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The effect of revibration and intermittent vibration on the compressive and flexural strengths of cement pastes.

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THE EFFECT OF REVIBRATION AND INTERMITTENT VIBRATION ON THE COMPRESSIVE AND FLEXURAL STRENGTHS OF CEMENT PASTES

A THESIS

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ABSTRACT

The use of revibration in concrete has been a subject of controversy for sometime, but after World War II most engineers started appreciating the beneficial effect of revibration on the strength of concrete. In the first few chapters of this thesis is an appreciation of the work already done by others and deals in some detail with the factors affecting the strength of concrete.

In the present experimental study the effect of revibration and intermittent vibration was studied on the compressive and flexural strengths of cement pastes using Type I Portland cement. The programme included mixes of water cement ratios 0.30, 0.35, 0.40 and 0.45, compression test cube specimens of size 2 x 2 x 2 in. and flexural test prism specimens of size 1 x 1 x 5 in. and three test ages - 7, 28 and 90 days. Standard reference specimens were vibrated once only for 5 minutes immediately after casting. Specimens revibrated had a total of 10 minutes vibration (5 minutes immediately after casting and 5 minutes after 2 hours and 40 minutes). Specimens subjected to intermittent vibration were vibrated 10 minutes at approximately one half hour intervals for a period of 2½ hours.

Both revibration and intermittent vibration were found effective in increasing both the compressive and flexural strengths of cement pastes. Intermittent vibration was found to be more effective than revibration for all the water cement ratios and at all three test ages.

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CHAPTER I

INTRODUCTION

As the primary function of all structures is to carry applied loads under a variety of conditions, the strength of concrete used in any structure is obviously very important, and strict control of concrete strength is normally required on all jobs. As the strength of concrete is also a good index of many other properties of practical significance, such as water tightness and resistence to weathering and other destructive agencies, these latter requirements provide further justification for careful control of concrete strength on jobs.

In the majority of cases, the specified minimum compressive strength at 28 days will normally be in the range of 2000 to 4000 psi. However, in recent years, it has been found that there are many situations in which high strength concrete can be used to advantage, e.g. in arches, shells, prestressed concrete etc. Accordingly, there has been increasing interest in obtaining strengths in excess of 5000 psi. This has led to

a) an appraisal of the considerable knowledge existing on the factors affecting the strength of concrete (which are discussed in Chapter II) and to

b) an increased interest in special techniques for increasing the strength of concrete, such as "seeding", high energy mixing, revibration, as well as the use of a variety of additives. In the recent past a good deal of work has been carried out at this University and elsewhere. This is discussed in Chapter III.

In particular it has been found that the "revibration" of mortars and concrete can produce significant increases in strength provided the concrete is again brought back to a plastic condition. A number of theories have been put forward to explain the increased strengths produced by revibration. It is hoped that the experimental programme reported in this thesis, which deals with the effect of revibration and intermittent vibration on the compressive and flexural strengths of cement pastes, will assist in the understanding of the beneficial effects produced by revibration.

CHAPTER II

FACTORS AFFECTING CONCRETE STRENGTH

The main factors affecting the strength of concrete are the characteristics of the component materials, the proportions in which they are combined and the care taken in mixing, compacting and curing the concrete. This Chapter will be devoted to a discussion of these factors. In addition, it is recognized that there are many "testing factors" which affect the indicated strength values. These are also discussed in this Chapter.

A) CHARACTERISTICS OF CEMENTING MATERIAL

In general the differences in strength development of the various types of portland cement arise from the relative proportions they possess of the four principal compounds and the fineness to which the cement clinker has been ground. The C_3S and C_2S constituents form 70 to 80 percent of all portland cements and they contribute most to eventual strength. The contribution of C_2S to strength takes place principally after 7 days and may continue up to one year. The C_3S hydrates more rapidly than C_2S and it therefore contributes more to the early strength. C_3A hydrates quickly and generates much heat, but makes only a small contribution to the strength, principally in the first 24 hours. The fourth component C_4AF is comparatively inactive and contributes little at any stage to the strength or heat of hydration of cement.

As the type names would suggest, the High Early Strength type of cement 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 strength 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 Strength cement will be somewhat lower than for Normal Portland.

High early strength can be obtained by increasing the C_3S component and by grinding the cement more finely.

The effects of other 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 have shown that increase in strength beyond the age of 28 days is strongly affected by the alkali content. Tuthill (19) found that increased alkali content of five cements tested reduced the compressive strength for both non air and air-entrained concretes.

B) CHARACTERISTICS OF AGGREGATES

Vertical cracking in a specimen subjected to uniaxial compression starts under a load equal to 50 to 75 percent of the ultimate load. This has been determined from measurements of the velocity of sound transmitted through the concrete (1 and 2) and also by using ultrasonic pulse velocity techniques. The stress at which the cracks form depends largely on the properties of coarse aggregate. Smooth gravel leads to cracking at lower stresses than rough and angular crushed rock, probably because mechanical bond is influenced by the surface properties and, to a certain degree, by the shape of the coarse aggregate.

The bond between cement paste and aggregate is influenced by the surface texture and cleanliness of the aggregate. A rough textured aggregate surface will have a better bond than a smooth surface.

Walker's investigations (5) showed that change in maximum size of coarse aggregate involves two opposing influences on the concrete strength. As the size of coarse aggregate is increased, the mixing water requirement is reduced, thus lowering the water cement ratio and so tending to improve strength. Apparently at the same time, inclusion of large aggregate particles is in itself detrimental to strength probably due to reduced surface area for bond and reduced total cross section area of the particles to resist shear. Another explanation for this could be some prior cracking of the paste around the larger aggregate particles due to shrinkage restraint.

The strength of aggregate also affects the strength of concrete and Jones (4) stated that aggregate should have a crushing strength at least equal to that of the hardened cement paste.

The grading of the aggregate also affects the amount of mixing water needed and the amount of paste required to fill the spaces between the aggregate particles.

Smith (7) stated that the use of coarse sand (Fineness modulus approximately equal to 3) in high compressive strength concrete was desirable. Kennedy (8) developed these investigations further and pointed out that there is a general tendency for strength to decrease with a decreasing fineness modulus of aggregate.

So it is evident that the selection of aggregates for a particular concrete is quite important, from the viewpoint of strength.

C) WATER-CEMENT RATIO

The importance of the proportion of water to cement in governing strength of paste has been recognized for years. Abrams (9) established a "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 concrete, so long as the mix is of workable plasticity".

According to Walsh (10) "for constant grading and workability, the amount of free water (i.e. excluding that absorbed by the aggregate) required in the mix is constant and is independent of the amount of cement". Although this cannot be accepted as an invariable rule, it does open up the possibility of fixing the amount of water per cubic yard of concrete to give the desired workability, and then fixing the amount of cement to give the desired water cement ratio or strength. It would seem however, that an increase in the amount of cement must require a slight increase in the amount of water to maintain the workability.

D) EFFECT OF RICHNESS OF MIX

It seems that mixes with very low water-cement ratios and an extremely high cement content (800 to 900 lbs/yd^3) exhibit retrogression of strength, particularly when large size aggregate is used. Thus, at later ages in this type of mix, a lower water-cement ratio would not lead to a higher strength. The reason for this may be due to stresses induced by shrinkage, whose restraint by aggregate particles causes cracking of cement paste or a loss of the cement-aggregate bond.

Unlike the anomalous behaviour of extremely rich mixes as mentioned earlier, the aggregate-cement ratio affects the strength of all medium and high strength concretes (i.e. those with a strength of about 5000 p.s.i. or more), although this is only a secondary factor in the strength of concrete, it has been found that for a constant water-cement ratio, a leaner mix produces a higher strength (11).

E) MIXING

The object of mixing is to coat the surface of all aggregate particles with cement paste and to blend all the ingredients of concrete into a uniform mass. With machine mixing there is an increase in the strength of concrete with mixing times up to perhaps 5 to 10 minutes. With moderate size mixers and for mixing up to 1 minute, the increase in strength is large, but with times in excess of 2 minutes there seems to be insufficient gain in strength to justify the cost of longer mixing. Mixing time in general depends on the type and size of the mixer, larger mixers requiring a longer mixing time. Current practice usually requires a minimum mixing time of not less than 1 minute for mixers having a capacity of 1 cubic yard or less, and an additional 15 seconds for each additional cubic yard or fraction thereof.

Excessive mixing is harmful because some grinding of the aggregates can occur which results in a higher water requirement to maintain the desired consistency.

F) COMPACTION

Immediately upon placement, concrete must be compacted to ensure close contact of the constituent materials with themselves as well as with the forms and reinforcement. It can be said that the object of compaction is to reduce air voids to a minimum and hence obtain as dense a mass as possible.

Klieger (12) pointed out that the restriction limiting the use of the water cement ratio law to "Plastic Workable" mixtures properly, should be interpreted to mean fully compacted mixtures with a minimum of entrapped air voids.

There are various methods by which concrete can be compacted but it is proposed to deal only with the vibration method of compaction. Vibration of concrete can be effected with either form vibrators, surface vibrators, immersion vibrators or with a vibrating table.

The frequency, amplitude and acceleration of vibration have a marked effect on compaction. Davis (13) found that vertical circular vibration was more effective than horizontal circular or linear vertical vibration. There was little difference between the effect of vertical linear and horizontal circular vibration. The degree of compaction was generally dependent on amplitude except the amplitudes of vibration as small as 0.002" were of little use. He found frequency also is not so important except for its effect on acceleration. The degree of compaction depended largely on acceleration and increased appreciably with acceleration up to 12g and thereafter slowly up to an acceleration of 20g.

The joint committee of the Institution of Civil and Structural Engineers reported two facts:

a) At a constant acceleration of 4g and a period of vibration of 2 minutes frequency had little effect on strength for the wetter mixes.

b) But for dry mixes the strength decreased as frequency was increased.

A critical point occurs at a given water cement ratio and at a given acceleration and frequency which gives an increased strength.

Theoretically there are considerable advantages in increasing the frequency and decreasing the amplitude as consolidation progresses. The reason for this is in the fact that initially the particles of the mix are far apart and the movement induced has to be of corresponding magnitude; on the other hand once the particle compaction has taken place, the use of higher frequency permits a greater number of adjusting movements in a given time. So vibration at too large an amplitude relative to the interparticle space, results in the mix being in a constant state of flow, so that full compaction is never achieved.

Kirkham and Whiffin (15) found that the acceleration of vibration had little effect on compaction.

G) CURING

The object of curing is to keep concrete saturated or as nearly saturated as possible, and to maintain favourable temperature conditions until the originally water filled space in the fresh concrete has been filled to the desired extent by the products of hydration.

Obviously, therefore, in order to attain maximum strength it is necessary to keep the concrete moist as long as hydration is taking place.

The favourable range in curing temperature for most concretes appears to be from 60°F to 90°F.

In general a rise in curing temperature speeds up the chemical reaction of hydration and thus affects beneficially the early strength of concrete without any ill effects on the later strength. However, a higher temperature during placing and setting, although it increases the very early strength, may adversely affect the strength from about 7 days onwards. The explanation is that a rapid initial hydration appears to form products of a poorer physical structure, probably more porous, so that a large proportion of the pores will always remain unfilled.

In general for curing temperatures below 90°F, the lower the temperature at which the concrete is continuously cured, the lower the strength at any given age, although temperatures as low as 40°F will ultimately produce satisfactory strengths, provided the concrete is kept moist for a sufficiently long period.

Temperatures below freezing are decidedly harmful to fresh concrete, as the expansion of water when transformed into ice, causes separation of the solid particles, thus reducing their bond at all ages.

H) TESTING FACTORS

Strength tests can broadly be classed into mechanical tests to destruction and non-destructive tests which allow repeated testing of the same specimen and thus makes possible a study of variation in properties with time. There are a variety of destruction type tests in use, but it is probably true to say that no universally accepted standard test is available. Different methods and techniques are used in different countries and sometimes even in the same country. The effect of differences in test specimen size and shape as well as environmental factors and testing methods on indicated strength values are discussed in the following paragraphs.

1) SPECIMEN VERSUS STRUCTURES

For a concrete structure which is subject to a variety of stresses and other conditions affecting strength, any test of a relatively small specimen does not necessarily give a very representative strength value for the concrete. In general, load tests on structures and on specimens of hardened concrete from structures indicate higher strengths than those obtained from standard specimens and hence many standard methods are considered to be conservative.

2) EFFECT OF SIZE AND SHAPE OF SPECIMEN

The two most commonly standardized shapes for compression testing are cylinders and cubes. In general with either cube specimens or cylinder specimens the larger the specimen, the lower is the indicated strength. Also it should be pointed out that cubes produce somewhat higher strengths than cylindrical specimens. This is considered to be due to the restraining effect of the platens in the testing machine, which has a different effect on these two shapes of specimens.

In regard to cylindrical specimens, the greater the ratio of specimen height to diameter the lower is the indicated strength. For this reason it is customary to standardize cylinders at an l/d of 2. Such a cylindrical specimen is not so short that small variations in length affect the strength significantly and yet is not so long that column action is a significant factor.

3) EFFECT OF END CONDITIONS OF SPECIMEN

The end conditions of test specimens have a significant effect on the test values obtained, and it is therefore important for the tops of specimens to be flat and smooth and for loads to be applied parallel to the axis of the specimen.

Cylinders with a trowelled top will indicate lower compressive strengths than cylinders with either capped or ground ends; also convex and concave end surfaces will result in lower indicated strengths, convex ends reducing strengths four times more than concave ends.

An inclination of the cylindrical axis by ½ inch causes a reduction of 5 to 8 percent in strength.

Wetting and greasing the cylinder top before testing while showing very slight reductions in strength, cannot be regarded as significant particularly as the 2 percent reduction found, might easily be accounted for by accidental variations occurring in any two sets of cylinders.

4) EFFECT OF MOISTURE CONTENT OF SPECIMEN

A compression specimen tested in an air dried condition gives 20 to 40 percent higher strength than a corresponding concrete specimen tested in a saturated condition. The reason for this is probably the following:

a) The greater density of dry paste.
b) Initial greater tensile stresses in the paste due to localised restraint of paste shrinkage by the pieces of aggregate.
c) Possible development of hydrostatic pressure in saturated paste.

So the usual standard requirement that compression specimens be saturated at times of test is conservative (16).

5) EFFECT OF RATE OF LOADING ON SPECIMEN

The more rapid the static loading of concrete, the higher the observed compressive strength. As compared with a normal rate of loading (about 35 pounds per inch^2 per second) loading at 1 psi per second reduces the indicated strength approximately 12 percent and loading at 1000 psi per second increases the indicated strength approximately 12 percent. Normally a static loading is completed in 2 to 3 minutes in a test.

The effect of rate of loading on flexural strength is somewhat greater than for compressive strength. The basis of loading rate differs as between hydraulic and screw gear testing machines. For flexural specimens the prescribed loading rate in hydraulic machines is such that the increase in extreme fibre stress does not exceed 150 psi per minute and in screw gear machines is at an idling speed of 0.05 per minute (16). Measurable creep was noted in cylinders loaded for a one minute interval. With increasing loads, the ratio of creep to load increased rapidly as the maximum load was approached, the creep forming a very considerable part of the total deformation.

6) EFFECT OF TEMPERATURE OF SPECIMEN

The higher the temperature of specimen at the time of testing, the lower the strength indicated. Tests at the University of California indicated in a typical case that the compressive strength at 25°F was 40 percent higher and at 130°F was 15 percent lower than that of corresponding specimens tested at 70°F. Tests at the University of Wisconsin (16) showed that the compressive strength of concrete at 0°F was 40 percent higher, and at 200°F to 250°F about 10 percent lower, than at 70°F.

At the University of Texas tests on flexure specimens showed that the modulus of rupture at 40°F was 12 percent higher and at 100°F was 20 percent lower, than at 70°F.

J) CONCLUDING REMARKS

From the foregoing, it is obvious that many factors affect the indicated strength to be obtained from a test specimen, thereby emphasizing the necessity of standardizing test procedures very carefully so that none of these factors will be allowed to mask differences in strength produced by the parameters being investigated.

CHAPTER III

EFFECT OF REVIBRATION

Even since the first patent for Portland cement was issued in 1824, the concept that the set of "green" concrete should not be disturbed has prevailed among engineers, although it has been found necessary, on occasion, to disturb the hardening process, with no detrimental effects upon the properties of the finished concrete. The latter has happened when the delivery of the concrete to a partially complete pouring has been somehow delayed, thus presenting the problem of avoiding cold joints. In many such instances, the problem has been overcome by having workmen tamp and agitate the surface of the concrete, often for several hours, until the fresh concrete has arrived. This practice has often been quite successful in direct contradiction to the traditional opinion concerning the hardening process (18).

In 1938, Tuthill and Davis (19) reported that as long as the concrete remains in a fairly plastic state, say up to perhaps two hours after mixing, slight inadvertent revibration, such as may occur on the job would cause no damage and possibly would result in some benefit. A limited amount of test data were presented to support this statement. Concrete in 6 x 12 inch cylinders was revibrated successfully after intervals as long as 10 hours from the time of mixing, and compressive strength increases of as much as 25 percent were obtained, the greatest strength increases being obtained when the interval between time of mixing and time of revibration was between 2 to 5 hours (19). They also reported some data on bond which showed that for plain bars a 30 percent to 50 percent increase, and for deformed bars, a maximum of 100 percent increase in bond strength was possible if revibration was carried out 2 to 5 hours after casting (19). At the same time that this work was reported Purandare (26) was conducting similar studies at the University of London, although his results were not published until 1946. Using a 1 : 2 : 4 concrete (water cement ratio of 0.55), both cubes and beam specimens were cast and were revibrated after intervals of 1 to 5 hours. Specimens were tested at the 7-day age. He reported a maximum increase in compressive strength of 34.3 percent, and a maximum increase of ultimate beam strength of 35.2 percent, both maxima obtaining when revibration took place two hours after casting.

In 1952, Larnach (25), in obvious contradiction to the foregoing, reported that his results showed no tendency for revibration of the partially set concrete to improve either the compressive or the bond strength. In his studies, the interval between casting and revibration varied from 15 minutes to 6 hours. One possible reason for his negative results could be the fact that he used very dry mixes, so that in fact revibration may not have brought them back to a plastic state.

In 1956, Sawyer and Lee (18) reported on fairly extensive studies of the effects of revibration on various properties of concrete. Their two major findings pertaining to strength were that

a) Revibration will increase the strength of concrete after any period of delay as long as the mix can be brought to a plastic state, even if the vibrator must be forced into the concrete and

b) the optimum time after casting to revibrate occurs when the vibrator will just sink into the concrete of its own accord.

Vollick (21) conducted studies on two mixes (4½ and 5½ sacks/yard) and the mixes in each of the tests included plain, air-entrained and set-retarded concrete. He concluded that revibration increased the 28 day strength of concrete by an average of 13.8 percent for his particular tests and that maximum strength gain is obtained when the concrete is vibrated 1 or 2 hours after placing.

Thomson (31) was the first one to investigate the effect of revibration on high strength mixes, i.e. at water cement ratios below 0.40. He worked with mortar mixes at water-cement ratios of 0.31, 0.35 and 0.39, and tested strengths at the 7, 28 and 90 day ages. In all cases but one, the revibrated mixes produced higher strengths than the standard, and these ranged from 1.2 to 25 percent. He concluded that this technique holds promise for improving strength in the high compressive strength ranges.

Kostenuik (34) followed up Thomson's work with tests on concrete mixes in the high compressive strength range (water-cement ratios, 0.30, 0.35 and 0.40). He found that revibration produced significant strength increases for all water-cement ratios and at all test ages. Strength increases ranged from 3 to 9 percent and were most pronounced at the water cement ratio of 0.35 at each test age. The highest percentage (9%) was produced at the age of 7 days with a water-cement ratio of 0.35.

From the foregoing discussion it is obvious (despite Larnach's results) that revibration can produce increased strength in both mortar and concrete mixes over a broad range of strength levels; and it would seem that the main criterion to be met is that the revibration should bring the concrete again to a plastic state.

CHAPTER IV

MECHANISMS BY WHICH REVIBRATION INCREASES STRENGTH

At the present time several theories have been suggested as to the exact mechanism by which revibration produces an increase in the strength of concrete. Each of these will be discussed in the following paragraphs.

A) One of the most popular theories was suggested by Sawyer and Lee (18), which is that revibration causes the mortar and concrete to become more densely consolidated, thereby permitting more advantageous deployment of hydration products. This certainly is in agreement with the general theory that strength is a function of void cement ratio so that any decrease in this ratio would result in an increase in strength. This also ties in with observations by Tuthill and Davis (19) that "while the concrete at a very early stage (before the time of the initial set of cement) is vibrated a noticeable amount of air and water may be expelled from the mass and hence causing better consolidation."

B) Another theory put forward by Sawyer and Lee (18) is that "the vibrating disturbances in some way accelerate and extend the production and consequently increase the amount of strengthening hydrates at the particular ages up to 90 days". They offered the following in explanation of this theory, "when the hydration of cement starts the initial structure is determined by either C_3A or C_3S which ever hydrates first. In a normally retarded set, the C_3S is presumed to hydrate first and to establish the primary structural bonds. If, on the other hand C_3A hydrates first, revibration may displace this weaker structure and allow the normal structure of C_3S to develop as in an otherwise normally retarded set. The extent of hydration of C_3S is relatively insignificant up to 4 to 6 hours while that of C_3A may be (unless normally retarded) almost complete within 10 hours. These factors could have a significant influence on the rate of strength development and even the ultimate strength" (18). Also in line with this theory is the idea that revibration tends to break the gel structure surrounding hydrating cement particles thereby allowing the more ready access of water to the unhydrated portions of the cement particles and allowing more hydration to take place.

C) Neville (14), has suggested that improvement in strength due to revibration may be due to a relief of the plastic shrinkage stresses around aggregate particles caused by revibration. If this theory has any validity then revibration should not produce any strength increases (or at least, smaller strength increases) in the plain cement pastes.

D) Lea (27) has suggested that revibration causes a strength increase by facilitating the expansion and dispersion of the cement paste. He explains the mechanism, as follows, "After hardening has commenced, the rigid mass can no longer accomodate itself to a localized growth of the solids around the cement grains and an expansion occurs if a supply of water is maintained to continue the hydration. And as during hydration the saturated cement gel has more volume (about 2.2 times) and so revibration of concrete after this expansion has started will or should facilitate the expansion and dispersion of the cement paste. This dispersion as stated earlier should increase the strength."

E) Just after the addition of water in the cement the crystals of calcium hydrauxide appear with the formation of gel (silicate hydrates). When the paste is revibrated before it has hardened, these crystals break and thus each cement particle has an uneven surface. Thus as a result of vibrating disturbances the cement particles get a better grip on each other resulting in better consolidation which causes an increase in strength (26).

F) Another theory is that as a result of revibration, the pressure due to crystals at the outer surface is reduced and strength increases as a result of better consolidation.

G) The effect of revibration on bleeding has also been considered a factor in the increased strength produced. Due to revibration some of the water comes to the surface of the concrete (or paste or mortar) resulting in a reduced water-cement ratio in the mass and thus causing an increase in strength.

CHAPTER V

EXPERIMENTAL PROGRAMME

The detailed literature study (summarized in Chapters III and IV) has revealed that, so far, no studies have been reported on the effect of revibration on the strength of plain cement pastes. This, therefore, seemed to be an interesting area to investigate, especially since some of the theories proposed in explanation of the strength increases produced by revibration would seem to depend on the presence of aggregate materials in the mix.

Also it has been noted that no work has been reported on the effect of intermittent vibration. If one period of revibration can produce increased strengths, it seems logical to investigate if repeating this a number of times on the same specimen could result in increased strength benefits.

The primary purpose of this experimental programme, therefore was to evaluate the effectiveness of revibration and intermittent vibration in increasing the compressive and flexural strength of cement pastes at various water-cement ratios and test ages.

A) WATER-CEMENT RATIOS

Mixes of four different water cement ratios were included in the programme, i.e. 0.30, 0.35, 0.40 and 0.45, by weight.

B) TEST AGES

Specimens (both compression and flexural) were provided for testing at the ages of 7, 28 and 90 days.

C) CEMENT

Type I Portland cement (Lake Ontario). Some physical properties and chemical analysis are presented in Appendix B.

D) TEST SPECIMENS

Compression test specimens were 2 inch cubes and the flexural test specimens were prisms, 1 inch x 1 inch x 5 inch. All moulds used were machined and constructed as per ASTM method C 234-62.

CHAPTER VI

EXPERIMENTAL PROCEDURES

The procedures involved in mixing, casting, compaction, curing and testing of specimens are presented in the following paragraphs:

A) MIXING

Mixing was carried out in a Blakeslee mixer having a capacity 2/3 cuft and three adjustable speeds of 102, 180 and 354 RPM. The mixing procedure was as follows. First the mixing water was put into the bowl; then the cement was added and the mixture was left for 30 seconds to allow time for absorption of water by cement particles. Mixing was then started at the low speed and after 30 seconds the mixer was stopped for 15 seconds, while any paste on the sides of the bowl was scrapped down into the bowl. Then the mixer was started again at the medium speed and mixing was continued for 1 minute. This procedure was carefully followed for all the batches.

B) PLACING AND COMPACTION OF PASTE IN MOULDS

The inside surfaces of all moulds were lubricated with a thin oil, the joints between the side walls and the bottoms were sealed with a thick paste of cement and grease and the moulds were then clamped to the vibrating table (VIBCO table vibrator, Model U.S. 450, 9000 VPM with vertical circular vibration).

After the paste was placed in the moulds the vibration schedule for the different specimens was a follows:

1) The standard specimens were vibrated for 5 minutes just after being filled with paste.

2) The revibrated specimens were vibrated for 5 minutes just after casting and for 5 minutes after 2 hours and 40 minutes.

3) The intermittently vibrated specimens were vibrated for 5 minutes just after casting and were subjected to five subsequent periods of vibration (10 minutes each) at intervals of one half hour.

In order to eliminate sources of error as far as possible, specimens were provided for each of the three test conditions and each of the three test ages from any one batch; also the two batches prepared on any one day were always of different water-cement ratios.

C) CURING

After completion of vibration the specimens were covered with wet burlap for 24 hours and then taken out of the moulds, labelled and placed under water (temperature ranged $70^{o}F$ to $72^{o}F$) for the required curing period.

D) TESTING OF SPECIMENS

After removal of the specimens from the curing tank, compressive specimens were allowed to dry out for 45 minutes before being tested, but the flexural specimens were kept moist till tested. Compression specimens were tested in a hydraulic compression testing machine (RIEHLE by A.M. & Metal Inc., capacity 300,000 lbs). The flexural specimens were tested at a span of 5" under centre loading in a hydraulic compression testing maçhine (Upton Bradeen and Dames Ltd., capacity 60,000 lbs). Before testing, the actual cross sectional dimensions of the specimens were measured. The following equations were used for calculation purposes:

1) Compressive Strength = P/ab

   where P is load (lbs) on specimen at failure.

   a & b are cross sectional dimensions at mid-section.

2) Flexural Strength = 7.5 P/bd^2, where

   b and d are the width and depth of specimen in inches at mid-section.

CHAPTER VII

TEST RESULTS

The experimental results are presented in tables 1 to 8 and figures 1 to 14. The tables include the mean strengths, the percentage increase in strengths of revibrated and intermittently vibrated specimens over the specimens vibrated once only (standard specimens), the standard deviation of each set, the coefficient of variation and an indication of the significance of the differences in strength. Each individual result in these tables represents the average of a set of 10 specimens for the 7-day and 28-day flexural tests and the average of a set of 7 specimens for the 90-day flexural tests. The 7 and 28 day compressive values are the average of 8 test specimens and the 90 day values represent the average of 6 test specimens. The statistical significance was calculated for different sets by application of the "t" test to two corresponding sets (i.e. standard and revibrated and standard and intermittently vibrated).

A) COMPRESSIVE STRENGTH

Revibration was found to produce fairly high increases (9.2 to 16 percent) in the 7-day compressive strengths. The maximum increase (16 percent) was produced at the 0.30 water cement ratio and the minimum increase (9.2 percent) at the 0.45 water cement ratio (fig. 1 to 3). The increases in the strength due to intermittent vibration were more than those produced by revibration, and ranged from 13.2 to 21.2 percent at the water cement ratios of 0.45 and 0.30 respectively.

The increases in strength at 28 days were less than for 7 days, ranging from 4.2 to 12.7 percent at the 0.45 and 0.35 water cement ratios respectively for the vibrated mixes, and from 9.1 to 14.2 percent at the 0.40 and 0.35 water cement ratios respectively for the intermittently vibrated mixes.

The increases in strength at 90 days were considerably less than those for the 7 and 28 day ages ranging from 1.1 to 2.8 percent at the 0.35 and 0.3 water cement ratios respectively for the revibrated mixes and ranging from 7 to 17 percent at the 0.40 and 0.45 water cement ratios respectively for the intermittently vibrated mixes.

In other words, the revibrated (and intermittently vibrated) specimens developed strength at a faster rate. As the percentage increase in strength at 90 days was considerably less than at the earlier ages it is possible that the strength benefit at ages of one year and beyond may not be significant.

With regard to the effect of intermittent vibration, it can be seen that in all cases (see figure 1 to 6) the average strengths produced were slightly higher than for specimens which were revibrated once only. However, in almost all cases the strength differences were not statistically significant.

B) FLEXURAL STRENGTH

Increases in flexural strength after 7 days due to revibration were found to range from 3 to 4.2 percent. The maximum increase (4.2%) was produced at the 0.35 and 0.45 water cement ratios, and the minimum increase (3%) at the 0.40 water cement ratio (figure 3 to 6). The increase in flexural strength due to intermittent vibration were more than those produced by one period of revibration and ranged from 5.9 to 7.5 percent at the water cement ratio of 0.40 and 0.30 respectively.

The increases in strength at 28 days were found to be slightly higher than at 7 days and ranged from 4 to 5.4 percent at 0.35 and 0.30 respectively for the revibrated mixes and from 5.7 to 7.8 percent at the 0.45 and 0.40 water cement ratios respectively for the intermittently vibrated mixes.

The increases in strength at 90 days were less than those for 28 days, ranging from 2.8 to 3.1 percent at the 0.45 and 0.30 water cement ratios respectively for the revibrated mixes and ranging from 3.3 to 5 percent at the 0.40 and 0.45 water cement ratios respectively for the intermittently vibrated mixes.

It should be pointed out that at the 7 and 28 day ages most of the indicated strength differences between the standard specimens and the revibrated (or intermittently vibrated) specimens were found to be statistically significant at the 5 percent level of significance. However, at the 90 day age none of the strength differences were found to be statistically significant.

Also, it should be noted that although the intermittently vibrated specimens always produced slightly higher average strengths than the specimens subjected to only one period of revibration, in no case were these differences statistically significant.

CHAPTER VIII

DISCUSSION AND CONCLUSIONS

This experimental programme was designed to explore the relative effectiveness of revibration and intermittent vibration on the compressive and flexural strengths of cement pastes. On the basis of results obtained the following points can be made.

1) One period of revibration and intermittent vibration were both found to be effective in increasing the compressive and flexural strengths of cement pastes, significantly.

2) In general, the strength increases due to revibration appear to be greater in mortars and concretes than in cement pastes. The possible reason for this may be the pressence of aggregate, causing more air and water pockets beneath the particles, thus helping revibration in showing its effectiveness over such mixes.

3) Both one period of revibration and intermittent vibration were found to produce greater strength increases at early ages than at later ages due to a reduced rate of gain of strength of normal concretes at later ages. This would suggest that revibration, primarily increases the rate of strength development. The test data is not available but due to the decreasing trend of the strength increases at later ages it appears that there may not be

any strength increase at the age of one year and after; however, the other beneficial side effects of revibration (increased unit weight, water tightness and better finished surface, etc.) will remain.

4) In general, the compressive strength increases due to revibration at different ages are more than the increases in flexural strengths, probably because the depth of the flexural specimens was relatively small in comparison to that of the compression specimens, thus preventing the full utilization of the potential benefits from revibration.

5) There were not significant differences in the flexural strength increases produced by revibration and intermittent vibration at the 28-day and 90-day ages, which shows that the effect of revibration on flexural strengths is manifested primarily at ages up to 28 days.

6) Intermittent vibration was found to be slightly more effective (in all mixes and at all ages) than one period of revibration, in increasing both the compressive and flexural strengths of cement pastes. However, in no cases were the strength differences produced by these found to be significantly different (statistically), so it would appear in general that one period of revibration will produce close to the full strength benefits to be expected.

7) The test results on cement pastes show that both revibration and intermittent vibration increase both the compressive and flexural strengths; it would appear therefore that the theory that revibration increases strength by relieving the shrinkage stresses surrounding the aggregate particles is not valid.

8) It appears that the theory that revibration causes the mortars and concrete to become more densely consolidated by expelling the noticeable amounts of air and water is valid (which can be visualized physically also) as this reduces the void cement ratio resulting an increase in strength. This mechanism must therefore account for at least part of the strength increases.

9) The theory that revibration breaks the calcium hydrauxide crystals thus producing closer contact by revibration appears to have some validity, as these disturbances should also result in breaking the gel, thus allowing the free water to reach the unhydrated part of cement particles more readily, thereby resulting in further hydration, and probably more rapid hydration.

10) As tests on sealed specimens have well established (27) the fact that during hydration the saturated cement gel has more volume (about 2.2 times the original cement volume) and the expansion occurs after the hardening has commenced, if a supply of water is maintained to continue hydration. So revibration should facilitate this expansion and dispersion of the cement paste resulting in increases in the strength. This theory also appears

reasonable.

11) The effect of revibration on concrete properties needs further investigation on a wide range of cement compositions, mix proportions, of a wider range of workabilities and methods and periods of vibration. The mechanism of revibration as per the theory proposed by Sawyer and Lee (Chapter IV) that revibration replaces the weaker structure of C_3A (which hydrates first being most unstable in all the four main compounds of cement) which allow the normal structure of C_3S (strengthening hydrate) to develope, needs further investigation. The effect of revibration should be studied on concretes made of different cement compositions, e.g. one containing a relatively higher amount of C_3A than the other in order to prove the validity of this theory.

12) The effect of revibration on strengths after the 90-day age of concrete also is not really known. This aspect needs further study for both compressive and flexural strength.

13) The technique of revibration may be suggested for use in the manufacture of small precast units, where a large number of units can be vibrated at a time; but it cannot be recommended for the construction of massive structures, as it adds an extra step in concrete construction and also uniformity of revibration may not be achieved.

TABLES

STATISTICAL ANALYSIS

TABLE 1

COMPRESSION TEST

TEST AGE	CONDITION OF VIBRATION	WATER CEMENT RATIO	MEAN COMPRESS. STRENGTH PSI	% INCREASE OVER STANDARD	STANDARD DEVIATION	COFF. OF VARIATION	STATISTICAL SIGNIFICANCE
7 DAYS	STANDARD	0.45	5755.0	0	607	10	0
	REVIBRATED	"	6282	9.2	752	11.9	SIGNIF.
	INTERMITTENTLY VIBRATED	"	6536	13.2	609	9.3	SIGNIF.
28 DAYS	STANDARD	"	7761.0	0	544	7.0	0
	REVIBRATED	"	8094	4.2	592	7.3	SIGNIF.
	INTERMITTENTLY VIBRATED	"	8704	12.1	603	6.9	SIGNIF.
90 DAYS	STANDARD	"	8990	0	875	9.7	0
	REVIBRATED	"	9209	2.5	623	6.8	NOT SIGNIF.
	INTERMITTENTLY VIBRATED	"	10508	17.0	452	4.3	SIGNIF.

Level of Significance = 5%

STATISTICAL ANALYSIS

TABLE 2

COMPRESSION TEST

TEST AGE	CONDITION OF VIBRATION	WATER CEMENT RATIO	MEAN COMPRESS. STRENGTH PSI	% INCREASE OVER STANDARD	STANDARD DEVIATION	COFF. OF VARIATION	STATISTICAL SIGNIFICANCE
7 DAYS	STANDARD	0.40	7808	0	638	8.1	0
	REVIBRATED	"	8661	10.8	728	8.4	SIGNIF.
	INTERMITTENTLY VIBRATED	"	9034	15.6	1338	14.8	SIGNIF.
28 DAYS	STANDARD	"	9264	0	840	9.00	0
	REVIBRATED	"	9821	6	670	6.8	SIGNIF.
	INTERMITTENTLY VIBRATED	"	10132	9.1	812	8.	SIGNIF.
90 DAYS	STANDARD	"	11891	0	1309	11.0	0
	REVIBRATED	"	12093	1.2	1006	8.3	NOT SIGNIF.
	INTERMITTENTLY VIBRATED	"	12715	7.0	1234	9.8	SIGNIF.

Level of Significance = 5%

TABLE 3

STATISTICAL ANALYSIS

COMPRESSION TEST

TEST AGE	CONDITION OF VIBRATION	WATER CEMENT RATIO	MEAN COMPRESS. STRENGTH PSI	% INCREASE OVER STANDARD	STANDARD DEVIATION	COFF. OF VARIATION	STATISTICAL SIGNIFICANCE
7 DAYS	STANDARD	0.35	8776	0	690	7.8	0
	REVIBRATED	"	9958	13.7	1338	13.4	SIGNIF.
	INTERMITTENTLY VIBRATED	"	10101	15.3	1153	11.4	SIGNIF.
28 DAYS	STANDARD	"	9941	0	1379	13.8	0
	REVIBRATED	"	11217	12.7	1248	11.1	SIGNIF.
	INTERMITTENTLY VIBRATED	"	11435	14.5	1074	9.3	SIGNIF.
90 DAYS	STANDARD	"	13133	0	514	4.0	0
	REVIBRATED	"	13291	1.1	816	6.1	NOT SIGNIF.
	INTERMITTENTLY VIBRATED	"	14694	11.6	1565	10.7	NOT SIGNIF.

Level of Significance = 5%

TABLE 4

STATISTICAL ANALYSIS

COMPRESSION TEST

TEST AGE	CONDITION OF VIBRATION	WATER CEMENT RATIO	MEAN COMPRESS. STRENGTH PSI	% INCREASE OVER STANDARD	STANDARD DEVIATION	COFF. OF VARIATION	STATISTICAL SIGNIFICANCE
7 DAYS	STANDARD	0.30	9000	0	622	6.9	0
	REVIBRATED	"	10461	16	731	6.9	SIGNIF.
	INTERMITTENTLY VIBRATED	"	10921	21.2	1046	9.5	SIGNIF.
28 DAYS	STANDARD	"	10613	0	687	6.4	0
	REVIBRATED	"	11309	6.5	745	6.5	SIGNIF.
	INTERMITTENTLY VIBRATED	"	12127	14.2	936	7.7	SIGNIF.
90 DAYS	STANDARD	"	13614	0	1017	7.5	0
	REVIBRATED	"	14041	2.8	1242	8.8	NOT SIGNIF.
	INTERMITTENTLY VIBRATED	"	15171	11.2	3201	21.1	NOT SIGNIF.

Level of Significance = 5%

STATISTICAL ANALYSIS

TABLE 5

FLEXURAL TEST

TEST AGE	CONDITION OF VIBRATION	WATER CEMENT RATIO	MEAN FLEXURAL STRENGTH PSI	% INCREASE OVER STANDARD	STANDARD DEVIATION	COFF. OF VARIATION	STATIST. SIGNIF.
7 DAYS	STANDARD	0.45	1111	0	72	6.4	0
	REVIBRATED	"	1159	4.2	59	5.0	SIGNIF.
	INTMT. VBRT.	"	1180	7	52	4.3	SIGNIF.
28 DAYS	STANDARD	"	1165	0	82	7	0
	REVIBRATED	"	1221	4.8	66	5.4	SIGNIF.
	INTMT. VBRT.	"	1232	5.7	79	6.3	SIGNIF.
90 DAYS	STANDARD	"	1182	0	67	5.6	0
	REVIBRATED	"	1216	2.8	51	4.2	NOT SIGNIF.
	INTMT. VBRT.	"	1241	5.0	31	2.5	NOT SIGNIF.

Level of Significance = 5%

STATISTICAL ANALYSIS

TABLE 6

FLEXURAL TEST

TEST AGE	CONDITION OF VARIATION	WATER CEMENT RATIO	MEAN FLEXURAL STRENGTH PSI	% INCREASE OVER STANDARD	STANDARD DEVIATION	COFF. OF VARIATION	STATISTICAL SIGNIFICANCE
7 DAYS	STANDARD	0.40	1143	0	79	6.9	0
	REVIBRATED	"	1178	3.0	60	5.1	NOT SIGNIF.
	INTERMITTENTLY VIBRATED	"	1214	5.9	81	6.6	SIGNIF.
28 DAYS	STANDARD	"	1181	0	93	7.8	0
	REVIBRATED	"	1243	5.2	69	5.5	NOT SIGNIF.
	INTERMITTENTLY VIBRATED	"	1277	7.8	58	4.5	SIGNIF.
90 DAYS	STANDARD	"	1231	0	150	12.2	0
	REVIBRATED	"	1270	3.0	51	4.0	NOT SIGNIF.
	INTERMITTENTLY VIBRATED	"	1273	3.3	71	5.6	NOT SIGNIF.

Level of Significance = 5%

STATISTICAL ANALYSIS

TABLE 7

FLEXURAL TEST

TEST AGE	CONDITION OF VARIATION	WATER CEMENT RATIO	MEAN FLEXURAL STRENGTH PSI	% INCREASE OVER STANDARD	STANDARD DEVIATION	COFF. OF VARIATION	STATISTICAL SIGNIFICANCE
7 DAYS	STANDARD	0.35	1159	0	94	8.1	0
	REVIBRATED	"	1211	4.2	82	6.7	NOT SIGNIF.
	INTERMITTENTLY VIBRATED	"	1245	7.2	90	7.2	SIGNIF.
28 DAYS	STANDARD	"	1211	0	75	6.2	0
	REVIBRATED	"	1271	4 .	67	5.2	SIGNIF.
	INTERMITTENTLY VIBRATED	"	1295	7.1	70	5.3	SIGNIF.
90 DAYS	STANDARD	"	1243	0	69	5.6	0
	REVIBRATED	"	1280	3.0	69	5.4	NOT SIGNIF.
	INTERMITTENTLY VIBRATED	"	1288	3.6	59	4.7	NOT SIGNIF.

Level of Significance = 5%

STATISTICAL ANALYSIS

TABLE 8

FLEXURAL TEST

TEST AGE	CONDITION OF VIBRATION	WATER CEMENT RATIO	MEAN FLEXURAL STRENGTH PSI	% INCREASE OVER STANDARD	STANDARD DEVIATION	COFF. OF VARIATION	STATISTICAL SIGNIFICANCE
7 DAYS	STANDARD	0.30	1203	0	67	6	0
	REVIBRATED	"	1249	4	79	6	SIGNIF.
	INTERMITTENTLY VIBRATED	"	1294	7.5	77	5.9	SIGNIF.
28 DAYS	STANDARD	"	1234	0	113	9.1	0
	REVIBRATED	"	1302	5.4	104	8	SIGNIF.
	INTERMITTENTLY REVIBRATED	"	1315	6.7	60	4.5	SIGNIF.
90 DAYS	STANDARD	"	1258	0	44	3.5	0
	REVIBRATED	"	1299	3.1	71	5.4	NOT SIGNIF.
	INTERMITTENTLY VIBRATED	"	1302	3.7	80	6.1	NOT SIGNIF.

Level of Significance = 5%

F I G U R E S

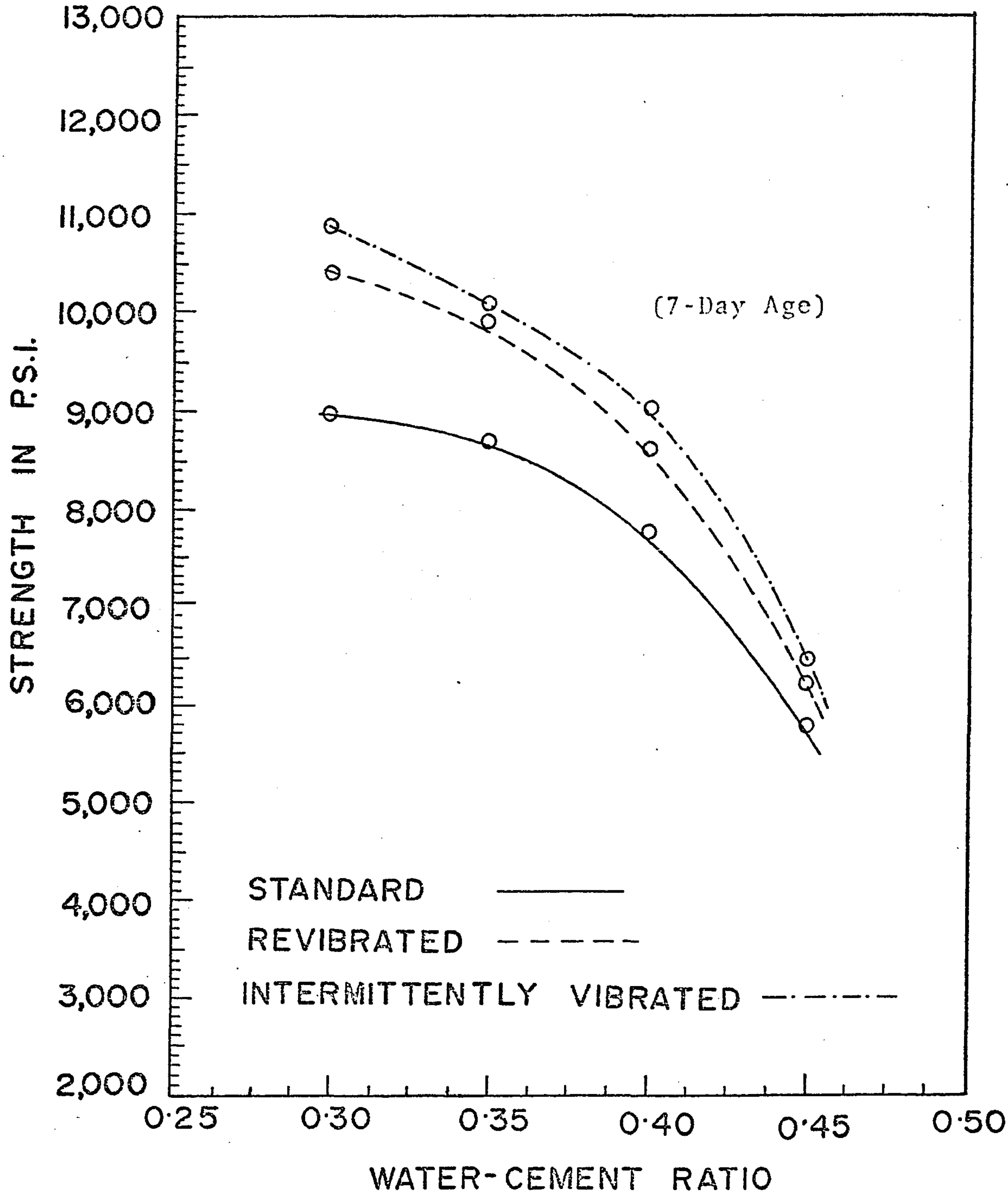


Fig. 1 The effect of revibarion and intermittent vibration on compressive strength of cement pastes (7 days).

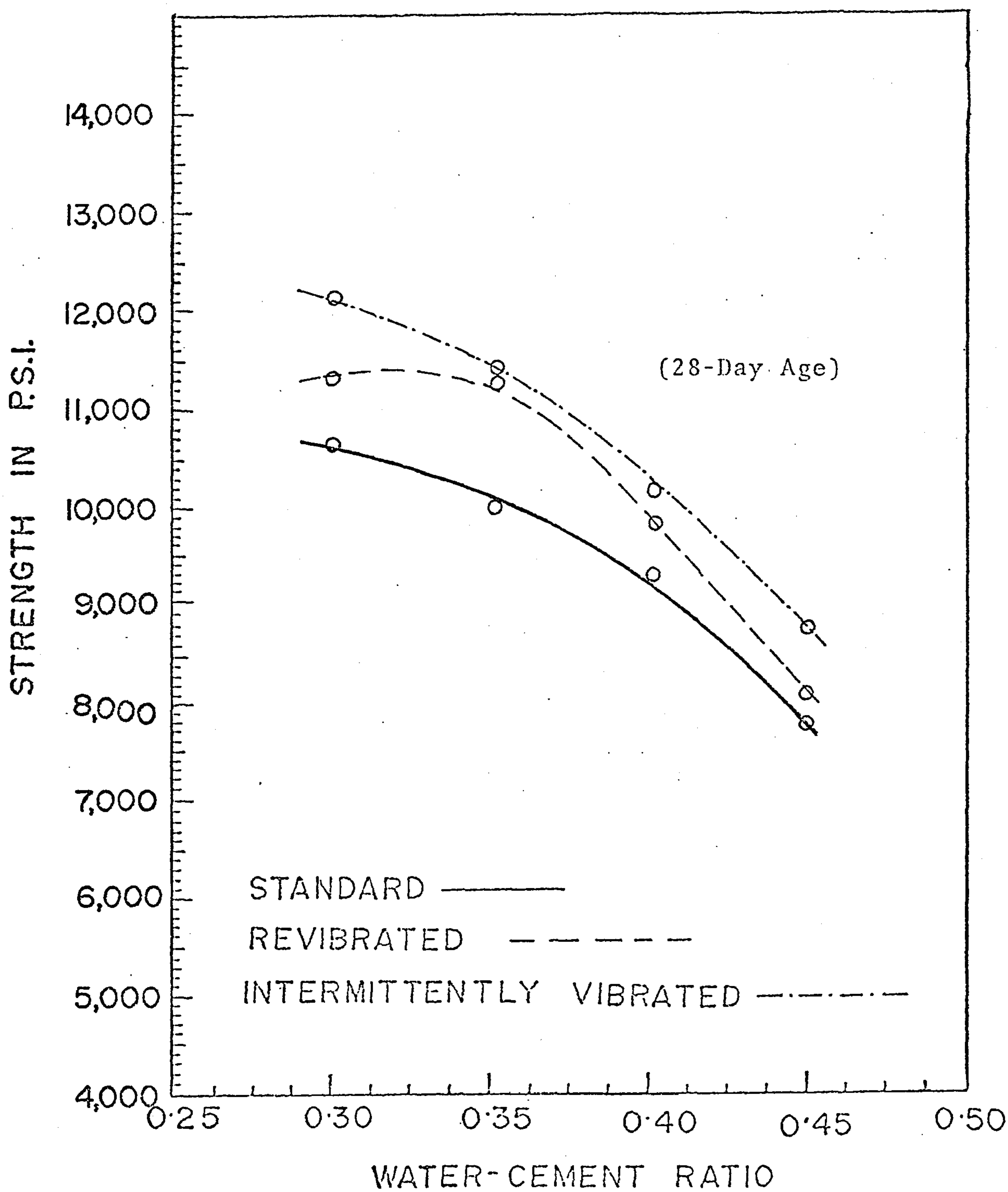


Fig. 2 The effect of revibration and intermittent vibration on compressive strength of cement pastes (28 days).

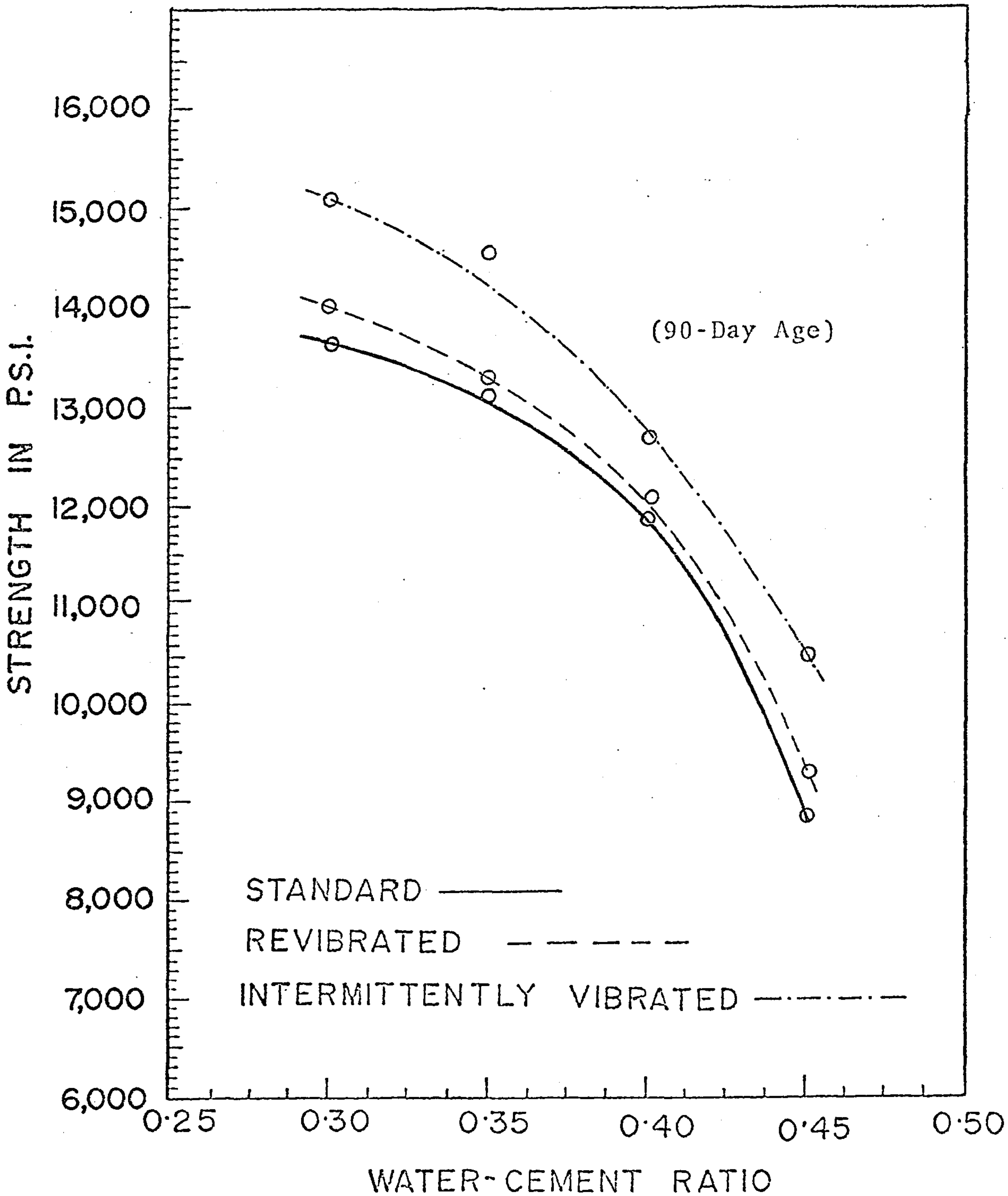


Fig. 3 The effect of revibration and intermittent vibration on compressive strength of cement pastes (90 days).

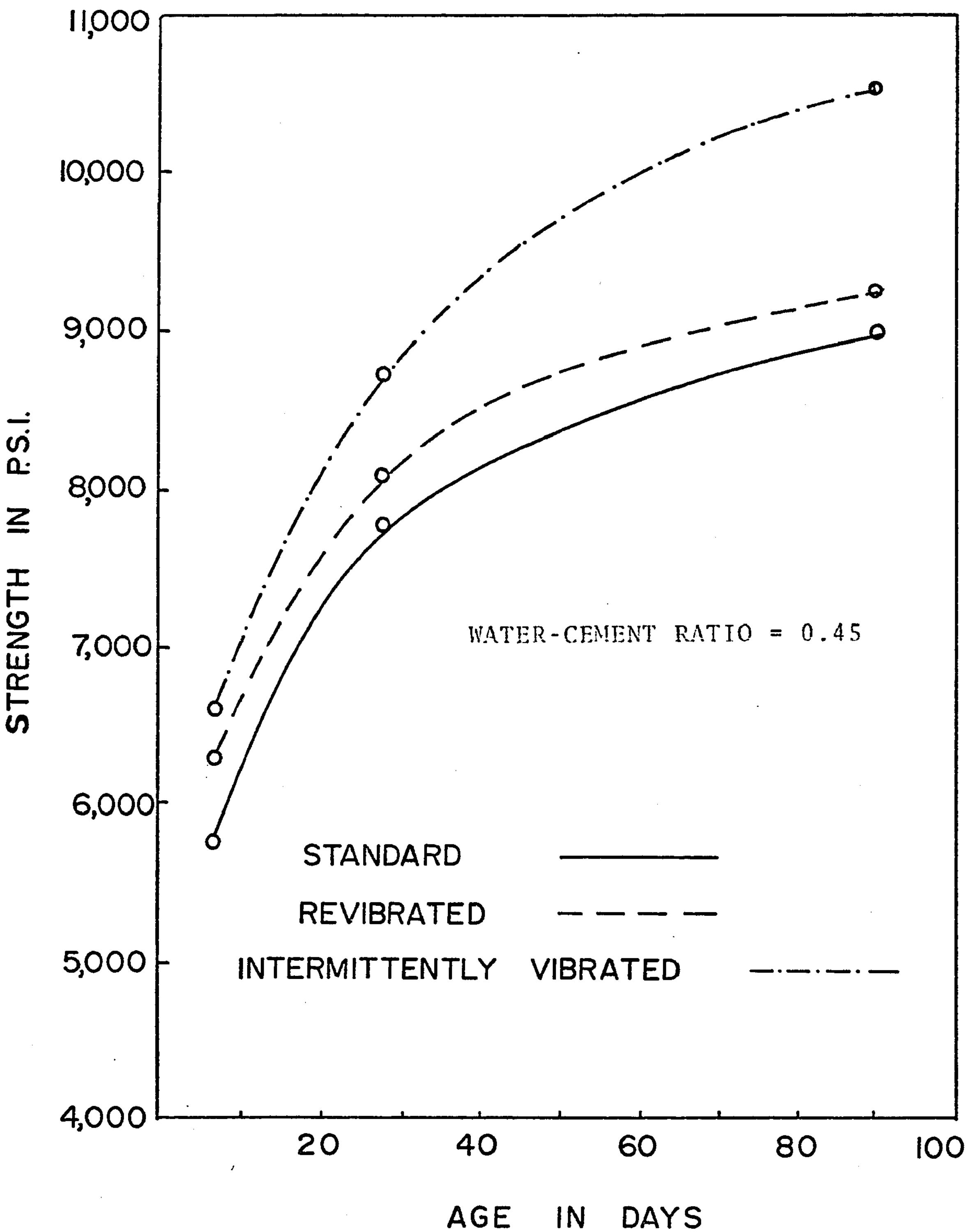


Fig. 4 The relation between age and strength (compressive) of cement paste.

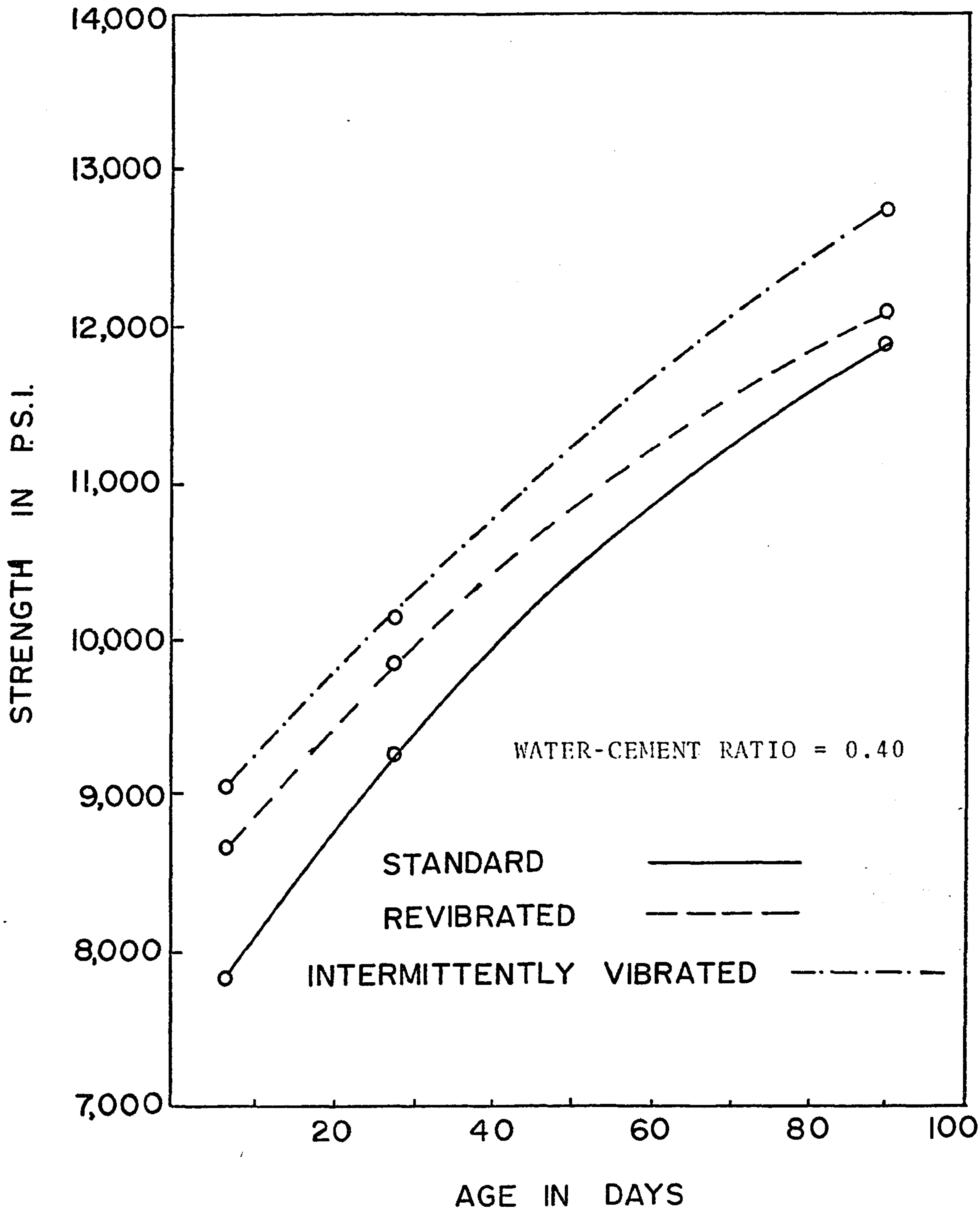


Fig. 5 The relation between age and strength (compressive) of cement paste.

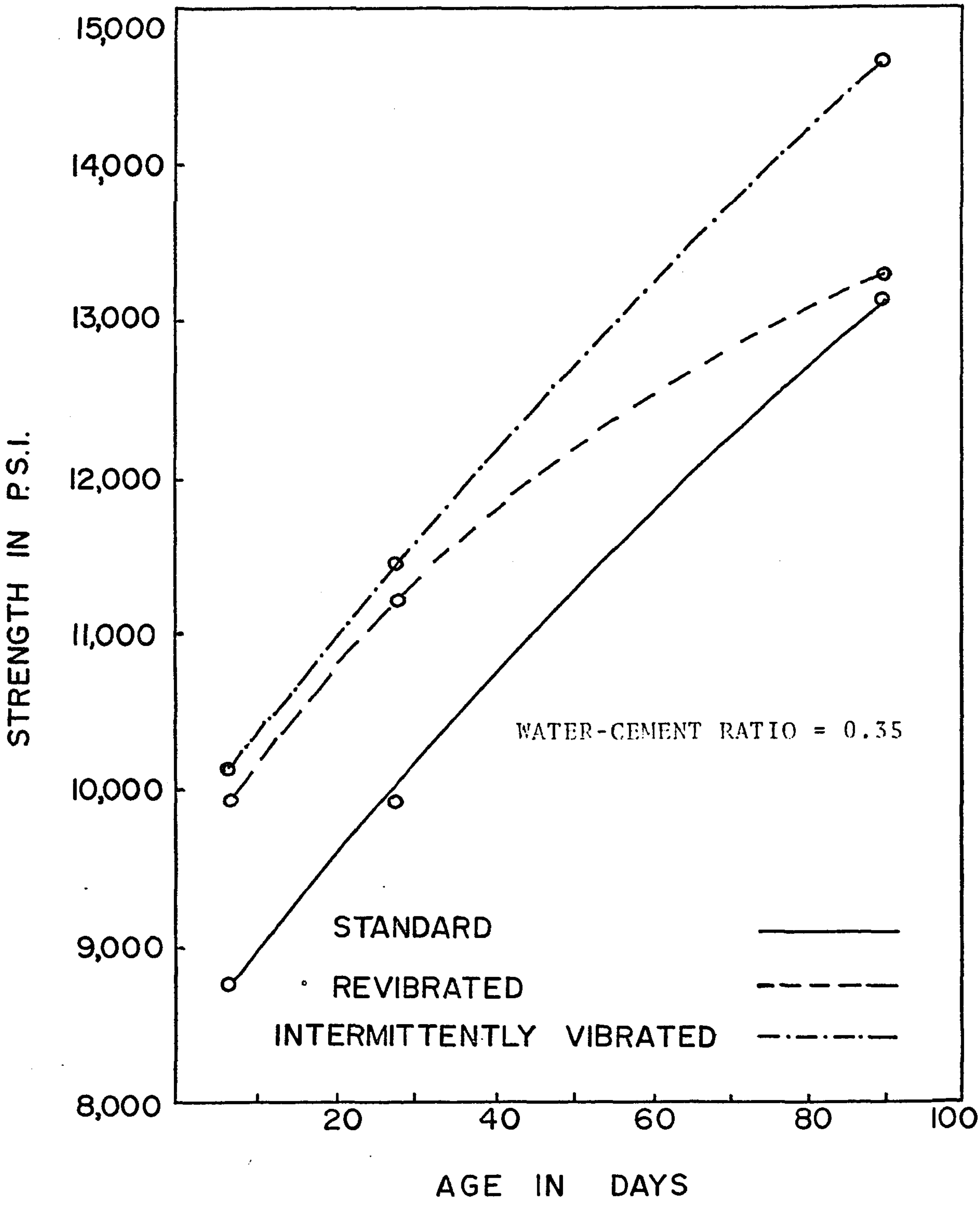


Fig. 6 The relation between age and strength (compressive) of cement paste.

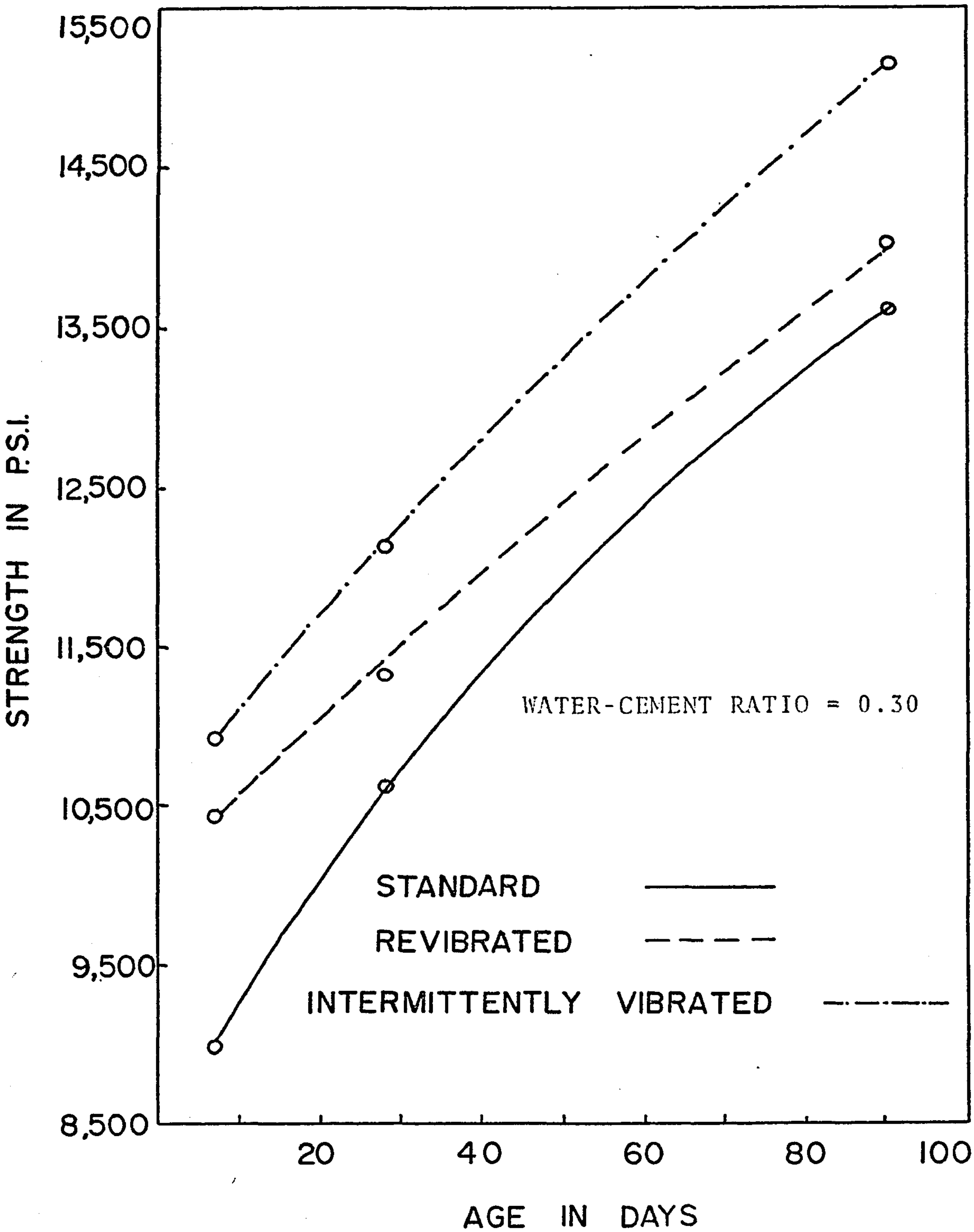


Fig. 7 The relation between age and strength (compressive) of cement paste.

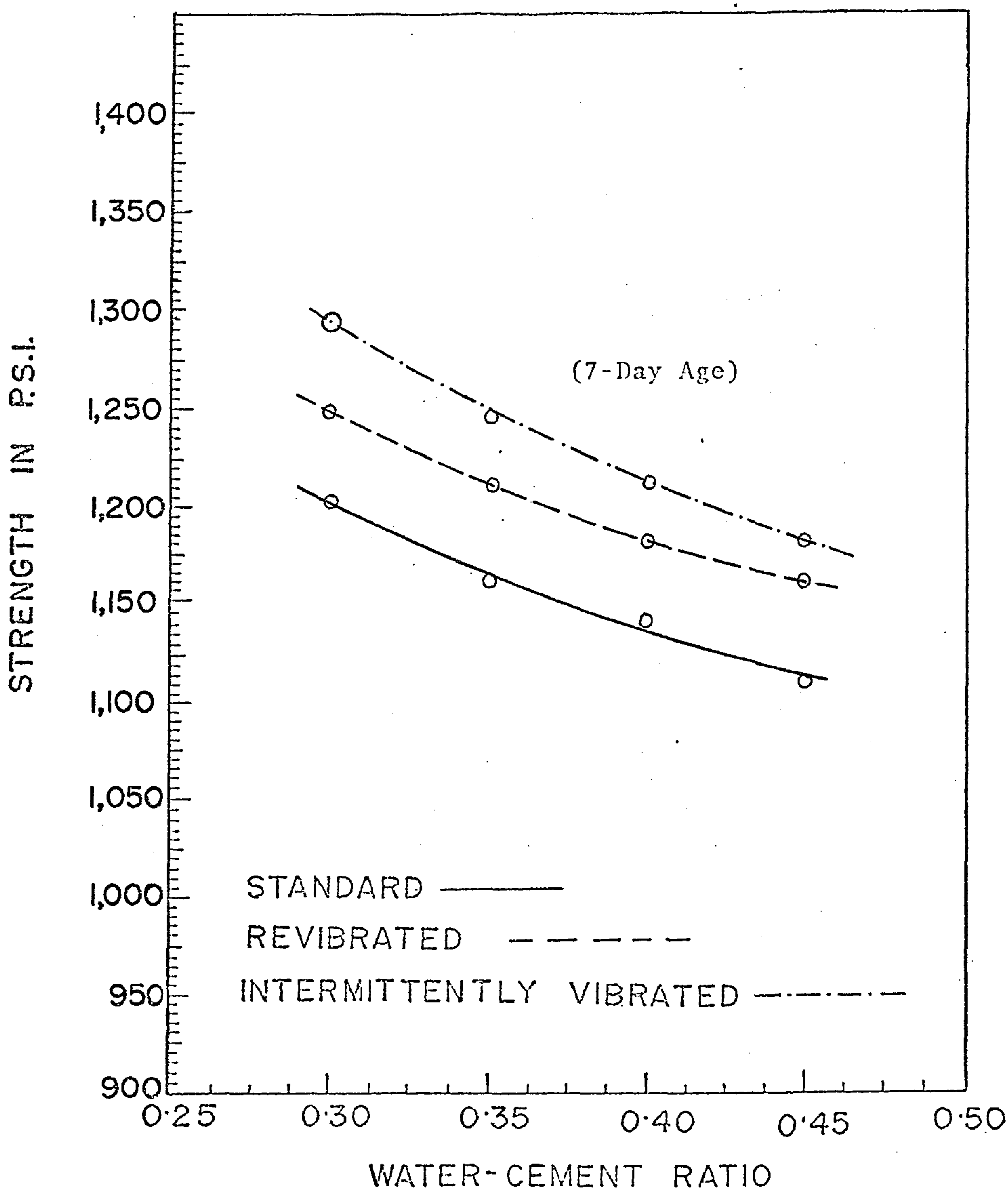


Fig. 8 The effect of revibration and intermittent vibration on flexural strength of cement pastes (7 days age).

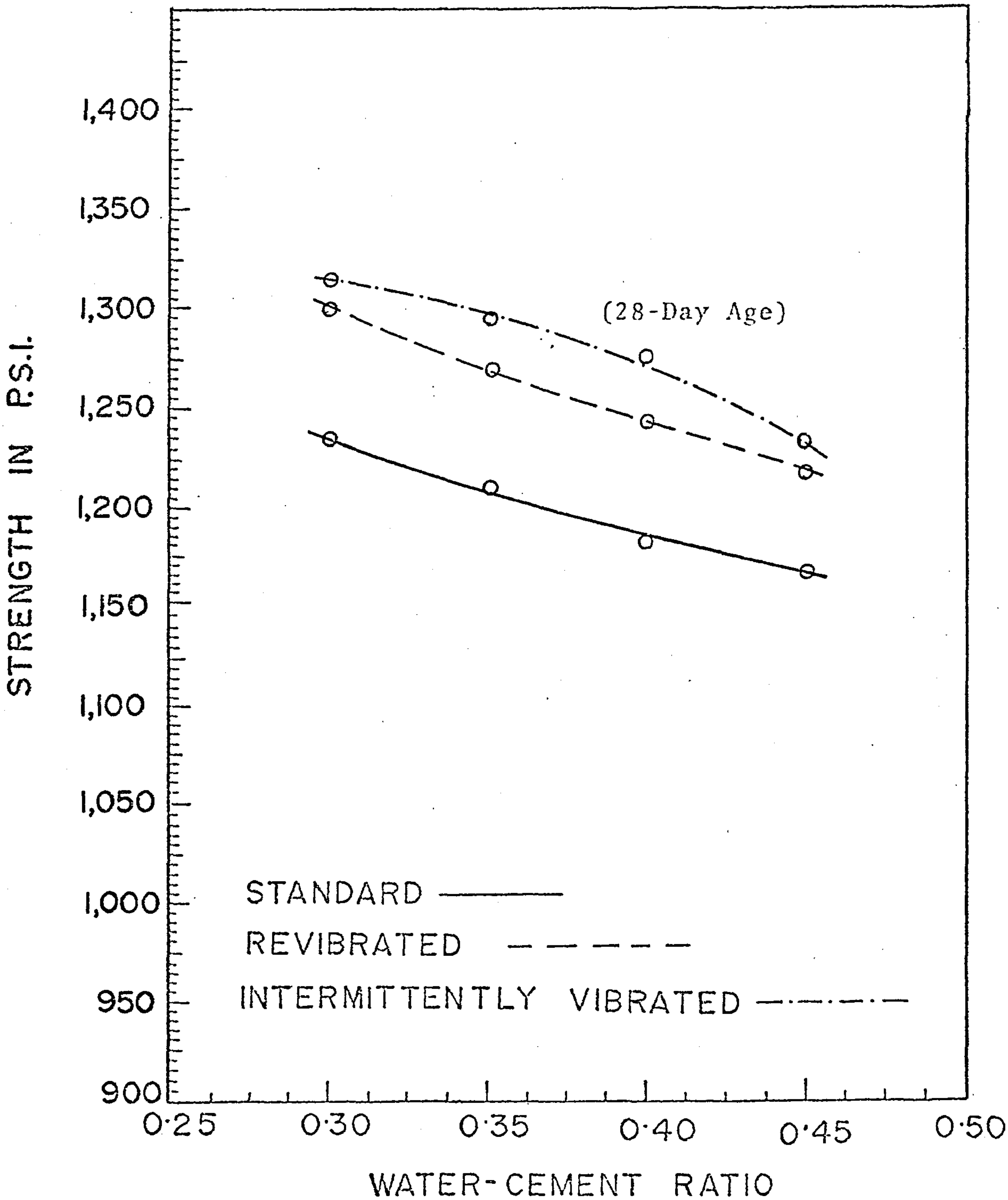


Fig. 9 The effect of revibration and intermittent vibration on flexural strength of cement pastes (28 days age).

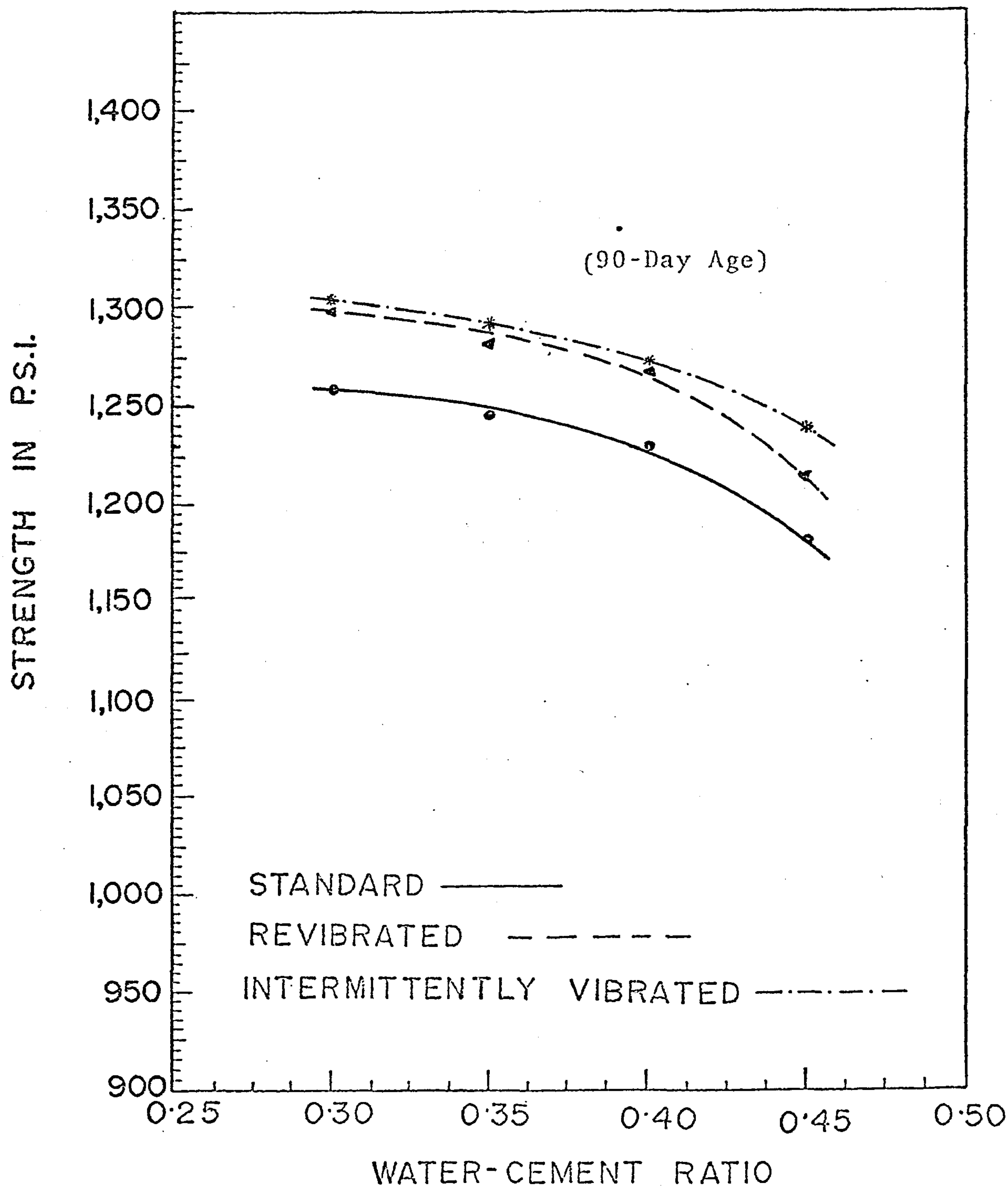


Fig. 10 The effect of revibration and intermittent vibration on flexural strength of cement pastes (90 day age).

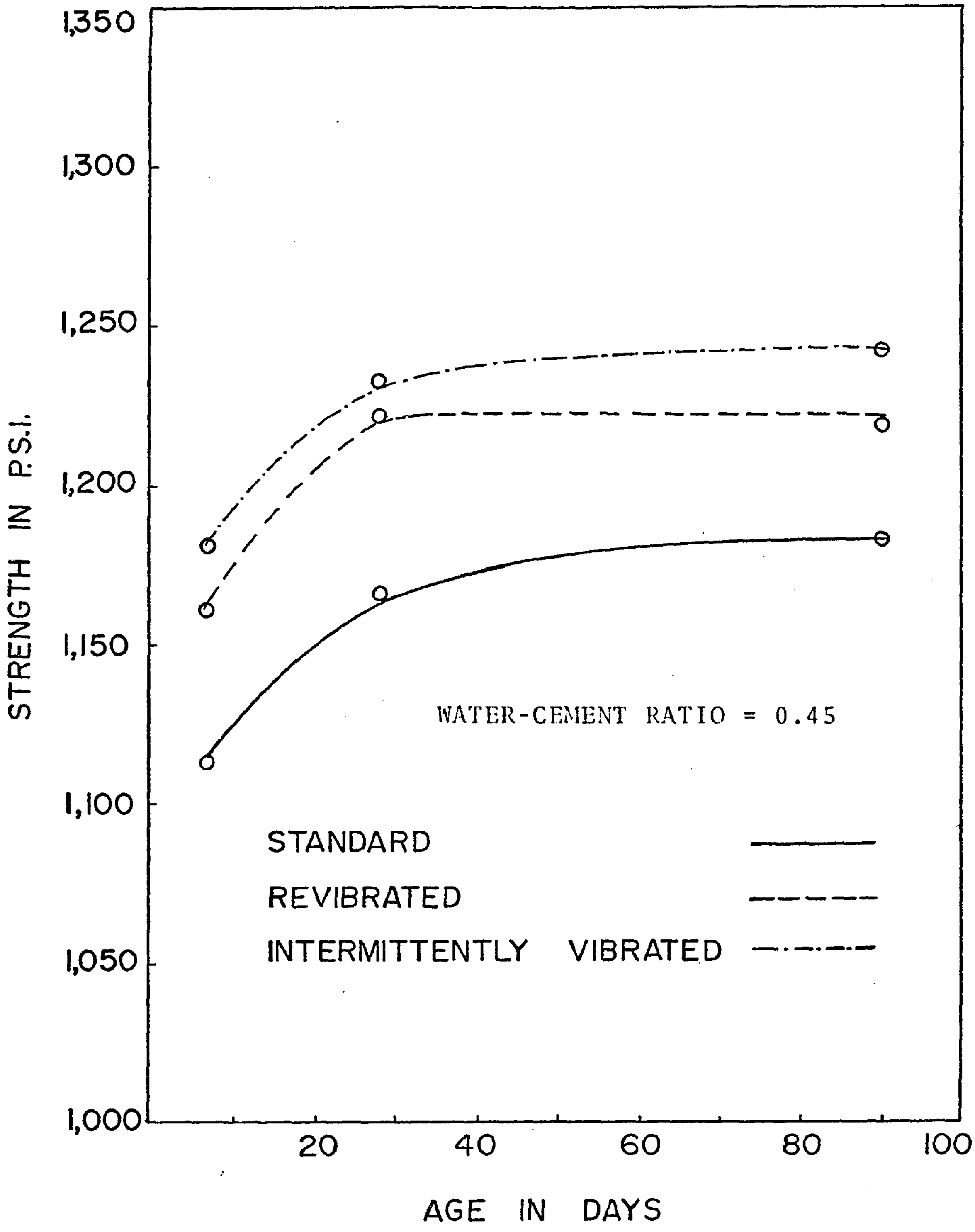


Fig. 11 The relation between age and strength (flexural) of cement paste.

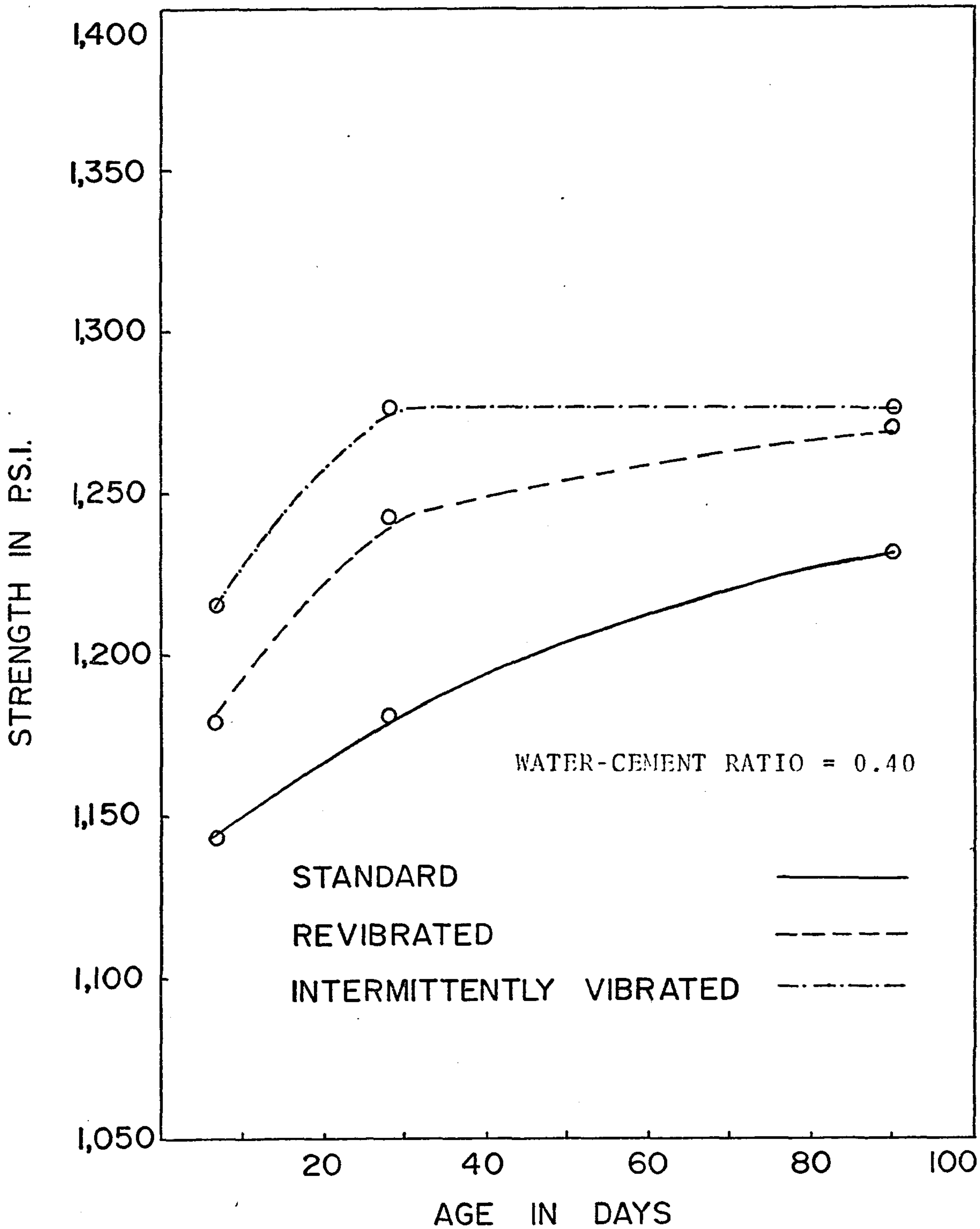


Fig. 12 The relation between age and strength (flexural) of cement paste.

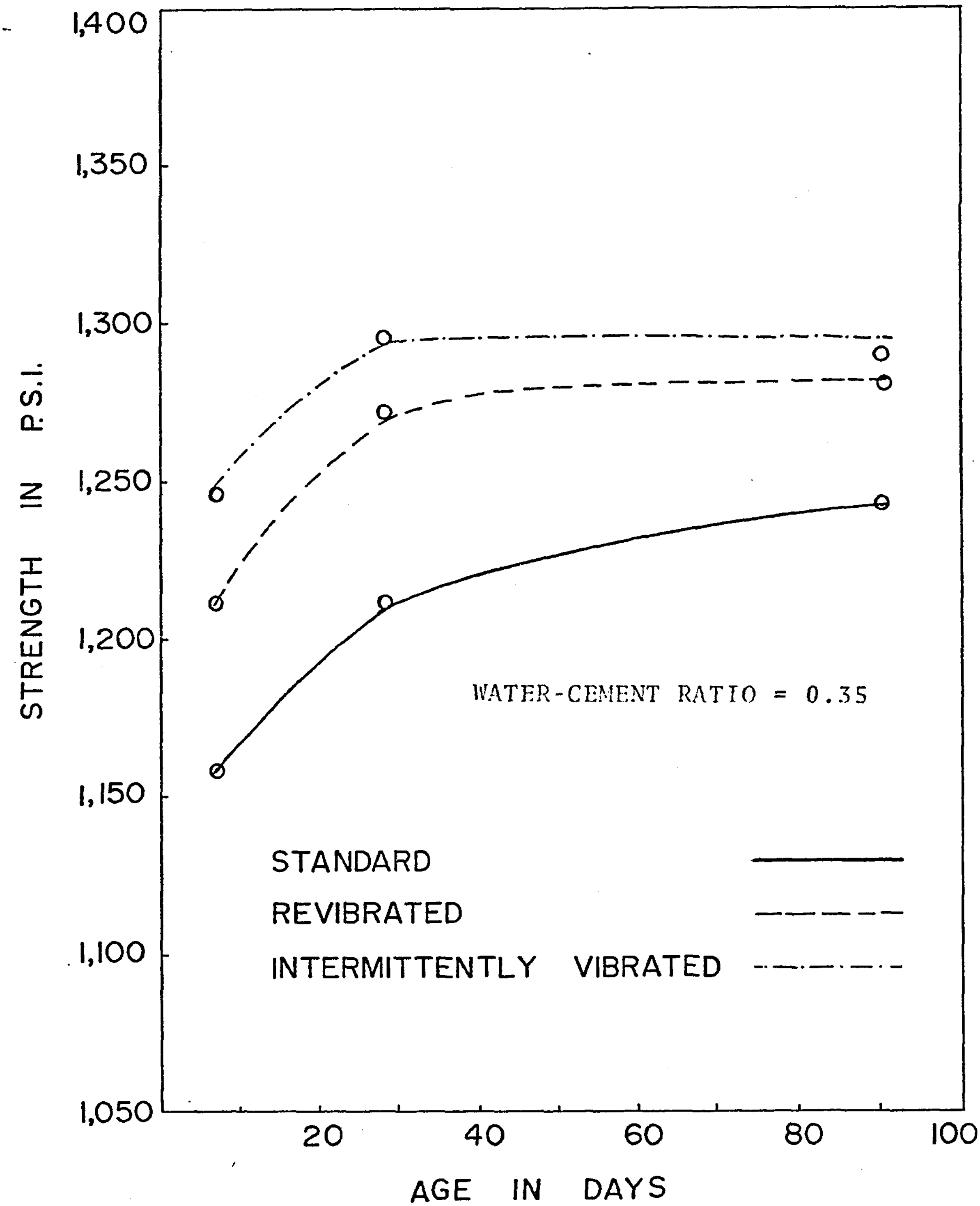


Fig. 13 The relation between age and strength (flexural) of cement paste.

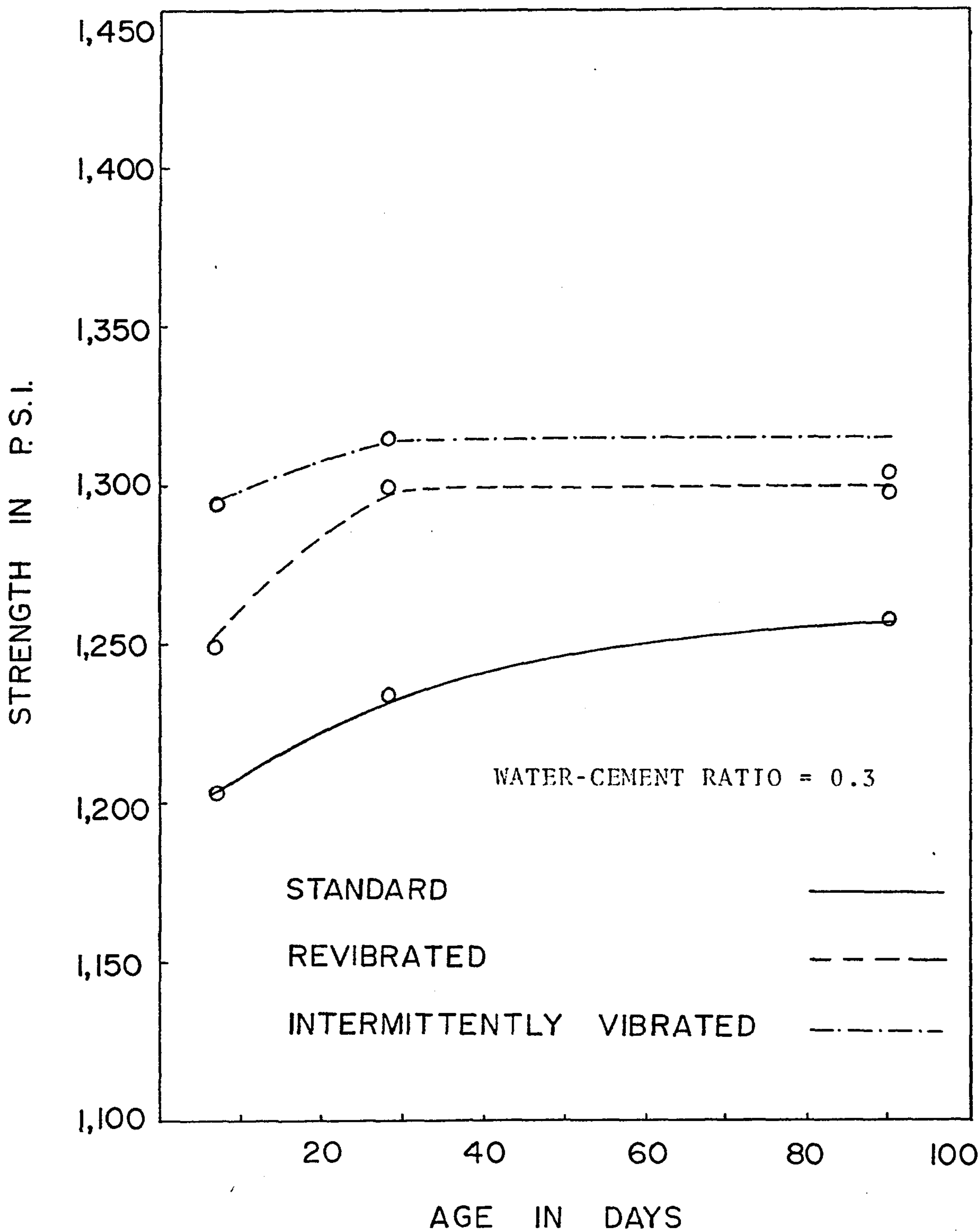
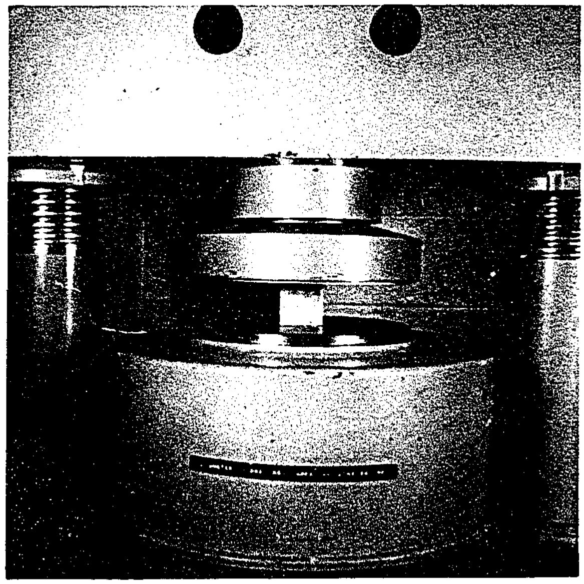


Fig. 14 The relation between age and strength (flexural) of cement paste.



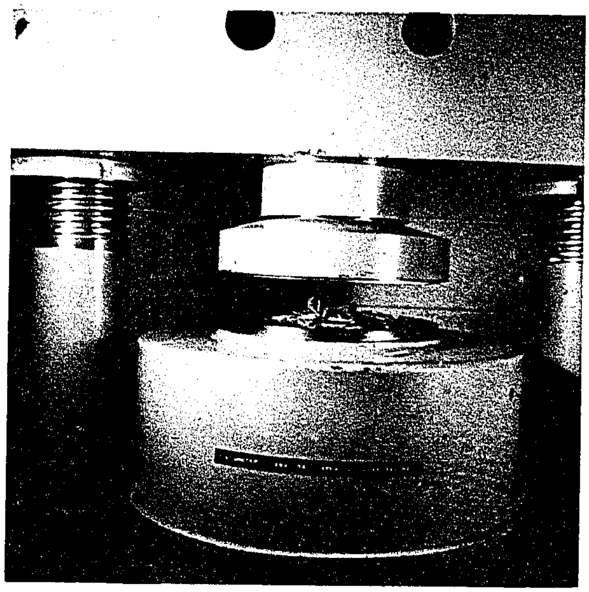
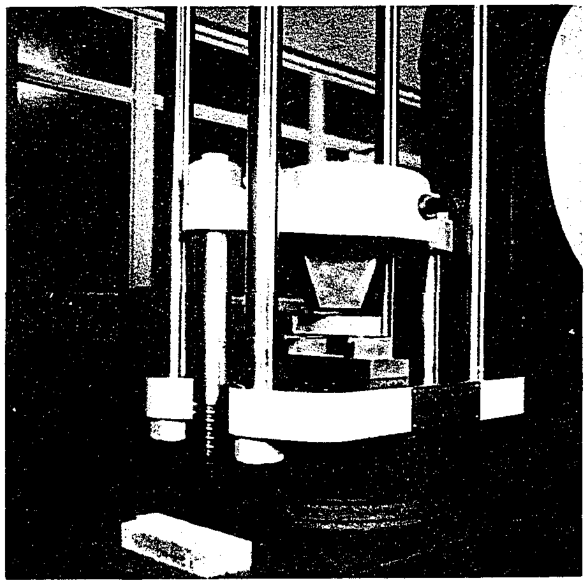


Fig. 15 The testing arrangement for compression specimens.



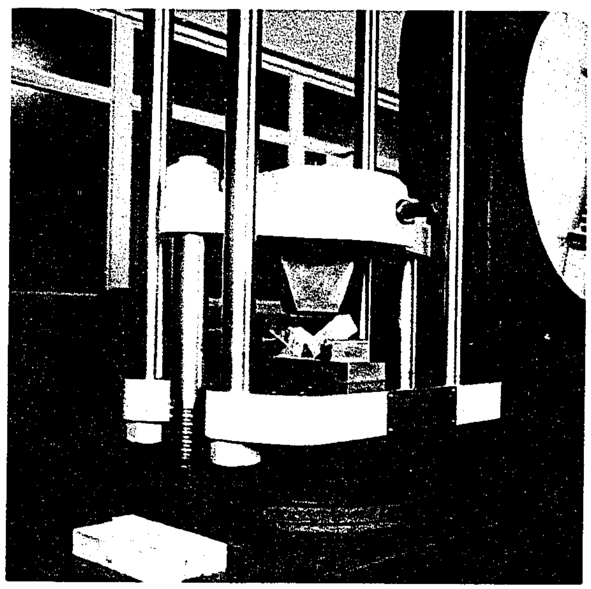


Fig. 16 The testing arrangement for flexural specimens.

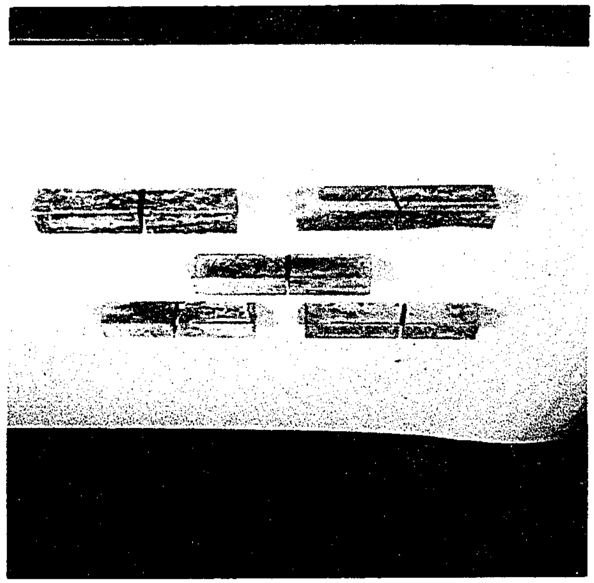


Fig. 17 The mode of breaking of flexural specimens.

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APPENDIX A

EXPERIMENTAL TEST DATA

Compressive Strength Test Data

WATER CEMENT RATIO	7 DAYS STRENGTH			28 DAYS STRENGTH			90 DAYS STRENGTH		
	STANDARD	RE VIBRATED	INTMT. VIBRATED	STANDARD	RE VIBRATED	INTMT. VIBRATED	STANDARD	RE VIBRATED	INTMT. VIBRATED
0.45	5502	6675	5510	7069	8172	9623	9358	8485	9725
"	4573	4651	6001	6781	6972	7839	9959	9335	10426
"	5926	5900	5955	7719	7707	9226	9784	8336	10301
"	6704	7325	7413	8150	8384	8389	8482	9261	10653
"	5871	6290	6702	7905	8250	8971	7367	9833	10735
"	6074	6471	6838	7961	8053	9118	8992	10004	11207
"	6163	6898	6731	7912	7996	7875			
"	5227	6044	7136	8591	9221	8593			
MEAN	5755	6282	6536	7761	8094	8704	8990	9209	10508

ALL STRENGTHS IN P.S.I.

Compressive Strength Test Data

WATER CEMENT RATIO	7 DAYS STRENGTH			28 DAYS STRENGTH			90 DAYS STRENGTH		
	STANDARD	RE VIBRATED	INTMT. VIBRATED	STANDARD	RE VIBRATED	INTMT. VIBRATED	STANDARD	RE VIBRATED	INTMT. VIBRATED
0.4	8423	9375	9425	10198	10656	11452	12880	13454	14417
"	7674	8537	7415	9406	9903	9423	13954	13468	13490
"	8501	9802	11598	10124	10598	10418	12419	11752	13620
"	8456	8725	9324	8255	9394	9862	10660	11474	11700
"	7601	7702	8516	8306	9953	10116	11212	10852	12230
"	7202	8804	9325	10283	10294	11272	10220	11556	10830
"	8025	8876	9669	9299	9225	9121			
"	6582	7467	7000	8245	8593	9392			
MEAN	7808	8661	9034	9264	9821	10132	11891	12093	12715

ALL STRENGTHS IN P.S.I.

Compressive Strength Test Data

WATER CEMENT RATIO	7 DAYS STRENGTH			28 DAYS STRENGTH			90 DAYS STRENGTH		
	STRENGTH	RE VIBRATED	INTMT. VIBRATED	STANDARD	RE VIBRATED	INTMT. VIBRATED	STANDARD	RE VIBRATED	INTMT. VIBRATED
0.35	8975	9225	10805	8302	10903	11206	12389	13513	13680
"	7208	8034	8841	9023	11609	9947	13307	13021	14219
"	9787	11601	10795	9121	10552	11245	12638	12692	15374
"	8825	11625	11794	11625	11575	11981	13792	12130	12892
"	8556	11474	10100	8703	9801	10096	12989	13679	17778
"	8652	9652	7894	11268	12548	13251	13682	14710	14220
"	9024	8541	9922	12084	13350	12632			
"	9181	9512	10657	9402	9398	11122			
MEAN	8776	9958	10101	9941	11217	11435	13133	13291	14694

ALL STRENGTHS IN P.S.I.

COMPRESSIVE STRENGTH TEST DATA

WATER CEMENT RATIO	7 DAYS STRENGTH			28 DAYS STRENGTH			90 DAYS STRENGTH		
	STANDARD	RE VIBRATED	INTMT. VIBRATED	STANDARD	RE VIBRATED	INTMT. VIBRATED	STANDARD	RE VIBRATED	INTMT. VIBRATED
0.30	8903	10985	10802	11271	11766	12501	12135	16609	20687
"	7790	9969	9846	11097	10978	11500	13980	14302	15438
"	8952	8992	9150	10198	10797	10821	13469	12819	16620
"	9891	10697	10946	9908	11937	12928	12956	13606	14098
"	8875	10969	11605	11388	10943	12847	15465	13785	14182
"	8795	9876	10705	11314	12561	13042	13679	13125	10000
"	9875	11354	12822	10202	11495	12783			
"	8921	10846	11492	9526	9995	10595			
MEAN	9000	10461	10921	10613	11309	12127	13614	14041	15171

ALL STRENGTHS IN P.S.I.

Flexural Strength Test Data

WATER CEMENT RATIO	7 DAYS STRENGTH			28 DAYS STRENGTH			90 DAYS STRENGTH		
	STANDARD	RE VIBRATED	INTMT. VIBRATED	STANDARD	RE VIBRATED	INTMT. VIBRATED	STANDARD	RE VIBRATED	INTMT. VIBRATED
0.45	1064	1154	1212	1246	1241	1307	1243	1245	1200
"	1031	1090	1155	1189	1222	1251	1191	1179	1205
"	1175	1176	1059	1257	1283	1305	1160	1275	1290
"	1037	1118	1158	1075	1082	1086	1072	1139	1235
"	1052	1103	1147	1151	1212	1293	1245	1289	1227
"	1079	1089	1189	1204	1333	1256	1254	1193	1260
"	1103	1175	1212	1002	1165	1144	1107	1190	1267
"	1252	1166	1249	1248	1278	1303			
"	1112	1254	1181	1197	1190	1124			
"	1205	1262	1235	1083	1200	1256			
MEAN	1111	1159	1180	1165	1221	1232	1182	1216	1241

ALL STRENGTHS IN P.S.I.

Flexural Strength Test Data

WATER CEMENT RATIO	7 DAYS STRENGTH			28 DAYS STRENGTH			90 DAYS STRENGTH		
	STANDARD	RE VIBRATED	INTMT VIBRATED	STANDARD	RE VIBRATE	INTMT. VIBRATED	STANDARD	RE VIBRATE	INTMT VIBRATED
0.40	1185	1189	1298	1206	1245	1254	1239	1280	1161
"	1069	1082	1097	1124	1138	1231	1049	1305	1230
"	1040	1164	1184	1349	1379	1385	1562	1285	1285
"	1172	1243	1333	1024	1179	1239	1143	1152	1248
"	1205	1090	1291	1205	1202	1385	1155	1259	1257
"	1165	1246	1245	1242	1284	1240	1257	1289	1321
"	1038	1120	1128	1193	1188	1301	1213	1317	1407
"	1233	1220	1106	1116	1240	1228			
"	1261	1251	1272	1075	1337	1242			
"	1065	1177	1185	1276	1271	1262			
MEAN	1143	1178	1214	1181	1243	1277	1231	1270	1273

ALL STRENGTHS IN P.S.I.

Flexural Strength Test Data

WATER CEMENT RATIO	7 DAYS STRENGTH			28 DAYS STRENGTH			90 DAYS STRENGTH		
	STANDARD	RE VIBRATED	INTMT. VIBRATED	STANDARD	RE VIBRATED	INTMT. VIBRATED	STANDARD	RE VIBRATED	INTMT VIBRATED
0.35	1264	1295	1282	1272	1281	1252	1220	1225	1210
"	1162	1183	1159	1229	1223	1321	1387	1241	1285
"	1092	1139	1088	1059	1168	1290	1185	1175	1385
"	1251	1354	1323	1174	1376	1335	1252	1280	1262
"	1068	1182	1148	1268	1341	1289	1287	1392	1275
"	1102	1194	1221	1289	1284	1281	1190	1297	1189
"	1078	1096	1228	1258	1313	1356	1180	1353	1302
"	1285	1308	1355	1119	1157	1118			
"	1268	1119	1382	1157	1272	1385			
"	1021	1242	1261	1285	1299	1325			
MEAN	1159	1211	1245	1211	1271	1295	1243	1280	1288

ALL STRENGTHS IN P.S.I.

Flexural Strength Test Data

WATER CEMENT RATIO	7 DAYS STRENGTH			28 DAYS STRENGTH			90 DAYS STRENGTH		
	STANDARD	RE VIBRATED	INTMT. VIBRATED	STANDARD	RE VIBRATED	INTMT. VIBRATED	STANDARD	RE VIBRATED	INTMT. VIBRATED
0.30	1152	1165	1309	1209	1262	1285	1275	1287	1379
"	1233	1384	1292	1136	1138	1271	1280	1184	1154
"	1195	1198	1399	1363	1351	1353	1273	1342	1385
"	1063	1175	1199	1115	1212	1217	1202	1226	1231
"	1232	1262	1268	1249	1265	1348	1314	1376	1299
"	1147	1140	1245	1376	1379	1369	1279	1290	1369
"	1246	1323	1317	1294	1459	1386	1183	1390	1295
"	1211	1216	1210	1033	1200	1244			
"	1327	1347	1455	1377	1467	1395			
"	1220	1284	1247	1192	1290	1282			
MEAN	1203	1249	1294	1234	1302	1315	1258	1299	1302

ALL STRENGTHS IN P.S.I.

APPENDIX B

APPENDIX B

CHEMICAL AND PHYSICAL TEST RESULTS FOR LAKE ONTARIO PORTLAND CEMENT

Chemical Analysis

C_3S	54 %
C_2S	22 %
C_3A	10.2 %
C_4AF	6 %

Physical Tests

Blaine Fineness	
Fineness, sq. cm./g	3600
Soundness	
Autoclave Expansion, percent	0.12 %
Time of Set, Vicat Needle	
Initial, hr., : min.	2:15
Final, hr., : min.	4:15
Compressive Strength, psi	
1 Day	1491
7 Days	2257
28 Days	4375

Normal Consistency 23.7 %

VITA AUCTORIS

1943	Born May 2, Saharanpur (U.P.) India.
1961	Passed Intermediate Science Examination at S.D. College Saharanpur (U.P.) India.
1962	Passed B.Sc. (Part I) at M.S. Degree College Saharanpur (U.P.) India.
1966	Graduated from Birla Institute of Technology (Ranchi University) with a Bachelor's Degree in Civil Engineering.
1966	October, joined Continental Construction (P) Limited, New Delhi, as Assistant Civil Engineer.
1968	October, joined the University of Windsor in order to obtain the Degree of Master of Applied Science in Civil Engineering.