4	6761	9789	10599	5634	8873	8099
		5	6479	8521				
Canada High Early	.35	1	7183	11268	12430	7500	11021	10423
		2	7711	10739	12254	7958	10387	11972
		3	6655	7993	11901	6901	10070	11408
		4	6972	11479	11056	8099	11338	12746
		5	9507					

APPENDIX B

Test Data Showing the Effect of Seeding

Cement Brand	Water-Cement Ratio	Batch Number	Standard Comp. Strength psi 7 day	Standard Comp. Strength psi 28 day	Standard Comp. Strength psi 3 mo.	Seeding Comp. Strength psi 7 day	Seeding Comp. Strength psi 28 day	Seeding Comp. Strength psi 3 mo.
Canada Normal	.31	1	4282	5211	12535	9542	9894	11021
		2	6796	6338	11725	8134	9683	11232
		3	7148	10493	11338	7852	7711	10704
		4	7359	10775	10845	5880	8380	10282
		5	8275	9085				
		6	8556	9542				
Canada Normal	.35	1	6268	5669	12183	6937	7782	8732
		2	5775	8028	6880	7183	8486	8838
		3	6901	10493	11620	7887	9014	9472
		4	5282	10352	12254	7923	8556	7359
		5	7817	9085				
		6	5423	6197				
Canada Normal	.39	1	6162	7570	9683	7570	8908	10070
		2	5951	6127	10528	7359	8662	9859
		3	6549	8239	10669	7148	8979	9331
		4	5775	10317	10423	6338	8451	9577
		5	8169	9577				
		6	7641	9331				
St.Mary's Normal	.35	1	6761	7042	10951	5493	7570	9155
		2	4577	7394	10493	3697	7465	8873
		3	6408	9930	10880	4296	7817	8099
		4	6761	9789	10599	5563	7075	8838
		5	6479	8521				
Canada High Early	.35	1	7183	11268	12430	8944	10246	11831
		2	711	10739	12254	7676	10634	11338
		3	6655	7993	11901	7887	10000	11127
		4	6972	11479	11056	9014	9930	11127
		5	9507					

Test Data Showing the Effect of Water Reducer

Cement Brand	Water - Cement Ratio	Batch Number	Standard Comp. Strength psi 7 day	28 day	3 mo.	Water Reducer L.S. Comp.Strength psi 7 day	28 day	3 mo.
Canada Normal	.31	1	4282	5211	12535	7394	9507	11620
		2	6796	6338	11725	8592	10282	10528
		3	7148	10493	11338	6831	9331	9894
		4	7359	10775	10845	8345	10000	10007
		5	8275	9085				
		6	8556	9542				
Canada Normal	.35	1	6268	5669	12183	4542	9648	10986
		2	5775	8028	10880	6444	11197	12254
		3	6901	10493	11620	5458	10211	11937
		4	5282	10352	12254	5458	10563	10915
		5	7817	9085				
		6	5423	6197				
Canada Normal	.39	1	6162	7570	9683	8908	9296	11303
		2	5951	6127	10528	8627	7465	11831
		3	6549	8239	10669	9120	8451	11268
		4	5775	10317	10423	9331		12077
		5	8169	9577				
		6	7641	9331				
St. Mary's Normal	.35	1	6761	7042	10951	6866	9789	10423
		2	4577	7394	10493	7394	10317	10704
		3	6408	9930	10880	6866	10387	10704
		4	6761	9789	10599	7183	9859	12183
		5	6479	8521				
Canada High Early	.35	1	7183	11268	12430	9155	12958	14577
		2	7711	10739	12254	8169	13239	13662
		3	6655	7993	11901	8556	13099	14154
		4	6972	11479	11056	7430	12394	14084
		5	9507					

Appendix B

Test Data Showing the Effect of Water Reducer (Carb.Hydrox.)

Cement Brand	Water-Cement Ratio	Batch Number	Standard Comp. Strength psi 7 day	28day	3 mo.	Water Reducer c.h. Comp. Strength psi 7 day	28 day	3 mo.
Canada Normal	.31	1	4282	5211	12535	8169	9190	10528
		2	6796	6338	11725	6197	6972	8732
		3	7148	10493	11338	8345	8169	10140
		4	7359	10775	10845	8521	9089	9507
		5	8275	9085				
		6	8556	9542				
Canada Normal	.35	1	6268	5669	12183	8556	9507	9788
		2	5775	8028	10880	7113	8134	7464
		3	6901	10493	11620	8556	9366	10246
		4	5282	10352	12254	7113	9507	10704
		5	7817	9085				
		6	5423	6197				
Canada Normal	.39	1	6162	7570	9683	8239	9437	10775
		2	5951	6127	10528	8169	10317	11162
		3	6549	8239	10669	8028	10387	10704
		4	5775	10317	10423	7993	9824	10458
		5	8169	9577				
		6	7641	9331				
St. Mary's Normal	.35	1	6761	7042	10951			
		2	4577	7394	10493			
		3	6408	9930	10880			
		4	6761	9789	10599			
		5	6479	8521				
Canada High Early	.35	1	7183	11268	12430			
		2	7711	10739	12254			
		3	6655	7993	11901			
		4	6972	11479	11056			
		5	9507					

APPENDIX B

Test Data Showing Effect of Revibration

Cement Brand	Water-Cement Ratio	Batch Number	Standard Comp. Strength psi 7 day	28day	3 mo.	Revibration Comp. Strength psi 7 day	28 day	3 mo.
Canada Ordinary	.31	1	4282	5211	12535	6725	10739	12500
		2	6796	6338	11725	7570	10423	12218
		3	7148	10493	11338	6303	11479	12641
		4	7359	10775	10845	6268	10246	12289
		5	8275	9085				
		6	8556	9542				
Canada Ordinary	.35	1	6268	5669	12183	6197	10493	11831
		2	5775	8028	10880	6796	9754	11937
		3	6901	10493	11620	6338	10458	11866
		4	5282	10352	12254	6268	9648	10458
		5	7817	9085				
		6	5423	6197				
Canada Ordinary	.39	1	6162	7570	9683	6690	9859	11092
		2	5951	6127	10528	7042	8838	
		3	6549	8239	10669	5916	8451	11338
		4	5775	10317	10423	6479	8732	10810
		5	8169	9577				
		6	7641	9331				
St. Mary's Ordinary	.35	1	6761	7042	10951	5458	8415	9366
		2	4577	7394	10493	4401	7254	8627
		3	6408	9930	10880	4965	7887	9789
		4	6761	9789	10599	5070	7465	7535
		5	6479	8521				
Canada High Early	.35	1	7183	11268	12430	5634	11585	11690
		2	7711	10739	12254	7711	11127	11761
		3	6655	7993	11901	5634	10986	11725
		4	6972	11479	11056	7782	11268	12676
		5	9507					

VITA AUCTORIS

1942 Donald Vincent Thomson was born in Kirkland Lake, Ontario,on November 9, 1942.

1948 In September, 1948, he entered Holy Name Separate School where he obtained his elementary education.

1956 In September, 1956, he enrolled at Kirkland Lake Collegiate and Vocational Institute where he obtained his secondary education.

1961 In September, 1961, he enrolled in first year engineering at Assumption University of Windsor.

1965 In September, 1965, he enrolled at the University of Windsor in order to obtain the degree of Master of Applied Science in Civil Engineering. In October, 1965, he was graduated from the University of Windsor with a Bachelor of Applied Science Degree.