EFFECT OF REPEATED REVIBRATION AND STEAM CURING ON THE STRENGTH OF CONCRETE

A THESIS

PRESENTED TO THE

FACULTY OF GRADUATE STUDIES

THE UNIVERSITY OF MANITOBA

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

MASTER OF SCIENCE (CIVIL ENGINEERING)

BY

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1971

ABSTRACT

EFFECT OF REPEATED REVIBRATION AND STEAM CURING ON THE STRENGTH OF CONCRETE

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Concrete was subjected to repeated vibration during the initial 18-hour period after casting; this process was also combined with low pressure steam curing; compressive strengths for these two cases were compared with those of concretes subjected to steam curing alone and normal air curing. The variables investigated were water/cement ratios, duration of vibration at each application, interval between successive applications, and the test age of concrete.

Type I normal Portland cement and table vibrators with frequency of 3000 rpm and acceleration of 8g were used for this investigation.

Revibration repeated too frequently during the first few hours after casting was found to have a detrimental effect on the strength of concrete and resulted in test cylinders having surface cracks and deep fissures. However revibration repeated at longer intervals (say every 4 hrs.)

during the initial 18-hour period after casting did not have such adverse effect and even improved the compressive strength in some cases; this increase in strength was especially marked at early age. Also concretes with higher water/cement ratios seemed to benefit comparatively more from revibration.

Combined revibration and steam curing showed strength gains over steam curing alone only in a few cases; mostly this advantage was only marginal. Again the strength gain was mostly realized at early age.

ACKNOWLEDGMENTS

The research work for this thesis was carried out at the University of Manitoba under the guidance of Prof. R. Lazar of the Department of Civil Engineering. The writer is indebted to him also for his suggestions and assistance in obtaining much needed equipment and materials.

Cooperation and help of the technical staff of the Civil Engineering Department, D. Gillis and E. Lemke, and of the writer's friends and colleagues, Bob Petri and Bob Steele, in the casting and testing of some of the concrete cylinders is gratefully acknowledged.

Special thanks are due to Allan Priestly of Canada Cement Limited for arranging to donate a generous supply of cement for this project.

Above all, the writer is indebted to his wife, Cecilia Jethi, for her help, encouragement and patience in making this thesis possible.

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ABBREVIATIONS

ACI	American Concrete Institute, P.O.Box 4754, Redford Station, Detroit, Michigan 48291, U.S.A.
ASCE	American Society of Civil Engineers, 345 East 47th St., New York, N.Y. 10017.
ASTM	American Society for Testing Materials, 1916 Race St., Philadelphia 3, Pa.
W/C Ratio	Water/Cement Ratio.
Revib.	Revibrated or Revibration.
PSI	Pounds per Square Inch.
C/A Ratio	Cement/Aggregate Ratio.

CHAPTER I

INTRODUCTION

Steam curing is now accepted as an essential process in the precast concrete industry for the rapid turnover of precast products. Basically it is a heat treatment imparted to concrete at early age to accelerate its strength development, and in so far as steam curing has certain advantages over dry heat treatment, it has found considerable favour in precasting plant operations. Steam curing may be applied at low pressure (or atmospheric pressure), medium pressure, or high pressure. Use of steam curing at medium pressure[5] seems to have no particular advantage over low pressure, and high pressure necessitates the use of special autoclaves and an intermittent process for production. Hence steam curing at low pressure or atmospheric pressure is the most common form of treatment used in the manufacture of precast concrete products.

Vibration for the purpose of achieving proper compaction is a routine procedure in concrete construction today. The discovery of the beneficial effects of vibration has had a profound effect on the advancement of concrete technology, and with the present-day high cost of labour and competition from other types of building materials, use of vibration is now absolutely indispensable in concrete work.

Some research(8), (14), (16) has been done to study the effect of revibration or delayed vibration on the strength of concrete. Concrete has been subjected to vibration with varying periods of delay after casting, and the effect of this process has been reported on the different properties of concrete. In most of these investigations, optimum periods of delay have been found ranging from 2 to 5 hours, depending on the vibration characteristics and concrete mixes used, where gains of up to 35% have been obtained in the compressive strength. Strength gain appears to have been particularly pronounced at early age. This technique of strength gain by means of revibration would seem to be ideally suited to a precasting plant, but to the writer's knowledge no such practice exists on a commercial scale. Presumably the art of revibration has not been developed enough to encourage practical application. Besides, little work seems to have been done to study the effect of a combination of this process with steam curing, something closer to the operations of the precast industry and possibly of more interest to it.

This investigation is primarily concerned with the effect of repeated revibration on the strength of concrete. It is an extension of the technique of revibration or delayed vibration; here the delayed vibration is repeated, not once but several times at predetermined intervals after casting. In so far as the investigation also covers a combination of steam curing and repeated revibration, the results could be of interest to the precast concrete industry.

For the maximum utilization of their facilities and the optimization of their processes, many high production precasting plants are set up on a 24-hour cycle. Generally, 6 hours are required for the combined operations of prestress release, stripping, clean up and re-assembly of forms, and application of pretension or positioning of reinforcement. The rest of the 18-hour period has to suffice for the operations of casting, presteam period and steam curing.

This investigation was conducted more or less along the same lines, simulating the operations and schedule of a precasting plant as described above. The cut-off time for the processes of repeated revibration and steam curing, applied individually and in combination to different sets of concrete cylinders, was 18 hours after casting. A control set, cast from each batch of concrete mixed and not subjected to any further operations after casting, was designated the "Air Cured" set. Four sets of three cylinders each were cast from every batch of concrete mixed, and these were designated as follows according to the process used:

Set (A): Revibrated

" (B): Revibrated and Steamed

" (C): Steamed

" (D): Air Cured

"Revibrated" as above refers to repeated revibration, and "Steamed" refers to steam curing. By varying(a) the water/cement ratios of the mixes(b) the revibration characteristics (i.e. the duration of each application of vibration and the interval between successive applications), and(c) the test age of specimens subjected to identical operations, it was thought that enough data would be obtained to determine whether these processes can yield encouraging results to justify further research and/or adoption by the precast industry.

Considering the fact that steam curing causes a loss [(2), (28)] in the ulitmate strength of concrete whereas delayed revibration possibly has the effect of increasing the compressive strength, it was surmised that a combination of the two processes might yield strength values higher than those of normal concrete both at early and later ages.

Compressive strength is the most important physical property of concrete, and is usually the only requirement specified in its use. Therefore to keep the scope of this investigation within manageable proportions, and to ascertain the feasibility and potential of the processes for practical application, it was decided to limit this project to the study of compressive strength only.

CHAPTER II

GENERAL REVIEW OF MATERIALS AND PROCESSES

A brief review of the basic properties of the materials used in this investigation, and the effects and characteristics of the various processes to which these materials are subjected is given in this chapter. Certain aspects of both have been dealt with in somewhat greater detail as these have an important bearing on the results obtained.

2.1 Manufacture of Cement.

Portland cement is manufactured from raw materials which contain lime (CaO), alumina (Al_2O_3), iron oxide (Fe_2O_3) and silica (SiO_2). Generally these raw materials are found in the form of limestone and clay. Two different processes are used in the manufacture of cement: a "dry" process, in which the constituent materials are pulverized without the addition of water; and a "wet" process, which involves the addition of large quantities of water to facilitate pulverization, the resulting materials being in the form of a slurry; pulverization is usually carried out in tube mills. Basically, blended mixtures of limestone and clay as obtained above are burnt in huge rotary kilns at temperatures of between 1400° and $1600^{\circ}C$. Here reactions and incipient fusion of the materials take place, which results in clinkering. The clinker thus obtained is cooled and, after the addition of gypsum in the correct proportions, is ground to the requisite fineness to obtain Portland cement.

2.2 Composition of Cement.

The composition of cement and its properties depend to a great extent upon the characteristics and proportions of the raw materials used. These vary with different manufacturers and may even vary with different batches from the same manufacturer, so that a close supervision of the raw materials and an appropriate adjustment of the proportions and manufacturing processes is constantly required for the end product to meet the specifications laid down. The following tables represent the relative proportions of the constituents in the raw materials and the composition of the finished product in a typical manufacturing process:

TABLE I

CONSTITUENTS OF PORTLAND CEMENT

Name	Formula	Symbol	Content % Typical	Content % Range
Lime	CaO	C	63.1	60 - 70
Silica	SiO_2	S	20.6	17 - 25
Alumina	Al_2O_3	A	6.3	3 - 8
Iron Oxide	Fe_2O_3	F	3.6	0.5 - 6
Gypsum	$CaSO_4 2H_2O$	-	3.0	1 - 3
Others (e.g. Magnesia etc.)	-	-	3.4	1 - 5

TABLE II

COMPOUND COMPOSITION OF PORTLAND CEMENT

Compound	Formula	Symbol	Content % (TYP.)
Tricalcium silicate....	$3CaO.SiO_2$	C_3S	50
Dicalcium Silicate	$2CaO.SiO_2$	C_2S	24
Tricalcium aluminate...	$3CaO.Al_2O_3$	C_3A	10
Tetracalcium alumino-ferrite...	$4CaO.Al_2O_3.Fe_2O_3$	C_4AF	8
Calcium sulphate dihydrate......	$CaSO_4.2H_2O$	-	3
Magnesia	MgO	-	3
Minor Constituents.....	-	-	2

The characteristics of the compounds identified in Table II that influence the behaviour and properties of cement may be briefly described as follows:

(a) C_3S: This compound hydrates faster than C_2S and contributes more to early strength development as well as heat of hydration. It is only slower than C_3A in the rate of heat evolution, and is chiefly responsible for the resistance of concrete to action of acids, alkalies and corrosive salts; it is one of the most stable compounds in cement. It constitutes 50 per cent of normal Portland cement, proportionately more in high early strength cements. Together with C_2S, it forms 70 to 80 per cent of all Portland cement.

(b) C_2S: This compound hydrates slower than C_3S and its chief strength contribution takes place after 7 days and may continue up to one year. Least heat of hydration is generated due to this compound compared to others; it contributes to resistance of concrete to the action of alkalies, acids and corrosive salts, and like C_3S is one of the most stable compounds. It constitutes approximately 24 per cent of normal Portland cement, relatively greater percentage in low heat cements and proportionately less in high early strength cement.

(c) C_3A: It hydrates quickly generating much heat; in fact, it has the greatest rate of heat evolution compared to other compounds in cement. Its strength contribtuion is small, and that principally within the first 24 hours. It is the least stable of the four principal compounds and liable to decompose to hydroxides of Ca and Al on exposure to air and water. It is easily attacked by salts and alkalies and its presence is undesirable for hydraulic or marine works. Normal Portland cement contains approximately 10 per cent of C_3A while sulphate resisting cement contains very low percentages of this compound.

(d) C_4AF: Comparatively an inactive compound, it contributes little to strength at any age or to the heat of hydration. It is less stable than C_3S or C_2S but more so than C_3A. It constitutes about 8 per cent of the composition of normal Portland cement.

(e) Gypsum: It acts as a retarding agent to prevent the cement from setting too rapidly. It is usually added to the clinker at the grinding stage in amounts of up to 3 per cent for normal Portland cement; excessive amounts cause unsoundness and tend to reduce the strength of cement.

(f) Magnesia: It forms periclase (crystalline magnesia) in setting cement if present in quantities larger than 5 per cent; this hydrates very slowly and is accompanied by expansion which causes unsoundness and disintegration of cement. It constitutes about 3 per cent of normal Portland cement.

2.3 Types of Cement.

The Canadian Standards Association covers the following classification of cements:-

I. Portland cements:

(a) Normal Portland cement

(b) High early strength Portland cement

(c) Sulphate-resisting Portland cement

II. Masonry cements:

(a) Type H - Masonry cement for general use in masonry construction.

(b) Type L - Masonry cement for use in masonry construction where high strength mortar is not required.

In actual practice many more types of cements are used for specific applications and the following may be cited:

(a) Extra-rapid hardening Portland cement.

(b) Portland blast furnace cement.

(c) Low heat Portland cement.

(d) White Portland cement.

(e) Coloured Portland cement.

(f) High alumina cement.

(g) Expansive cement.

(h) Oil well cement.

Some of these are covered by the British Standard Specifications and the A.S.T.M. Standards, but quite often on-site conditions dictate special specifications. This is especially so for large projects like dams where vast quantities of cements are required but locally available materials may have peculiar properties. The special specifications are generally based on results obtained by trial mixes subjected to the same conditions as the structure will be exposed to, and are usually a compromise between economy and quality.

The relative proportions of the four principal compounds and the fineness of grinding determine to a large extent the properties of Portland cements that differentiate the various types in this group. Most of the other kinds of cements derive their particular properties from the addition of certain materials designed to give the required effect.

This investigation covers only normal Portland cement, mainly because this is the type of cement most commonly used and also because this limitation reduces one more variable in an investigation that potentially has an extremely large number of these. Thus any unqualified reference to cement hereafter shall be taken to mean normal Portland cement.

2.4 Hydration of Cement.

The chemical and physical transformations, termed the hydration of cement, start with the addition of water and may continue for a very long time under suitable conditions, although at a progressively slower rate.

The anhydrous compounds of cement are decomposed by water to form hydrated products. Supersaturated and unstable solutions are formed temporarily, but these gradually deposit their excess solids and tend to come into equilibrium with the hydrated compounds produced.

Hydration of tricalcium silicate (C_3S) may be represented as: $3\ CaO.SiO_2 + Water \rightarrow Ca\ (OH)_2 + xCaO.ySiO_2\ aq.$ Calcium hydroxide, one of the by-products of this reaction, is deposited in the form of crystals, whereas the hydrated calcium silicate appears as a gelatinous mass or gel. The gel quickly forms a coating around the original grains and being relatively impervious to water, slows down further attack. However hydration can again be accelerated if the gel coating could be broken down to expose fresh surfaces of the unattacked cores of C_3S.

Dicalcium silicate (C_2S) is only slowly attacked by water and even after some weeks the original crystals show only a surface coating of an amorphous hydrated silicate, the thickness of which slowly increases with the passage of time.

Tricalcium aluminate (C_3A) reacts very rapidly with water though much less so in a saturated lime solution; in presence of excess water a plentiful formation of hexagonal plate crystals is observed. These, when seen on edge, appear as needles in clusters radiating from a centre. These crystals begin to form within a few minutes and increase rapidly in size and in amount. No calcium hydroxide or hydrated alumina is produced.

Tetracalcium alumino ferrite (C_4AF) reacts quickly with water, though less rapidly than C_3A, to form hexagonal plate crystals. When mixed to a paste with water, it shows excellent crystal formation within a day.

In the presence of gypsum, the manner of hydration of C_3S and C_2S is apparently unchanged but that of C_3A is much altered whereby formation of the hexagonal plates and needles commences, but very soon other extremely fine needles begin to grow and steadily increase in length and thickness.

Microscopic examination of a thin section of set Portland cement reveals three main contituents: (a) unhydrated grains of cement, (b) crystals of calcium hydroxide and (c) the gel mass of hydrated products. Capillary voids may also be observed interspersed at random in the gel mass, their number dependent on the water/cement ratio at time of mixing.

2.5 Setting and Hardening of Cement and Concrete.

The additions of water to a mixture of cement and aggregate followed by rapid and thorough mixing results in a plastic heterogeneous mass called concrete. In properly made concrete, the aggregate particles are completely coated with cement paste, and all the spaces in between the particles are also filled with the paste.

The cement paste, immediately after mixing, consists of the cement compounds in an aqueous solution or suspension, tiny particles of clinker and powdered gypsum. A typical specimen of fresh paste may be composed of 40% solids and 60% aqueous solution by absolute volume. Since about 65% of the cement particles are larger than the average distance of 7 microns between adjacent particle surfaces, the cement paste is made up of solid particles much larger than the water filled spaces between them. Therefore the basic structure is a network of closely spaced discrete particles in a flocculent mass having very little rigidity.

The discrete particles are brought closer together by the process of sedimentation or "bleeding"; hydration products bridge and surround these particles and the process of cementation begins.

There are four distinct stages in the hydration of normal cement, discernible by the different rates of heat evolution. The first stage begins immediately with the addition of water to cement when dissolution and an exothermic chemical reaction takes place. The rate of heat evolution builds up rapidly and peaks in about 5 minutes after which a rapid drop in the rate is noticeable marking the end of the first stage. The second stage is characterized by a uniform and low rate of heat evolution and is known as the dormant stage; this lasts for about an hour. A renewed increase in the rate indicates the beginning of the third stage, reaching a peak at about the sixth hour after the addition of water to cement. A fall in the rate of heat evolution shows the beginning of the fourth stage which continues more or less throughout the life of the cement mass.

The end of the second stage or dormant period denotes the completion of the process of sedimentation and is marked by the ending of bleeding in the concrete. The third stage is a period of set, initial set being obtained sometime during the beginning of this stage and final set at the end when the rate of heat evolution peaks. The fourth stage with a continuously decelerating rate of heat evolution is called the period of hardening.

As pointed out earlier, dissolution of the various compounds in water and the accompanying chemical reactions take place during the first stage. Calcium silicate gel is produced as a result of the chemical reaction and crystals of C_3S tend to get coated with this gel. The dormant period is probably due as much to the reaction between C_3A and gypsum with the production of calcium sulfoaluminate hydrate, as to the thin coat of gel surrounding the C_3S particles which inhibits a rapid and ready attack by water. After the reaction intensity between C3A and gypsum has diminished to a low level and water has again found its way through the gel pores to the unattacked cores of C_3S due to osmosis, a progressive breakdown of the gel coating takes place, probably due to osmotic pressure, with the formation of more calcium silicate gel and precipitation of calcium hydroxide crystals. The ruptures in the original gel coating are resealed by this further gel formation; the thickness of the coatings is also constantly being increased due to the reactions taking place at the interface between the gel and the C_3S cores. This is a rapidly decelerating process after the initial ruptures have taken place because the gel envelopes become thick enough to resist rupture due to osmotic pressure and the diffusion paths for water to get through the gel pores become increasingly longer.

The general picture of setting cement is that of gel masses containing cores of unhydrated cement particles coalescing to form links with other similar masses, interspersed with numerous capillary spaces containing water, and enmeshing crystals of calcium hydroxide and other hydrated products. The further hydration of the unattacked cores, more linkages between adjacent groups of gel masses, wedging action of the crystals, drying out of the capillary water, stiffening of the gel masses, all contribute to the hardening process.

2.6 Vibration of Concrete.

The strength of a given mix of concrete is very much dependant on the percentage of voids in it. These voids are due to entrapped air in freshly mixed concrete; some more may develop later due to evaporation of water during the setting and drying periods. Vibration is generally used in concrete work to eliminate air voids and obtain the desired compaction. Fig. 1 illustrates the loss in concrete strength with increasing amounts of air voids,[46]. In the presence of 30 per cent air voids, concrete loses over 90 per cent of its strength at full compaction.

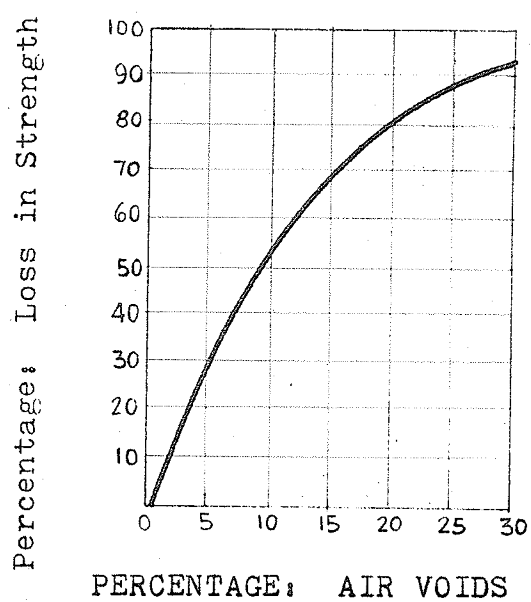


Fig. 1. The effect of air voids on the strength of concrete (Ref.46).

Compaction of concrete can also be achieved by various means other than vibration, though their use is limited to specific applications. Other methods of compacting concrete are:

(a) Punning or tamping with rods for cast in place or pre-cast applications. This was the principal method before vibration was developed for this purpose.

(b) Centrifugal force by means of high speed rotation or spinning, used for the manufacture of pre-cast pipe and other similar sections.

(c) Pressure applied through a hydraulic press, used in the manufacture of paving flags and curbstones.

(d) Compaction by rolling, involved in the manufacture of very thin products like tiles. It is also used sometimes in road construction.

(e) Shock or jolting as a means of compaction, used for precast products and achieved by lifting the mould with the help of cams and dropping it onto a hard surface. This may also be classified as low frequency very high amplitude type of vibration.

Vibration of concrete may be achieved by the following methods:

(a) Immersion, shaft or rod vibrators which are plunged directly into fresh concrete to be compacted.

(b) Form or shutter vibrators which are attached directly to the forms or moulds in which concrete is cast.

(c) Vibrating screeds or pans which are applied to the exposed upper surface of concrete.

(d) Vibrating tables where the entire mould including the concrete is subjected to vibration.

The advantages of using vibration as a means of compacting concrete may be listed as follows: (a) a higher state of compaction can be achieved than by hand punning, with an accompanying increase in strength due to a decrease in void ratio; (b) lower water/cement ratios can be used, again yielding increased strength; (c) alternatively, the same strength can be achieved by using less cement with consequent economy; (d) lowered cost of concrete due to ease of placement; (e) greater density, homogeneity and better appearance; (f) improved bond with reinforcement and at construction joints; (g) greater durability; and (h) reduced shrinkage.

Immersion vibrators are used at frequencies between 7000 and 9000 rpm for use in most cast-in-situ and pre-cast concrete work, like walls, columns, beams, slabs, piles etc., the higher frequency for thinner sections and lower for massive applications. Immersion spuds with head diameters of 5" to 6" and operated at 6000 rpm are used for mass concrete like dams, massive piers, etc.

Vibrating screeds are usually operated at 3000 rpm and may be up to 40' long and 18" wide. They are effective to a maximum depth of about 12" and are useful for highway and airport pavement construction.

Form vibrators are generally clamped to the forms at predetermined points and are more suitable for steel forms and thin walled precase sections like pipes, thin wall panels, high, slender columns etc. They may range in frequency from 3000 to 9000 rpm and accelerations of 10g to 25g.

Vibrating tables can only be used for pre-casting and as such are extensively used in the pre-cast industry. They may be operated by electromagnetic forces, or electric motors driving shafts mounted with eccentric weights. The usual frequencies used are 3000 to 8000 rpm, and acceleration varies from 3g to 10g. Amplitudes can be varied by adjusting the eccentric weights, and the magnitude required depends on the frequency used and the job requirement.

Much research has been done to determine the optimum conditions of vibration to obtain the beneficial effects of proper compaction and to study the effect of different combinations of frequency, acceleration and amplitude on various properties of concrete.

Cusens [15] used a table vibrator driven electromagnetically and capable of being adjusted with regard to frequency, amplitude and acceleration. He noted that there is an optimum frequency for each mix, the lower frequencies (about 3000 vib./min.) being suitable for dry mixes and higher frequencies (more than 6000 vib./min.) are best for normal use. He also concluded that there is a minimum value of amplitude of about 0.002 in., below which vibration has no effectiveness for compaction, and above this value acceleration becomes a convenient criterion of effectiveness; for general use the minimum value for acceleration recommended was 4g. He also suggested that for sections of depth greater than 6", the amplitude should be as high as possible with low frequency.

The Institutions of Civil Engineers and Structural Engineers, London, England set up a joint sub-committee to investigate the vibration of concrete. They reported [11] that, at a constant acceleration of 4g and a period of vibration of 2 minutes, frequency of vibration had little effect on the strength of the wetter mixes, but for very dry mixes, decrease in strength was noticeable with increase in frequency. However frequencies in the range 1500 - 3000 did not exhibit the same tendencies. The effect of prolonged vibration during setting and hardening did not seem significant with a water/cement ratio of 0.4, but at 0.6 a 70 per cent increase in strength was obtained when the period of vibration was extended from 2 minutes to 3 hours. This was due to the fact that a lowering of water/cement ratio took place by allowing the water forced upward by vibration to be run off.

Stewart (10) observed that if frequency and amplitude are satisfactory, vibration can be continued indefinitely without bringing about any further changes in the condition of concrete, once stabilization phase has reached during the process of consolidation.

That segregation is not so much the fault of over-vibration as of bad mix-proportioning, has been concluded by many researchers (7), (8), (10), (17).

2.7 Rotational Instability.

An interesting phenomenon was reported by Cusens(15) during his investigations of the effect of vibration on concrete. He observed that under certain circumstances, vibration induces the concrete to to roll up in the form of a ball and begin(s) to rotate centred about two diagonally opposite corners or about two opposite vertical faces. If the amplitude of vibration of the table is maintained, rotation continues and compaction ceases to take place. However if the amplitude of vibration is diminished, the mix settles down, compaction takes place and any later increase of amplitude fails to bring about further rotation.

A possible cause of the phenomenon appeared to be uneven vibration of the table platform". He termed this phenomenon 'rotational instability'. He concluded:

"Concrete mixes liable to rotational instability have the appearance of loose damp earth before vibration. After an initial few seconds of vibration, they become vay viscous in appearance and behaviour. The particles cannot adjust themselves to the velocity gradient across the mould and the whole mix tends to roll up and rotate. The rotation prevents the vibration from breaking down the paste to a viscosity low enough to allow the particles to move freely.

In the author's experience, the incidence of rotational instability is confined to:

(1) small moulds, e.g. 4 in. cube moulds;

(2) large amplitudes (0.005 in. and above);

(3) dry mixes of high sand content."

It is curious that no other investigator has reported this phenomenon but the writer of this thesis came across such an occurrence during the course of the current investigation.

2.8 <u>Revibration of Concrete</u>.

After the initial vibration for compaction, concrete is usually left undisturbed until it has hardened and attained a specific strength. The feeling is generally prevalent that any kind of disturbance after the initial set, and before the concrete has hardened appreciably, is detrimental to its strength. Some research has been done to study the effect of revibration on concrete, with varying periods of delay after casting, and it has led many authorities (7), (11), (17) to conclude that the effect of controlled revibration is not necessarily detrimental to concrete; in fact most investigators (8),(14), (16) etc. have obtained marked increase in strength attributable to this operation.

Mattison (14) termed revibration as delayed vibration when the specimen was initially compacted by rodding only, and repeated vibration when initial compaction, at time of casting, was achieved by vibration. Cubes were used for compression tests, and cylinders for indirect tension test using a method described by Blakey. He concluded that for some concretes of high workability, delayed vibration and repeated vibration can increase the compressive strengths above those by hand punning by one-sixth. These effects are somewhat reduced in the case of mixes with coarse sand. The effect of delayed vibration on the tensile strength showed large variations, but a general increase was observed. Concretes of low workability showed strength increase, due to repeated vibration, of about one-sixth.

Concretes with higher cement contents generally showed a lower proportional increase in strength due to delayed and repeated vibration. He also observed that there is some relationship between maximum bleeding and increase in strength due to repeated vibration. His equipment consisted of a table vibrator operating at a frequency of 3000 cycles per second and having an amplitude of 0.04 in. The revibration was applied at three hours after casting. He surmised that the reason for increase in strength was due to re-bonding of the aggregate after the completion of bleeding. Normally settlement of mortar under bridged pieces of aggregate causes a loss of bond and zones of weakness in concrete; with revibration, bleeding marked the re-bonding of aggregate and mortar.

Purandare(16) also used a table vibrator, and his test specimens were cast in the form of cubes and beams. Maximum strength increases in both cases were obtained with specimens revibrated 2 hours after casting and these amounted to 35% above unrevibrated specimens. There was a marked decrease in strength due to revibration after 2 hours delay. The periods of delay used in his investigation varied by 1 hour intervals up to 5 hours after casting. Test age of specimens was 7 days and high early strength type of cement was used. No values for frequency or acceleration of vibration used were given. The author surmised that the increase in strength was due to the water reacting with the exposed cores of unhydrated cement, made possible by breaks in the gel, and a wedging action of the calcium hydroxide crystals.

Tuthill and Davis(8) conducted various tests to determine the effect of revibration on concrete. (a) Concrete cylinders (6" dia. x 12" high) were revibrated up to 10 hours after casting in moulds clamped to the vibrating platforms. High frequency vibration was used and the increase in compressive strength over unrevibrated concrete was up to 25 per cent. Greatest strength gain was obtained when interval between time of mixing and time of revibration was 2 to 5 hours. (b) Two wall panels, 6' x 6' x 4" were subjected to revibration by means of form vibrators. In one case, revibration applied 2 hours after casting was successful, but in the other case revibration applied after 10 hours caused small cracks in the panels which could not be successfully closed up again even with prolonged vibration. This was evidence of the harmful effect of revibration. (c) Vibration was applied to plain round reinforcing bars cast vertically in 6" x 6" concrete cylinders. When bars were revibrated 4 hours after casting, it was observed that immediately after vibration was begun, bond was apparently broken and at the top a small annular space was visible between the bar and the surrounding concrete. On continuation of the revibration, this void soon filled with paste and water and some air was expelled from the viscous mass surrounding the bar. For revibrated bars, bond strengths were 30 to 50 per cent higher than unrevibrated specimens. (d) In another series of experiments, deformed reinforcing bars were cast vertically in 6" x 6" cylinders. Vibration was applied to bars after intervals ranging from 2 to 9 hours after time of casting. Both low frequency and high frequency vibration was tested. Increase in bond strength up to 100 per cent as recorded compared to unrevibrated specimens.

The authors concluded that substantial benefits could be derived from revibration of partially set concrete if carried out under proper conditions; i.e. where the possibility existed that the concrete could be effectively reconsolidated with prolonged vibration. This could be taken advantage of in the manufacture of pre-cast products, but they did not think it was feasible to use revibration on an ordinary construction job. The authors thought that the likely reason for the beneficial effect of revibration on the compressive strength might be due to the reduction of voids within the concrete as the mass tends to settle.

2.9 Low Pressure Steam Curing.

As mentioned in Chapter I, steam curing of precast concrete products at low (or atmospheric) pressure is a widely prevalent practice in the pre-cast industry. The main advantages of using curing as such, and in using low pressure steam curing as against other types, may be cited as follows:

(a) Curing accelerates the strength development of concrete. Early high strength facilitates stripping and handling of the products.

(b) These products can be put to use at an earlier age due to the high strength attained.

(c) The products can be delivered quickly after manufacture, and storage space requirement can be reduced.

(d) For a given facility, a greater volume of products can be manufactured and in a shorter time.

(e) Moulds, pallets, casting beds and forms represent a major portion of the large capital investments in pre-casting plants. Their more frequent use represents efficiency and economy of production and consequently a better return on the capital outlay.

(f) Low pressure steam curing may be used in an intermittent or continuous process whereas high pressure steam curing is suited to intermittent production only.

(g) The steam chamber for low pressure curing may be an ordinary box, or room, or a tunnel with tarpaulin flaps at each end, or the forms themselves may be enclosed by tarpaulins and steam introduced under them; the necessity of pressure chambers or autoclaves is eliminated.

(h) Steam heats the products evenly although there may be only a small gap between adjacent units, something that cannot be achieved by radiant or dry heat.

(i) Heat is mainly transferred to the units by condensation and the release of latent heat. Condensation ensures even moist curing, which is lacking in dry heat.

(j) Lighter coloured products are obtained with steam curing which have a pleasing appearance.

The main stages in a steam curing cycle are as follows:

(a) Presteam Period: After the completion of casting operations, concrete should be allowed to hydrate at normal temperatures (70 - 90°F) for a short length of time before being subjected to steam curing. This delay of 1 to 7 hours, depending on the type of operation, before exposure to steam, is called the presteam period. Experience has shown that a reasonable presteam period is very important for proper strength development, and a very short or complete absence of presteam period is injurious to concrete. Each steam curing cycle probably has an optimum presteam period below which the strength of concrete decreases and above which benefits are small compared to the delay involved and therefore increasingly uneconomical.

Hanson [2] conducted a comprehensive investigation into steam curing using a fixed 18-hour cycle which had to accommodate both the pre-steam and steaming periods. Thus an increase in the pre-steam period caused a proportionate decrease in the steam curing period. He found that the 18-hour strength of his specimens increased with an increase in the presteam period from 1 to 5 hours, after which the early strength showed a consistent decrease; this decrease was due to the effect of shorter steam curing periods left over in the fixed time cycle. The 7-and 28-day curves exhibit a characteristic S-shape reaching a maximum strength for 5 to 7 hours of presteaming. With only 1 hour of presteaming, cracking and severe strength reductions were experienced. Hanson concluded that a presteaming period of about 5 hours produced maximum strength at all ages. This also introduced economies in plant operation due to the relatively short period used for steam curing.

Shideler[28] reported the presence of circumferential cracking and swelling in concrete cylinders subjected to early steam curing and a rapid rise in temperature. His results indicated 3 hours as being the best presteaming period.

The findings of Merritt and Johnson[34] are also in close agreement with those of Hanson. They observed that higher steam curing temperatures require longer delay periods to produce maximum strength.

Tests by various researchers on concrete block also generally showed strength reductions and evidence of fine cracks due to too early applications of steam.

(b) Temperature Rise Period. Starting with the first introduction of steam to concrete, this period extends to the time that the concrete reaches the maximum specified temperature. This really determines the rate of temperature rise in concrete during the curing operation, which also has a great bearing on the strength and stress properties of steam cured concrete products. The rate of temperature rise is generally restricted to 20 - 60°F per hour, and the temperature rise period generally extends from 1 to 6 hours.

Length of presteam period and rate of temperature rise are inter-related. Very small presteam periods are required for low rates of temperature rise (less than 20°F per hour) while longer delay periods are desirable for high rates of temperature rise (60°F per hour). Lower rates are generally favoured since there is less risk of injury to concrete and smaller capacity boilers are required.

Hanson[2] recommends a temperature-rise rate of 40°F/ hour for best results. His investigations revealed serious damage to specimens with rates in excess of 40°F per hour with presteam periods of less than 3 hours, but only slight reduction in strength in the case of presteaming periods extended to 3 hours or more.

(c) Period at Maximum Temperature: This is the period during which the maximum specified temperature for curing purposes is maintained at a constant level. This is also the period during which the major strength development of the curing concrete takes place. A wide range of maximum temperatures can be used, varying between 130 and 212°F, but these have to correspond to appropriate presteam and temperature rise periods.

Hanson[2] concluded that compressive strengths improve rapidly as the maximum temperature increases to about 150°F, with only a moderate additional advantage gained by using temperatures higher than 150°F. The gain in strength by using a maximum temperature of 175°F with type I cement and temperature rise rate of 40°F per hour was only about 5% more than using maximum temperature of 150°F. Even lesser increases were recorded for temperature rise of 20°F/hour and for type III cement.

Chamberlin concluded that 165°F produced optimum results with strengths slightly higher than those obtained with 130°F at early ages and equal strength at later ages.

Most investigators found the range 150° - 180°F for maximum temperature as yielding the best results.

(d) Soaking Period: This period is usually in lieu of the maximum temperature period, although it may sometimes be used in conjunction with it. In this period, the product being cured is brought up to the maximum temperature when the supply of steam is cut off, and the product is subsequently allowed to soak in the residual heat and moisture of the steaming chamber. This is more commonly used in the manufacture of concrete masonry block.

The ultimate compressive strength of steam cured concrete is not as great as that of concrete continuously moist cured at lower temperature[1]. Therefore the acceleration of early strength is achieved at the expense of some potential development in compressive strength. This is the finding of most investigators like Saul[31], Shideler[28], Higginson[33], Hanson[2] et. al.

Saul suggested that the reason for this was that high temperature curing caused an impermeable coating to develop around tricalcium silicate (C_3S) grains which inhibited further hydration. Such a coating develops when C_3A hydrates in the presence of insufficient amounts of calcium sulphate (gypsum). Higher temperatures tend to accelerate the hydration of C_3A at the same time as diminishing the solubility of gypsum.

Lea and Desch[24] have also shown that hydration products of cement are somewhat different when obtained at elevated temperatures than at normal temperature, which could account for the loss in ultimate strength. However the reaction rates of all the compounds are greatly accelerated by high temperatures and this accounts for the increase in early strength.

2.10 Combined Vibration and Steam Curing.

To this author's knowledge, no research has been done on concrete subjected to a combination of revibration and steam curing, or even vibration and steam curing.

However a paper published in Russia came to the author's attention which dealt with the effect of vibration and dry heat on the strength of concrete.

Mironov[12] et. al. in their paper: "High Strength Concrete Subjected to Vibratory Rolling and Thermal Treatment" (translated from Russian) describe their tests on concretes using various types of Russian cements to determine the possibility and optimum conditions for the manufacture of thin-walled and reinforced panels by means of vibration.

The test specimens were in the form of cubes made from concrete with different mixes and water/cement ratios.

The batches were vibrated on tables at 3000, 6000 and 12,000 vib./min. with corresponding amplitudes of 0.35, 0.23 and 0.08 mm. The samples were put in a heating chamber in 3 rows, each row subjected to a different frequency of vibration. Rubber spacers were used between rows, with 10-15 kg. weights placed on the uppermost specimens.

The specimens were heated at 100 ^{o}C for 3 hours. It appears some sort of dry heat was used; either radiant heat or hot plates under the specimens may have been employed.

Samples made with cement and sand were strongest when vibrated at a frequency of 3000 vib./min., less so at 6000 vib./min. and least at 12,000 vib./min. In samples made with chip gravel, highest strength was obtained with 6000 vib./min., less with 3000, and least with 12,000 vib./min. The sand-cement cubes vibrated at 6000 and 12,000 vib./min. showed presence of oriented micro-cracks, which probably accounts for their lower strengths. The authors recommended that for the production of reinforced panels by vibration, cement:sand mixes of 1:2, high early strength cement and large grained sands (fineness modulus not less than 2) should be used with 2 hours heating at 100 ^{o}C.

CHAPTER III

TEST MATERIALS AND EQUIPMENT

The choice of materials for this investigation was restricted to their local and ready availability, as this must ultimately be the criterion in a cost conscious and competitive industry; their suitability, of course is a prime requisite.

The choice of equipment was greatly limited by the lack of funds in an unsponsored investigation of this nature; thus the equipment actually used was restricted to what was already installed in the concrete Laboratory at the University of Manitoba and that obtainable on loan from other departments. This was not an ideal situation, or even a satisfactory one, because much of the equipment was in constant demand by others during the normal working hours of the Laboratories, and the use of equipment for this investigation had to be restricted to breaks during the work periods or to time outside of normal working hours.

3.1 Materials used in Investigation.

(a) Cement. As mentioned earlier, this thesis is concerned with the investigation of concrete made with normal Portland cement only. The cement was very kindly supplied by Canada Cement Company Limited from their plant at Fort Whyte, Manitoba.

The preliminary investigation was conducted using cement from the standard 87½ pound paper bags already in stock at the laboratory and presumably in storage for some time. However all the final testing was done using batches of fresh cement obtained directly from the Fort Whyte plant. The characteristics of the cement as given in the mill test report are as follows:

CEMENT MILL TEST

a.) Chemical Analysis

Insoluble Residue	0.29
SiO_2 (Silica)	20.54
Al_2O_3 (Alumina)	5.89
Fe_2O_3 (Iron)	2.66
Total Lime (CaO)	63.17
Free Lime	0.74
Combined Lime	62.44
MgO	2.64
SO_3	2.70
Ignition Loss	1.74
Total	99.34

b.) Potential Compounds (calculated)

C_4AF	8.1%
C_3A	11.1
C_3S	49.1
C_2S	21.1
$CaSO_4$	4.6

c.) Physical Tests

Fineness (Specific Surface) sq. cm./gm.	
Blaine	3110
Wagner	1700
200 mesh sieve (per cent passing)	97.6
325 mesh sieve (per cent passing)	92.5
Autoclave Expansion (per cent)	0.21
Setting Times (Vicat)	
Initial (hrs:min)	2:50
Final (hrs:min)	4:50
Tensile Strength - psi.	
3 - day	315
7 - day	435
28 - day	510
Compressive Strength - psi.	
3 - day	2530
7 - day	3810
28 - day	5270

(b) Fine Aggregate. The sand constituting the fine aggregate in the concrete, was obtained from a local source known as Bird's Hill. This was stored inside the laboratory, in an enclosed space well protected from weather or contamination, and only the top layer was exposed to the somewhat drying influence of the Laboratory atmosphere. Thus although initially much of the sand used was completely dry as obtained from the top layers which had had 24-48 hours time to dry out between successive batches, the volume of sand required subsequently due to more frequent mixing necessitated the use of the relatively moister layers which in themselves were quite uniform in moisture content. Thus adjustments had to be made in the calculation of W/C ratios of some batches which resulted in W/C ratios not originally planned to be investigated.

The following properties characterize the Bird's Hill sand used in this investigation:

Fineness Modulus:	2.71 to 2.77.
Moisture Content: (per cent)	0, for dried out top layers.
	2.4, maximum for moist layers underneath.
24 hour Absorption: (percent)	1.6
Specific Gravity:	2.57 (oven dry).
	2.60 (Saturated surface dry).
	2.63 (Apparent).

TABLE III

SIEVE ANALYSIS: BIRD'S HILL SAND

Sieve No.	Percent Passing	Percent Retained Cumulative
4	97	3
8	87	13
18	69	31
30	49	51
50	19	81
100	4	96
Fineness Modulus of Sample:		2.75

(c) <u>Coarse Aggregate</u>. Crushed limestone, 3/4" size, angular and somewhat dusty in appearance, was used throughout these series as coarse aggregate in the concrete. It was the type commonly used locally for this purpose. This aggregate was also stored inside the laboratory under practically perfect conditions. The aggregate was dry and quite uniform in gradation and the following represent its typical characteristics:

Fineness Modulus:	1.84.	
Moisture Content, (percent):	0	for dried out top layers.
	0.1	for moist layers underneath.
24 hour Absorption, (percent):	0.9	
Specific Gravity:	2.63	(oven dry)
	2.65	(Saturated Surface Dry).
	2.69	(Apparent).

TABLE IV

SIEVE ANALYSIS: 3/4" CRUSHED LIMESTONE

Sieve No.	Percent Passing	Percent Retained Cumulative
1/2"	100	0
3/4"	95	5
3/8"	18	82
4	3	97
Finess Modulus of Sample:		1.84

(d) Water. Clean and potable water drawn from the University water mains ~~is~~ used through out these series for mixing concrete. A special line was provided specifically for this purpose, and a meter and valve arrangement was incorporated as part of the concrete mixer.

(e) Capping Materials. The material used for capping the cylinders for compression tests was mostly sulphur as recommended by A.S.T.M. Specification: C192-47T, although a proprietary black compound specifically manufactured for capping had to be used when the stock of sulphur in the laboratory was occasionally exhausted.

3.2 Equipment Used In Investigation.

(a) Concrete Mixer. A fixed batch mixer of the non-tilting type installed in the concrete laboratory, University of Manitoba, was used through-out this investigation for mixing concrete. (See Fig.2) The drum rotates about a vertical axis and the blades rotate similarly but in a counter direction. This ensures adequate and efficient mixing of the ingredients. A charging bucket runs up inclined guides to deposit the charge into the drum; this arrangement permits the bucket to be charged at ground level. Mixing water could be introduced directly into the drum through a pipe provided for this purpose and connected to a meter and valve, but this was bypassed in the actual mixing operations to prevent mishaps, and instead the water was metered out into a pail and poured manually into the drum. The discharge mechanism consists of a movable plate approximately 12" in diameter located in the centre of the drum bottom and a system of gears and levers actuated by a handle that adjust the angle of the fixed blade in the drum and move the bottom plate for discharge of the concrete. During normal mixing operations the movable plate lies flush with the drum bottom.

A wheelbarrow was used to receive the discharging concrete, the maximum vertical drop of concrete being 2½ feet. The rated capacity of the mixer is 2.5 cu. ft. The

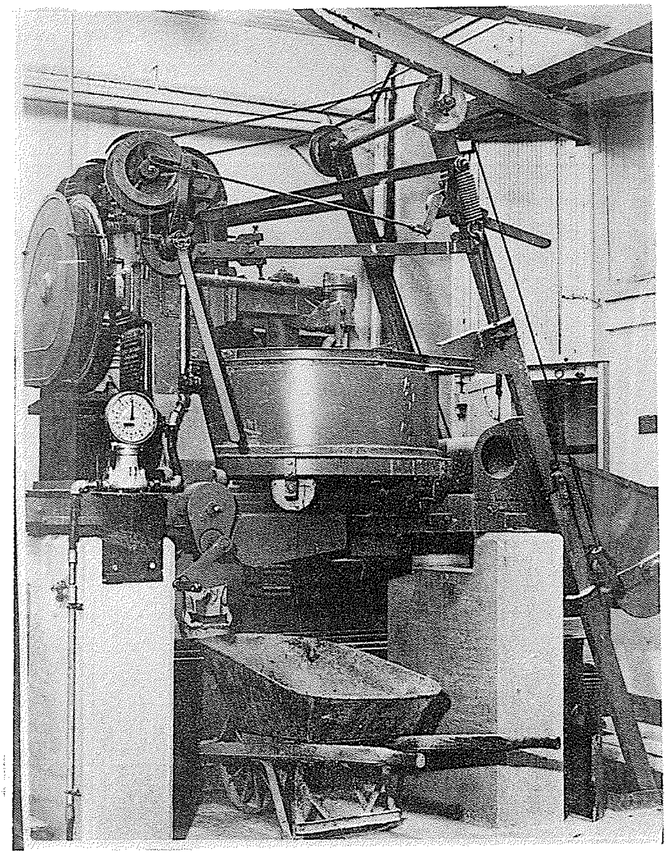


Fig. 2. Drum mixer with wheelbarrow in position to receive discharging concrete.

charging and mixing operations of the mixer were found to be quite satisfactory although the discharging operation was found to be somewhat deficient; a thin layer of mortar tended to be left sticking to the bottom of the drum after the discharge. Also during the initial wetting of the drum and blades before the charging operation, some water was retained at the bottom, and had to be mopped up. A sloping bottom might have solved this problem.

(b) Scales. Two platform scales were used for weighing out calculated quantities of coarse and fine aggregates and cement; tare weights of the containers for these materials were also taken into account. The scales were properly adjusted initially to eliminate zero error. A metering device was used to obtain the required quantity of water and this was initially checked against one of the scales.

(c) Moulds. Heavy steel moulds were used to cast Standard 6 x 12 inch cylinders to test the compressive strength of concrete. The moulds were fabricated from steel tubes with 5/16" wall thickness, split along one side and provided with bolts and wing nuts to close the split well enough to prevent any mortar loss. Provision was also made to secure bottom plates to the moulds, with the contact surfaces machined to ensure water-tightness. Mineral oil was used to coat the inner surfaces of the moulds before pouring concrete.

It was intended to mix two identical batches of concrete every time, one for early strength tests (18 - 22 hours), and the other for 3-day or later strength tests, for each of 3 variables involved plus the control specimens. Three test specimens for each variable were to be made, thus the total number of cylinders required at a time was 24 but since only 18 steel moulds were available, the control specimens had to be cast in standard cardboard moulds which were plentifully available in the laboratory. These were however completely unsuitable for repeated vibrations or steam curing. The cardboard was coated with wax and the moulds were completely waterproof.

To determine the extent of variation in the diameters of the test cylinders, a test batch consisting of six sets of 3 specimens each (i.e. a total of 18 cylinders) was subjected to careful measurements with the help of a pair of calipers and a steel scale. Readings were taken at three locations near the top, middle and bottom of each specimen, with two readings at right angles to each other at each location. The following table, summerizes the result:

TABLE V

DIAMETERS OF CONCRETE TEST CYLINDERS AND PERCENTAGE OF VARIATION OF CROSS SECTIONAL AREA FROM STANDARD.

Mould Used	Set	SpecimentNo.	Diameter, in. (Av. of six readings)	Cross Sectional Area, Sq. in.	Variation % of Cross Sectional Area.
Cardboard	A	(1)	6.00	28.3	0
		(2)	6.00	28.3	0
		(3)	6.00	28.3	0
Cardboard	B	(1)	6.00	28.3	0
		(2)	5.99	28.2	-0.35
		(3)	5.99	28.2	-0.35
Steel	C	(1)	5.99	28.2	-0.35
		(2)	6.00	28.3	0
		(3)	6.02	28.4	+0.35
Steel	D	(1)	5.98	28.1	-0.7
		(2)	6.00	28.3	0
		(3)	6.03	28.5	+0.7
Steel	E	(1)	6.00	28.3	0
		(2)	6.02	28.4	+0.35
		(3)	5.99	28.2	-0.35
Steel	F	(1)	6.00	28.3	0
		(2)	6.03	28.5	+0.7
		(3)	6.02	28.4	+0.35

Thus the maximum variation in the cross-sectional area of a specimen amounted to 0.7%, as compared to the specified standard cylinder having a 6" diameter. If this variation were overlooked, it would introduce a proportional error in the strength of a specimen; a maximum error of the order of 0.7% for a specimen and 0.35% for a set in the strength calculations is obviously insignificant when considering the appreciable variation that normally occurs due to a host of other factors in the strength tests for concrete. Hence all concrete specimens were assumed to have a diameter of 6", and their strengths were calculated on this basis during the present investigation.

(d) Vibrating Tables. Two box-shaped vibrating forms, (see Fig. 3) installed in the concrete laboratory, University of Manitoba, and used for casting reinforced concrete beams for flexure tests were adapted as table vibrators for the purpose of this investigation. The boxes have an open top and removable side plates.

They are 15" deep, 9" wide and have an overall length of 8' - 0". Each is mounted on four heavy springs anchored to bed plates cast in the foundations. The vibrating elements consist of two long steel shafts with eccentrically mounted weights, and rotated by a motor through V-belts and pulleys. The shafts are mounted on the underside of the tables and the eccentric weights are so adjusted that they counteract their effects in the horizontal plane but act simultaneously in the vertical plane. Thus the tables vibrate only in the vertical plane.

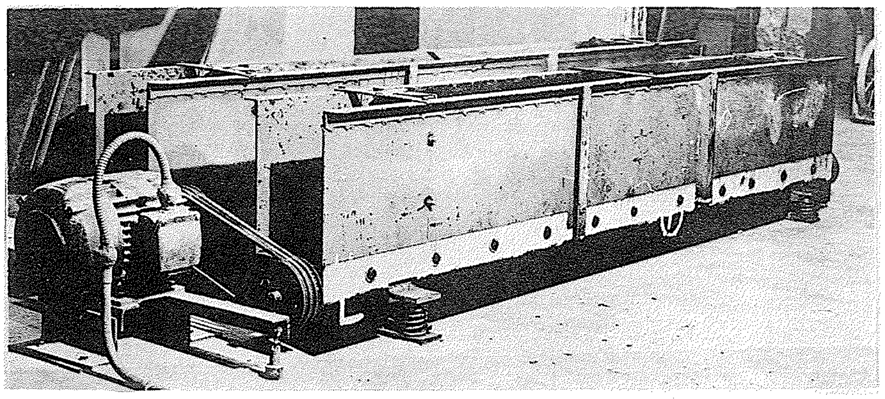


Fig. 3 Vibrating tables used for initial compaction of test cylinders as well as revibration.

Two sets of three cylinders each could be vibrated at a time in either of the vibrating tables. The moulds were placed inside the box in sets on either side of the vibrating table. The moulds rested on top of three layers of plywood pieces cut to size. A 2" x 2" timber piece 2' - 6" long was placed along the top edges of a set of moulds and pressed down firmly with the help of 2 cross pieces made of heavy angle-sections and clamped down to the top edge-angles of the vibrating form by four heavy duty C-clamps. This arrangement (see Fig. 4) proved quite satisfactory in keeping the moulds fixed to the vibrating tables during initial vibration at the time of casting, and for revibration. Occasionally the clamps worked loose, especially during prolonged periods of revibration, and the pieces had to be re-arranged and the clamps secured more tightly.

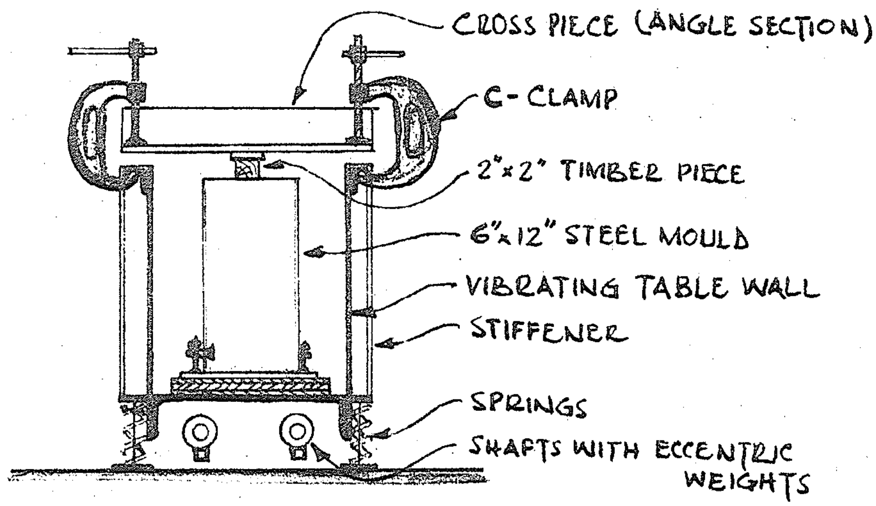


Fig. 4 Arrangement used to fix steel moulds to vibrating table.

The Westinghouse motor, installed for operating the vibrating tables, had the following specification shown on the identification plate:-

H.P. = 5; Phase = 3, Cycles = 60, Volts = 205/220/240

Amps = 13.9/13.2/6.6; RPM = 3500.

Equipment used to evaluate the frequency, amplitude and acceleration of the vibrating tables consisted essentially of a displacement transducer, a D.C. battery and a cathode ray oscilloscope. (see Fig. 5 and Fig. 6)

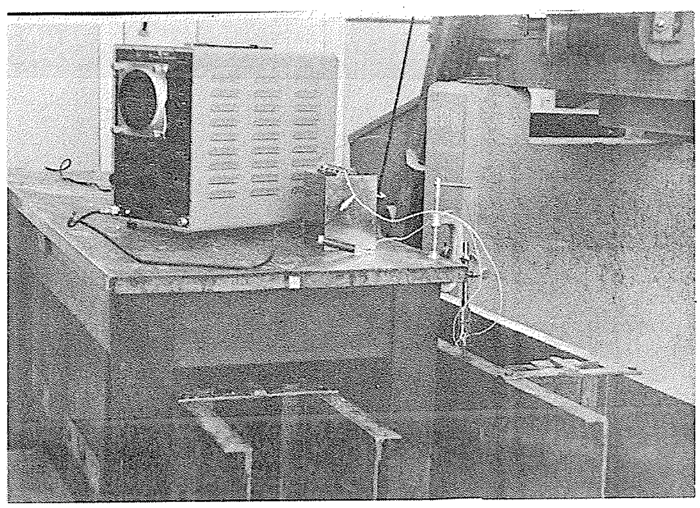


Fig. 5. General arrangement of equipment used to determine frequency, amplitude and acceleration of vibrating tables.

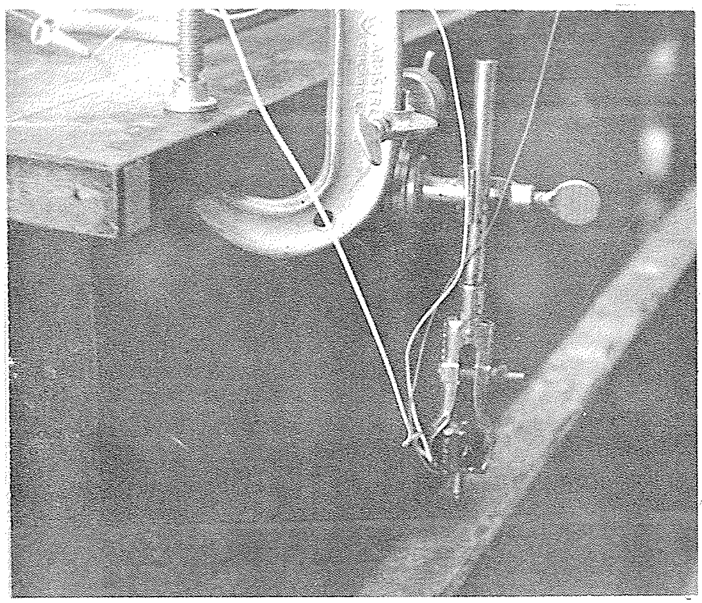


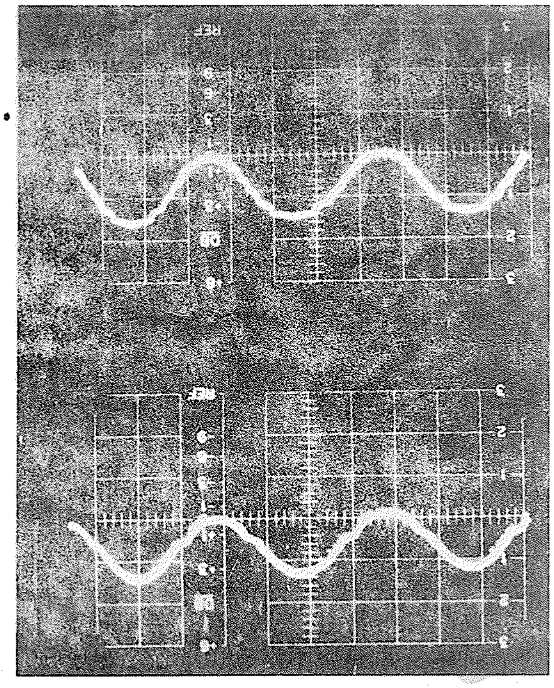
Fig. 6 Detail showing transducer positioned for taking displacement readings.

The set up was initially calibrated to determine the oscilloscope constants corresponding to a known displacement of the transducer shaft as shown by a dial gauge. These were then used to calculate the frequency, amplitude and acceleration of the vibrating tables at three different locations each, for various conditions of loads during vibration. This was done using characteristics of the wave forms as registered on the oscilloscope screen. The wave forms were also recorded photographically with the help of a Polaroid Land camera; a typical result is shown in Fig. 7. The loads consisted of 2 sets of 3 moulds each, full of fresh concrete and designated as A and B. Load A was the one positioned on the left-hand side of the vibrating tables, and Load B was that positioned on the right hand side. Concrete with typical mix proportions as used for batches with a 0.4 water -cement ratio was utilized for these tests. The nearside vibrating table was designated No. I and the farside No. II. The result obtained can be summarised as shown in Table VI.

TABLE VI

AMPLITUDE OF VIBRATING TABLES AT THREE LOCATIONS UNDER VARYING LOAD CONDITIONS.

	Load Condition	Vibrating Table No.	Amplitude, ins. Left Side	Centre	Right Side
1	Both A & B	I	0.028	0.034	0.028
2	Load A only	I	0.023	0.032	0.034
3	Load B only	I	0.028	0.025	0.023
4	No Load	I	0.031	0.033	0.032
5	No Load	II	0.028	0.036	0.036



(a) Wave form corresponding to vibration of right side of table, Load Condition No. 2, Table VI.

(b) Wave form corresponding to vibration at centre of table, Load Condition No. 2, Table VI.

Fig. 7 Characteristic wave forms registered on oscilloscope screen due to operation of vibrating table No. I.

Characteristics of Vibrating Tables I and II:

Frequency	= 3000 vibrations/min.
Minimum Acceleration	= 6 g.
Maximum Acceleration	= 9 g.

It appears that when both A & B loads are used, the amplitude of vibration is maximum in the centre. This is probably due to the fact that since the vibrating tables are supported at the ends, the middle undergoes extra flexural deflection caused by the loads and their inertial momentum during vibration. When a load is placed on one side only, it seems to have a dampening effect on the loaded end; consequently the magnitude of vibration is less on that end and more on the unloaded end. This also results in uneven vibration of the table.

Generally speaking, both the vibrating tables appeared to behave similarly during operation and maintained a fairly constant frequency of 3000 vibrations/minute. The vibrating tables were fabricated in a way that neither the frequency nor the amplitude of vibration could be changed readily. Hence this constituted another constant during this investigation. The values of the frequency and amplitude are such that they seem to be ideal for this type of set up as recommended by various investigators in this field (7), (11), (15).

(e) Steam Curing Chest. Certain sets of test specimens were required to be subjected to low pressure steam curing and this was carried out either in the vibrating table forms or in a wooden steam curing chest specifically rigged up for this purpose.

Vibrating Table II was lined with a special polythene sheet and the specimens that required low pressure steam curing and delayed revibration were placed on 3 layers of plywood and clamped firmly in place. More polythene sheeting was draped over the vibrating table forms to provide an enclosure for steam curing of the specimens. An outlet to drain the water due to steam condensation, and a steam hose to introduce the steam into the enclosure completed this set up. This obviated the need for removing the specimens from the steam chest and transferring them to the vibrating table everytime the specimens needed to be revibrated according to schedule.

The wooden steam chest, measuring 4' - 6" by 4' - 6" in plan and 1'-6" high, was essentially an open top shallow box covered with 2 layers of thick polythene. Enough openings were provided at the bottom to drain the condensation readily and a steam-hose provided an inlet for the steam. The steam chest could accomodate a maximum of 16 cylinders at a time for low pressure steam curing of the concrete specimens.

Both the steam enclosures were crude and unsatisfactory, and needed constant attention in order to regulate the desired temperature rise of $40^{\circ}F$ per hour and maintain the planned maximum temperature of $150^{\circ}F$ during the 13 hour steam curing period. Valves were provided on each of the steam lines and these had to be constantly adjusted; also the dissimiliar characteristics of the wooden steam chest and the steel vibrating form made things more difficult because different adjustments were needed for each. Although the ideal conditions of temperature rise and maximum temperature were seldom reproduced by the arrangements described above, it was felt that the discrepancy in most cases was not too drastic.

Constantine-iron thermo-couples were used to monitor the temperatures in the cylinders subjected to steam curing. These were embedded in two cylinders during the casting operations, one in a specimen to be subjected to steam curing and another in a specimen to be subjected to steam curing and delayed revibration. A similar junction, kept constantly immersed in melting ice at a known standard temperature of 32°F was used to complete the circuit as shown diagramatically in Fig. 8; the current generated was measured in milli-volts by the potentiometer.

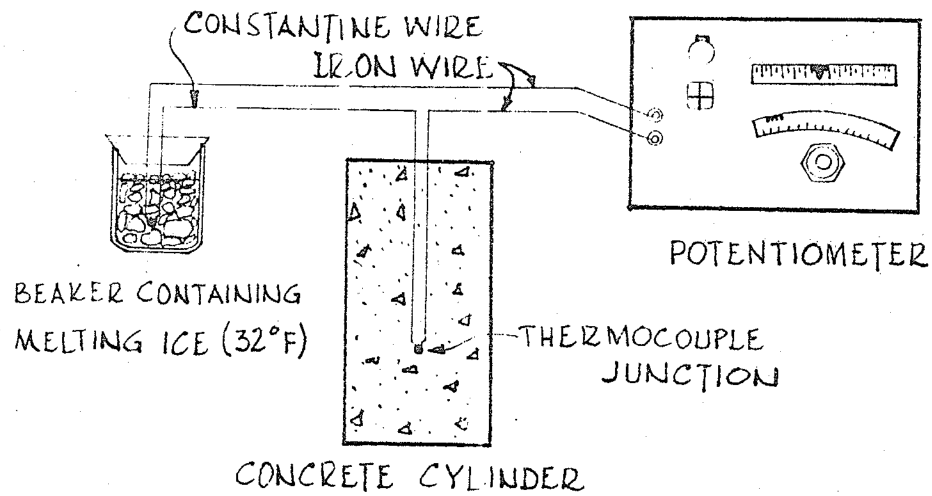


Fig. 8 Arrangement used for determining temperature inside a concrete cylinder.

The temperature of the specimen was determined from a chart showing values of temperatures corresponding to values of current in milli-volts as recorded by the potentiometer. The set up was initially celibrated using known temperatures of the hot junction.

During preliminary investigations, a batch of test specimens subjected to curing in the steam chest was closely monitored to determine the ease and extent to which the temperature rise could be controlled and the maximum temperature maintained.

The following table shows the results of this trial:

TABLE VII

TEMPERATURE RECORD OF A STANDARD CONCRETE CYLINDER SUBJECTED TO STEAM CURING.

Time Sequence	Ideal Temperature Required (°F)	Actual Temperature Recorded (°F)
At start of steaming	-	72
after 0 hr.-15 min.	82	82
0 - 30	92	91
1 - 0	112	126
1 - 15	122	134
1 - 30	132	140
1 - 45	142	146
2 - 0	150	151
3 - 0	150	152
--------	-------	------
--------	-------	------
12 - 45	150	153
13 - 0	150	150

The desired ideal was a temperature rise of $40^{o}F/hr.$ up to a maximum of $150^{o}F$, which was to be maintained for the rest of the steam curing period of 13 hours. This is in accordance with the recommendations of Hanson in his paper (2) "Optimum Steam Curing Procedure in Precasting Plants". As evident from Table VII, the actual behavior of temperature rise and maximum reached differed from the planned ideal, in spite of constant adjustments of the valve controlling the entry of steam. The following were the probable reasons: (a) Since the thermocouple junction was embedded approximately in the centre of the concrete cylinder, a time-lag took place before the effect of any adjustment of the ambient temperature could be registered at its core. Thus any tendency to exceed or fall short of a desired value could not be corrected until the error had been registered; also whether enough corrective adjustment had been made could not be ascertained until the situation had stabalized. (b) The steam chest was not very well insulated and therefore subject to external conditions which were somewhat changeable and not subject to immediate control. (c) The source of steam supply was a centralized steam generating plant for the whole University Campus, located quite far from the concrete laboratory. The long distance involved and the low production of steam due to a greatly reduced demand at night, when most of the steam curing process had to be scheduled, caused a somewhat erratic supply of steam in the concrete laboratory. (d) The error was compounded by the fact that part of the temperature recorded was due to heat evolved during chemical reactions of setting cement, the magnitude of which was unknown.

An attempt was made specifically to determine whether the presence of thermocouple wires in a test specimen, or its proximity to the steam inlet affected its compressive strength in any way. Five different batches were cast, all with 0.4 water/cement ratios and 1:4 cement/aggregate ratios but with varying percentages of sand in the aggregate, as part of the preliminary investigations. Thermocouple junctions were embedded in one specimen each, from the three different sets, and the specimens were arranged in the steam chest as shown in Fig. 9. The sets are indicated by letters A, B, C, D, & E, and the specimens in each set are identified by the numbers 1, 2 & 3.

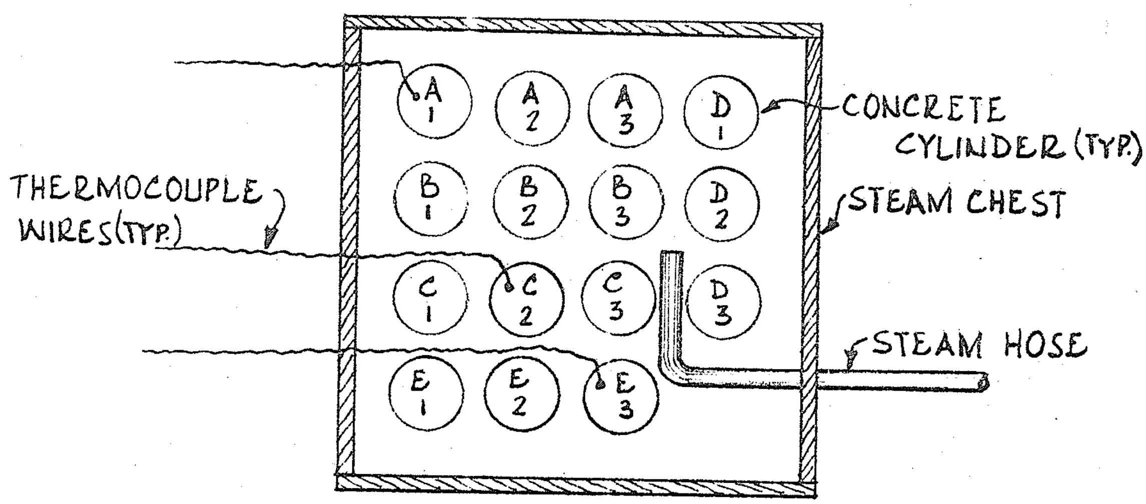


Fig. 9 Arrangement of test cylinders in steam chest during steam curing period.

TABLE VIII

7 DAY COMPRESSIVE STRENGTH OF CONCRETE CYLINDERS

% Sand in Aggregate	No / Set	Strength of Specimen,PSI 1	2	3	Average Strength,PSI
48	A	6630*	6550	6740	6640
49	B	6860	6520	6270	6550
50	C	6100	6690*	6270	6350
51	D	5890	5850	5850	5860
52	E	6140	5940	6100*	6060

(* Indicate specimens with thermocouple wires).

From the above results, it can be concluded that no gain in strength is necessarily involved due to the presence of thermocouple wires in the test specimens; this was borne out by a similar review of the results of other batches also.(All such specimens in the final investigation have been marked). A similar conclusion can be arrived at with regard to the proximity of the specimens to the steam inlet; no definite pattern is indicated in the strength of specimens nearest to the steam inlet when compared to the strengths of the other specimens in the same set. Thus these factors were ignored when comparing the results of cylinder tests in this investigation.

(f) Fog Curing Room. A fog curing room was provided adjacent to the concrete laboratory, for moist curing of concrete test specimens. The room measures approximately 10'-0"x 6'-0" by 10'-0" high and has slatted wooden racks for storing small test specimens. It provides 100% humidity in accordance with the requirements of A.S.T.M. specification: C192-47T. Due to the limited storage available and the demands of other users of the laboratory, many test specimens for this investigation had to be moved out much before their scheduled testing time and stored in the open laboratory. Whenever this was necessitated, sets representing different variables were moved out of the humidity room as a batch, so that all the sets in a batch would be subjected to the same type of conditions. Thus although storage conditions were uniform for specimens of the same batch, they were not necessarily uniform from batch to batch in the same series.

(g) Capping Stand. The jig used for capping test cylinders was a simple device consisting of a base-plate and a vertical guide welded to it. The base-plate had a shallow tapering recess with a machined bottom to act as a mould for the sulphur cap. A standard concrete cylinder when butted against the vertical guide was easily centered over the recess with its axis at right angles to the plane of the bottom machined surface. The recess was coated with oil to prevent the sulphur cap from adhering to it. This arrangement was quite satisfactory except when air bubbles were trapped under the concrete cylinder while being lowered into the molten sulphur in the mould; the air bubbles caused cap failure during loading of the cylinder and the results obtained for such specimens were invariably lower than other specimens in the same set with non-defective caps.

(h) Testing Machine. A Forney Testing Machine, capacity 300,000 lb., was used throughout for determining the crushing strength of the concrete cylinders cast during this investigation. Each cylinder was placed on the lower movable platen (see Fig. 10) and the load applied hydraulically; the upper platen was spherically seated. Two dial gauges were provided to register the loads, one for a low range of values and the other for a higher range, and each equipped with a dummy pointer to indicate the maximum load reached.

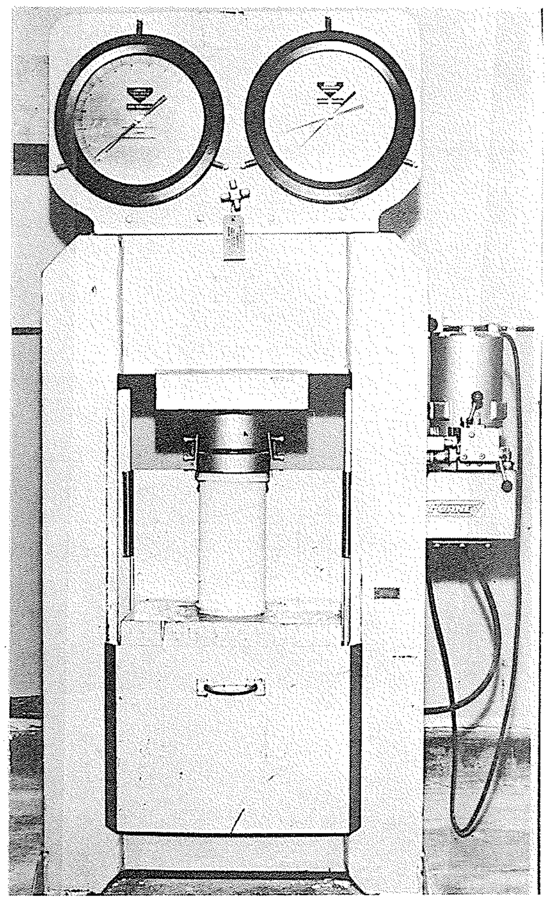


Fig. 10 Forney Testing Machine used for compression tests of Standard Concrete Cylinders.

The design and operation of the machine conformed to A.S.T.M. Specifications: C39-44 and E4. The machine was usually operated to give a uniform rate of loading of approximately 40 PSI/Sec.

CHAPTER IV

TEST PROCEDURES

The procedures used in this investigation were based on current good practice in mixing and placing of concrete and on the findings and recommendations of researchers[1] [2] [7] [8] with regard to specialized processes that have not yet been universally adopted by the industry. The objective was to obtain consistent and accurate values, and thus to provide a fair basis for comparison and analysis of results. Ready and uniform availability of specified materials, and availability for use and reliable performance of equipment installed in the laboratory were presumed when formulating these procedures; unforseen circumstances, however, subsequently necessitated some modifications.

4.1 Outline Of Test Programme

An investigation of this nature involves a formidable number of variables and their combinations, and to research all of them fully would be practically impossible.

In order to bring the task within manageable proportions, objectives had to be defined, guidelines established, and suitable restrictions imposed. To give an idea of the vast number of variables involved, some of the important ones are enumerated below:

(a) Type of cement.

(b) Type of admixtures, if any, and their combinations.

(c) Type and grading of coarse aggregate.

(d) Type and grading of fine aggregate.

(e) Water-cement ratios (W/C ratios).

(f) Cement-aggregate ratios (C/A ratios).

(g) Fine aggregate/coarse aggregate ratios.

(h) Specified strength requirements.

(i) Specified slump requirements.

(j) Mixing and casting procedures.

(k) Moist curing procedures.

(l) Type of strength tests: Tensile, compressive, shear etc.

(m) Various other characteristic requirements: creep, shrinkage, modulus of elasticity, durability, etc.

(n) Type of steam curing: low pressure or high.

(o) Presteaming periods and duration of steam curing.

(p) Temperature rise rate and maximum temperatures.

(q) Alternative types of heat treatment.

(r) Amplitude, frequency and acceleration of vibrations.

(s) Periodicity and duration of vibrations.

(t) Numerous combinations of the foregoing.

As mentioned in the introductory paragraph of Chapter III, some of the restrictions imposed on this investigation were due to the availability of specific types of materials in the locality, and of the equipment already installed in the laboratory. To limit the scope of this investigation, the following specifications were observed:-

1. Normal Portland Cement as specified in Section 3.1 (a), Chapter III.
2. No admixtures to be used in the concrete.
3. Type and grading of fine aggregate as specified in Section 3.1 (b), Chapter III.
4. Type and grading of coarse aggregate as specified in Section 3.1 (c), Chapter III.
5. Mix proportions as specified in Section 4.9.
6. Mixing and casting procedures as specified in Section 4.3.
7. Low pressure steam curing as specified in Section 4.5.
8. Vibrating equipment as specified in Chapter III, Section 3.2 (d), with frequency, amplitude and acceleration of vibration constant.
9. Testing equipment as specified in Chapter III, Section 3.2 (h).
10. Test procedure as specified in Section 4.7.

The following variables were considered for investigation in various combinations:-

1. Water/cement ratios.
2. Processes used on test specimens.
   - (A) Delayed revibration.
   - (B) Delayed revibration and steam curing.
   - (C) Steam curing.
   - (D) Normal air curing.
3. Intervals between and duration of delayed revibrations.
4. Age of test specimens.

The investigation consisted generally of first determining the proper concrete mix with the help of trial batches during preliminary investigations. Three specimens constituted a set, and four such sets were usually cast from one mix operation and designated as a batch. Each of the four sets forming a batch were subjected to different processes and conditions during the first 18 hours after casting: Set (A) was subjected to delayed revibration, Set (B) to delayed revibration and steam curing, Set (C) to steam curing only as specified herein, and Set (D) was the control set not subjected to any of the above processes and kept in the Laboratory at normal temperatures of between 72^{o} - 75^{o}F.

Subsequently, either the sets were tested for 18 hour strength, or all of them stored under the same conditions of temperature and humidity until tested at a specific age. Usually two similar batches were cast one after another for testing at different ages. The test results were finally tabulated and analyzed. Standard concrete cylinders, 6" diameter x 12" high were used as test specimens.

4.2 Identification And Arrangement of Test Specimens.

Each individual mould was identifiable by a tag bearing the set designation: A, B, C or D, and the specimen number (1), (2) or (3). Batches of concrete were numbered 1, 2, 3----39 etc., in the same consecutive order as they were mixed in the concrete mixer.

For a major portion of this investigation the sets were designated as follows:

Sets Subjected to:	1st Batch (for early strength test)	2nd Batch (for later strength test)
Revibration only...............	A_1	A_2
Revibration and steam curing...	B_1	B_2
Steam curing only	C_1	C_2
Normal air curing only	D_1	D_2

When casting the specimens, compaction of the concrete was achieved by an initial vibration lasting 2 minutes (unless otherwise indicated on the Casting Report) on vibrating table No. I only. The sets and specimens were always positioned in the same order during this operation as illustrated by Table IX.

TABLE IX

ARRANGEMENT OF MOULDS ON VIBRATING TABLE I
FOR COMPACTION OF CONCRETE DURING CASTING.

Batch Sequence	Casting Sequence	Position on Vibrating Table: Left Hand Side			Position on Vibrating Table: Right Hand Side		
1	1	A_1 (1)	A_1 (2)	A_1 (3)	B_1 (1)	B_1 (2)	B_1 (3)
	2	C_1 (1)	C_1 (2)	C_1 (3)	D_1 (1)	D_1 (2)	D_1 (3)
2	1	A_2 (1)	A_2 (2)	A_2 (3)	B_2 (1)	B_2 (2)	B_2 (3)
	2	C_2 (1)	C_2 (2)	C_2 (3)	D_2 (1)	D_2 (2)	D_2 (3)

A similar system was adopted also for the revibration and steam curing cycles. After casting the eight sets from two batches mixed in rapid succession, Sets A_1 & A_2 (to be revibrated only) were clamped in vibrating Table I, Sets B_1 & B_2 which were to be revibrated and subjected to steam curing were enshrouded with polythene sheets and clamped in vibrating Table II, and Sets C_1 & C_2 were placed in the steam curing box and covered with polythene top sheets, but without the steam valve turned on.

Sets D_1 & D_2 were stored in a corner of the laboratory, covered with a polythene sheet and left undisturbed during the initial 18-hour period after casting; these constituted the control sets as mentioned earlier.

Thermocouple junctions were invariably embedded in specimens $B_1(2)$ and $C_2(1)$ during casting, and the thermocouples were later used during the steam curing period to monitor the temperatures of the cylinders in the steam chest and the vibrating form adapted for steam curing.

Identification as to batch, set and specimen number was printed in indelible ink on top and side of each concrete cylinder as soon as it was stripped from the mould; this helped in avoiding any confusion or mistakes at the time of testing.

Note: Set designation A_1, A_2, B_1, B_2 etc. as given here have been rationalized for the purpose of this report. During actual casting operations, set designations used were: A, B, C, D, E, F, G & H, and the following relationship exists between the old and the new designations respectively: $A = A_1$; $B = B_1$, $C = A_2$; $D = B_2$; $E = C_1$; $F = C_2$; $G = D_1$, and $H = D_2$

4.3 Mixing And Casting Procedure.

To maintain quality control over the concrete, a standard mixing and casting procedure was drawn up during the planning stage which was adhered to rigidly during actual operations; this also insured efficiency of performance and elimination of errors. This procedure was posted as follows:

1. Make sure the concrete mixer is in a clean condition and operates normally.
2. Have the steel moulds cleaned and ready for use by coating their inner surface with heavy machine oil.
3. Arrange the moulds in their proper order by sets and specimens. Clamp sets A_1 & B_1 on vibrating Table I to be followed by sets C_1 & D_1 for casting as first batch. The second batch will consist of sets A_2 & B_2, in the order specified, and shown in Table IX, to be followed by sets C_2 & D_2 similarly arranged.
4. Have thermocouple junctions ready in moulds $B_1(2)$ and $C_2(1)$.
5. Weigh out the required quantities of coarse and fine aggregates, cement and water in the respective containers designated for each material, due account being taken of the tare weights as marked on them. Use the "Tally Sheet" to make up the number of times each container is used for depositing materials in the charging bucket.
6. Deposit the coarse aggregate first in the charging bucket, and sandwich the cement between layers of sand on top of the gravel.
7. Wet the wheelbarrow, scoops, shovel, trowel and the slump test equipment, and drain off any excess water.
8. Position the wheelbarrow directly under the discharge hole.

9. Wipe the drum and blades of the mixer with a damp cloth.
10. Start the concrete mixer and charge it with the materials previously deposited in the charging bucket.
11. Let dry mixing continue for two minutes.
12. Add the previously weighed out mixing water in a slow continuous stream taking one minute for this operation.
13. Let the wet mixing take place for two minutes more, so that a total of 5 minutes elapse after the mixer is charged.
14. The concrete discharged into the wheelbarrow should be remixed with the shovel provided.
15. Perform the slump test.
16. Fill the moulds clamped in the vibrating table with concrete. For compaction start the vibrator and keep it on for 2 minutes, in the meantime making good any subsidence in the level of concrete in the moulds.
17. Unclamp the moulds, strike off the top surface of the concrete with a trowel and store the specimens under a polythene sheet in a corner of the laboratory.
18. Clamp sets C_1 & D_1 next. Cast and store them in the same way as sets A_1 & B_1 above.
19. Clean the vibrating table and drum mixer of all concrete left from this batch and dispose of it outside the laboratory in the manner provided.

20. Clamp sets A_2 & B_2 in the vibrating table and repeat the above cycle of mixing and casting for the 2nd batch also.

21. After the final casting for the day, hose down the mixing drum and blades with plenty of water and wash thoroughly all the equipment including wheelbarrow, trowels etc. used for these operations.

4.4 Vibrating and Revibrating Procedures.

In this investigation, vibration of concrete refers to that used for initial compaction only during the process of casting the test specimens. For this purpose use was made of vibrating Table I with the moulds firmly clamped to it as explained in Chapter III. The initial compaction was generally achieved by operating the vibrating table for a period of 2 minutes; in the case of some batches with high water-cement ratios where segregation became evident, the duration of vibration was limited to one minute; it is so indicated in the Casting Reports. (see Appendix A.) Thus all the sets in a batch, (including the control set) were subjected to the same condition of vibration for the purpose of achieving compaction of concrete and elimination of air voids.

As distinct from the initial vibration used during casting for the purpose of achieving satisfactory compaction, revibration refers to delayed and repeated vibration to which some of the concrete specimens were subjected after casting. Revibration was one of the most important variables used in this investigation and it was varied in terms of duration as well as interval between vibrations. Duration of revibration refers to the length of time for which the specimens were again vibrated continuously at any one application; this ranged from $\frac{1}{2}$ minute up to 8 minutes, but the greatest number of specimens made were for a revibration time of 2 minutes. The revibrations were repeated at specified intervals during the initial period of 18 hours, the intervals between vibrations generally varying from one hour to four hours depending on the vibration characteristics specified for a particular batch. Every batch in this series is distinguished by its vibration characteristics: thus 2 minutes at 4 hr. means that the sets subject to revibration were vibrated for a period of 2 minutes each at intervals of 4 hours during the first 18 hours after casting. The following table lists the revibration characteristics investigated:

TABLE X

REVIB. CHARACTERISTICS PERTAINING TO DIFFERENT BATCHES

Revibration Characteristics	Batch Nos.
1/2 min. at 4 hours	18 to 21
2 min. at 1 hour	15 to 17
2 min. at 1 hour for first 5 hours only	26, 27
2 min. at 1 hour for last 3 hours only	28, 29
2 min. at 4 hours	9 to 14, 30 to 37
4 min. at hours	38, 39
8 min. at 4 hours	22 to 25

It will be noticed that a variation was introduced in the case of Batches 26 to 29: Batches 26 & 27 had revibration characteristics of 2 min. at 1 hr. for the first five hours only, where the relevant sets were revibrated for a period of 2 minutes each every hour for the first five hours only after casting; also Batches 28 & 29 had sets which were revibrated for 2 minutes each at hourly intervals during the last 3 hours only of the 18 hour period after casting. In comparison with sets having revibration characteristics of 2 min. at 1 hr. for the full 18 hour period after casting, these batches were intended to show whether any significant increase in strength took place due to an earlier or later revibration.

Batch 17 was cast with five sets, each revibrated once only for 2 minutes, but after an interval of 1, 3, 6, 10 and 16 hours respectively after casting; the control set was not revibrated at all. This last set was a case of delayed revibration rather than repeated revibration.

4.5 Low Pressure Steam Curing.

Each typical batch contained a set of specimens subjected to steam curing only, designated Set C, and another set subjected to both revibration and steam curing, designated Set D.

The steam curing cycle involved a presteam period of 5 hours, followed by a steam curing period of 13 hours during which the specimens were subjected to steam at atmospheric pressure. The admission of steam was regulated to achieve a temperature rise of 40°F per hour in the specimens up to a maximum of 150°F; this was to be maintained for the rest of the steam curing period. The presteam period and specifications regarding temperature rise and maximum temperature are in accordance with the recommendations of Hanson[2] and others[(1), (4), (5), (28) et al]; these are accepted and widely practised by the precast concrete industry with slight modifications.

As described in detail in Chapter III, the regulation of steam was achieved by manual controls, which, although not very precise, generally gave values within acceptable limits. The sets intended for steam curing alone, generally C1 & C2 were transferred to the steam curing box immediately after casting, covered with the polyethylene top sheet and allowed to stand for 5 hours. Sets B1 and B2 subject to revibration and steam curing, were generally clamped to vibrating Table II immediately after casting and also covered with polyethylene to undergo a presteam period of 5 hours. At the end of this period, the temperature of the specimens was noted and steam admitted into the steam curing box as well as into vibrating Table II converted into a steam curing enclosure; the entry of steam was regulated to obtain the desired temperature rise ($40^{o}F$ per hour) and the maximum temperature ($150^{o}F$). The temperatures were initially monitored every 15 minutes to check the rate of temperature rise, but after the maximum was reached, the interval between temperature checks was extended to half and then one hour. Steam was shut off after 13 hours of steam curing.

The end of steam curing also marked the end of the 18 hour period after casting; during this period, the specimens so required were also reviberated; after this period no physical operations were performed on the specimens and they were either tested immediately for early-strength tests or stored away for testing at later ages. Usually the first batch cast, consisting of sets A_1, B_1, C_1, & D_1 was intended for early strength tests and the second batch consisting of sets A_2, B_2, C_2, & D_2 was intended for testing at later ages.

Although it was originally desired to obtain 18-hour strengths of the specimens, practical difficulties involved in achieving this objective proved insurmountable; consequently most of the early strength values were for 20 - 22 hours. It was found impossible to perform 18-hour strength tests due to the time involved in stripping moulds from all the twelve specimens, capping and testing them one by one.

4.6 Storage And Moist Curing.

Batches planned for testing at later ages were stored away soon after the specimens were removed from the moulds and batch, set and specimen numbers were marked in indelible waterproof ink on their sides and tops; the latter was done to record the identity of each concrete cylinder and eliminate subsequent confusion or errors.

Initially it was planned to store the cylinders in the fog curing room until about six hours before their scheduled testing time when they would be removed for drying out and capping before being tested. However this plan proved impossible to implement due to the limited storage space available and the demands made on it by other users of the laboratory. Consequently many batches had to be removed from the fog curing room much ahead of the scheduled time; there were five batches which could not be accommodated at all in the fog curing room and had to be left in a corner of the laboratory under normal room conditions of temperature and humidity. Thus curing conditions were not constant from batch to batch during storage and account will have to be taken of this fact during evaluation of the results. However, precautions were taken to maintain uniform conditions for all the sets in the same batch by storing the whole batch as a unit under humid or dry conditions; this ensured that results of the various sets in a batch are comparable in every case.

4.7 Testing Procedure.

With the exception of the first four batches during initial trials, all concrete cylinders during preliminary and final investigations were capped before testing. Capping material used was mainly sulphur, and occasionally sulphur mixed with a black proprietary compound manufactured specifically for this purpose.

After removing the test specimens from the moulds at the end of the 18 hour period, those specimens designated for strength tests at 18 hours were capped immediately and subjected to compression tests. These specimens were usually tested at an age of 20 - 22 hours, due to delays in stripping, capping, allowing the caps to harden and testing them. The age of the test specimens was taken to be the mean age of the batch during compression tests.

Specimens to be tested at later ages were usually taken out of the fog curing chamber at least 6 hours ahead of time to allow them to dry out before capping, and the caps to harden before testing.

The specimens were usually tested batchwise and all remarks pertaining to the physical description of the specimens and their behaviour under loading were noted in "Test Report" forms at time of testing. Specifically the following information was noted:

(a) Identity of Specimen: Batch set and specimen markings.

(b) Test Age of Specimen: In terms of days and hours after casting.

(c) Description of Specimen:
   (i) Whether rough or smooth surface.
   (ii) Whether surface pock marked due to superficial air holes and greatest dimension of holes.
   (iii) Evidence of deep holes.
   (iv) Evidence of mortar loss.
   (v) Whether cap defective.

(d) Mode of failure:

   (i) Bond failure, when failure took place due to crushing of mortar only and the failure plane did not pass through the aggregate. This occurred in the case of specimens where the mortar had not developed sufficient strength due to lack of curing at early age.

(ii) Aggregate failure, where the plane of failure substantially passed through aggregates due to the cement mortar having attained sufficient strength to be at least as strong as the aggregates in the concrete mix.

(iii) Tension failure, when vertical splitting of the cylinder took place, usually accompanied by an explosive sound. This happened in the case of specimens with Convex surfaces top and/or bottom, or those possessing very high strengths.

(iv) Diagonal Shear, where the plane of failure was inclined at approximately 45^{o} to the longitudinal axis of the cylinder. This was the most common mode of failure.

(v) Cone or Wedge Shear, where top and/or bottom cone (or in some cases, wedge) formation was observed during the process of failure. Many specimens failed in this fashion.

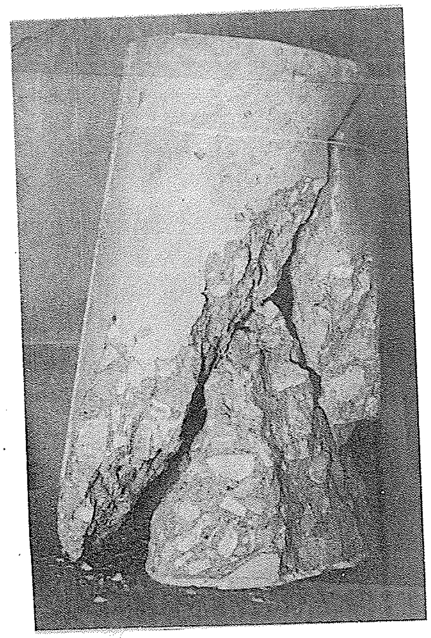
(vi) Edge failure, when just a small portion of the edge broke away, usually due to defective capping. After an apparent initial failure, the specimen was usually able to sustain more load until final failure. In some cases more than one cycle of partial failure and reloading took place.

(vii) Cracking, where a general cracking over the surface of the cylinder could be observed due to crushing of the mortar and/or aggregate.

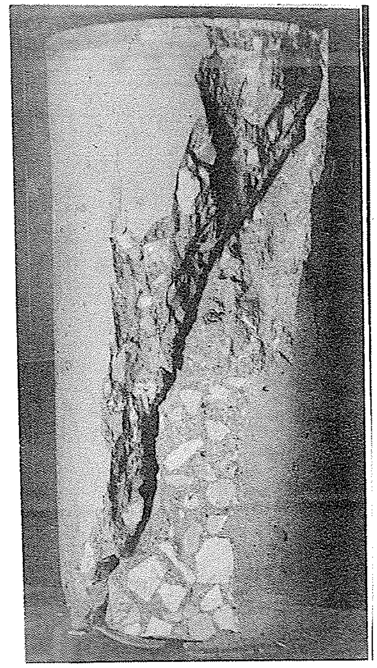
(e) Maximum Load at failure, to give the strength of the specimen under test.

(f) Storage Characteristics in the case of specimens tested at later ages to help in the proper evaluation of the strength test results.

Fig. 11 illustrates the various modes of failure of the test specimens mentioned above:

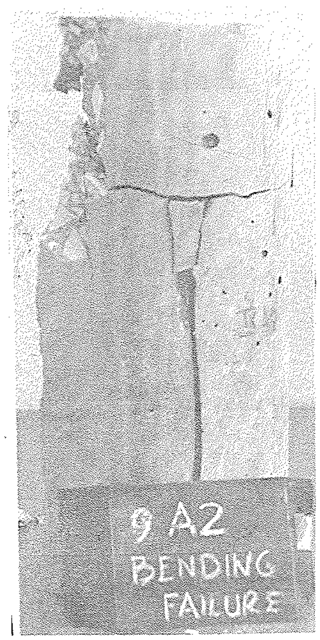


Failure involving cone formation.



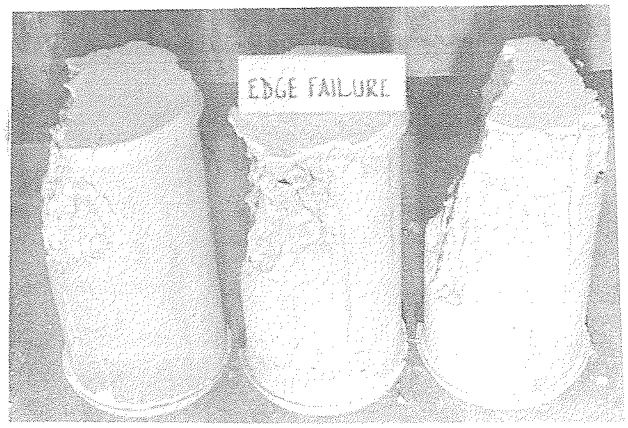
Diagonal shear failure.

Typical vertical split failure of a high strength test cylinder.

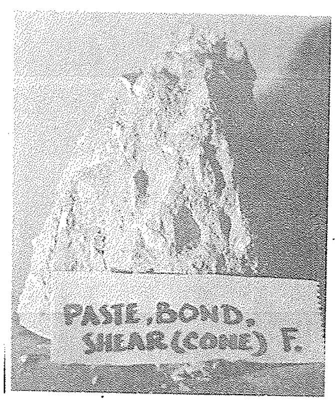


Tension failure due to bending.

Fig. 11 Mode of failure of concrete cylinders under compression.



Edge failure in test specimens.



Bond failure in mortar paste.

Close-up view showing bond-shear failure of cement mortar only; the aggregate is intact.

Fig. 11 (Contd.)

4.8 Preliminary Trials for Mix Design.

A preliminary investigation was undertaken to determine the most efficient mix design for concrete using the materials available locally and the equipment installed in the laboratory. The criteria for efficiency of the mix design were economy and high early strength necessary for precast concrete products. Apart from the normal factors affecting the strength of concrete, like the size and shape of coarse aggregate, grading of the fine and coarse aggregates, type of cement, efficiency of the mechanical mixer etc., an important factor in this investigation was the affect of the vibrating table used; this is a highly indeterminate quantity from the theoretical standpoint and hence resort to trial mixes was quite imperative. Also mix designs based on trial batches are a common practice in many situations: for example, on very large projects where a great cost saving could be realized with an economical mix, or for dam construction where peculiar features like the heat of hydration or the availability of unusual type of aggregates could be critical factors.

Reference may be made to Chapter III for detailed properties of the materials and the equipment used; earlier parts of this Chapter list the procedure followed for mixing and casting the concrete.

Given the basic constituents of concrete, namely cement, fine aggregate, coarse aggregate and water.

variables involved in the design of concrete mixes are:

(i) Water to cement ratio (W/C Ratio).

(ii) Cement to aggregate ratio (C/A Ratio).

and (iii) Fine Aggregate to coarse aggregate ratio:

Since it was the intention to ultimately investigate the effect of delayed revibration and steam on concrete conforming to various water-cement ratios, the preliminary trials were designed to evolve the best mix for each W/C ratio; for convenience these were selected as 0.3, 0.4, 0.5, and 0.6. The cement to aggregate ratios selected for investigation were: 1:4, 1:5, 1:5.5, 1:6 and 1:7. The percentages of sand (fine aggregate) in the total aggregate were selected as 48%, 49%, 50%, 51% and 52%.

Obviously a combination of all the variables involved in each of the three ratio-catagories would result in a total of 100 trial mixes; to research these would require an unrealistic expenditure of time and effort, just for the determination of optimum mixes. Consequently, the following procedure was followed during the preliminary investigation.

After completing Batch Nos. I to VI; and based on an assessment of the results obtained, it was decided to further curtail the preliminary investigation. The results of the 30 sets investigated were deemed significant enough to apply to other batches not so investigated.

Behaviour of the concrete in various combinations of its constituents as listed in Table XI is reproduced in graphical form in Figs. 12 & 13. Details of the preliminary investigation are given in the Appendix.

TABLE XI

CONCRETE MIXES USED FOR PRELIMINARY INVESTIGATION

Batch No.	Set No.	W/C Ratio	C/A Ratio	% Sand in Aggregate
I	1	0.6	1:4	50
	2	"	1:5	"
	3	"	1:5:5	"
	4	"	1:6	"
	5	"	1:7	"
II	1	0.6	1:4	48
	2	"	"	49
	3	"	"	50
	4	"	"	51
	5	"	"	52
III	1	0.3	1:4	48
	2	"	1:5	"
	3	"	1:5.5	"
	4	"	1:6	"
	5	"	1:7	"

TABLE XI (contd.)

Batch No.	Set No.	W/C Ratio	C/A Ratio	% Sand in Aggregate
IV	1	0.3	1:4	48
	2	"	"	49
	3	"	"	50
	4	"	"	51
	5	"	"	52
V	1	0.4	1:4	50
	2	"	1:5	"
	3	"	1.5.5	"
	4	"	1.6	"
	5	"	1.7	"
VI	1	0.4	1.4	48
	2	"	"	49
	3	"	"	50
	4	"	"	51
	5	"	"	52
VII	1	0.5	1:4	50
	2	"	1:5	"
	3	"	1:5.5	"
	4	"	1:6	"
	5	"	1:7	"
VIII	1	0.5	1:4	48
	2	"	"	49
	3	"	"	50
	4	"	"	51
	5	"	"	52

Conclusions. The following conclusions can be drawn from the curves in Figs. 12 & 13.

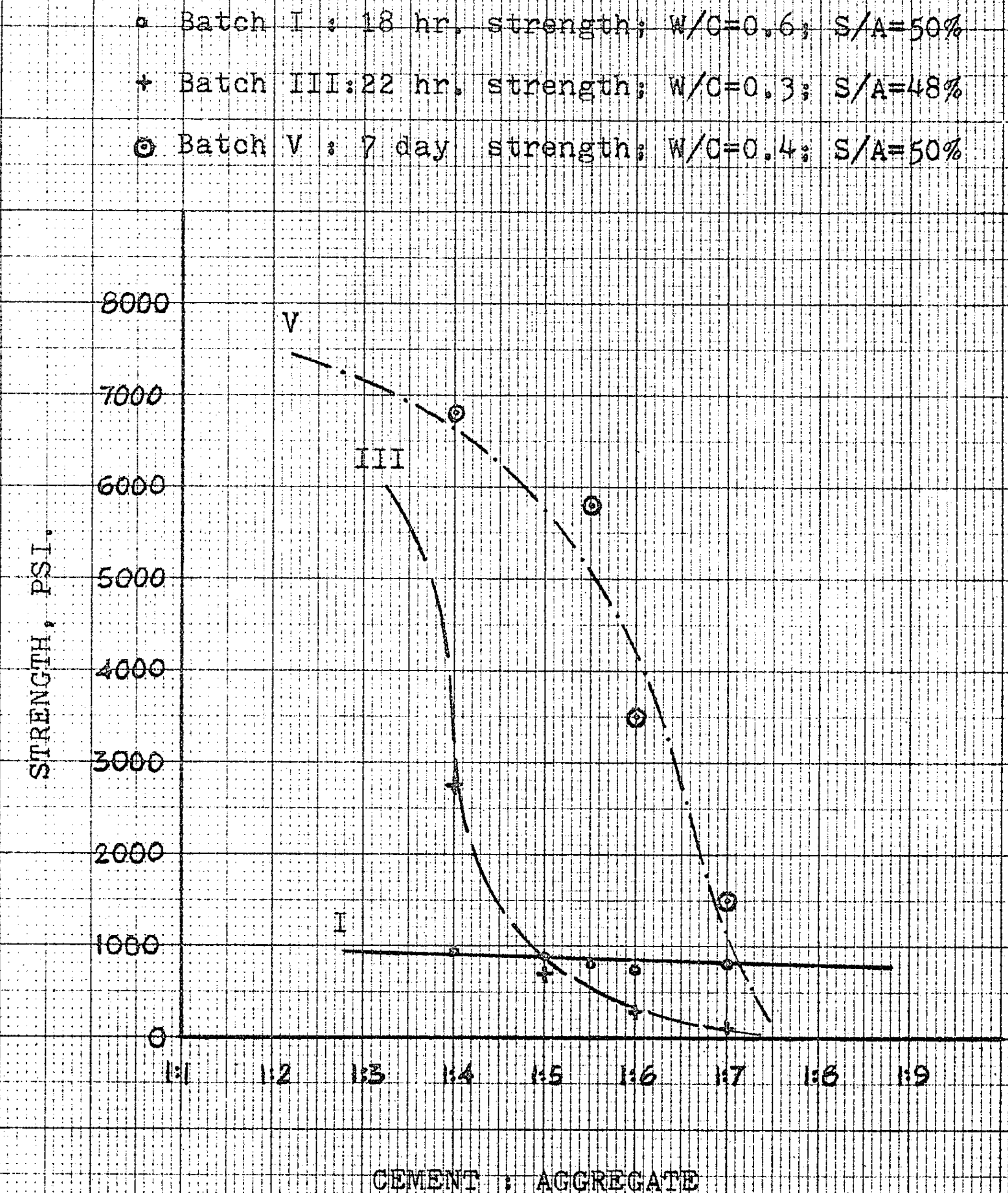


Fig. 12. Strength of Concrete Vs. Cement/Aggregate Ratio

	Batch	Strength	W/C Ratio	C/A Ratio
▫	II	18 hr.	0.6	1:4
x	IV	18 hr.	0.3	1:4
o	VI	7 day	0.4	1:4

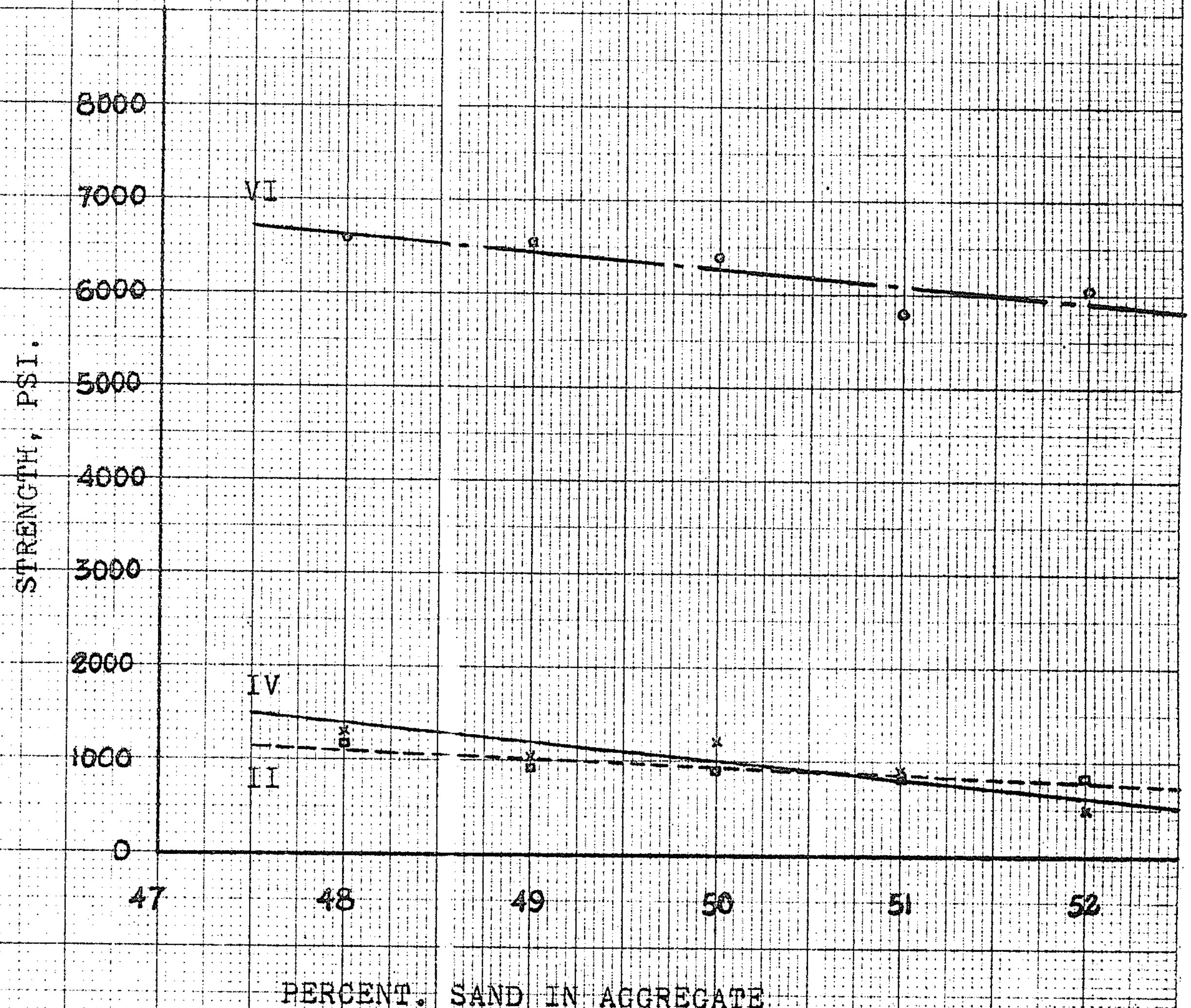


Fig. 13. Strength of Concrete Vs. Percentage of Sand in Aggregate.

1) The strength of concrete increases with decreasing proportion of aggregate in the cement: aggregate ratio. (Fig. 12).

2) This effect is much more marked in the case of concrete with water/cement ratio equal to 0.3 and 0.4 than with 0.6 (Fig. 12).

3) Curiously, early strength with higher aggregate proportion is observed to be lower in concrete having water/cement ratio = 0.3 than with W/C = 0.6. This is probably due to the fact that the available water was not sufficient to hydrate all the cement present and hence loss in strength.

4) Median strength values are found to be at or near cement/aggregate ratio of 1:5 (Fig. 12).

5) Strength increase is very rapid in mixes richer than 1:5. C/A ratio except for concrete with W/C ratio = 0.6 (Fig. 12).

6) A decrease in the strength of concrete is observed with increase in percentage of sand in the aggregate within the range investigated i.e. 48 - 52% (Fig. 13).

7) The loss in strength is not very appreciable at 7 days, being a maximum of 8%: but early age tests show a decrease in strength of up to 60%.

8) Median strength values seem to be at 50% sand proportion.

4.9 Final Mix Design.

On the basis of results obtained from the foregoing trials, it was deemed adequate to design just one mix for each W/C ratio to be investigated. The W/C ratios considered for this purpose were 0.4, 0.5 and 0.6. Table XII shows the mixes used in this investigation.

TABLE XII

CONCRETE MIXES USED FOR FINAL INVESTIGATION

No.	W/C Ratio	% Sand in Aggregate	C:A Ratio
1	0.4	48	1:4
2	0.5	49	1:4
3	0.6	50	1:4

Certain batches had to be cast immediately after a fresh lot of sand was delivered to the laboratory; since it had no time to dry out, its moisture content had to be accounted for, and the water/cement ratio of the batch was consequently not the same as intended. Batches so affected are numbered 12, 17, 34 and 35 and their characteristics have been noted in Appendix A and in Table XIII.

Mixes with W/C ratio = 0.6 were also adjusted to account for the moisture content in the fine and coarse aggregates as determined by laboratory tests.

The following are the actual weights of constituents used for casting the principal concrete mixes. Concrete thus obtained was enough to make 12 cylinders: i.e. 4 sets of 3 cylinders each for each batch.

Mix No. 1:-	W/C Ratio	= 0.4
	C:A	= 1:4
	% Sand in aggregate	= 48
	Water	= 28 lbs.
	Cement	= 70 "
	Sand	= 134.4 lbs.
	Gravel	= 145.6 "
Mix No. 2:-	W/C Ratio	= 0.5
	C:A	= 1:4
	% Sand in aggregate	= 49
	Water	= 34 lbs.
	Cement	= 68 "
	Sand	= 133.3"
	Gravel	= 138.7"
Mix No. 3:-	W/C Ratio	= 0.6
	C:A	= 1:4
	% Sand in aggregate	= 50
	Water	= 34.6

Cement	= 67.84.	
Sand	= 140.0	Moisture Content = 3%
Gravel	= 137.4	Moisture Content = 1%

CHAPTER V

TEST RESULTS

5.1 Summary of Test Results Obtained:

Results of all the tests conducted in the final part of the investigation are given in Table XIII. They are listed batchwise starting from Batch No. 9. Batches No. 1 to 8 were investigated during preliminary trials described in Chapter IV.

5.2 Average Values:

The values given in Table XIII are based generally on an average of three test cylinders. However test results of some cylinders had to be rejected because of the following conditions:

a) Defective Capping: Due to the presence of an air pocket in the cap or unevenness of the surface, crushing of the cap took place in some specimens during compression tests accompanied by edge failure of the concrete cylinder. The characteristic noted was that only a small part of the cylinder sheared off (see Fig. 14) resulting in a rapid

TABLE XIII

AVERAGE COMPRESSIVE STRENGTH OF CONCRETE CYLINDERS: (PSI)
SUMMARY OF FINAL INVESTIGATION

Batch No.	Vib. Characteristics	W/C Ratio	Test Age Hrs.	Revib. A	Revib. & Steamed B	Steamed C	Air Cured D
9	2 min. at 4 hrs.	0.4	815	8450	8630	9230	8500
10	"	"	240	7080	6270	6430	7180
11	"	"	222	8100	7500	7250	7210
12	"	0.43	21	2740	5040	5060	2170
13	"	0.4	20	3060	5520	4830	2750
14	"	"	177	6660	6900	7200	6680
15	2 min. at 1 hr.	"	2080	*	*	8650	8310
16	"	"	2104	*	*	8280	7610
17	No revib.	0.5	2320	8220	-	-	-
"	2 min. after 1 hr.	"	"	7870	-	-	-
"	2 min. after 3 hrs.	"	"	8530	-	-	-
"	2 min. after 6 hrs.	"	"	7930	-	-	-
"	2 min. after 10 hrs.	"	"	7320	-	-	-
"	2 min. after 16 hrs.	"	"	7850	-	-	-
18	½ min. at 4 hrs.	0.4	20	2860	4920	4770	2570
19	"	"	79	5460	5750	6050	5600
20	"	"	168	5300	5930	6490	6900
21	"	"	668	4390	5840	6580	6450
22	8 min. at 4 hrs.	"	184	6540	6630	5890	6800

TABLE XIII (Contd.)

Batch No.	Vib. Characteristics	W/C Ratio	Test Age Hrs.	Revib. A	Revib. & Steamed B	Steamed C	Air Cured D
23	8 min. at 4 hrs.	0.4	667	6920	5750	5770	7650
24	"	"	20	1940	4050	4110	1750
25	"	"	1530	7200	7290	73708	7670
26	2 min. at 1 hr. for first 5 hrs. only	"	83	*	*	5990	5420
27	"	"	1770	*	*	8170	7530
28	2 min. at 1 hr. for last 3 hrs. only	"	1554	8270	8640	8750	-
	"	"	45	-	-	-	4880
29	"	"	1983	10,070	9650	9750	9650
30	2 min. at 4 hrs.	0.5	20	1350	3410	3250	860
31	"	"	82	3730	4040	3320	3380
32	"	"	242	5160	4230	4420	4720
33	"	"	666	4980	3770	5020	4940
34	"	0.45	22	2240	3710	4000	1730
35	"	"	665	5110	5230	4660	4730
36	"	0.6	20	2000	2850	3240	1900
37	"	"	666	5000	4300	4420	4520
38	4 min. at 4 hrs.	"	22	1690	2930	3000	1490
39	"	"	666	5500	4310	3950	5000

Note: * indicates results unreliable due to badly damaged cylinders.
- indicates results not applicable or not available.
Batches Nos. 1 to 8 were tested during preliminary investigation.

reduction of load on the indicator dial; a gradual build up of load usually took place again and sometimes the load reached at this stage was greater than that at first partial failure. In some cases this cycle was repeated several times. Invariably load at failure in these specimens was much lower than in normal ones failing by diagonal shear or cone shear. To exemplify this, results of Batch No. 34 are reproduced in Table XIV.

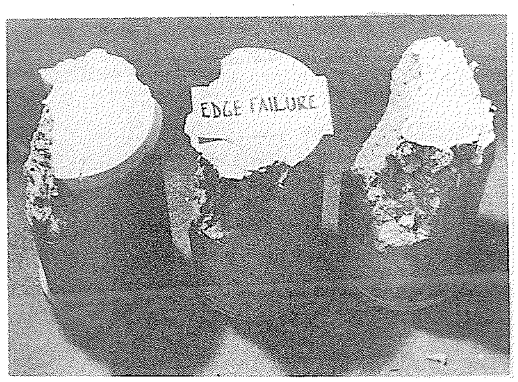


Fig. 14. Edge Failure
Due to Defective Capping.

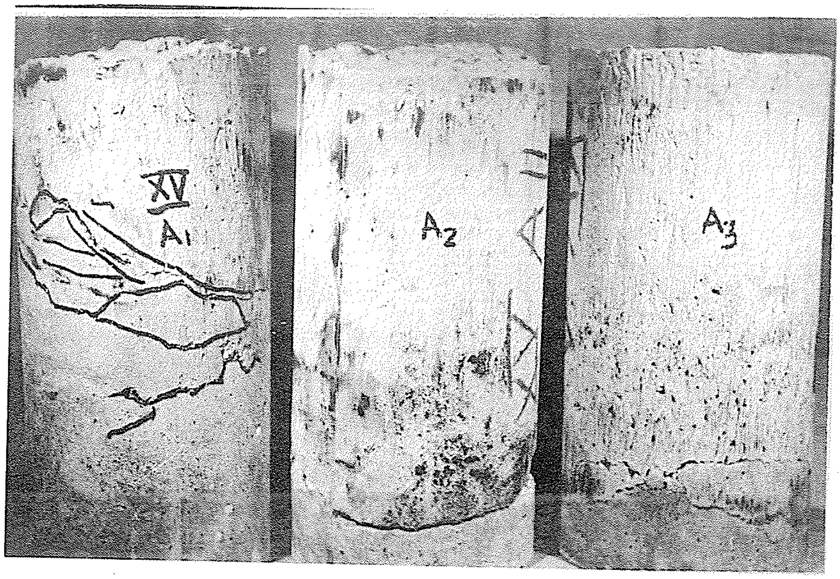
TABLE XIV

COMPRESSIVE STRENGTH OF CONCRETE: BATCH NO. 34

Set		No.	Mode of Failure	Cylinder Strength PSI	Av. Strength PSI
A	Revib.	1	Shear, cracking	2260	
		2	" "	2200	2240
		3	" "	2260	
B	Revib. & Steamed	1	Shear,	3450	
		2	Diag. Shear	3780	3710
		3	" "	3910	
C	Steamed	1	Diag. Shear	4040	
		2	" "	3960	4000
		3	Cap. Edge Failure	2040*	
D	Air Cured	1	Shear cracking	1660	
		2	" "	1780	1730
		3	" "	1760	

It is obvious from Table XIV, that the result of Specimen No. 3 in the Steamed Set (Set C) is not representative of that set and it would be unfair to use it for obtaining the average strength of the set. Hence all such values were rejected in the average evaluations, since to include them would have given erratic and misleading results. In some cases two out of three specimens failed in edge shear and the strength of the set had to be based on the value of the single good specimen.

b) Damage in Test Cylinders: Signs of extensive damage in some test cylinders were indicated by the presence of fissures or cracks on the surface extending deep into the body of the cylinders. (see Fig. 15, (A) (B) (C)). In some cases the cracks extended right across the section with the cylinders broken into two or more pieces. (Fig. 15). This damage invariably occurred in cylinders subject to repeated revibration at frequent intervals usually in the first few hours after casting. Examples of this type of damage are Batches 15 & 16 with revibration characteristics of 2 min. every hour and Batches 26 & 27 with revibration characteristics of 2 min./1 hr. for the first 5 hours only. The conclusion about the adverse effect of frequent revibration in the first few hours after casting is substantiated by comparing results of Batches No. 9 etc. with revibration characteristics: 2 minutes at 4 hour intervals, and Batches 28 & 29, revibrated 2 minutes every hour during the last 3 hours only of the 18 hour cycle. Cylinders for these batches showed no cracks whatsoever. The damaged cylinders were also subjected to compressive strength tests but the results were too low and divergent to be useful as an indication of the true strength of the concrete. Therefore results of these specimens were also rejected in the final analysis.



(A)

(B)

(C)

Fig. 15. Revibration Cracks In Test Cylinders.

c) Miscellaneous Causes: Malfunction of the test machine, in either loading the specimens too suddenly or the platens bearing down on the cylinders at an angle, usually caused failures similar to edge failure. (Fig. 16). Sometimes tensile failure was also caused, evidenced by a horizontal crack near the middle of the cylinder (Fig. 17) accompanied by an abrupt drop in load. These tests were also rejected as being unrepresentative of the true indication of concrete strength. Quite often it was difficult to distinguish between this type of failure and the true edge failure as described earlier.

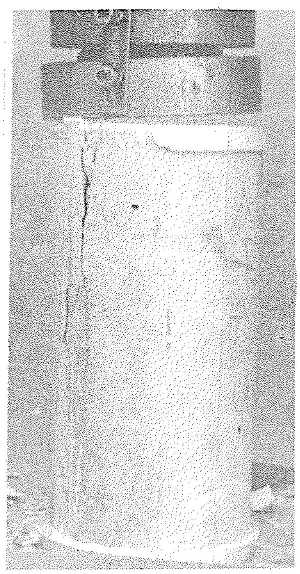


Fig. 16 Edge Failure In Test Specimen

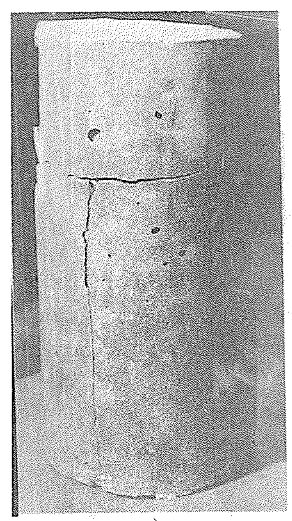


Fig. 17 Tensile Failure in Test Specimen

5.3 Empirical Equation And Curve Fitting.

By defination, an empirical equation is derived from experimental data. Since it has no theoretical basis its form and arbitrary constants are unknown. Hence quite often, selection of a satisfactory empirical equation to represent a set of experimental data involves a process of trial and error.

Ideally an empirical equation should represent all the experimental data closely, yet have few arbitrary constants. Therefore the choice is between precision of fit and simplicity; considering the inaccuracies inherent in experimental data, a compromise between the two is usually the best answer.

The solution to a satisfactory empirical equation is greatly facilitated by the selection of suitable coordinates yielding as nearly a straight line as possible. Such an equation can then be tested for suitability. 'The Graphical Suitability Test' for an empirical function to represent a set of data involves the following steps:

1. Writing an assumed relation, $f(X, Y, a, b) = 0$. in linear form $F_1 = A + F_2$.
2. Calculating F_1 & F_2 for widely separated points.
3. Plotting F_1 as a function of F_2. If a straight line is obtained, then the equation is satisfactory.

The final step in the solution of the equation is the evaluation of the arbitrary constants. The Method of Least Squares, though cumbersome, is the most accurate.

The data obtained in this investigation was desired to be represented by graphical curves for comparison and easy evaluation. Since the Age versus Strength curve is not of the linear form, it was found difficult to select the best curve to fit the points plotted on an Age-Strength graph. Hence it was endeavoured to obtain an equation to relate the Age & Strength of concrete, and then try to plot the best curve possible.

From an inspection of the plot of Age-Strength curves, it appeared that the curve is of the hyperbolic type represented by the equation $Y = {}^{X}/(a+bX)$. Following the procedures outlined above for the selection of empirical equations, it was decided to verify the assumption regarding the equation of the curve by a test plot of the points using coordinates: X, ${}^{X}/Y$. It was found that the points so plotted approximated a straight line. It was therefore concluded that the assumption was correct.

The arbitrary constants 'a' and 'b' were calculated using the 'Method of Least Squares' as follows:-

Case where: X, the independent variable, is exact:

Y, the dependent variable, is liable to

and the chosen equation can be reduced to

the form: $Y = a + bX$ .... (1)

Let: Y represent values defined by above equation,

Yo, the observed values,

and N, number of observed points.

Then $Na + b\sum X = \sum Yo$ .... (2)

$a\sum X + b\sum X^2 = \sum XYo$ .... (3)

Solving (2) and (3) simultaneously:

$$a = \frac{\sum X^2 \sum Yo - \sum X \sum XYo}{X\sum X^2 - (\sum X)^2} \quad \text{.............................. (4)}$$

$$\text{and } b = \frac{X\sum XYo - \sum X \sum Yo}{X\sum X^2 - (\sum X)^2} \quad \text{.............................. (5)}$$

Solve for 'a' & 'b' and substitute in equation (1).

The whole procedure will now be illustrated for the results of tests on batches conforming to W/C ratio 0.4 and revibration characteristic of 8 min./4 hrs. The rest results were as follows:-

TABLE XV

COMPRESSIVE STRENGTH OF CONCRETE (PSI)
WATER-CEMENT RATIO: 0.4, REVIBRATION CHARACTERISTIC: 8min/4 hr.

Batch No.	Test Age Hrs.	(A) Revib.	(B) Revib. & Steamed	(C) Steamed	Air Cured
24	20	1940	4050	4110	1750
22	184	6540	6630	5890	6800
23	668	6920	5700	5770	7650
25	1531	7200	7290	7370	7670

Detailed calculations as follows for Set (A) are typical of all sets of batches tested in this investigation.

	X	X^2	Y	X/Y	X^2/Y
1	20	400	1940	.0103	.2062
2	184	33856	6540	.0281	5.1768
3	668	446224	6920	.0965	64.4832
4	1531	2343961	7200	.2126	325.5501
$\sum$	2403	2824441		.3476	395.4163

The hyperbolic eqn.- $Y = X/(a + bX)$.

can be rewritten in the linear form as:

$$\frac{X}{Y} = a + bX \qquad (6)$$

with coordinates $\left(\frac{X}{Y}\right)$ and X.

Here X is Age of test specimen in hours,

& Y is compressive strength of the specimen in PSI.

Using the Method of Least Squares for determining the arbitrary constants 'a' and b of eqn. (6), we have :-

$$Na + b\sum X = \sum\left(\frac{X}{Y}\right).$$

$$a\sum X + b\sum X^2 = \sum\left(\frac{X^2}{Y}\right).$$

Substituting the values for N (=4), $\sum X, \sum \frac{X}{Y}, \sum X^2, \sum \frac{X^2}{Y}$ as tabulated above we get:

$$4a + 2403b = 0.3476$$

$$2403a + 2824441b = 395.4163$$

Solving the above equations simultaneously, we get:

$$a = 0.005727$$

$$\& \ b = 0.000135.$$

Then the straight line equation with the coordinates $(\frac{X}{Y})$ & (X) is:

$$(\frac{X}{Y}) = 0.0005727 + 0.000135X \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

Here a is the intercept on the ordinate $(\frac{X}{Y})$ and b is the slope of the line.

Eqn (7) can be transformed to the hyperbolic equation of the type $Y = X/a + bX$ with the coordinates X and Y as follows:

$$Y = X/(0.005727 + 0.000135X) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

Equation (8) is the empirical equation representing the Age Vs Strength relationship of the four tests conducted on specimens of Set (A) and the curve corresponding to the above equation drawn with X, Y coordinates would be the best curve for the experimental data. Fig. 18 illustrates the results of set (A) graphically.

Figs. 19, 20 and 21 were similarly plotted for the data in Sets (B), (C) and (D) of Table XV. Graphs of all similar data have been drawn and are included in Appendix B.

Recapitulating and summarising, test results of all specimens with similar characteristics, i.e. those belonging to similar sets and having the same W/C ratio, were plotted on a graph with the coordinates $\frac{X}{Y}$ and X. X represents the

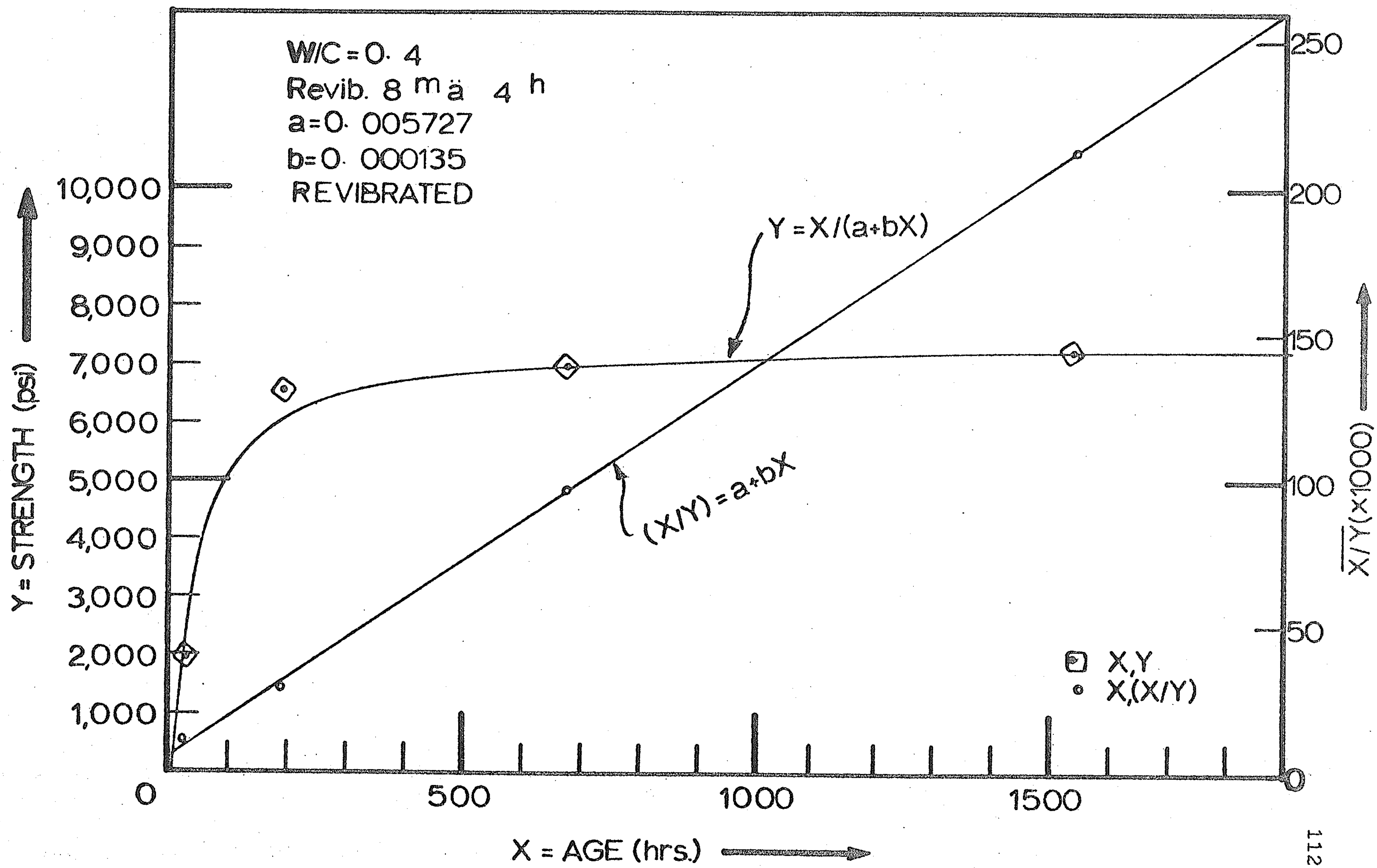


Fig. 18. Age Vs. Strength Curve for Concrete: Revibrated Only; W/C = 0.4; Revib. 8 min./4 hrs.

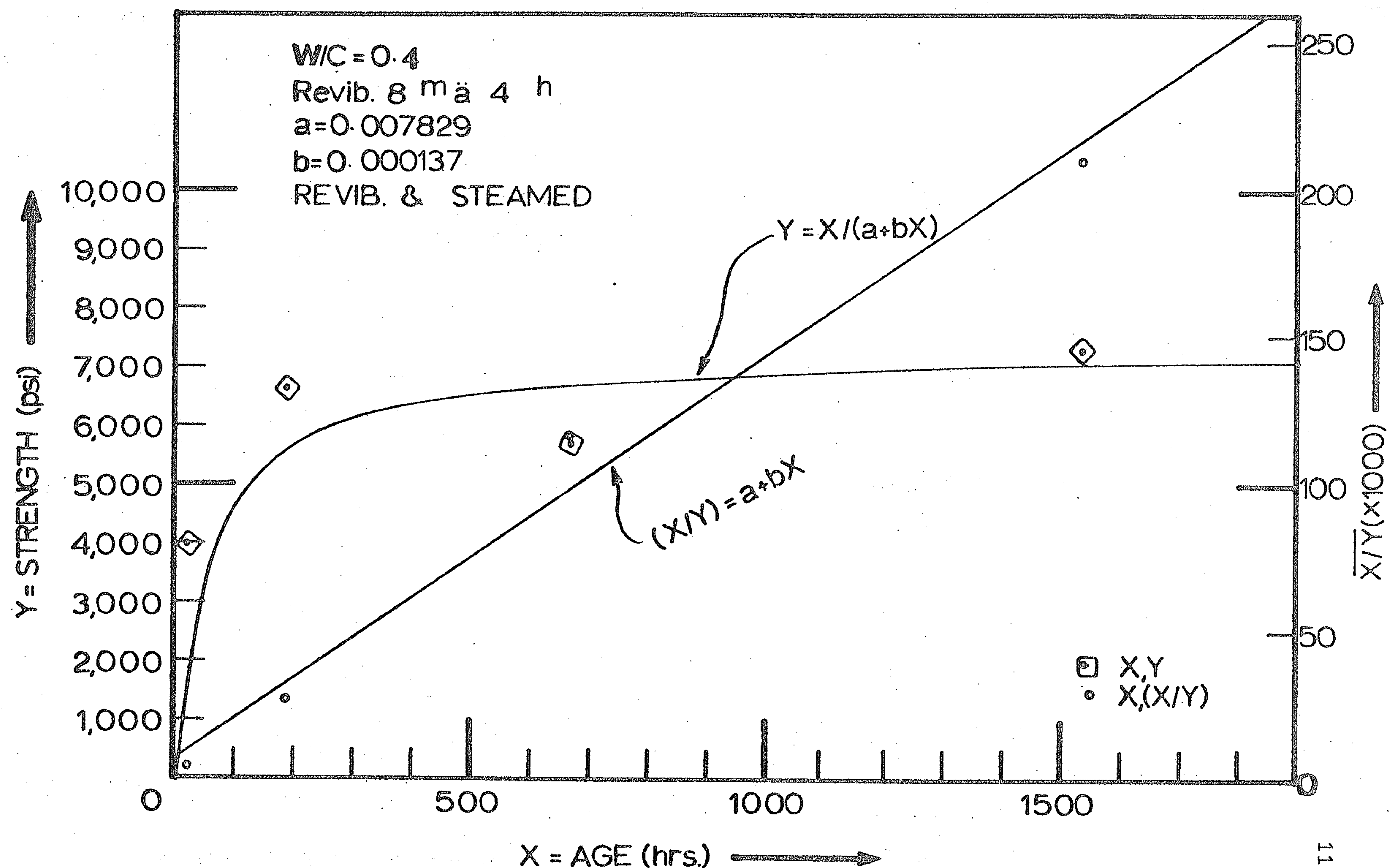


Fig. 19. Age Vs. Strength Curve for Concrete: Revibrated and Steamed; W/C = 0.4; Revib. 8 min./4 hrs.

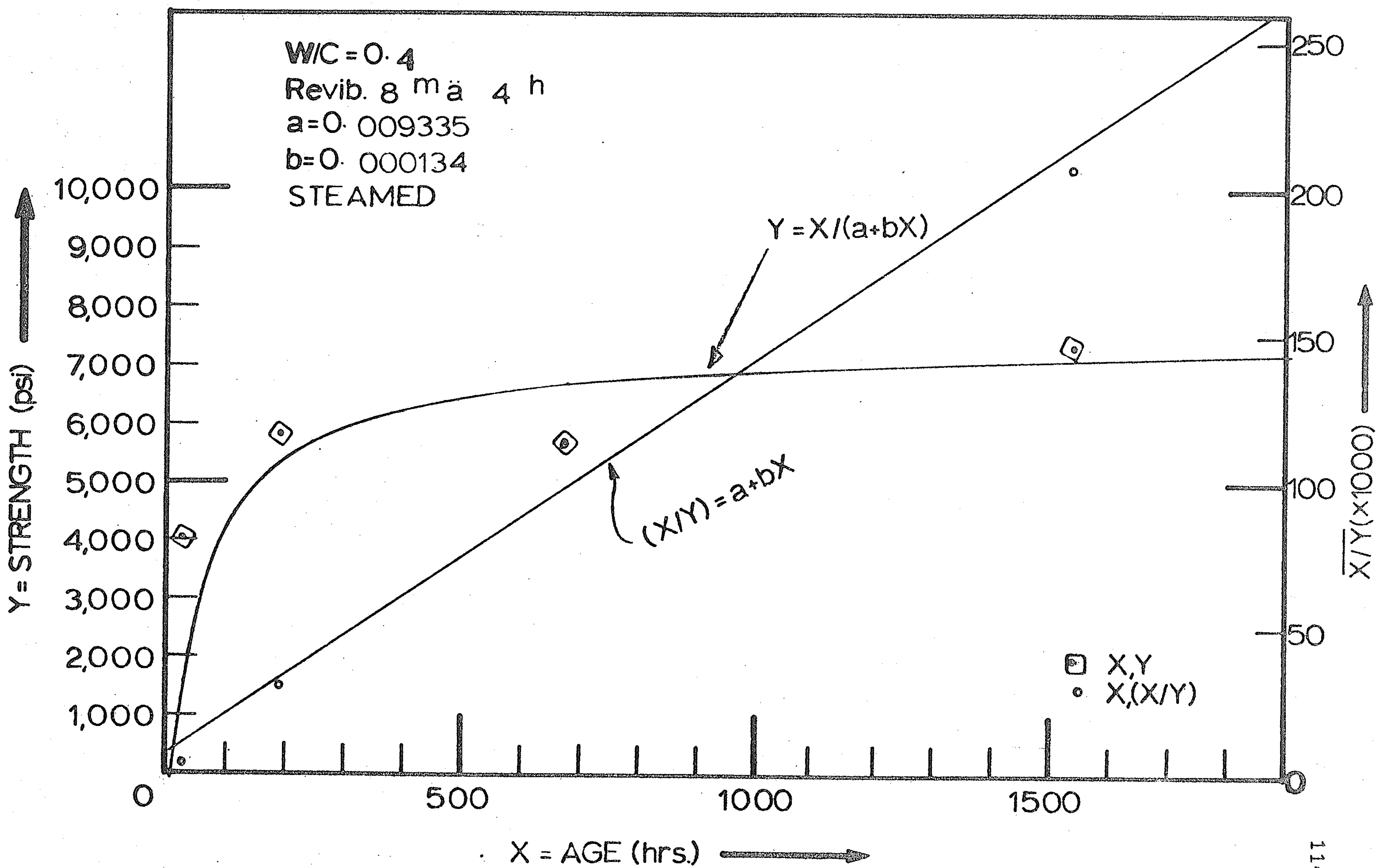


Fig. 20. Age Vs. Strength Curve for Concrete: Steamed Only; W/C = 0.4; Revib. 8 min./4 hrs.

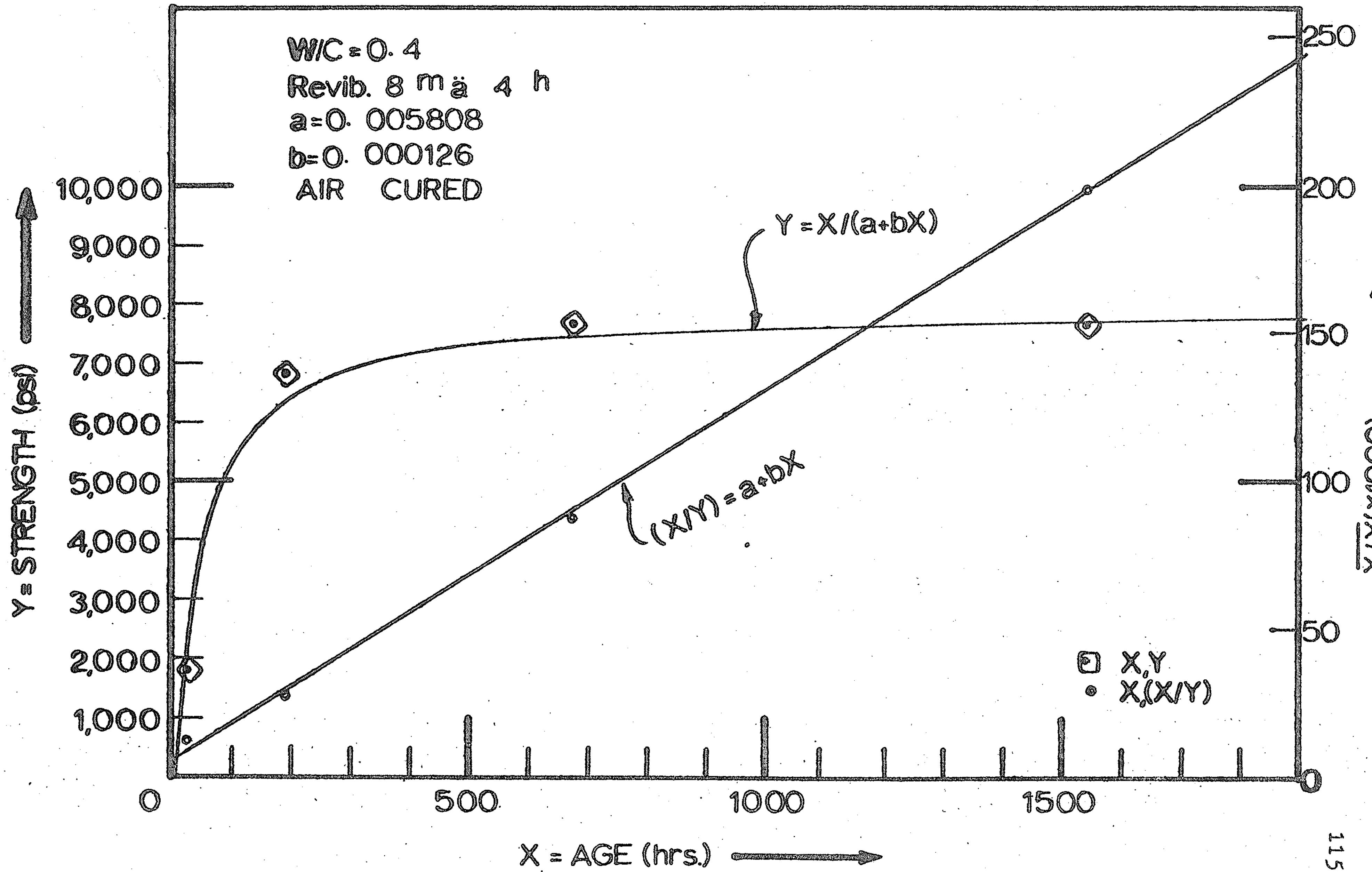


Fig. 21. Age Vs. Strength Curve for Concrete: Air Cured; W/C = 0.4; Revib. 8 min./4 hrs.

age of the test specimen in hours and Y represents its compressive strength in PSI. A linear equation representing the best fit for the experimental data was derived using the method of least squares. A line was plotted on the basis of values of 'a' & 'b' as calculated from the above equation; and designated as $(\frac{X}{Y}) = a + bX$. This line was transformed to the type $Y = X/(a + bX)$, using the same values of 'a' & 'b' and plotted on graph with X - Y coordinates. By inspection this curve appears to be the best fit for the experimental data plotted; therefore it is concluded that the form of the empirical equation is a correct one.

5.4 <u>Analysis Of Test Results:</u>

Using the above technique, strength curves were plotted for concretes conforming to various water/cement ratios and subjected to different processes. These strength curves were brought together for comparison, as shown in Figs. 22 to 34; in each case one variable was used for comparison of relative strength characteristics.

For the purpose of reading the graphs, the terms used therein are explained below:

Revibrated: refers to concrete specimens which were subjected to delayed and repeated vibration after casting. Revibration characteristic of ½ min. every 4 hours (or ½ min./4 hrs.) means the concrete was subjected to vibration for a duration of ½ minute and this was repeated every 4 hours after the time of casting, up to the cut-off time limit of 18 hours. Similarly 2 mins. every 4 hrs. or (2 min./4 hrs.) and 8 minutes every 4 hrs. or (8 min./4 hrs.) refers to vibration for the duration of 2 mins. and 4 mins. respectively, repeated every 4 hours up to the time limit of 18 hrs. after casting.

Steamed: refers to concrete specimens subjected to steam curing according to the standard procedure recommended by Hanson for pre-casting plants, this involved an initial presteaming period of 5 hours followed by low pressure steam curing, so regulated as to produce a temperature rise of 40°F per hour in the concrete specimens with a maximum of 150°F, which was to be maintained until 18 hours after casting.

Revib. and Steamed: refers to specimens which were subjected to both revibration and steam curing simultaneously during the first 18 hours after casting.

Air Cured: refers to control specimens which were not subjected to any of the processes as described above during the initial 18 hour period after casting.

During casting however, all specimens were subjected to 2 mins. initial vibration for the purpose of achieving proper compaction; exception was made in the case of concrete with water/cement ratio = 0.6, when only ½ min. of initial vibration was considered sufficient to achieve compaction. At the end of the 18 hour cycle during which the different sets in a batch were subjected to different processes as described above, all the cylinders were either prepared for compression test at 20 hr. age or was stored away for testing at a later age.

5.5 Relative Compressive Strengths Based On Strength Curves.

Strength curves of concretes subjected to different processes during the initial 18 hour period after casting as compared in Figs. 22 to 28. Figs. 22 to 24 compare concretes with water/cement ratio = 0.4, but with different revibration characteristics i.e. ½ min./4 hours, 2 min./4 hrs., and 8 min/4 hrs. respectively. Fig. 25 pertains to concrete with water/cement ratio = 0.45 and Fig. 26 to concrete with water/cement ratio = 0.5. Concrete with water/cement ratio = 0.6 is described in Fgs. 27 and 28; the revib. characteristics are 2 min./4 hrs. and 4 min./ 4 hrs. respectively. To facilitate evaluation and comparison of the test results, each Figure will be considered individually and commented upon.

Fig. 22 Relative Strength curves for concrete (water/cement ratio = 0.4; revibration characteristic: ½ min. every 4 hrs.):-

Comparison of early strength (1 day) indicates a fairly wide spread of compressive strength values; these tend to converge appreciably up to age: 10 days after which they seem to even out. Concrete subjected to simultaneous revibration and steaming (Set B) has the greatest strength at 1 day, followed by concrete subjected to steaming only. Concrete subjected to revibration only seems to have suffered somewhat having a lower value than the air cured concrete (Control Set). At age: 90 days, the Revibration & Steamed Set indicates the least strength compared to the other sets. Curiously, concrete subjected to steaming only appears to be the strongest, although only marginally, as compared to the normal air cured concrete. The set subjected to revibration only is slightly better than the steamed set. Based on results of Fig. I, Table XVI indicates the percentage gain or loss in strength compared to normal air cured concrete at 1, 28 and 90 days.

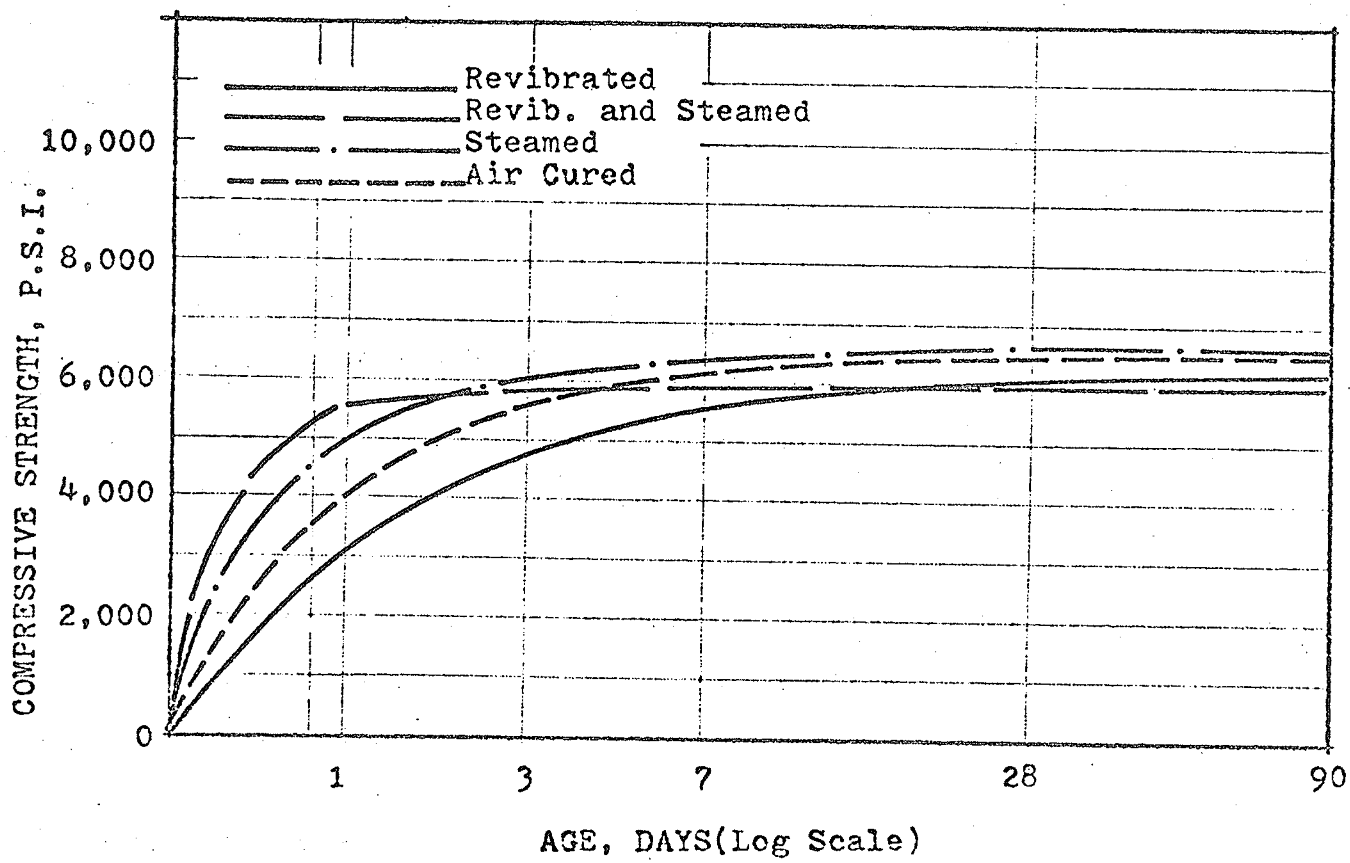


Fig. 22. Relative strength curves for concrete(water/cement ratio = 0.4; revibration charactistic: ½ min. every 4 hrs.)

TABLE XVI

STRENGTH OF CONCRETE SUBJECTED TO DIFFERENT PROCESSES COMPARED TO NORMAL AIR CURED CONCRETE (WATER/CEMENT RATIO = 0.4, REVIBRATION CHARACTERISTIC: ½ MIN./4 HRS.

Set	Type of Concrete	* Gain (+) or Loss (-) in Strength at:		
		1 Day	28 Days	90 Days
A	Revibrated	- 22%	- 6%	- 4%
B	Revib. & Steamed	+ 38%	- 8%	- 8%
C	Steamed	+ 25%	+ 3%	+ 3%

* Compared to Normal Air Cured Concrete.

Fig. 23: Relative Strength curves for concrete (water/cement ratio = 0.4, revibration characteristics: 2 min. every 4 hrs.):-

In this case the range of strength values at an early age is not appreciably different from that at later ages. Concrete subjected to both revibration and steaming is the strongest at 1 day; followed by Steamed Revibrated and Air Cured in that order. At 90 days, Steamed Concrete is the strongest followed by Revib. & Steamed, Air Cured and Revibrated respectively. Revibrated concrete starts out as being somewhat stronger than normal air cured concrete at an early age, but seems to lose this advantage at later ages. This is exemplified by Table XVII:-

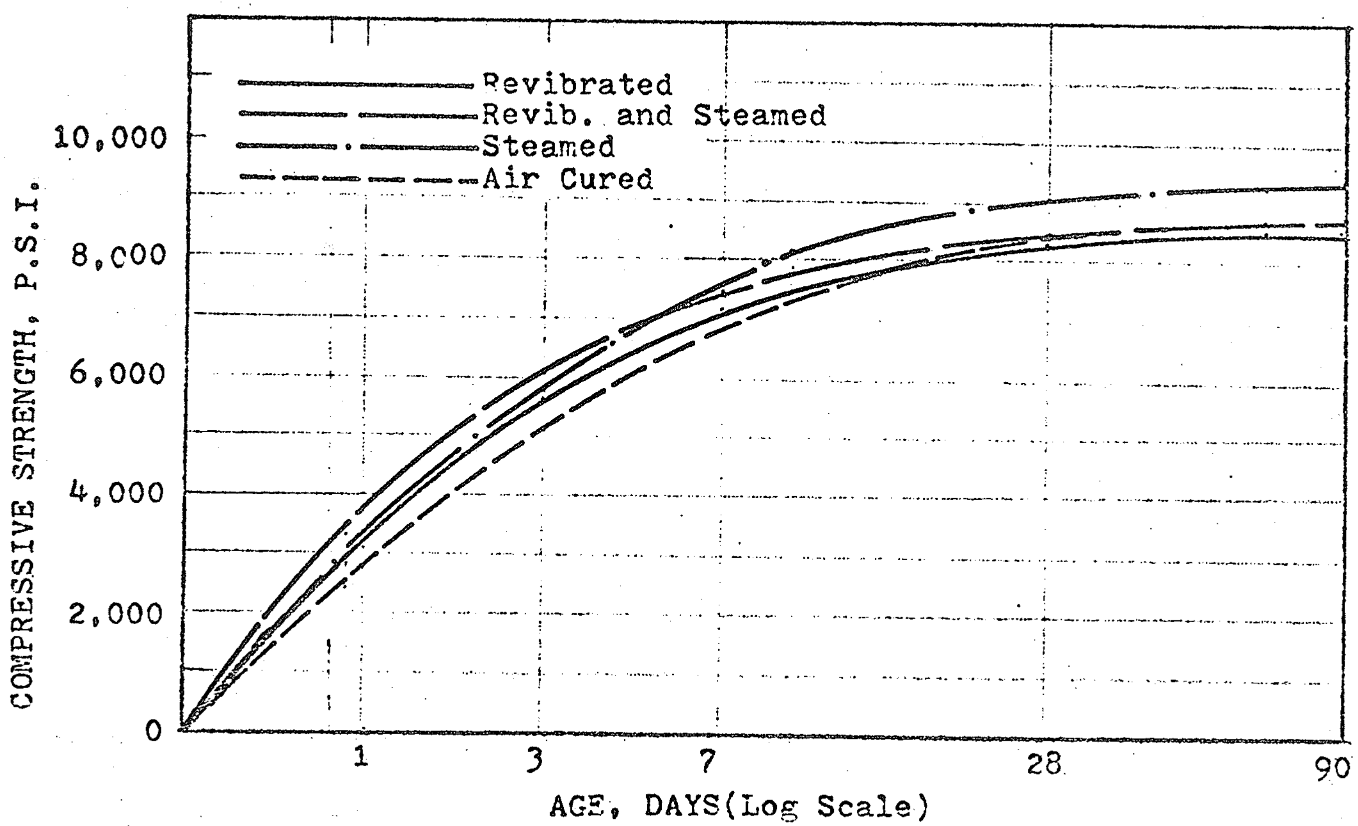


Fig. 23 . Relative strength curves for concrete(water/cement ratio=0.4; revibration characteristic: 2 min. every 4 hours).

TABLE XVII

STRENGTH OF CONCRETE SUBJECTED TO DIFFERENT PROCESSES COMPARED TO NORMAL AIR CURED CONCRETE (WATER/CEMENT RATIO = 0.4, REVIB. CHARACTERISTIC: 2 MIN./4 HRS.).

Set	Type of Concrete	* Gain (+) or Loss (-) in Strength at		
		1 Day	28 Days	90 Days
A	Revibrated	+ 14%	- 2%	- 2%
B	Revib. & Steamed	+ 35%	0	0
C	Steamed	+ 18%	+ 6%	+ 6%

* Compared to Normal Air Cured Concrete.

Fig. 24: Relative Strength curves for concrete (water/cement ratio = 0.4, revibration characteristics: 8 min./4 hrs.):-

In this case normal air cured concrete seems to hold the edge over all the other types as far as strength is concerned but the curves are somewhat misleading as far as early strength is concerned. Reference to results of Batch 24 (Table XIII) shows that in fact at a test age of 20 hours, the air cured specimens had the least strength. The reason for this discrepancy would seem to be that in Fig. 24 the strength at later ages has influenced the shape of the curve at early age, in the case of the air cured specimen. Therefore in this case curves of Fig. 24 will be disregarded, and test results of Batches 24, 23 and 25

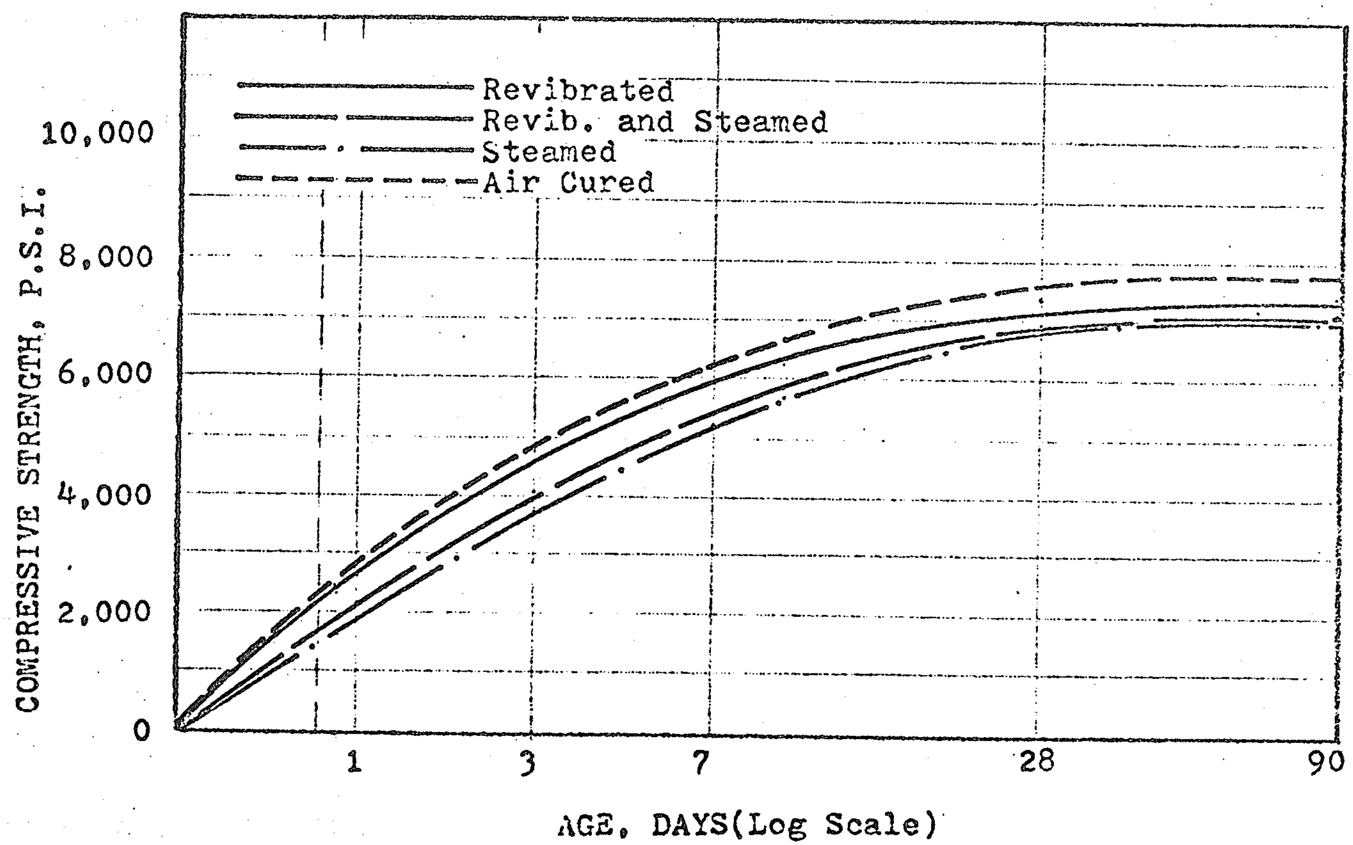


Fig. 24. Relative strength curves for concrete(water/cement ratio = 0.4; revibration characteristic: 8 min. every 4 hrs.).

(from Table XIII) respectively will be used for evaluation of percentage gain or loss in strength compared to normal air cured concrete.

TABLE XVIII

STRENGTH OF CONCRETE SUBJECTED TO DIFFERENT PROCESSES COMPARED TO NORMAL AIR CURED CONCRETE (WATER/CEMENT RATIO= 0.4, REVIB. CHARACTERISTICS: 8 MIN./4 HRS.)

Set	Type of Concrete	*Gain (+) or Loss (-) in Strength at 20 Hrs. (Batch 24)	28 Days (Batnh 23)	64 Days (Batch225)
A	Revibrated	+ 11%	- 9%	- 6%
B	Revib. & Steamed	+132%	-25%	- 5%
C	Steamed	+135%	-24%	- 4%

* Compared to Normal Air Cured Concrete.

Fig. 25: Relative Strength curves for concrete (water/cement ratio = 0.45 revibration characteristics: 2 min./4 hrs.):-

This Fig. shows a wide range of early strength values converging gradually towards 28 day strength, after which they even out. At early age (1 day) steamed set (C) is the strongest, closely followed by the Revib. & Steamed Set (B), then Revibrated Set (A), and lastly the Normal Air Cured Set. At 28 days, Revib. & Staamed Set (B) was the strongest followed by Revibrated Set (A), Air Cured Set (D) and Steamed Set (C) respectively. The curves in Fig. 25 closely follows the actual test values tabulated in Table XIII. Table XIX shows percentage gain or loss in strength for the different types of concretes compared to the normal air cured concrete.

TABLE XIX

STRENGTH OF CONCRETE SUBJECTED TO DIFFERENT PROCESSES, COMPARED TO NORMAL AIR CURED CONCRETE: (WATER/CEMENT RATIO = 0.45, REVIB. CHARACTERISTIC: 2 MIN./4 HRS.)

Set	Type of Concrete	*Gain (+) or Loss (-) in Strength at		
		1 Day	28 Days	90 Days
A	Revib.	+ 29%	+ 8%	+ 7%
B	Revib. & Steamed	+108%	+10%	+ 7%
C	Steamed	+122%	- 1%	- 5%

*Compared to Normal Air Cured Concrete (Set D).

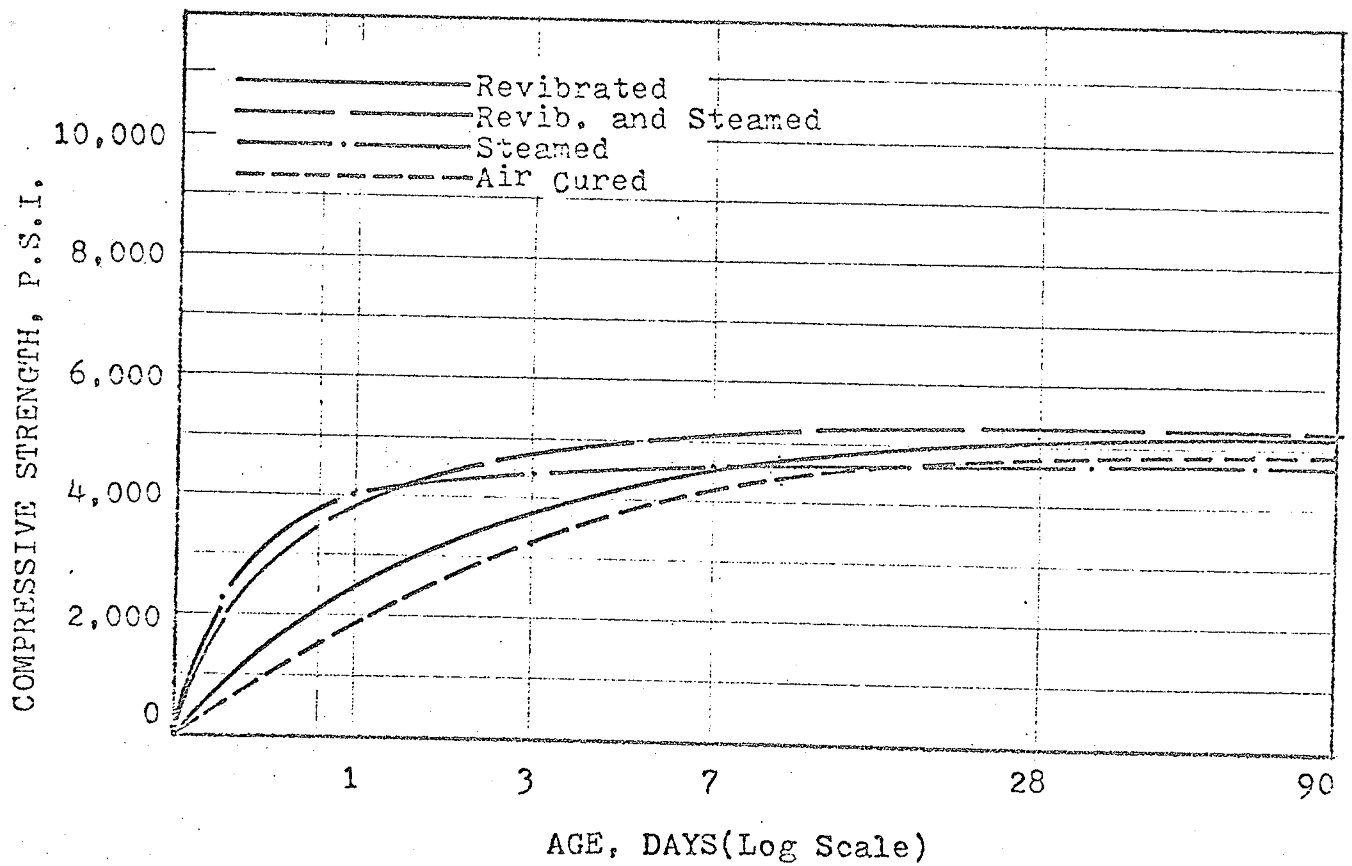


Fig. 25. Relative strength curves for concrete(water/cement ratio = 0.45; revibration characteristic: 2 min. every 4 hrs.).

Fig. 26 Relative Strength curves for concrete (water/cement ratio = 0.5, revibration characteristic: 2 min./4 hrs.):-

The Revibrated and Steamed Set (B) shows highest gain at early age but at about 7 days it shows a marked loss in strength compared to the other sets. The air cured set (D) starts out with least strength at early age but gains on the other types gradually so that by age 28 days it shows the highest strength compared to the others. The Revib. Set (A) and Steamed Set (C) have intermediate values, being stronger than normal air cured concrete at early age but slightly weaker after 28 days. Table XX illustrates the relative gain or loss in strength of the various type of concrete specimens.

TABLE XX

STRENGTH OF CONCRETE SUBJECTED TO DIFFERENT PROCESSES COMPARED TO NORMAL AIR CURED CONCRETE: (WATER/CEMENT RATIO = 0.5, REVIB. CHARACTERISTIC: 2 MIN. AT 4 HRS.):-

Set	Type of Concrete	*Gain (+) or Loss (-) in Strength at 1 Day	28 Days	90 Days
A	Revib.	+ 50%	+ 1%	- 3%
B	Revib. & Steamed	+154%	=15%	-20%
C	Steamed	+ 60%	- 1%	- 4%

* Compared to Normal Air Cured Concrete (Set D).

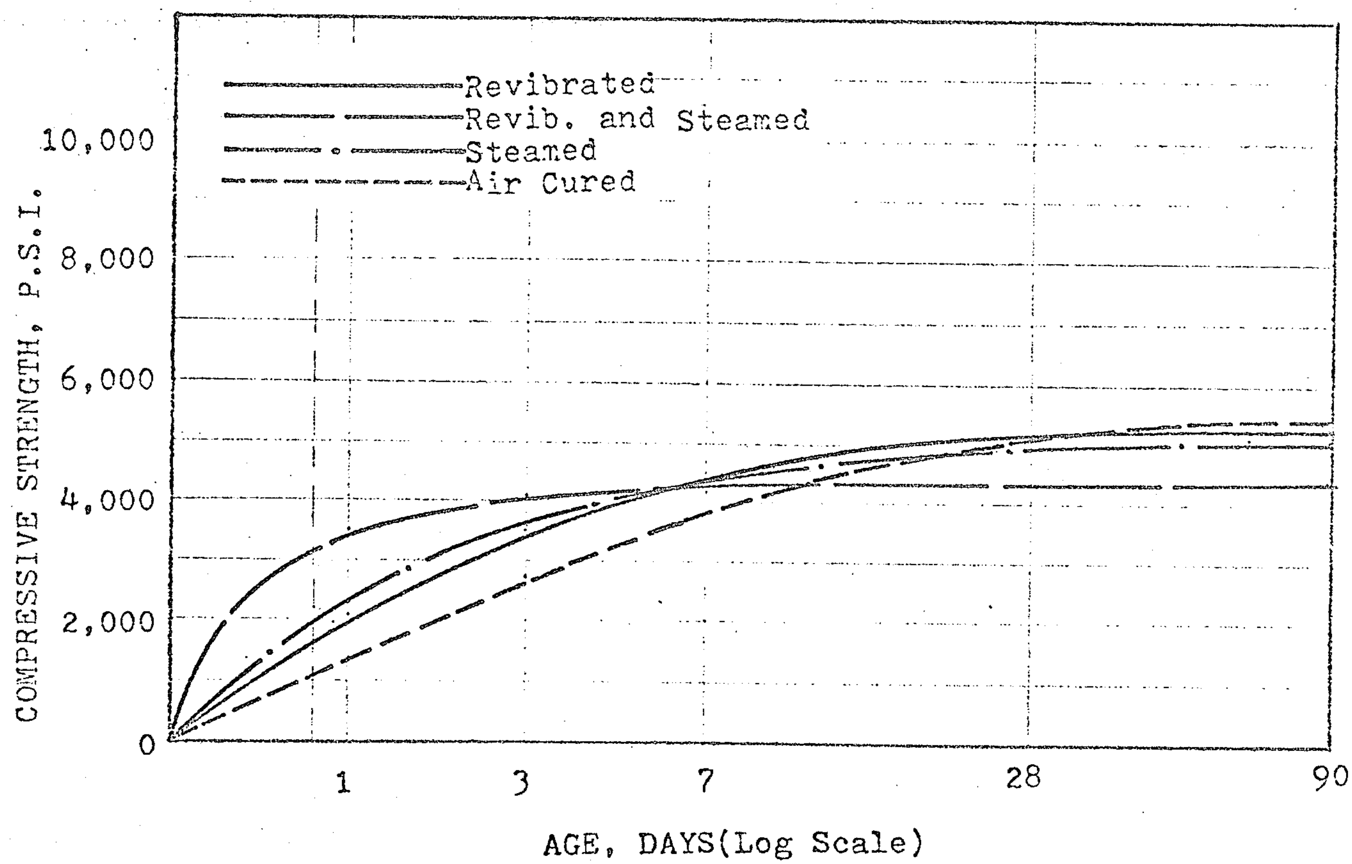


Fig. 26. Relative strength curves for concrete(water/cement ratio = 0.5; revibration characteristic: 2 min. every 4 hrs.).

Fig. 27 Relative Strength curves for concrete (W/C = 0.6, revibration characteristic: 2 min./4 hrs.):-

In this case also, the normal air cured concrete shows the least strength at early age; it gains over the Steamed sets at later ages, but remains weaker than the Revibrated Concrete. The Steamed Set (C) shows the maximum gain in strength at early age but loses this advantage completely at later ages being only marginally stronger than the Revib. & Steamed Set (B), but weaker than the Air Cured (D) and Revibrated (A) Sets. Table XXI illustrates these points qualitatively:-

TABLE XXI

STRENGTH OF CONCRETE SUBJECTED TO DIFFERENT PROCESSES COMPARED TO NORMAL AIR CURED CONCRETE: (WATER/CEMENT RATIO = 0.6, REVIB. CHARACTERISTIC: 4 MIN. AT 4 HRS.).

Set	Type of Concrete	* Gain (+) or Loss (-) in Strength at 1 Day	28 Days	90 Days
A	Revib.	+ 5%	+ 11%	+ 11%
B	Revib. & Steamed	+50%	- 5%	- 6%
C	Steamed	+70%	- 2%	- 4%

* Compared to Normal Air Cured Concrete (Set D).

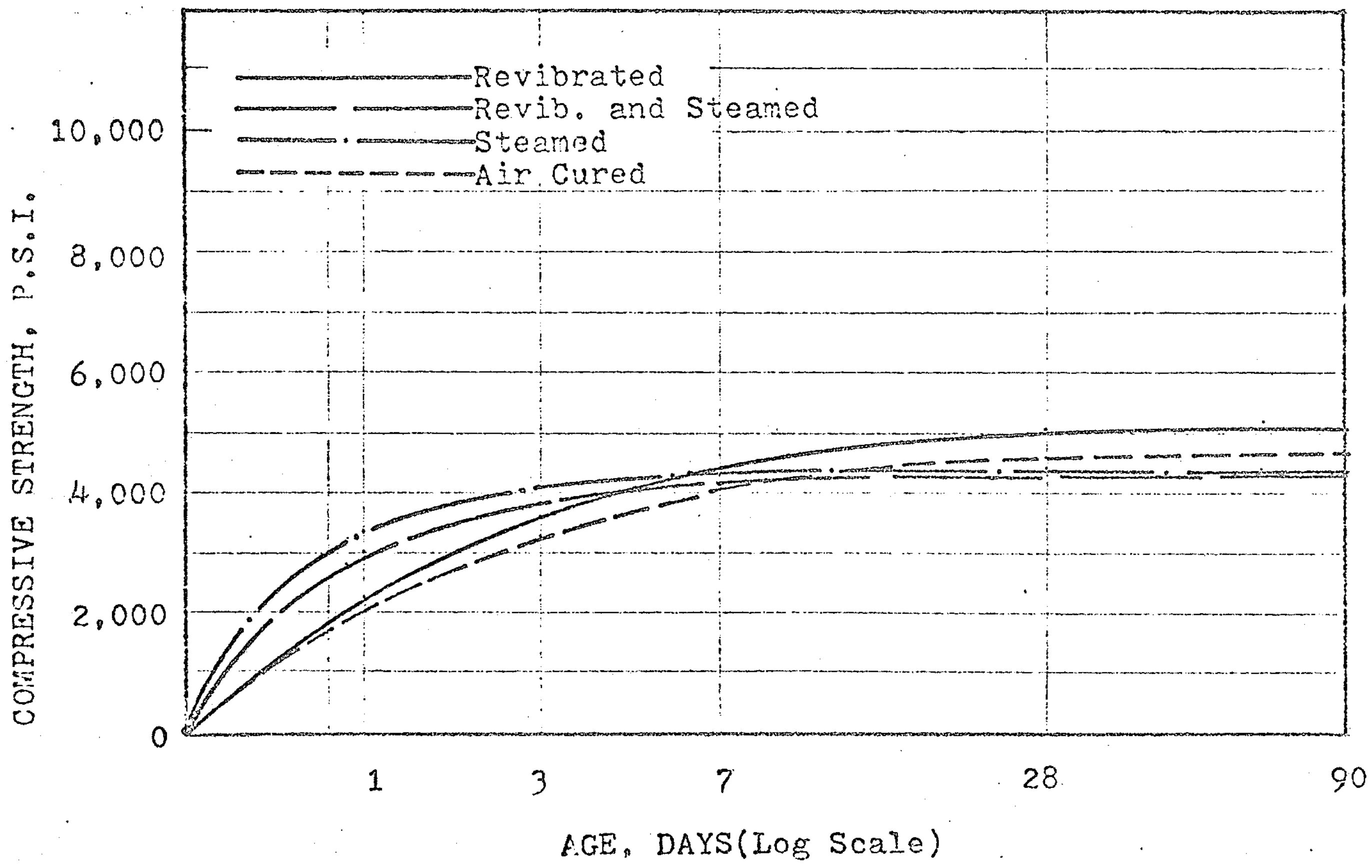


Fig. 27. Relative strength curves for concrete(water/cement ratio = 0.6; revibration characteristic: 2 min. every 4 hrs.).

Fig. 28: Relative Strength curves for concrete (W/C = 0.6, Revibration characteristic: 4 min./4 hrs.).

In this case there seems to be a wide range of values both at early and later ages. The Steamed (C), and Revibrated and Steamed (B) Sets are considerably stronger than the Revibrated (A) and Air Cured (D) Sets at early age but weaker at 28 days and later ages. The Revibrated Set is however always stronger than the Air Cured Set. Table XXII illustrates these points clearly.

TABLE XXII

STRENGTH OF CONCRETE SUBJECTED TO DIFFERENT PROCESSES COMPARED TO NORMAL AIR CURED CONCRETE: (WATER/CEMENT RATIO = 0.6, REVIB. CHARACTERISTIC: 4 MIN./4 HRS.).

Set	Type of Concrete	* Gain (+) or Loss (-) in Strength at		
		1 Day	28 Days	90 Days
A	Revib.	+ 14%	+ 10%	+ 12%
B	Revib. & Steamed	+ 97%	+ 14%	- 17%
C	Steamed	+102%	- 21%	- 24%

* Compared to Normal Air Cured Concrete (Set D).

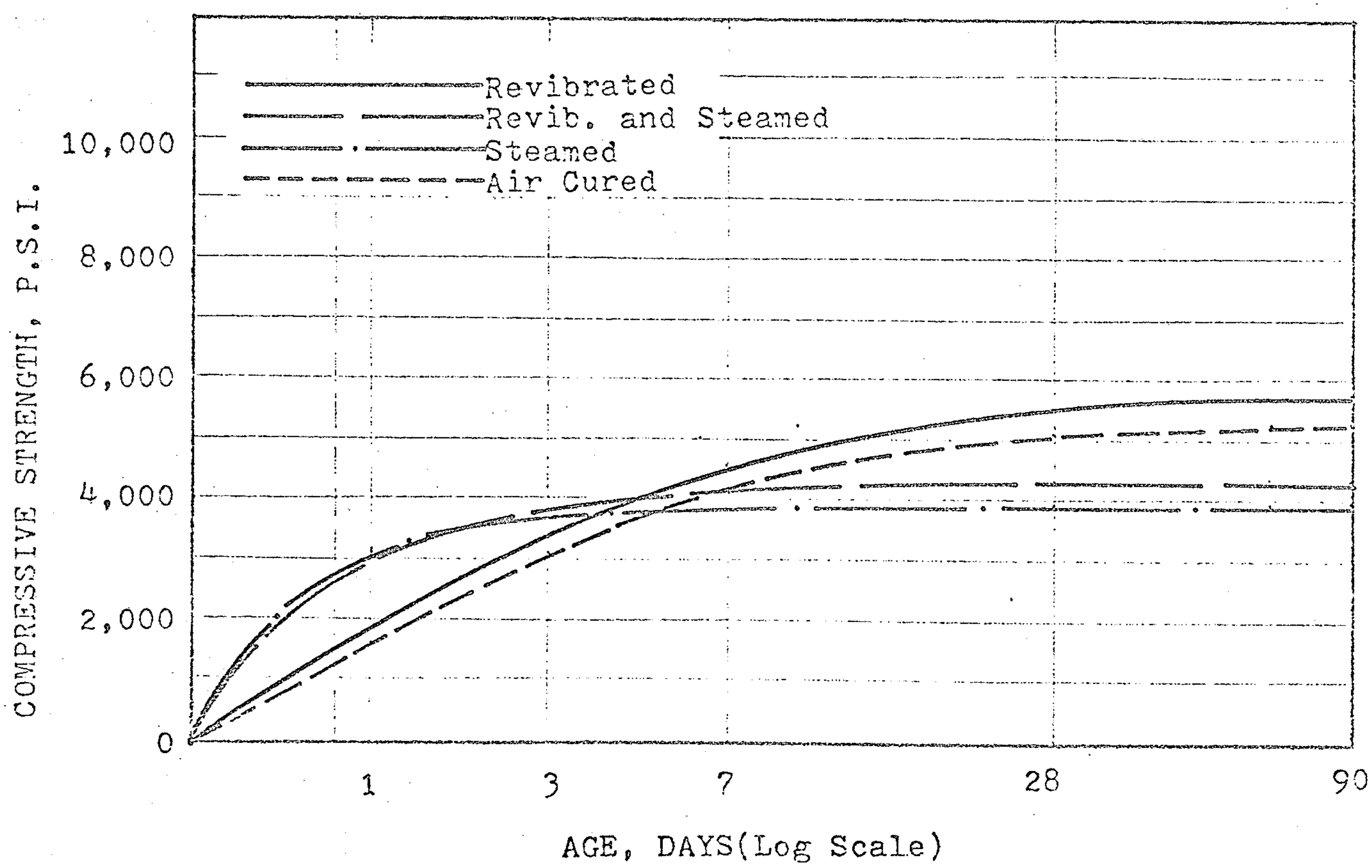


Fig. 28. Relative strength curves for concrete(water/cement ratio = 0.6; revibration characteristic: 4 min. every 4 hrs.).

Fig. 29: Relative Strength curves for concrete for different revibration characteristics (water/cement = 0.4, revibration specimens only: Set A).

This Figure indicates the effect of different revib. characteristics on the strength of concrete with water/cement ratio = 0.4, and subjected to revibration only of ½ min./4 hrs., 2 min./4 hrs. and 8 min./4 hrs. respectively. Compressive strength of concrete at 1 day, subjected to revibration of ½ min./4 hrs, seems to be almost the same as that subjected to 2 min./4 hrs.; but the strength falls off towards later ages, being 27% lower at 28 days. 1 Day strength of concrete subjected to 8 min./4 hrs. is 19% lower compared to the other two, but at 28 days it is 18% higher than concrete revibrated ½ min./4 hrs. and 15% lower than concrete revibrated 2 min./4 hrs. Therefore it would appear that revibration of 2 min./4 hrs. gives better results for concrete with water/cement ratio = 0.4 than revibration of ½ min./4 hrs. or 8 min./4 hrs.

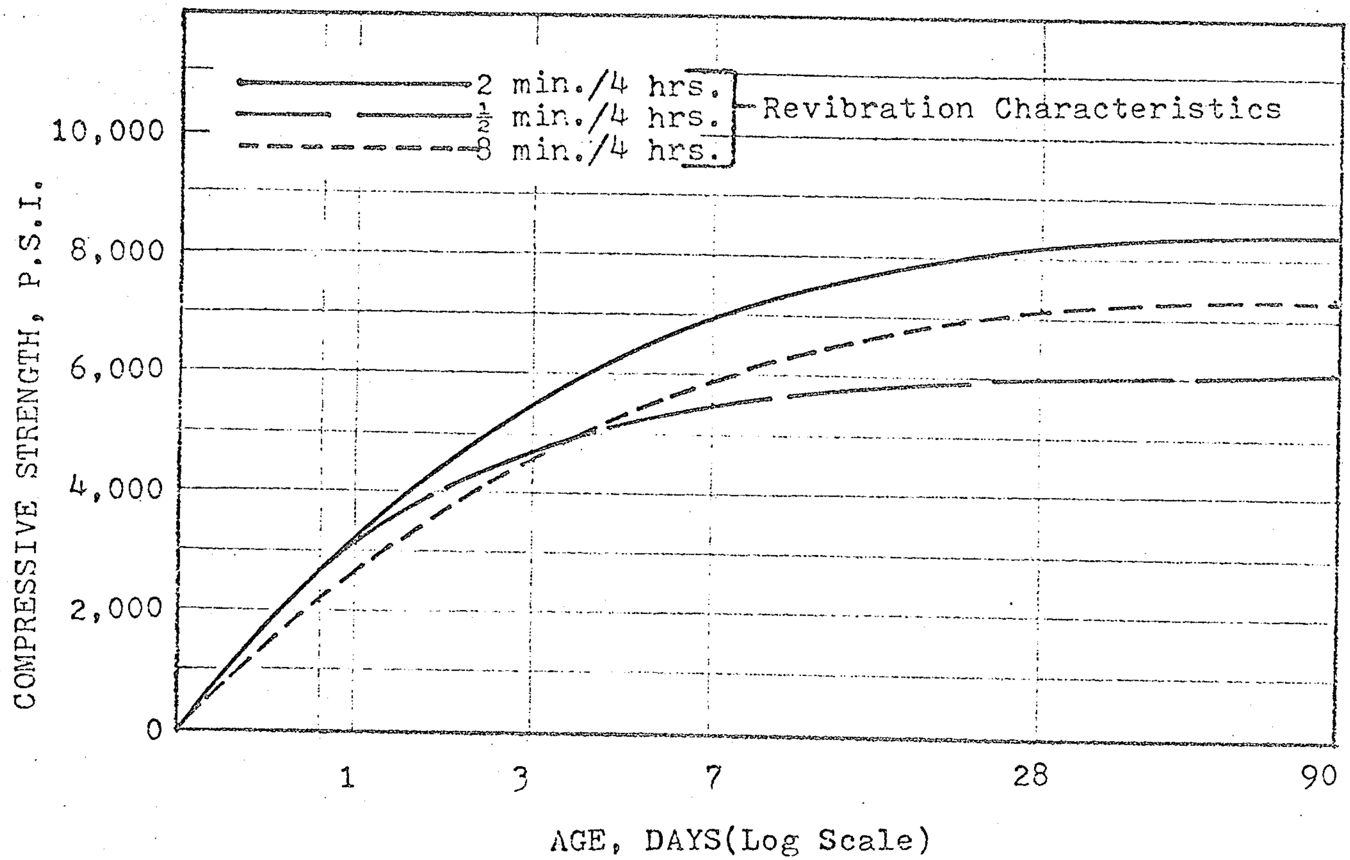


Fig. 29. Relative strength curves for concrete for different revibration characteristics(water/cement ratio = 0.4; revibrated specimens only: Sets 'A').

Fig. 30: Relative Strength curves for concrete for different revibration characteristics: (water/cement = 0.4, revib. & steamed specimens only: Set B).

The effect of different revibration characteristics on the strength of concrete, subjected to simultaneous revib. & steaming (Set B) during the initial 18 hour period after casting is considered here. This concrete has a water/cement ratio = 0.4. The strength curves seem to indicate that 1 day strength is 140% higher for concrete with ½ min./4 hrs. revibration, and 61% higher with 2 min./4 hrs. revibration compared to concrete with 8 min./hrs. revibration. However, this comparison is suspect because at this early age the rate and degree of steaming has a much more predominant effect than slight variation of revibration, and considering the somewhat crude setup of the steam curing arrangement, this is most likely the cause of this large disparity. However, variation in steam curing should not have such a great influence on the concrete strength at later ages (say 28 days) and the comparison of strength curves at this age would be more indicative of the effect of revibration. Therefore comparing the relative strength at 28 days in Fig. 30, it seems that concrete revibrated 2 min./4 hrs. is 46% stronger and that revibrated 8 min/4hrs. is 15% stronger compared to concrete revibrated ½ min./4 hrs. and 8 min./4 hrs. is generally similar and therefore

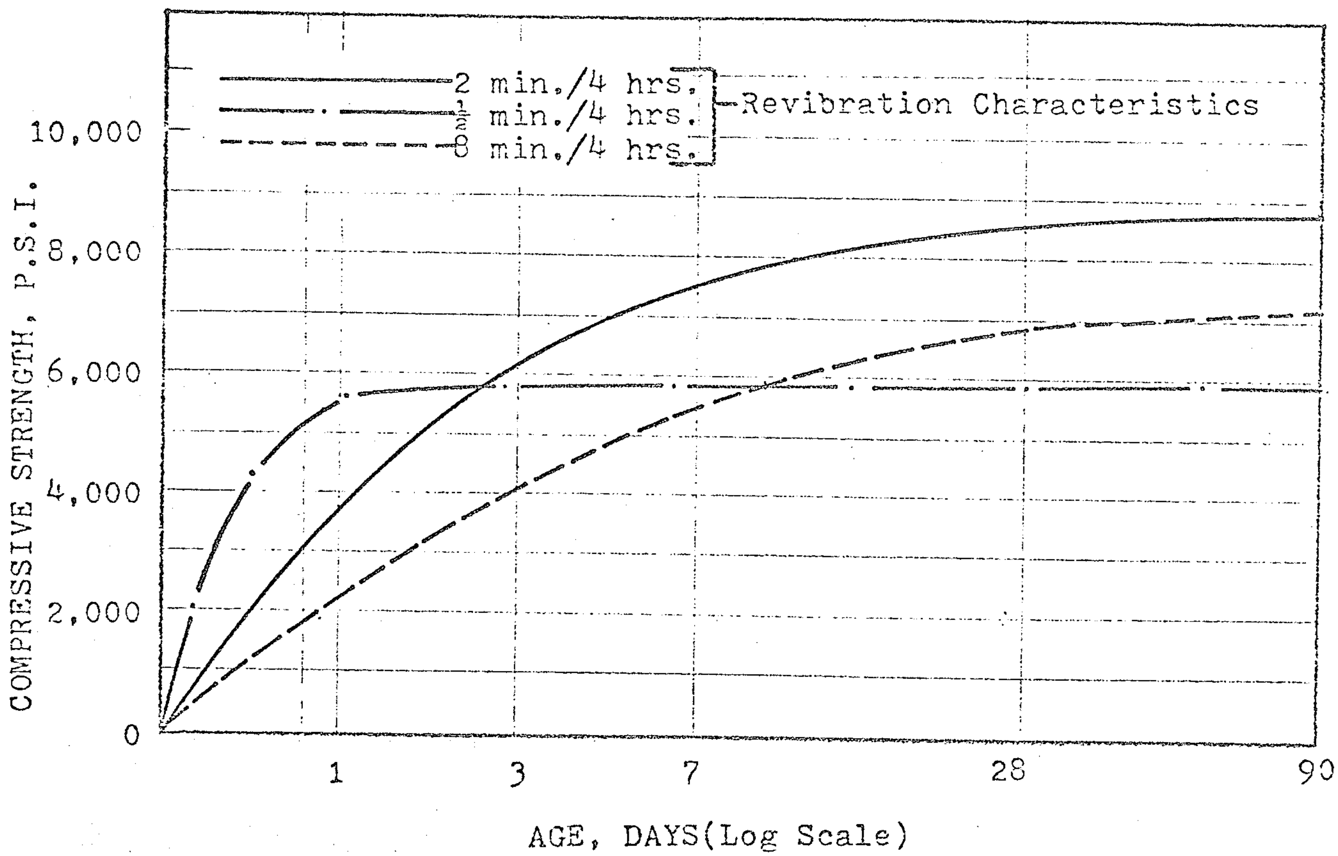


Fig. 30. Relative strength curves for concrete for different revibration characteristics(water/cement ratio = 0.4; revib. and steamed specimens only: Sets 'B').

comparison of values for these two cases is considered more reliable. Revibration of 2 min./4 hrs. seems to be better than revib. of 8 min./4 hrs. in this case also.

Fig. 31: Relative Strength curves for concrete for different revibration characteristics: (water/cement = 0.6, revibrated specimens only: Sets A.)

In this Fig. two strength curves corresponding to revibration characteristics of 2 min./4 hrs. and 4 min./4 hrs. respectively are compared for concrete with water/cement ratio = 0.6 and subjected to revibration only. The strength curves indicate that concrete revibrated 2 min./4 hrs. is stronger by 21% at 1 day compared to that revibrated 4 min./4 hrs., but gradually loses this advantage at later ages, being weaker by 15% at 28 days and 18% at 90 days. Therefore revibration of 2 min./4 hrs. induces an early strength gain over revibration of 4 min./4 hrs., but a strength loss is incurred at later ages for concrete with water/cement ratio = 0.6.

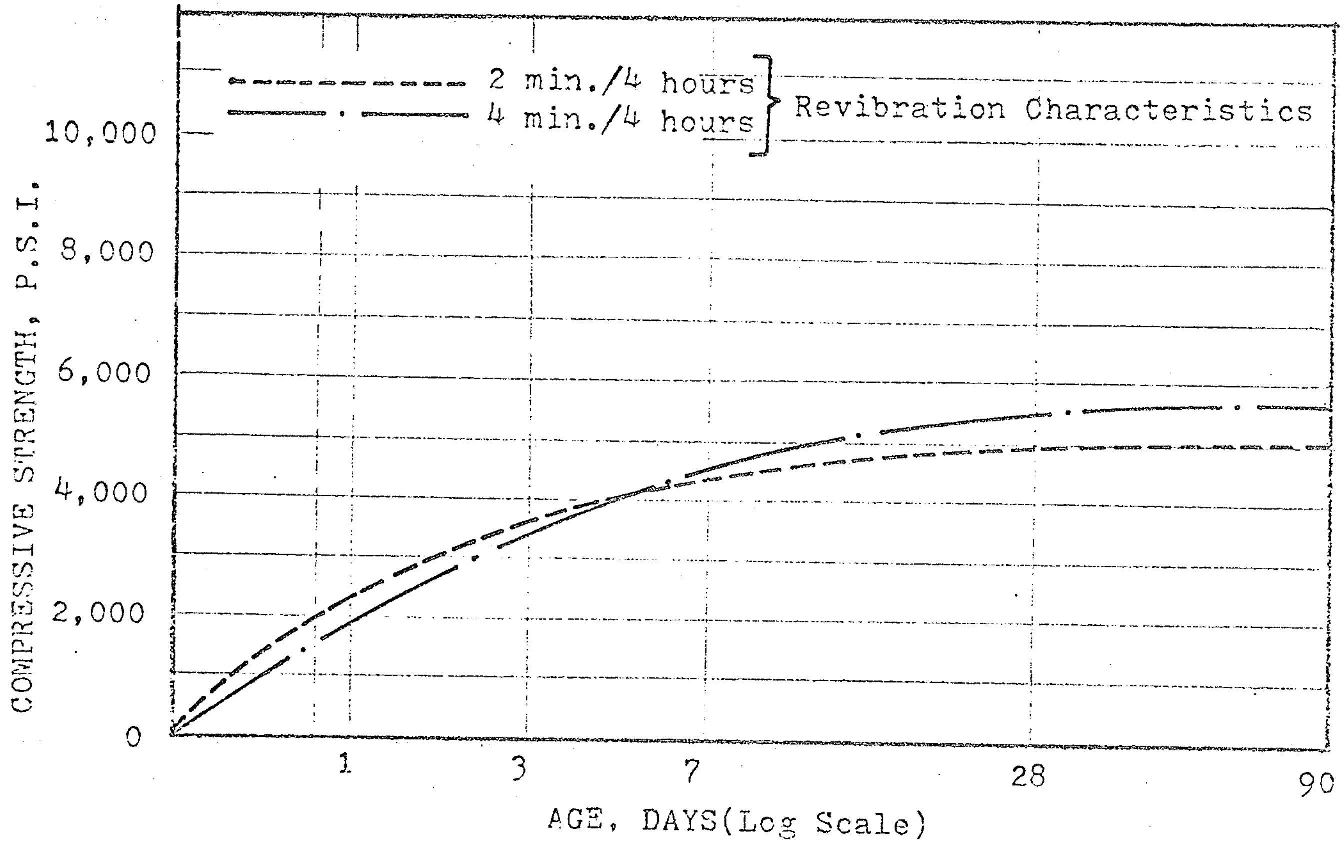


Fig. 31 . Relative strength curves for concrete for different revibration characteristics(water/cement ratio=0.6; revibrated specimens only: Sets 'A').

Fig. 32: Relative Strength curves for concrete for different revibration characteristics (water/cement ratio = 0.6, revibrated and steamed specimens only. Sets B.).

The strength curves for the two revibration characteristics: 2 min./4 hrs. and 4 min./4 hrs. compared in this Fig. are almost identical. This is the case for concrete with water/cement ratio = 0.6 and subjected to simultaneous revibration and steam curing.

Fig. 33: Relative Strength curves for concrete for different water/cement ratios: (Revibration characteristics: 2 min./ 4 hrs; revib. specimens only Sets A).

This Fig. illustrates the effect of different water/ cement ratio on concrete subjected to revibration of 2 min./ 4 hrs. The water/cement ratios compared are 0.4, 0.45, 0.5 and 0.6 respectively. Concrete with water/cement ratio = 0.4 clearly is much stronger than the others and gains this advantage quite rapidly; strength curves for the others seems to converge at 10 days and subsequently possess almost identical values. Table XXIII compares these strength curves quantitatively:

TABLE XXIII

W/C Ratio	*Relative Compressive Strength		
	1 Day	28 Days	90 Days
0.6	1.0	1.0	1.0
0.5	1.15	1.0	1.0
0.45	1.25	1.0	1.0
0.4	1.65	1.66	1.65

* Compared to Concrete with W/C Ratio = 0.6

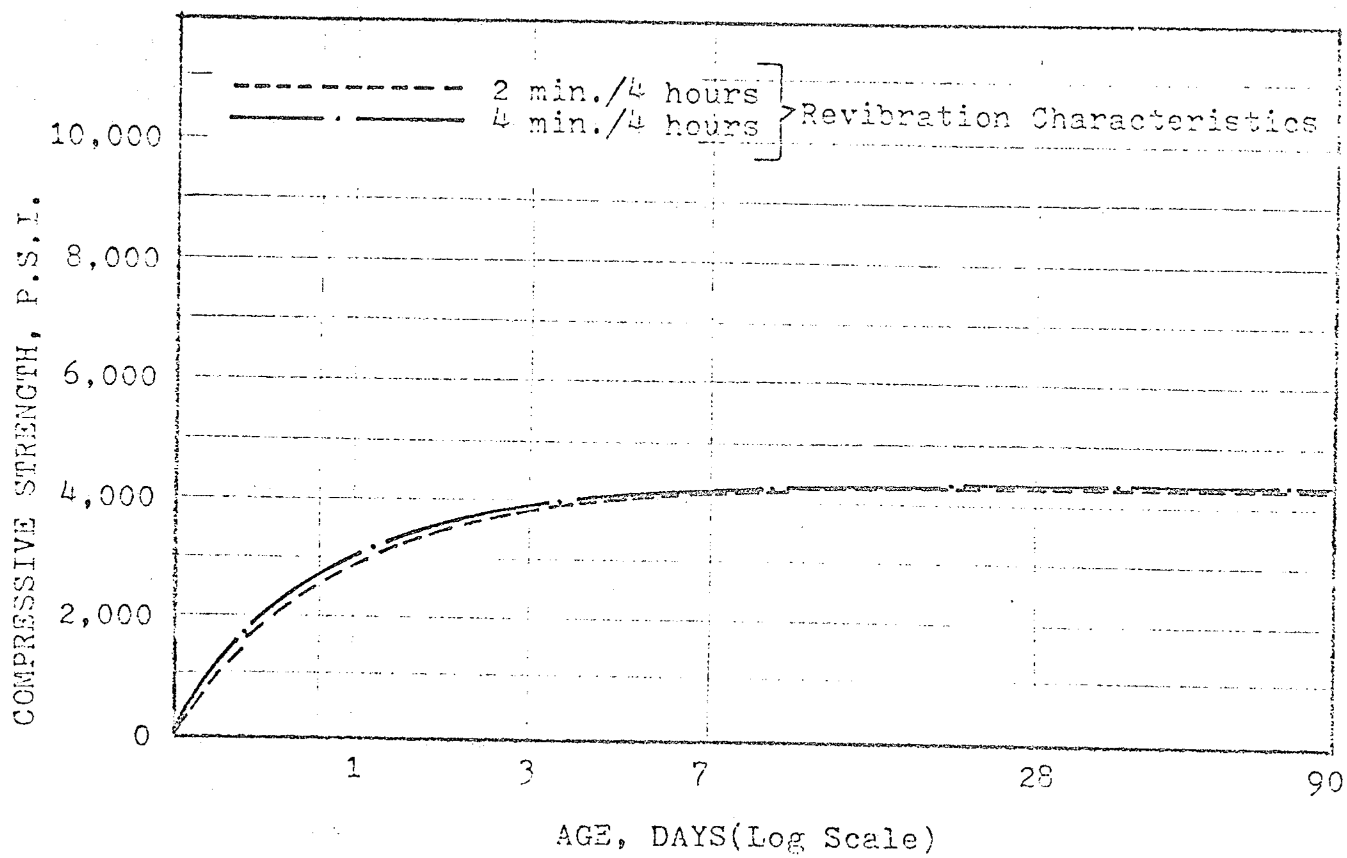


Fig. 32. Relative strength curves for concrete for different revibration characteristics(water/cement ratio=0.6; revib. and steamed specimens only: Sets 'B').

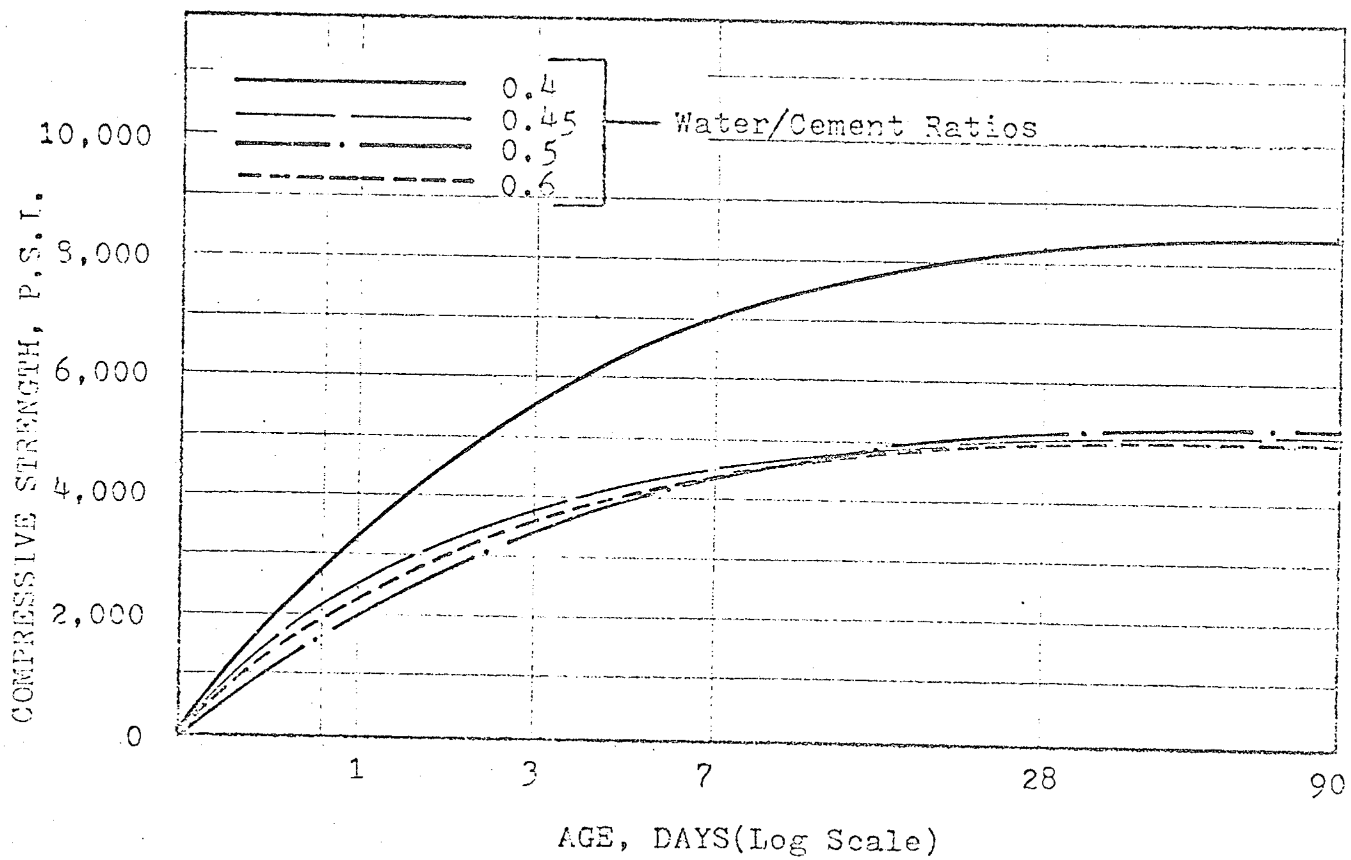


Fig. 33 . Relative strength curves for concrete for different water/cement ratios(revibration characteristics:2 min. every 4 hours; revibrated specimens only: Sets 'A').

Fig. 34: Relative Strength curves for concrete for different revibration characteristics (Revib. characteristic: 2 min./4 hrs.; Sets B).

Here the effect of different water/cement ratios is compared on concrete subjected to simultaneous revibration and steaming. Again concrete with water/cement ratio = 0.4 is by far the strongest, followed in descending order by concretes with water/cement ratio of 0.45, 0.5 and 0.6. Using concrete with water/cement ratio = 0.6 as base, strength gain for the others is given in Table XXIV.

TABLE XXIV

RELATIVE STRENGTHS OF CONCRETE WITH DIFFERENT WATER/CEMENT RATIOS: (REVIB. 2 MIN./4 HRS: SETS B).

W/C Ratio	* Relative Compressive Strength		
	1 Day	28 Days	90 Days
0.5	+ 17%	+ 5%	+ 7%
0.45	+ 29%	+30%	+30%
0.4	+ 30%	+180%	+110%

* Compared to Concrete with W/C Ratio = 0.6.

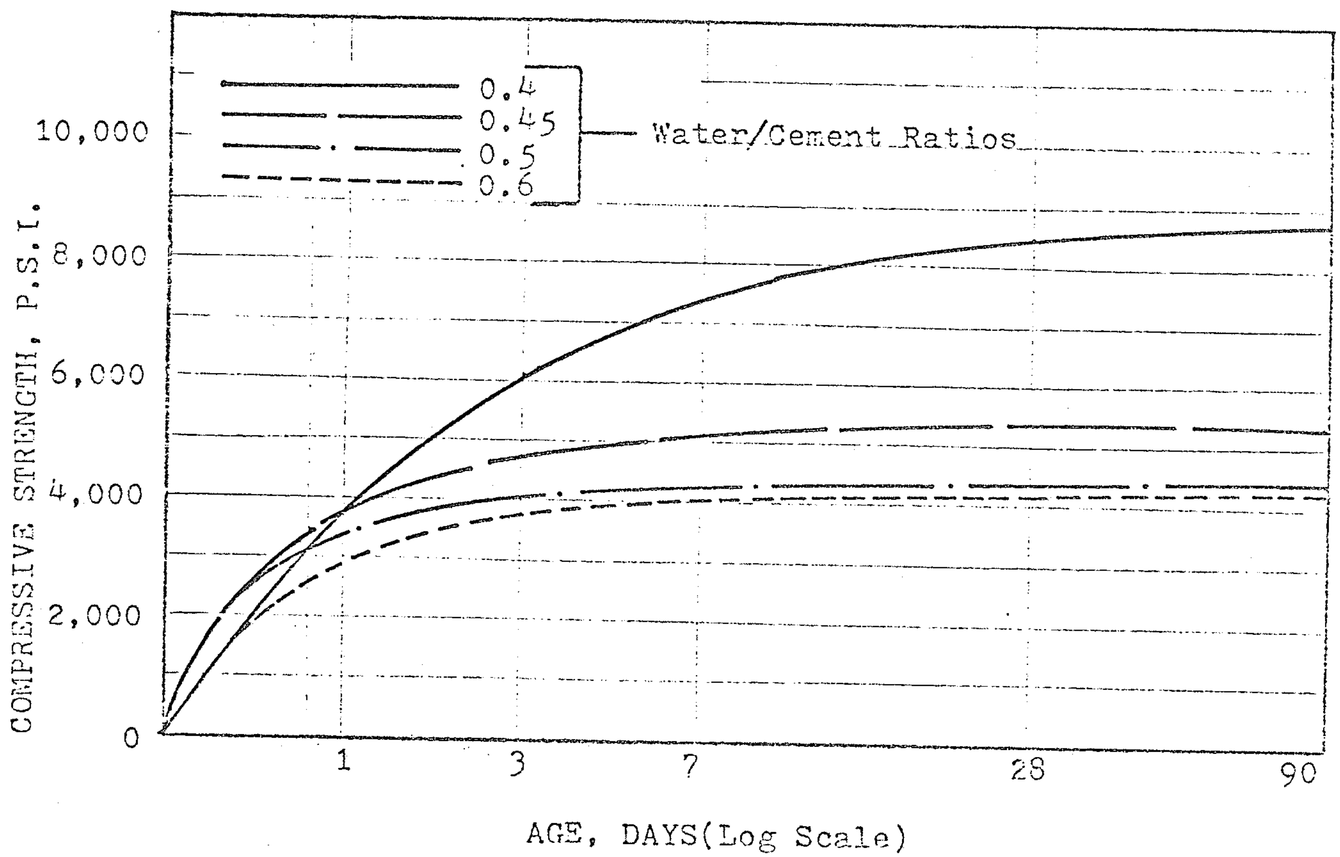


Fig.34 . Relative strength curves for concrete for different water/cement ratios(revibration characteristics:2 min. every 4 hours; revib. and steamed specimens only: Sets 'B').

5.6 Effect of Non-repeated Revibration.

Batch 17 (water/cement ratio = 0.5) consisted of five sets which were subjected to various periods of delayed revibration; the duration of revibration was 2 minutes in each case and was applied only once, not repeated as in the case of other batches. A sixth set was cast as a control set and not subjected to any revibration. All sets were however vibrated initially during casting to ensure proper compaction. The test age for this batch was 97 days; the test results are given in Table XXV.

TABLE XXV

EFFECT OF DELAYED REVIBRATION ON COMPRESSIVE STRENGTH (DURATION OF VIBRATION = 2 MIN., WATER/CEMENT RATIO = 0.5; TEST AGE = 97 DAYS

Set	Delay Period for Revibration	Compressive Strength, P.S.I.	Percentage gain (+) or loss (-) compared to Set F.
A	1 hr. after casting	7870	- 4%
B	3 hrs. " "	8530	+ 4%
C	6 " " "	7930	- 4%
D	10 " " "	7320	- 11%
E	16 " " "	7850	- 4%
F	No Revib. (Control Set)	8220	

Results of Table XXV suggest that for concrete with water/cement ratio = 0.5, a non-repetitive delayed revibration of 2 mins. does not make a significant difference in the long-term compressive strengths. Only one set, revibrated once 3 hours after casting, showed any increase in strength over the normal air cured concrete. This gain was of the order of 4%. The set revibrated 10 hrs. after casting showed a loss of 11% and the rest showed a loss of approximately 4% compared to the control set. Therefore it is apparent that no appreciable difference is indicated in compressive strength due to delayed revibration for this specific case.

5.7 Relative Compressive Strengths Using Tabulated Test Data.

In view of the fact that a strength-age curve is an average and therefore an approximate representation of actual test data, precise strength comparisons at any particular age are not possible if the values are obtained from these curves. Results of strength tests at different ages are subject to numerous variables even though they are made on specimens with the same normal mixes; not the least of these variables is the curing conditions under which the specimens have been stored before testing. Therefore to evaluate precisely the effect of the different processes on the compressive strength of concrete, figures from actual test data are used and assembled in Table XXVI. (see Table VIII, p. 120, and Appendix A).

TABLE XXVI

COMPRESSIVE STRENGTH OF CONCRETE SUBJECTED TO DIFFERENT PROCESSES. (TEST AGE = 20 HRS., REVIB. CHARACTERISTICS: 2 MIN./4 HRS.

W/C Ratio	Batch No.	Particulars	Revib. A	Revib. &Steamed B	Steamed C	Air Cured D
0.4	13	Compr. Str.	3060	5520	4830	2750
		*	+ 11%	+101%	+ 76%	-
0.425	12	Compr. Str.	2740	5040	5060	2170
		*	+ 27%	+132%	+134%	-
0.45	34	Compr. Str.	2240	3710	4000	1730
		*	+ 30%	+114%	+132%	-
0.5	30	Compr. Str.	1350	3410	3250	860
		*	+ 57%	+296%	+278%	-

Note: *: Gain (+) or Loss (-) is expressed as a percentage of the Air Cured Concrete Strength.

Study of the data from Table XXVI indicates that at early age (approx. 20 hrs.), there is a definite gain in compressive strength of concrete due to revibration, steaming and a combination of these two processes. The strength gain in Table XXVI and in this test is expressed as a percentage of the normal air cured concrete strength.

Generally speaking, the effectiveness of steam curing is much more than of revibration on early strength gain. For concrete with water/cement ratio of 0.4, the strength gain due to steam curing is 76% against 11% due to revibrations; 134% against 27% for water/cement ratio of 0.425; 132% against 30% for water/cement ratio of 0.45; and 278% against 57% for water/cement ratio of 0.5.

and 278% against 57% for water/cement ratio of 0.5.

Effect of combining steam curing and revibration compared to that of steam curing alone seems to indicate some advantage for concretes with water/cement ratio of 0.4 and 0.5 but a marginal disadvantage for concretes with water/cement ratios of 0.425 and 0.45. In the case of concretes with water/cement ratio of 0.4, Set (B) showed a strength gain of 101% as against 76% for Set (C).

In all cases, the strength gain at early age seems to increase with increasing water/cement ratios. It ranges from 11% to 57% for Set (A), 101% to 296% for Set (B), and 76% to 278% for Set (C), for variation of water/cement ratio from 0.4 to 0.5. Therefore the most gain due to these processes appears to be realized in the case of lean mixes.

TABLE XXVII

COMPRESSIVE STRENGTH OF CONCRETES SUBJECTED TO DIFFERENT PROCESSES. (NOM. TEST AGE: 28 DAYS; REVIB. CHARACTERISTICS: 2 MIN./4 HRS.).

W/C Ratio	Batch No.	Particulars	Revib. A	Revib. & Steamed B	Steamed C	Air Cured D
0.4	9	Strength, PSI	8450	8630	9230	8500
		*	0	+ 2%	+ 9%	-
0.45	35	Strength, PSI	5110	5230	4660	4730
		*	+ 8%	+11%	- 1%	-
0.5	33	Strength, PSI	4980	3770	5020	4940
		*	0	-24%	+ 2%	-
0.6	37	Strength, PSI	5000	4300	4420	4520
		*	+11%	- 7%	- 2%	-

Note: *: Gain (+) or Loss (-) is expressed as a percentage of the Air Cured Concrete Strength.

Table XXVII shows comparative strength values at a nominal test age of 28 days. The appreciable strength gain at early age seems to have been lost and the advantage over normal air cured concrete due to the different processes is only nominal, if that: some of the steamed and revibrated (Set B) specimens show a loss of strength. This is in keeping with the findings of other researchers [2], [28] and [33] as far as the steamed specimens are concerned. But concrete with water/cement ratios of 0.4 and 0.45 still shows a slight gain for Set (B) compared to normal air cured concrete. Set (A) subjected to revibration only still seems to hold an edge and shows up to 11% gain over normal concrete.

CHAPTER VI

CONCLUSIONS

The following represents a gist of the conclusions that can be drawn from the results of this research.

1. Repeated revibration at short intervals during the first two hours after casting can cause serious damage to the setting concrete.
2. Early strength generally showed an increase due to all the processes: revibration, steam curing, and a combination of the two. Greatest increase in early strength was obtained for concrete subjected to combined revibration and steam curing, less for steam curing only, and least in the case of revibration only.

3. A loss in strength was obtained at 28 days and later ages in most cases of steam cured and combined revibrated and steamed specimens. Generally concrete subjected to revibration only showed some increase in strength over normal air cured concretes; only in a few cases was there a marginal loss in strength due to revibration.
4. In the case of specimens with water/cement ratio of 0.4 and subjected to revibration only, revibration of 2 min. every 4 hours yielded the best results, followed by 8 min. every 4 hours, and $\frac{1}{2}$ min. every 4 hours respectively.
5. With water/cement ratio of 0.4, specimens subjected to revib. and steaming simultaneously showed greatest gain in strength with revibration of $\frac{1}{2}$ min. every 4 hours at early age, and with 2 min. every 4 hours at later ages.
6. With water/cement ratio of 0.4 and revibration only, revibration of 2 min. every 4 hours yielded greater strength at early age compared with revibration of 4 min. every 4 hours, but lower strength at later ages.
7. With water/cement ratio of 0.4 and combined revibration and steaming, there is very little difference in strength of concrete revibrated 2 min. at 4 hours or 4 min. at 4 hours.

8. For concrete revibrated at 2 min. every 4 hours, strength increases with decrease in water/cement ratios. Strength increase in the case of water/cement ratio of 0.4 is much greater than those of 0.45, 0.5 or 0.6.

9. The above observation is true also for concrete subjected to combined revibration and steam only.

10. Delayed vibration, i.e. revibration repeated only once after casting showed no definite gain in strength at later ages for water/cement ratio of 0.5.

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APPENDIXES

APPENDIX A

CASTING AND TEST REPORTS: BATCHES NO. 9 - 39

Explanation of Abbreviations Used:

Description of Specimen:

- C- defective cap.
- D- evidence of deep holes or cracks on surface.
- M- evidence of mortar loss.
- P- pock-marked surface.
- S- smooth surface.

Mode of Failure:

- B- bond failure between mortar and aggregate, and/or shear failure in mortar.
- E= explosive fracture of specimen.
- F- edge failure of specimen and/or cap failure.
- T- tensile or bending failure.
- V- vertical splitting of specimen during failure.
- W- wedge or cone formation at top and/or bottom during failure of specimen.
- X- diagonal shear.

Cylinder Strength: *- values marked thus have not been included in average strength computations; they pertain to cases of edge and/or cap failure, or to defective specimens.

Specimen No. marked with*, pertain to cylinders cast with thermocouple wires embedded in them.

CASTING AND TEST REPORT

Batch No. 9

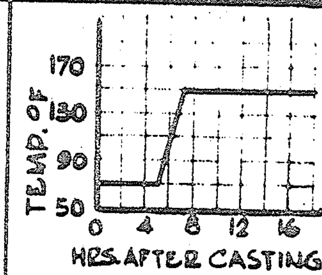
W/C RATIO: 0.4

REVIBRATION CHARACTERISTICS: ..... 2 min. at 4 hrs.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
22.4.64	9:00 a.m.	Casting	
	1:00 p.m.	Revib. 2 mins. A & B	
	2:00 "	Start Steaming, B & C	
	5:00 "	Revib., 2 mins. A & B	
	9:00 "	" " "	
23.4.64	1:00 a.m.	" " "	
	3:00 "	Stop Steaming.	Ideal Temp. —— Steam Chest - - - - Vib. Table —·—

CURING CONDITIONS: Fog. For last 9 days in air.

TEST RESULTS: Test Age: 34 days (nom.) 81.5 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	C, S	E, F	8040 *	8450
	2	P	E, X	8450	
	3	C, D, P, M	E, F	7420 *	
Revib. and Steamed	1	S, M	E, W	8400	8630
	2	S, C	E, F, T	7940 *	
	3	S	E, W	8850	
Steamed	1	S, C	E, F	8660 *	9230
	2	P, C	E, V	9100	
	3	S, D, C,	E, V	9360	
Air Cured	1	P, M	E, W	8910	8500
	2	D, M, C	E, V	8140	
	3	P, M, C	E, V	8450	

CASTING AND TEST REPORT

Batch No. 10

W/C RATIO: 0.4

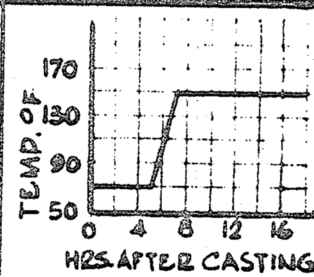
REVIBRATION CHARACTERISTICS: ..... 2 min. at 4 hrs.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
25.4.64	9:00 a.m.	Casting.	
	1:00 p.m.	Revib. 2 min. A & B.	
	2:00 p.m.	Start Steaming B & C.	
	5:00 p.m.	Revib. 2 min. A & B.	
	9:00 p.m.	" " "	
26.4.64	1:00 a.m.	" " "	
	3:00 a.m.	Stop Steaming.	



Ideal Temp. ————
Steam Chest – – – –
Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS: Test Age: 10 days (nom) 240 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1			6050 *	7080
	2			7150	
	3			7000	
Revib. and Steamed	1			5890	6270
	2			6690	
	3			6220	
Steamed	1			6080	6430
	2			6470	
	3			6750	
Air Cured	1			6010 *	7180
	2			7100	
	3			7250	

CASTING AND TEST REPORT

Batch No. 11

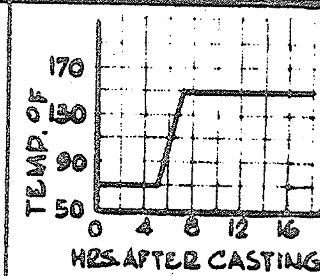
W/C RATIO: 0.4

REVIBRATION CHARACTERISTICS: ..... 2 min. at 4 hrs.

SET CLASSIFICATION:

Revibrated...............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
27.4.64	8:00 a.m.	Casting.	
	12:00 noon	Revib. 2 min. A & B	
	1:00 p.m.	Start Steaming B & C	
	4:00 p.m.	Revib. 2 min. A & B.	
	8:00 p.m.	" " "	
	12:00 m.n.	" " "	
28.4.64	2:00 a.m.	Stop Steaming.	Ideal Temp. ——— Steam Chest - - - - Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS:

Test Age: 9 days (nom.) 222 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1 2 3			7970 7740 8580	8100
Revib. and Steamed	1 2 3			7780 7330 7390	7500
Steamed	1 2 3			7250 7250 6680 *	7250
Air Cured	1 2 3			7000 7420 5730 *	7210

CASTING AND TEST REPORT

Batch No. 12

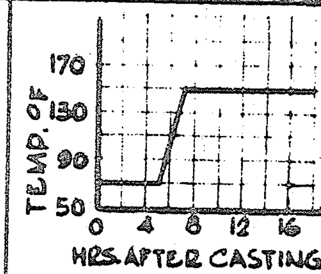
W/C RATIO: .... 0.429.

REVIBRATION CHARACTERISTICS: ..... 2 min. at 4 hrs.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
28.4.64	5:00 p.m.	Casting.	
	9:00 p.m.	Revib. 2 min. A & B.	
	10:00 p.m.	Start Steaming B & C.	
29.4.64.	1:00 a.m.	Revib. 2 min. A & B.	
	5:00 a.m.	" " "	
	9:00 a.m.	" " "	
	11:00 a.m.	Stop Steaming.	Ideal Temp. ——— Steam Chest - - - - Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS: Test Age: 21 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1			2830	2740
	2			2640	
	3			1340 *	
Revib. and Steamed	1			5000	5040
	2			4800	
	3			5320	
Steamed	1			3920 *	5060
	2			5100	
	3			5020	
Air Cured	1	Height 10½"		2090	2170
	2	" "		2160	
	3	" "		2260	

CASTING AND TEST REPORT

Batch No. 13

W/C RATIO: 0.4

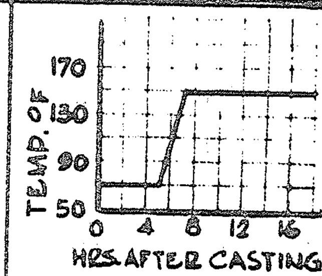
REVIBRATION CHARACTERISTICS:..... 2 min. at 4 hrs.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
30.4.64	6:00 p.m.	Casting.	
	10:00 p.m.	Revib. 2 min. A & B.	
	11:00 p.m.	Start Steaming B & C.	
	2:00 a.m.	Revib. 2 min. A & B.	
	6:00 a.m.	" " "	
	10:00 a.m.	" " "	
	12:00 a.m.	Stop Steaming.	



Ideal Temp. ————
Steam Chest - - - -
Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS:

Test Age: 20 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1			3020	3060
	2			3180	
	3			2970	
Revib. and Steamed	1		E	5250	5520
	2		E	5600	
	3		E	5700	
Steamed	1			4720	4830
	2			4420	
	3		E	5340	
Air Cured	1			2850	2750
	2			2740	
	3			2660	

CASTING AND TEST REPORT

Batch No. 14

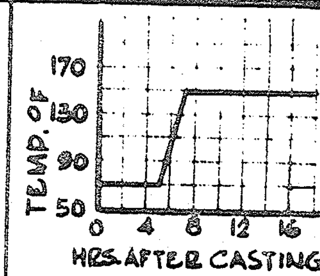
W/C RATIO: 0.4

REVIBRATION CHARACTERISTICS: ...... 2 min. at 4 hrs.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date : Time		Particulars	Temperature
30.4.64	6:00 p.m.	Casting.	
	10:00 p.m.	Revib. 2 min. A & B.	
	11:00 p.m.	Start Steaming B & C.	
1.5.64.	2:00 a.m.	Revib. 2 min. A & B.	
	6:00 a.m.	" " "	
	10:00 a.m.	" " "	
	12:00 noon	Stop Steaming.	Ideal Temp. ——— Steam Chest - - - - Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS:

Test Age: 7 days (nom.) 177 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	P, C	E, T, B	6190	6660
	2	P	E, F	6850	
	3	P, M	E, T	6930	
Revib. and Steamed	1	S	E, W	6900	6900
	2	S, C	F	6060 *	
	3	M, C, P	E, F	4740 *	
Steamed	1	S, M	E, F	7280	7200
	2	P	E, X	7120	
	3	S	F	6080 *	
Air Cured	1	P	E, W	6630	6680
	2	P	E, W	6580	
	3	P	E, W	6830	

CASTING AND TEST REPORT

Batch No. 15

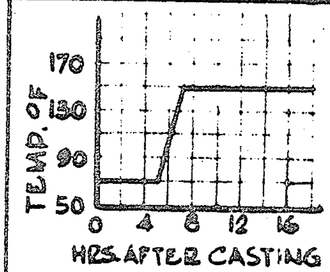
W/C RATIO: 0.4

REVIBRATION CHARACTERISTICS: .... 2 min. at 1 hr.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date : Time	Particulars	Temperature
1.5.64 7:30 p.m.	Casting.	
8:30 p.m.	Revib. 2 min. A & B.	
9:30- 11:30 hourly	" " "	
2.5.64 12:30 a.m.	" " " & Start Steaming.	
1:30 a.m.-12:30 p.m. hourly	Revib. 2 min. A & B	
1:30 p.m.	Stop Steaming.	Ideal Temp. ——— Steam Chest – – – – Vib. Table —·—

CURING CONDITIONS: Air Cured

TEST RESULTS:

Test Age: 87 days (nom.) 2080 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	Extensively damaged specimens		*	-
	2	"	" "	*	
	3	"	" "	*	
Revib. and Steamed	1	"	" "	*	-
	2*	"	" "	*	
	3	"	" "	*	
Steamed	1	S, P	E, X	8900	8650
	2	S, P	E, X	8310	
	3	S, P	E, W	8750	
Air Cured	1	S	E, W	8300	8310
	2	S	E, X	8370	
	3	S	E, X	8250	

CASTING AND TEST REPORT

Batch No. 16

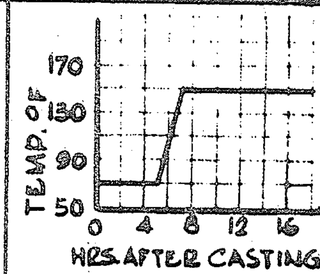
W/C RATIO: 0.4

REVIBRATION CHARACTERISTICS: .... 2 min. at 1 hr.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
1.5.64	7:30 p.m.	Casting.	
	8:30 p.m.	Revib. 2 min. A & B.	
	9:30-11:30 hourly	" " "	
2.5.64	12:30 a.m.	" " " & Start Steaming.	
	1:30 - 12:30 p.m. hourly	Revib. 2 min. A & B.	Ideal Temp. ———
	1:30	Stop Steaming.	Steam Chest – – – – Vib. Table —·—

CURING CONDITIONS: Air Cured

TEST RESULTS: Test Age: 88 days (nom.) 2104 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	Extensively damaged specimen		*	-
	2	"	"	" *	
	3	"	"	" *	
Revib. and Steamed	1	"	"	" *	-
	2	"	"	" *	
	3	"	"	" *	
Steamed	1*	S, P	E, T	8440	8280
	2	S, P	E, T	8380	
	3	S, P	E, W	8020	
Air Cured	1	S, P	E, W	7300	7610
	2	S, P	E, W	7860	
	3	S, P	E, W	7660	

CASTING AND TEST REPORT

Batch No. 17

W/C RATIO: 0.495

REVIBRATION CHARACTERISTICS: ..... As noted.

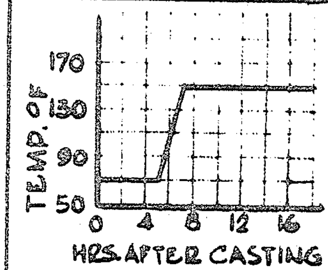
SET CLASSIFICATION:

Revibrated..............A,B,C,D,E
Air Cured .... F

SEQUENCE OF OPERATIONS:

Date	Time	Particulars
2.5.64	8:15 p.m.	Casting of A, B, C.
	8:45 p.m.	Casting D, E, F.
	9:15 p.m.	Revib. 2 min. A.
	11:15 p.m.	" " B.
3.5.64	2:45 a.m.	" " C.
	6:45 a.m.	" " D
	12:45 a.m.	" " E

Temperature



Ideal Temp. ———
Steam Chest - - - -
Vib. Table —·—

CURING CONDITIONS: Fog cured except last 6 days.

TEST RESULTS:

Test Age: 97 days (nom.)
2320 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib. A	1	S	E, X	7950	7870
	2	S	E, X	7790	
	3	S	E, F	7660 *	
Revib. B	1	S	E, W	8540	8530
	2	S	E, W	8600	
	3	S	E, W	8460	
Revib. C	1	S	E, X	7930	7930
	2	S	E, F	7660 *	
	3	S	E, F	7350 *	
Revib. D	1	S	E, X	7320	7320
	2	S	E, F	6720 *	
	3	S	E, F	7070 *	

(contd.)

CASTING AND TEST REPORT

Batch No. 17 (Contd.)

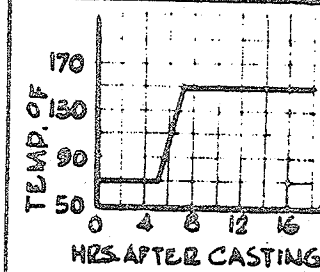
W/C RATIO:

REVIBRATION CHARACTERISTICS:

SET CLASSIFICATION:

SEQUENCE OF OPERATIONS:

Date : Time	Particulars	Temperature



Ideal Temp. ————
Steam Chest – – – –
Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS: Test Age:

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib. E	1 2 3	S, C S S	E, T E, X E, W	6400 * 7890 7800	7850
	1 2 3				
(Not F Revib.)	1 2 3	S S S	E, W E, X E, X	8280 8200 8170	8220
	1 2 3				

CASTING AND TEST REPORT

Batch No. 18

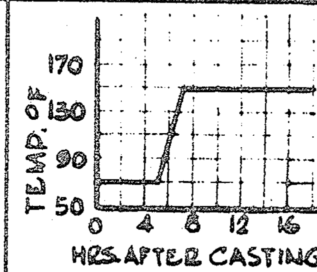
W/C RATIO: .... 0.4.

REVIBRATION CHARACTERISTICS: ...... ½ min. at 4 hrs.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
3.5.64	6:00 p.m.	Casting.	
	10:00 p.m.	Revib. ½ min. A & B.	
	11:00 p.m.	Start Steaming.	
4.5.64	2:00 a.m.	Revib. ½ min. A & B.	
	6:00 a.m.	" " "	
	10:00 a.m.	" " "	Ideal Temp. ———
	12:00 noon	Stop Steaming.	Steam Chest – – – – Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS: Test Age: 20 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1			2760	2860
	2			2940	
	3			2870	
Revib. and Steamed	1	M		4810	4920
	2*	M		4770	
	3	M		5180	
Steamed	1			4700	4770
	2			4040 *	
	3			4830	
Air Cured	1			2550	2570
	2			2550	
	3			2620	

CASTING AND TEST REPORT

Batch No. 19

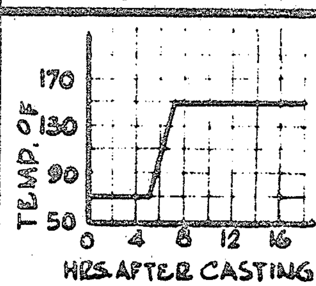
W/C RATIO: .... 0.4.

REVIBRATION CHARACTERISTICS:..... ½ min. at 4 hrs.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
3.5.64	6:00 p.m	Casting.	
	10:00 p.m	Revib. ½ min. A & B.	
	11:00 p.m	Start Steaming.	
4.5.64	2:00 a.m	Revib. ½ min. A & B.	
	6:00 a.m	" " "	
	10:00 a.m	" " "	
	12:00 noon	Stop Steaming.	Ideal Temp. —— Steam Chest - - - - Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS: Test Age: 3 days (nom.) 79 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	D, M	E, T	5730	5460
	2	D, M	T	5160	
	3	D, M	T	5490	
Revib. and Steamed	1	M	F	4830 *	5750
	2	M	E, W	5760	
	3	M	E, W	5730	
Steamed	1 *	P, D	T	5950	6050
	2	D, M	F	4310 *	
	3	S	E, W	6150	
Air Cured	1	P	F, T	5270 *	5600
	2	P. M	T	5660	
	3	D, M	E, W	5540	

CASTING AND TEST REPORT

Batch No. 20

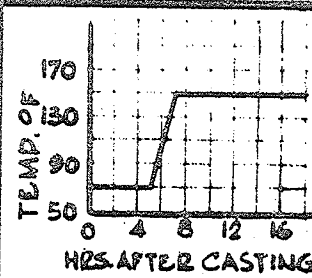
W/C RATIO: 0.4

REVIBRATION CHARACTERISTICS:..... ½ min. at 4 hrs.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
5.5.64	7:00 p.m.	Castings.	
	11:00 p.m.	Revib. ½ min. A & B.	
	12:00 m.n.	Start Steaming.	
6.5.64	3:00 a.m.	Revib ½ min. A & B.	
	7:00 a.m.	" " "	
	11:00 a.m.	" " "	
	1:00 p.m.	Stop Steaming.	Ideal Temp. ——— Steam Chest - - - - Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS: Test Age: 7 days (nom.) 168 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	P	B, F	3750 *	5300
	2	P	B	4640	
	3	P	B	5950	
Revib. and Steamed	1	P	T	5550	5930
	2 *	P	T	6310	
	3	P	T, F	4810 *	
Steamed	1	P, M	E, W	6140	6490
	2	S	E, W	6830	
	3	P	E, W	6500	
Air Cured	1	P	E, X	6850	6900
	2	P	E, W	7000	
	3	P, D	E, W	6850	

CASTING AND TEST REPORT

Batch No. 21

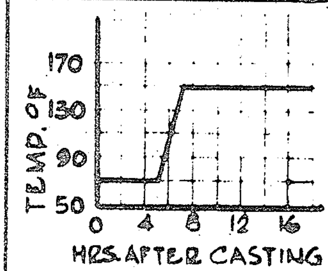
W/C RATIO: 0.4

REVIBRATION CHARACTERISTICS:..... ½ min. at 4 hrs.

SET CLASSIFICATION:

Revibrated...............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
5.5.64	7:00 p.m.	Casting.	
	11:00 p.m.	Revib. ½ min. A & B.	
	12:00 m.n.	Start Steaming.	
6.5.64	3:00 a.m.	Revib. ½ min. A & B.	
	7:00 a.m.	" " ".	
	11:00 a.m.	" " "	
	1:00 p.m.	Stop steaming.	
			Ideal Temp. ——— Steam Chest - - - - Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS: Test Age: 28 days (nom.) 668 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	S	F, T	4000	
	2	S	F, T	3750 *	4390
	3	S	V	4780	
Revib. and Steamed	1	S	V	6300	
	2	S	V	5740	5840
	3	S	V	5490	
Steamed	1+	S	V	6690	
	2	S	V	6710	6580
	3	S	V	6330	
Air Cured	1	S	V	6420	
	2	S	V	6480	6450
	3	S	F	6160	

CASTING AND TEST REPORT

Batch No. 22

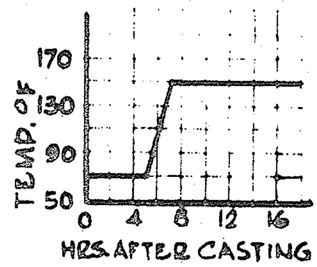
W/C RATIO: 0.4

REVIBRATION CHARACTERISTICS:..... 8 min. at 4 hrs.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date :	Time	Particulars	Temperature
6.5.64	7:30 p.m.	Casting.	
	11:30 p.m.	Revib. 8 min. A & B.	
7.5.64	12:30 a.m.	Start Steaming.	
	3:30 a.m.	Revib. 8 min. A & B.	
	7:30 a.m.	" " "	
	11:30 a.m.	" " "	
	1:30 p.m.	Stop Steaming.	Ideal Temp. ——— Steam Chest – – – Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS: Test Age: 7 days (nom.) 184 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	S, P	T, F	6110 *	6760
	2	S, P	X	6960	
	3	S	W	6550	
Revib. and Steamed	1	S	W	6680	6630
	2+	S	X	6700	
	3	S	W	6500	
Steamed	1	S	W	6660	5890
	2	S	X	5120	
	3	S, P, C	F, T	4990 *	
Air Cured	1	S	W	6750	6800
	2	S	X	6850	
	3	P, C	F, T	-- *	

CASTING AND TEST REPORT

Batch No. 23

W/C RATIO:........................ 0.4

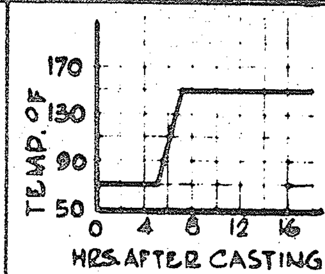
REVIBRATION CHARACTERISTICS:..... 8 min. at 4 hrs.

SET CLASSIFICATION:

Revibrated...............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
6.5.64	7:30 p.m.	Casting.	
	11:30 p.m.	Revib. 8 min. A & B.	
7.5.64	12:30 a.m.	Start Steaming.	
	3:30 a.m.	Revib. 8 min. A & B.	
	7:30 a.m.	" " "	
	11:30 a.m.	" " "	
	1:30 p.m.	Stop Steaming.	



Ideal Temp. ————
Steam Chest – – – –
Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS:

Test Age: 28 days (nom.) 667 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	P	E, V	7040	6920
	2	P	F, T	3400 *	
	3	P	E, V	6790	
Revib. and Steamed	1	S	E, V	6350	5740
	2	S	F	4000 *	
	3	S	E, V	5140	
Steamed	1*	S	E, V	6310	5770
	2	S	E, V	5800	
	3	P	E, V	5210	
Air Cured	1	P	E, V	7710	7650
	2	P	E, V	7690	
	3	P	E, V	7550	

CASTING AND TEST REPORT

Batch No. 24

W/C RATIO: 0.4

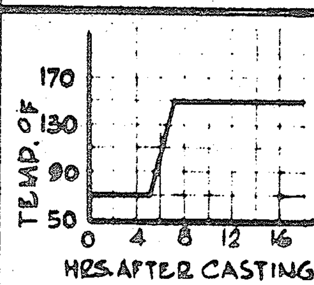
REVIBRATION CHARACTERISTICS: ..... 8 min. at 4 hrs.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
7.5.64	7:30 p.m.	Casting.	
	11:30 p.m.	Revib. 8 min. A & B.	
8.5.64	12:30 a.m.	Start Steaming.	
	3:30 a.m.	Revib. 8 min. A & B.	
	7:30 a.m.	" " "	
	11:30 a.m.	" " "	
	1:30 p.m.	Stop Steaming.	



Ideal Temp. ————
Steam Chest ?
Vib. Table ?

CURING CONDITIONS:

TEST RESULTS: Test Age: 20 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1			1950	1940
	2			1970	
	3			1910	
Revib. and Steamed	1			3570	4050
	2 *			4530	
	3			3980	
Steamed	1			3840	4110
	2			4210	
	3			4280	
Air Cured	1			1810	1750
	2			1770	
	3			1660	

CASTING AND TEST REPORT

Batch No. 25

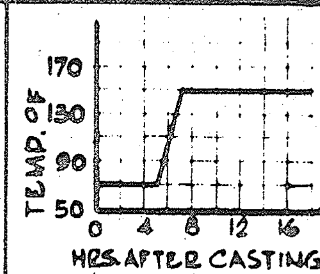
W/C RATIO:........................ 0.4

REVIBRATION CHARACTERISTICS:..... 8 min. at 4 hrs.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
7.5.64	7:30 p.m	Casting.	
	11:30 p.m	Revib. 8 min. A & B.	
8.5.64	10:30 a.m	Start Steaming.	
	3:30 a.m	Revib. 8 min. A & B.	
	7:30 a.m	" " "	
	11:30 a.m	" " "	
	1:30 p.m	Stop Steaming.	Ideal Temp. —— Steam Chest ---- Vib. Table —·—

CURING CONDITIONS: Air Cured.

TEST RESULTS:

Test Age: 64 days (nom.) 1530 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	R, P, M	E, F	6150 *	7200
	2	P, M	F	5900 *	
	3	P, M	E, W	7200	
Revib. and Steamed	1	R, P, M, C	F	4490 *	7290
	2	R, P	E, X	7290	
	3	R, M	F	4530 *	
Steamed	1*	S, P, M, C	F	5490 *	7370
	2	S, M, C	F	3680 *	
	3	S, M	E, X	7370	
Air Cured	1	P	E, W	7780	7670
	2	P	E, W	7550	
	3	P, D	F	6800 *	

CASTING AND TEST REPORT

Batch No. 26

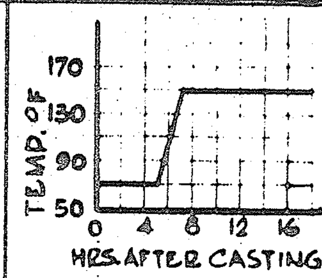
W/C RATIO: 0.4

REVIBRATION CHARACTERISTICS: ..... 2 min. at 1 hr. for first 5 hrs. only.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
8.5.64	7:30 p.m.	Casting.	
	8:30 p.m.	Revib. 2 min. A & B.	
	9:30 and 11:30 p.m. hourly.	" " "	
9.5.64	12:30 a.m.	" " "	
		Start Steaming.	
	1:30 p.m.	Stop Steaming.	Ideal Temp. ——— Steam Chest - - - - Vib. Table —·—

CURING CONDITIONS:

Test Age: 3 days (nom.) 83 hrs.

TEST RESULTS:

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	Extensively damaged specimen		*	-
	2	"	" "	*	
	3	"	" "	*	
Revib. and Steamed	1	"	" "	*	-
	2	"	" "	*	
	3	"	" "	*	
Steamed	1	S	E, F	5730 *	5990
	2	S	E, X	6010	
	3	S	E, X	5970	
Air Cured	1	S	E, X	5250	5420
	2	S, P	E, F	5240 *	
	3	S	V, W	5590	

CASTING AND TEST REPORT

Batch No. 27

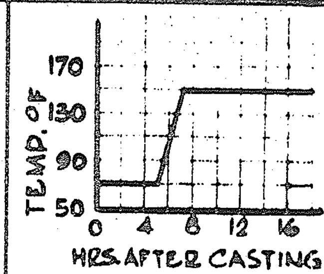
W/C RATIO: 0.4

REVIBRATION CHARACTERISTICS: .... 2 min. at 1 hr. for first 5 hrs. only.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
8.5.64	7:30 p.m. 8:30 p.m. 9:30 - 11:30 p.m. hourly.	Casting. Revib. 2 min. A & B. " " "	 Ideal Temp. Steam Chest Vib. Table
		" " "	
9.5.649	12:30 a.m. 1:30 p.m.	Start Steaming Stop Steaming.	

CURING CONDITIONS: Air Cured.

TEST RESULTS: Test Age: 74 days (nom.) 1770 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1 2 3	Extensively damaged specimens " "	 " "	* " * " *	--
Revib. and Steamed	1 2 3	" " "	" " "	" * " * " *	--
Steamed	1 * 2 3	S S, P S, P	E, X E, V E, V	8500 8050 7960	8170
Air Cured	1 2 3	S S S	E, X E, X E, X	7250 7790 7550	7530

CASTING AND TEST REPORT

Batch No. 28

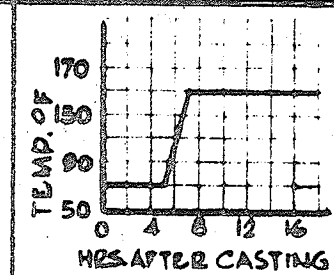
W/C RATIO: 0.4

REVIBRATION CHARACTERISTICS: .... 2 min. at 1 hr. for last 3 hrs. only.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
9.5.64	8:00 p.m.	Casting.	
10.5.64	1:00 a.m.	Start Steaming.	
	12 noon	Revib. 2 min. A & B.	
	1:00 p.m.	" " "	
	2:00 p.m.	" " "	
		Stop Steaming.	
			Ideal Temp. Steam Chest Vib. Table

CURING CONDITIONS: Air Cured.

TEST RESULTS: Test Age: 65 days (nom.) 1554 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	R	E,X,F	7300 *	8270
	2	R, P	E, W	8270	
	3	R	F	6150 *	
Revib. and Steamed	1*	S	E, F	8150 *	8640
	2	S	E, W	8730	
	3	S, P	E, W	8550	
Steamed	1	S, P	E, W	8750	8750
	2	S	E, F	7670 *	
	3	S, C	F, T	5850 *	
Air Cured	1			4780	4880
	2			4850	
	3			5020	

Note: Test age for Air Cured Set: 45 hrs.

CASTING AND TEST REPORT

Batch No. 29

W/C RATIO: 0.4

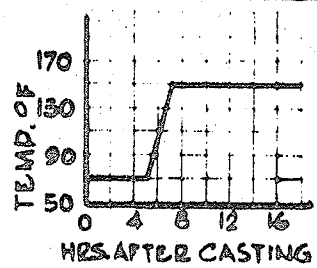
REVIBRATION CHARACTERISTICS:..... 2 min. at 1 hr. for last 3 hrs. only.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
9.5.64	8:00 p.m.	Casting.	
10.5.64	1:00 a.m.	Start Steaming.	
	12:00 noon	Revib. 2 min. A & B.	
	1:00 p.m.	" " "	
	2:00 p.m.	" " "	
		Stop Steaming.	



Ideal Temp. ————
Steam Chest - - - -
Vib. Table —·—

CURING CONDITIONS: Fog Cured; except for last 3 days.

TEST RESULTS: **Test Age:** 83 days (nom.) 1983 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	R	E, W	9860	10,070
	2	R	E, W, V	10,050	
	3	R	E, W	10,300	
Revib. and Steamed	1	S	E, W	9450	9650
	2	S	E, V	10,150	
	3	S	E, V	9340	
Steamed	1	S	E, V	9150	9750
	2	S	E, X	10,000	
	3	S	E, V	10,110	
Air Cured	1	R, P	E, W	9870	9650
	2	R	E, W, V	9570	
	3	R	E, W	9500	

Note: A mixture of sulfur and a black proprietary compound used for capping the test specimens.

CASTING AND TEST REPORT

Batch No. 30

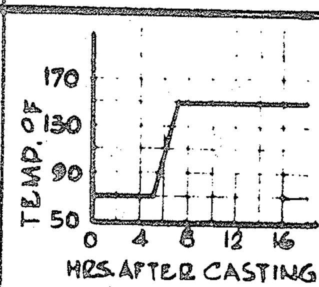
W/C RATIO:........................ 0.5

REVIBRATION CHARACTERISTICS:...... 2 min. at 4 hrs.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
10.5.64	8:30 p.m.	Casting.	
11.5.64	12:30 a.m.	Revib. 2 min. A & B.	
	1:30 a.m.	Start Steaming.	
	4:30 a.m.	Revib. 2 min. A & B.	
	8:30 a.m.	" " "	
	12:30 p.m.	" " "	
	2:30 p.m.	Stop Steaming.	
			Ideal Temp.——— Steam Chest- - - - Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS: Test Age: 20 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	S	X	1350	1350
	2	P, M, D	B	1360	
	3	S	B	1330	
Revib. and Steamed	1	S	B	3100	3410
	2 *	S, P	W	3570	
	3	S, P	X	3570	
Steamed	1	S	V	3200	3250
	2	S	B	3150	
	3	S	V	3400	
Air Cured	1	S	B	870	860
	2	S	B	900	
	3	S	B	820	

Slump = 7". Initial vibration during casting = 1 min.

CASTING AND TEST REPORT

Batch No. 31

W/C RATIO: 0.5

REVIBRATION CHARACTERISTICS:..... 2 min. at 4 hrs.

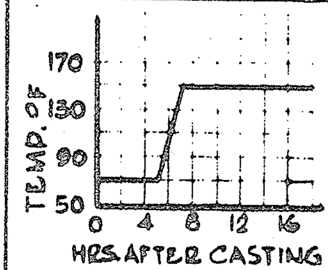
SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars
10.5.64	8:30 p.m.	Casting.
11.5.64	12:30 a.m.	Revib. 2 min. A & B.
	1:30 a.m.	Start Steaming.
	4:30 a.m.	Revib. 2 min. A & B.
	8:30 a.m.	" " "
	12:30 p.m.	" " "
	2:30 p.m.	Stop Steaming.

Temperature



Ideal Temp. ————
Steam Chest - - - -
Vib. Table —·—

CURING CONDITIONS:

3 days (nom.)

TEST RESULTS: Test Age: 82 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	P. M	B, T	3940	3730
	2	P	B, T	3820	
	3	P, M	B	3420	
Revib. and Steamed	1	S	B, T	4000	4040
	2	P	B, T	3840	
	3	P	B, T	4280	
Steamed	1*	S	T	3360	3320
	2	S	B	3720	
	3	S	B, T	2870	
Air Cured	1	S	B, T	3400	3380
	2	S	B, T	3420	
	3	S	B, T	3320	

CASTING AND TEST REPORT

Batch No. 32

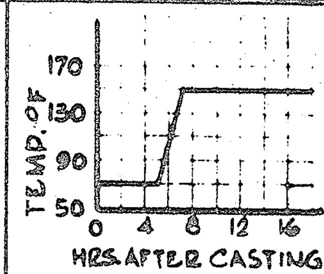
W/C RATIO: 0.5

REVIBRATION CHARACTERISTICS:..... 2 min.at 4 hrs.

SET CLASSIFICATION:

Revibrated...............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
11.5.64	9:30 p.m.	Casting.	
12.5.64	1:30 a.m.	Revib. 2 min. A & B.	
	2:30 a.m.	Start Steaming.	
	5:30 a.m.	Revib. 2 min. A & B.	
	9:30 a.m.	" " "	
	1:30 p.m.	" " "	
	3:30 p.m.	Stop Steaming.	Ideal Temp. ——— Steam Chest - - - - Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS: Test Age: 10 days (nom.) 242 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	P, D	E, V, W	5180	5160
	2	P, D	W	5130	
	3	P, C, D	T, F	4810 *	
Revib. and Steamed	1	P	V	4490	4230
	2*	P, D	W	4380	
	3	P, D, M	V, W	3820	
Steamed	1	S	V	4420	4420
	2	S, C	F	4150 *	
	3	S, C	F	- *	
Air Cured	1	S, C	F	- *	4720
	2	S	W	4740	
	3	S	E, X	4700	

Initial Vibration during casting - 1 min.

CASTING AND TEST REPORT

Batch No. 33

W/C RATIO: 0.5

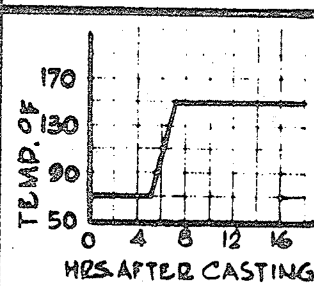
REVIBRATION CHARACTERISTICS:...... 2 min. at 4 hrs.

SET CLASSIFICATION:

Revibrated...............A
Revib. and Steamed.......B
Steamed..................C
Air Cured................D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
11.5.64	9:30 p.m.	Casting	
12.5.64	1:30 a.m.	Revib. 2 min. A & B.	
	2:30 a.m.	Start Steaming.	
	5:30 a.m.	Revib. 2 min. A & B.	
	9:30 a.m.	" " "	
	1:30 p.m.	" " "	
	3:30 p.m.	Stop Steaming.	



Ideal Temp. ————
Steam Chest – – – –
Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS: Test Age: 28 days (nom.) 666 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	S	E, V	4520	4980
	2	S	E, V	5450	
	3	P	W	4960	
Revib. and Steamed	1	S	E, V	3690	3770
	2	S	E, V	3710	
	3	S	E, V	3900	
Steamed	1*	S	E, V	5210	5020
	2	S	E, V	4860	
	3	S	E, V	4990	
Air Cured	1	S	E, V	4990	4940
	2	S	E, V	4900	
	3	S	E, V	4930	

Initial Vibration during casting = 1 min.

CASTING AND TEST REPORT

Batch No. 34

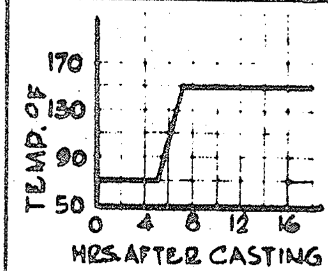
W/C RATIO: 0.45

REVIBRATION CHARACTERISTICS: ..... 2 min. at 4 hrs.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date : Time	Particulars	Temperature
12.5.64 9:30 p.m.	Casting.	
13.5.64 12:30 a.m.	Revib. 2 min. A & B.	
2:30 a.m.	Start Steaming.	
5:30 a.m.	Revib. 2 min. A & B.	
9:30 a.m.	" " "	
1:30 p.m.	" " "	
3:30 p.m.	Stop Steaming.	Ideal Temp. ——— Steam Chest – – – – Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS: Test Age: 22 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	P, M	B	2260	2240
	2	P, M	B	2200	
	3	P, M	B	2260	
Revib. and Steamed	1	P, M	V	3450	3710
	2	*S, M	X	3780	
	3	S, M	X	3910	
Steamed	1	S	W	4040	4000
	2	S	X	3960	
	3	S, C	F	2040 *	
Air Cured	1	P	B	1660	1730
	2	P	B	1780	
	3	P	B	1760	

Slump = 3/4"

CASTING AND TEST REPORT

Batch No. 35

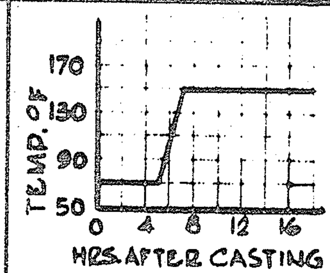
W/C RATIO: 0.45

REVIBRATION CHARACTERISTICS: ...... 2 min. at 4 hrs.

SET CLASSIFICATION:

Revibrated...............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date :	Time	Particulars	Temperature
12.5.64	9:30 p.m.	Casting.	
13.5.64	12:30 a.m.	Revib. 2 min. A & B.	
	2:30 a.m.	Start Steaming.	
	5:30 a.m.	Revib. 2 min. A & B.	
	9:30 a.m.	" " "	
	1:30 p.m.	" " "	
	3:30 p.m.	Stop Steaming.	Ideal Temp. —— Steam Chest - - - - Vib. Table —·—

CURING CONDITIONS:

28 days (nom.)

TEST RESULTS: Test Age: 665 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	P	E, V	4860	5110
	2	P	E, V	5650	
	3	P	E, V	4810	
Revib. and Steamed	1	P	F	3760 *	5230
	2	P	F	3890 *	
	3	P	E, V	5230	
Steamed	1*	S	E, V	4660	4660
	2	S	E, V	4560	
	3	S	E, V	4750	
Air Cured	1	S	F, V	- *	4730
	2	S	F, V	4350	
	3	S	E, V	5100	

Slump = 3/4"

CASTING AND TEST REPORT

Batch No. 36

W/C RATIO: 0.6

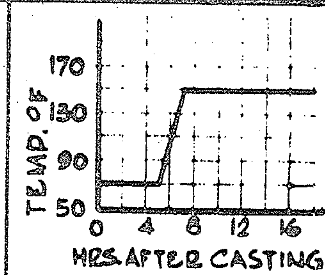
REVIBRATION CHARACTERISTICS: ..... 2 min. at 4 hrs.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date :	Time	Particulars	Temperature
13.5.64	9:30 p.m.	Casting.	
14.5.64	1:30 a.m.	Revib. 2 min. A & B.	
	2:30 a.m.	Start Steaming.	
	5:30 a.m.	Revib. 2 min. A & B.	
	9:30 a.m.	" " "	
	1:30 p.m.	" " "	
	3:30 p.m.	Stop Steaming.	



Ideal Temp. ————
Steam Chest - - - -
Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS: Test Age: 20 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	S	X, B	2040	2000
	2	S	V, B	2120	
	3	S	B	1830	
Revib. and Steamed	1*	S	B	2710	2850
	2	S	B	2940	
	3	S	X, B	2900	
Steamed	1	S	V	3240	3240
	2	S, C	T, F	1880 *	
	3	S, C	T, F	2070 *	
Air Cured	1	S	B	1890	1900
	2	S	B	1900	
	3	S	B	1900	

Slump = 9". Initial Vibration during casting = 15 secs.

CASTING AND TEST REPORT

Batch No. 37

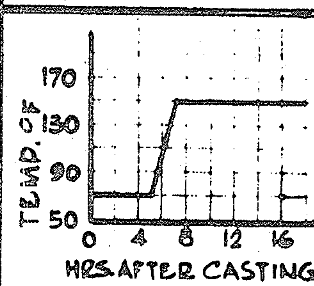
W/C RATIO:........................ 0.6.

REVIBRATION CHARACTERISTICS:..... 2 min. at 4 hrs.

SET CLASSIFICATION:

Revibrated...............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date : Time	Particulars	Temperature
13.5.64 9:30 p.m.	Casting.	
14.5.64 1:30 a.m.	Revib. 2 min. A & B.	
2:30 a.m.	Start Steaming.	
5:30 a.m.	Revib. 2 min. A & B.	
9:30 a.m.	" " "	
1:30 p.m	" " "	
3:30 p.m.	Stop Steaming.	Ideal Temp.——— Steam Chest– – – – Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS: Test Age: 28 days (nom.) 666 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	S	W	5290	5000
	2	S	W	4920	
	3	S	W	4790	
Revib. and Steamed	1	S, C	F	- *	4300
	2	S	F	2690 *	
	3	S	W	4300	
Steamed	1 *	S	W	4460	4420
	2	S	W	4420	
	3	S	W	4380	
Air Cured	1	S	W	4060	4520
	2	S	W	5020	
	3	S	W	4470	

Slump = 9". Initial Vibration during casting = 15 secs.

CASTING AND TEST REPORT

Batch No. 38

W/C RATIO: 0.6

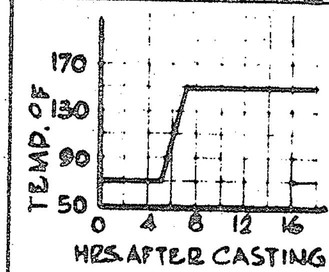
REVIBRATION CHARACTERISTICS: ...... 4 min. at 4 hrs.

SET CLASSIFICATION:

Revibrated..............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
14.5.64	9:30 p.m.	Casting.	
15.5.64	2:30 a.m.	Revib. 4 min. A & B. Start Steaming.	
	6:30 a.m.	Revib. 4 min. A & B.	
	10:30 a.m.	" " "	
	2:30 p.m.	" " "	
	3:30 p.m.	Stop Steaming.	



Ideal Temp. ————
Steam Chest – – – –
Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS: Test Age: 22 hrs.

Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi	Av. Strength psi
Revib.	1	S	W, B	1600	1690
	2	S	B	1730	
	3	S	B	1730	
Revib. and Steamed	1	S	B, F	2320 *	2930
	2*	S	B	3090	
	3	S	B	2760	
Steamed	1	S	B	3120	3000
	2	S, C	X, B	2870	
	3	S, C	F, T	- *	
Air Cured	1	S	B, T	1380	1490
	2	S	B, T	1590	
	3	S	B, T	1500	

Slump = 9"; Initial Vibration during casting = 15 secs.

CASTING AND TEST REPORT

Batch No. 39

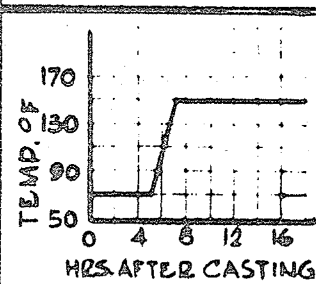
W/C RATIO: 0.6

REVIBRATION CHARACTERISTICS: ..... 4 min. at 4 hrs.

SET CLASSIFICATION:

Revibrated...............A
Revib. and Steamed......B
Steamed.................C
Air Cured...............D

SEQUENCE OF OPERATIONS:

Date	Time	Particulars	Temperature
14.5.64	9:30 p.m.	Casting.	
15.5.64	2:30 a.m.	Revib. 4 min. A & B. Start Steaming.	
	6:30 a.m.	Revib. 4 min. A & B.	
	10:30 a.m.	" " "	
	2:30 p.m.	" " "	
	3:30 p.m.	Stop Steaming.	Ideal Temp.—— Steam Chest---- Vib. Table —·—

CURING CONDITIONS:

TEST RESULTS:

Test Age: 28 days, 666 hrs.

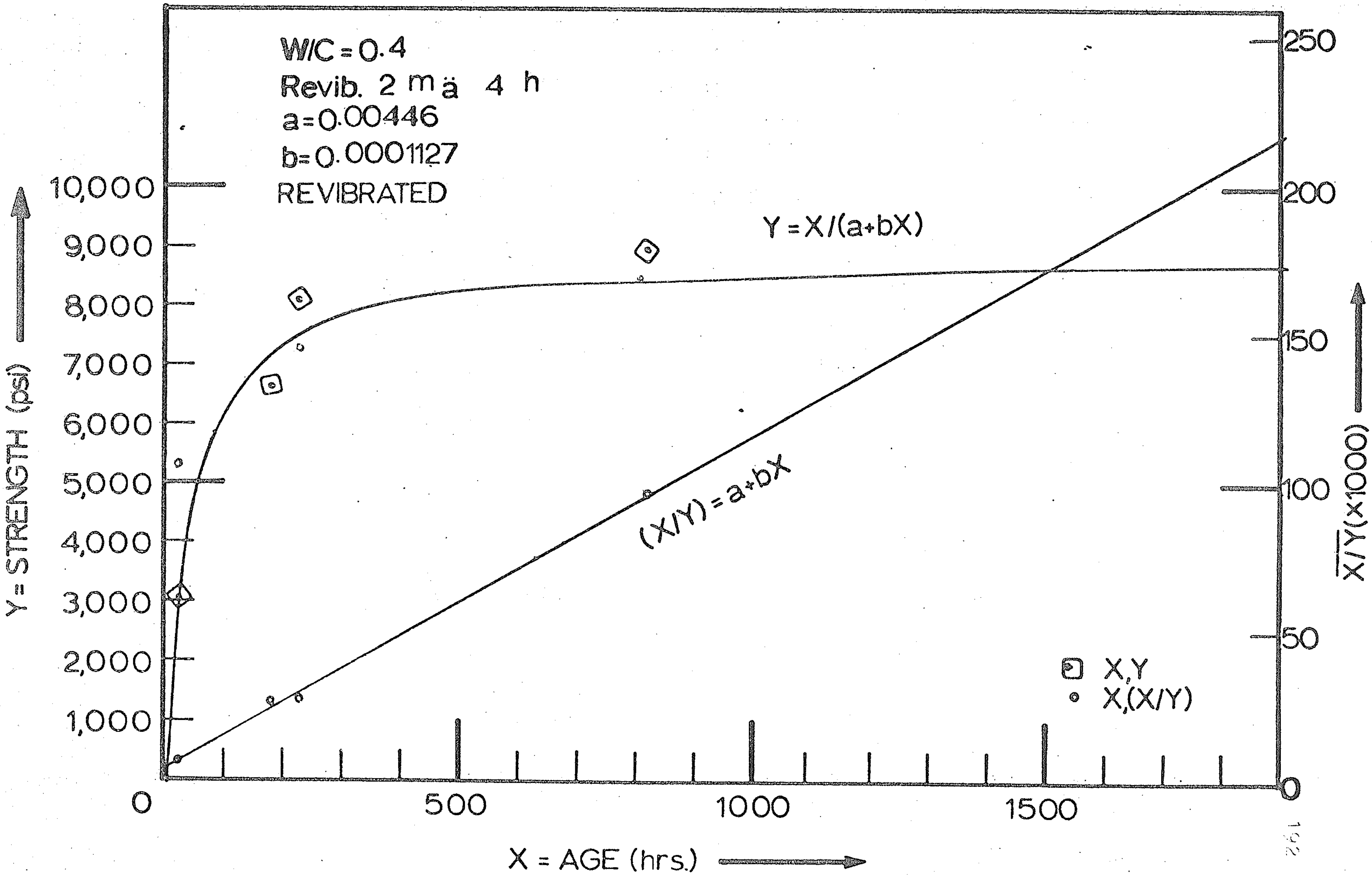
Set	No.	Description of Specimen	Mode of Failure	Cylinder Strength: psi		Av. Strength psi
Revib.	1	S	W, F	4990	*	5640
	2	S	W	5450		
	3	S	W	5820		
Revib. and Steamed	1	S	W	4500		4310
	2	S	F	3610	*	
	3	S	W	4110		
Steamed	1 *	S	W	3890		3950
	2	S	F	3430	*	
	3	S	W	4000		
Air Cured	1	S	F	–	*	5000
	2	S	W	5000		
	3	S	W, F	3100	*	

Slump = 9"; Initial Vibration during casting = 15 secs.

APPENDIX B

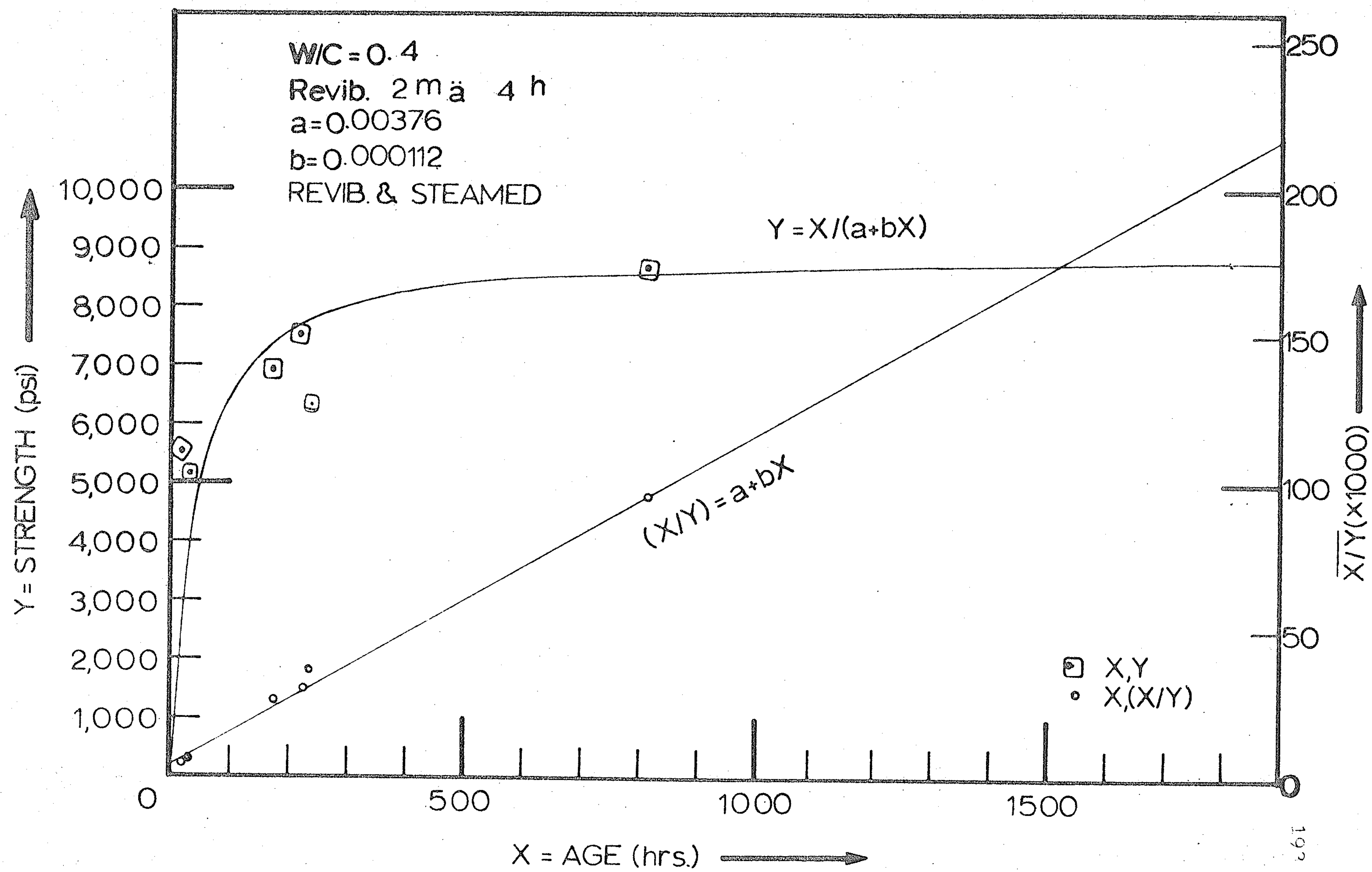
Figs. 35 - 59 : Age Vs. Strength Curves (X - Y)

Transformed (X - X/Y) Curves.



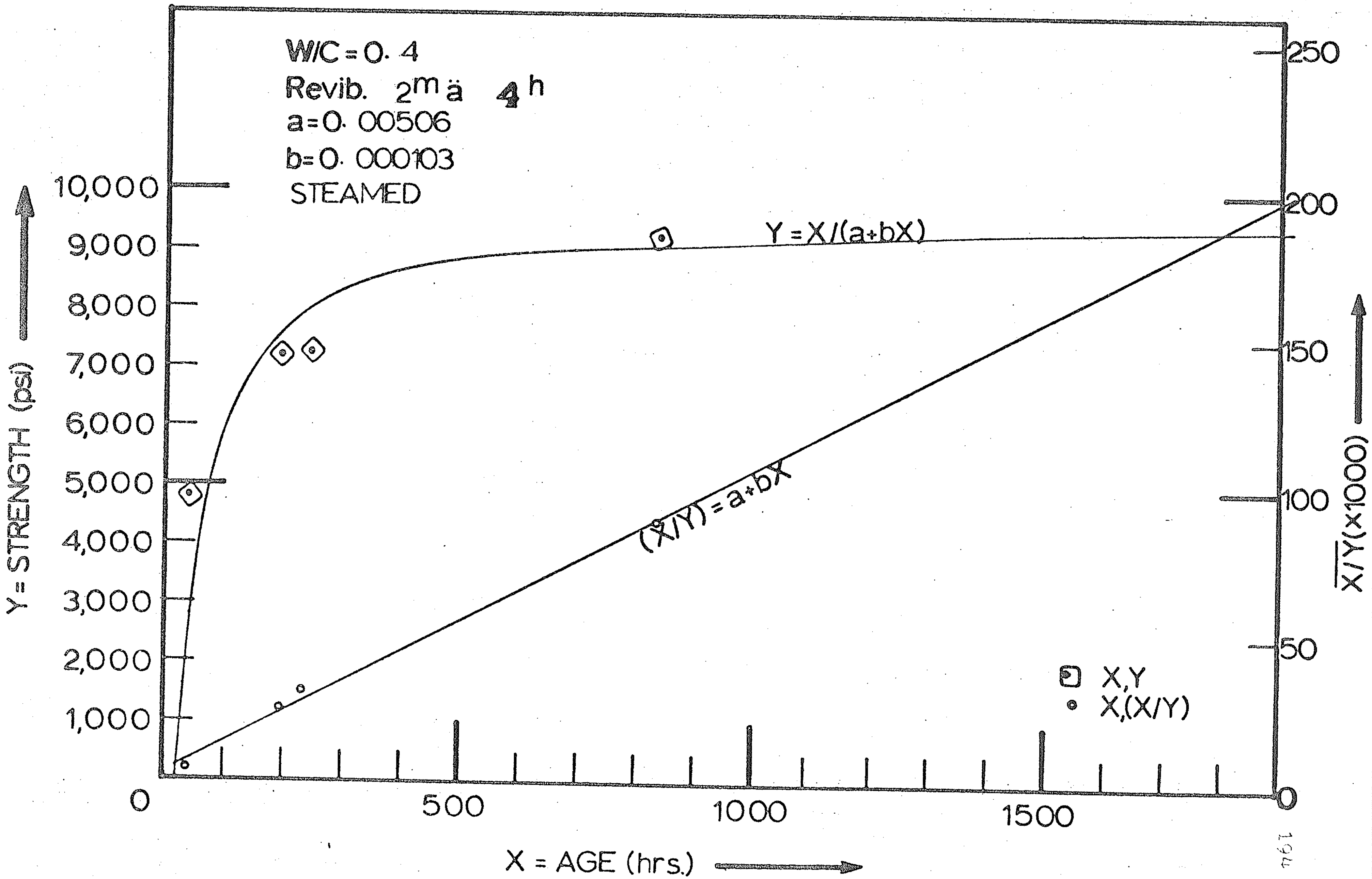
W/C = 0.4
Revib. 2 m ä 4 h
a = 0.00446
b = 0.0001127
REVIBRATED
Y = X/(a+bX)
(X/Y) = a+bX
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
0
X/Y (×1000)
X,Y
X,(X/Y)

Fig. 36



W/C = 0.4
Revib. 2 m ä 4 h
a = 0.00376
b = 0.000112
REVIB. & STEAMED
Y = X/(a+bX)
(X/Y) = a+bX
X,Y
X,(X/Y)
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
X/Y (×1000)

Fig. 36



W/C = 0. 4
Revib. 2m ä 4h
a = 0. 00506
b = 0. 000103
STEAMED
Y = X/(a+bX)
(X/Y) = a+bX
X,Y
X,(X/Y)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
250
200
150
100
50
Y = STRENGTH (psi)
X = AGE (hrs.)
X/Y(×1000)

Fig. 37

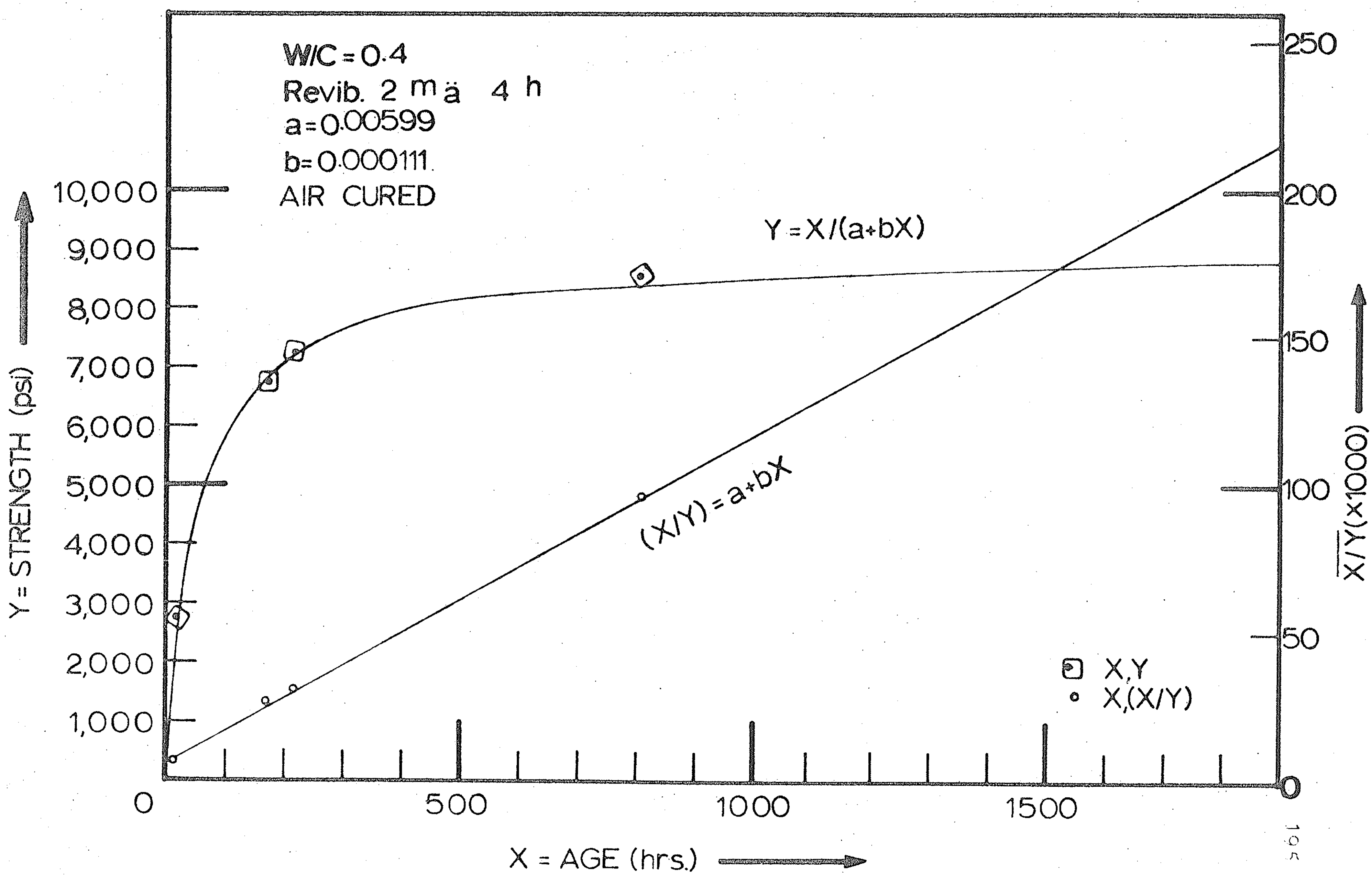

W/C = 0.4
Revib. 2 mä 4 h
a = 0.00599
b = 0.000111
AIR CURED
Y = X/(a+bX)
(X/Y) = a+bX
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
X/Y(x1000)
X,Y
X,(X/Y)

Fig. 38

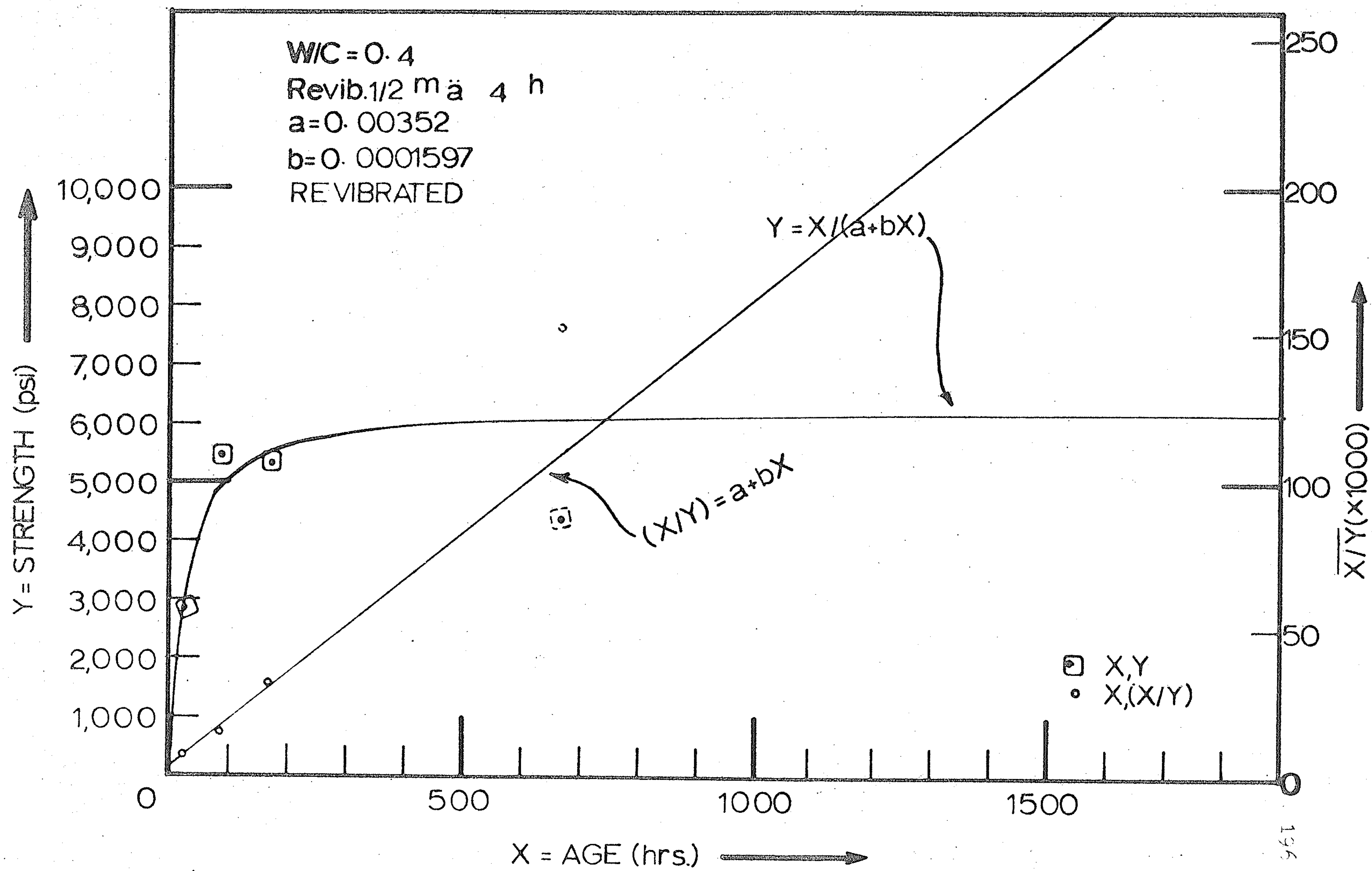
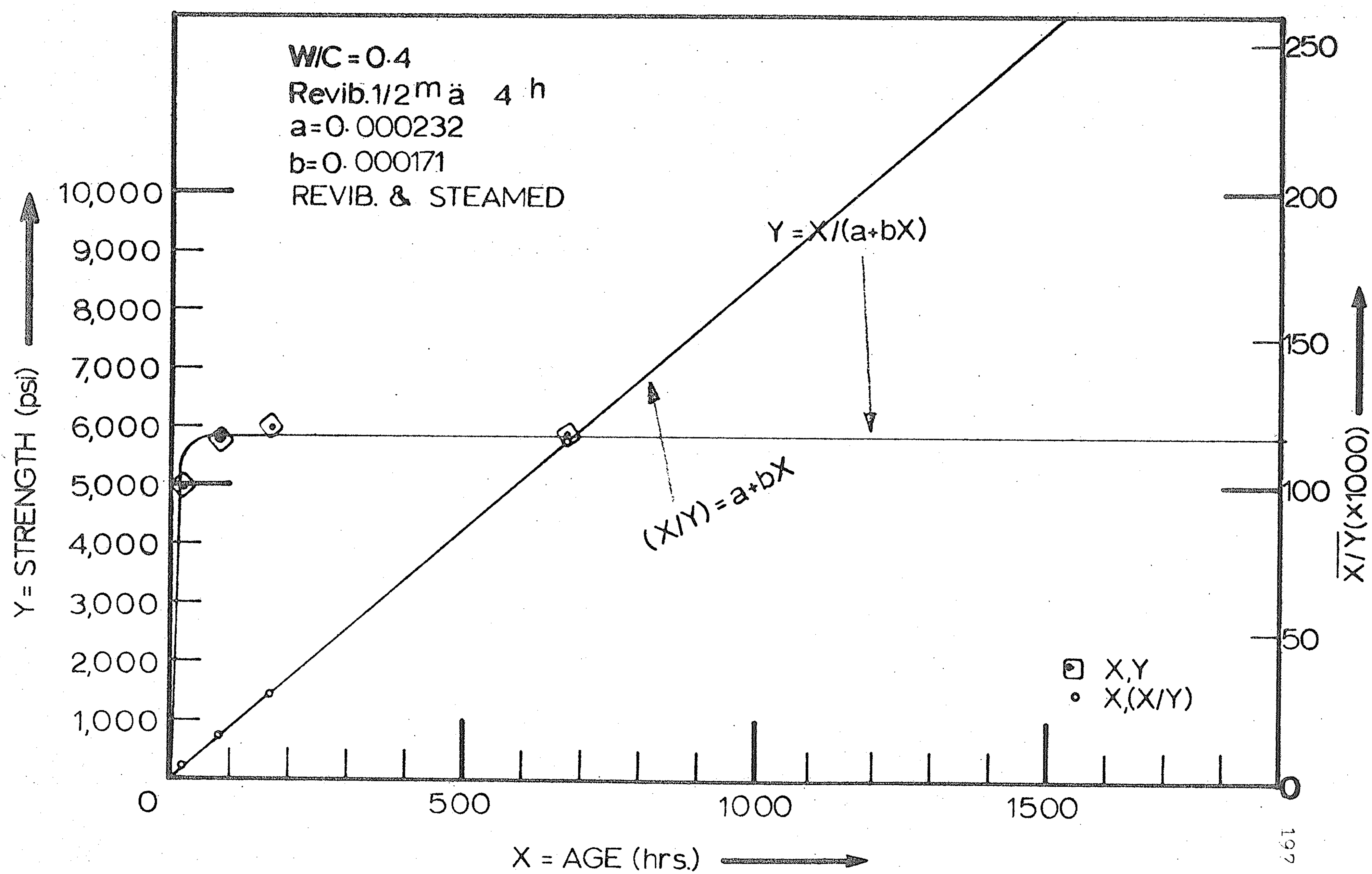
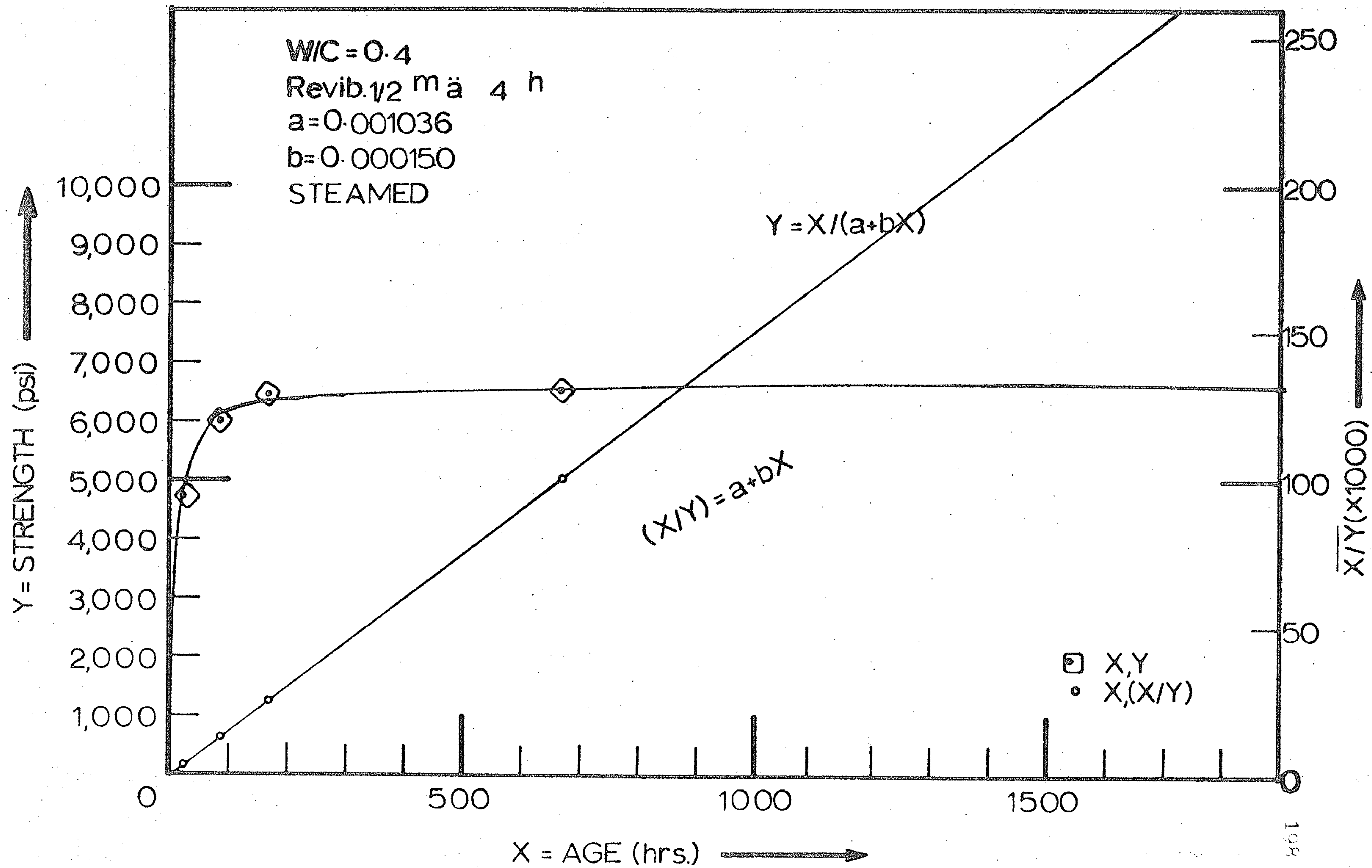

W/C = 0.4
Revib.1/2 m ä 4 h
a=0.00352
b=0.0001597
REVIBRATED
Y = X/(a+bX)
(X/Y) = a+bX
X,Y
X,(X/Y)
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
0
X/Y(×1000)

Fig. 39



W/C = 0.4
Revib.1/2 m ä 4 h
a=0. 000232
b=0. 000171
REVIB. & STEAMED
Y = X/(a+bX)
(X/Y) = a+bX
X,Y
X,(X/Y)
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
X/Y(x1000)
250
200
150
100
50
0

Fig. 40



W/C = 0·4
Revib.1/2 m ä 4 h
a=0·001036
b=0·000150
STEAMED
Y = X/(a+bX)
(X/Y) = a+bX
X,Y
X,(X/Y)
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
0
X/Y(×1000)

Fig. 41

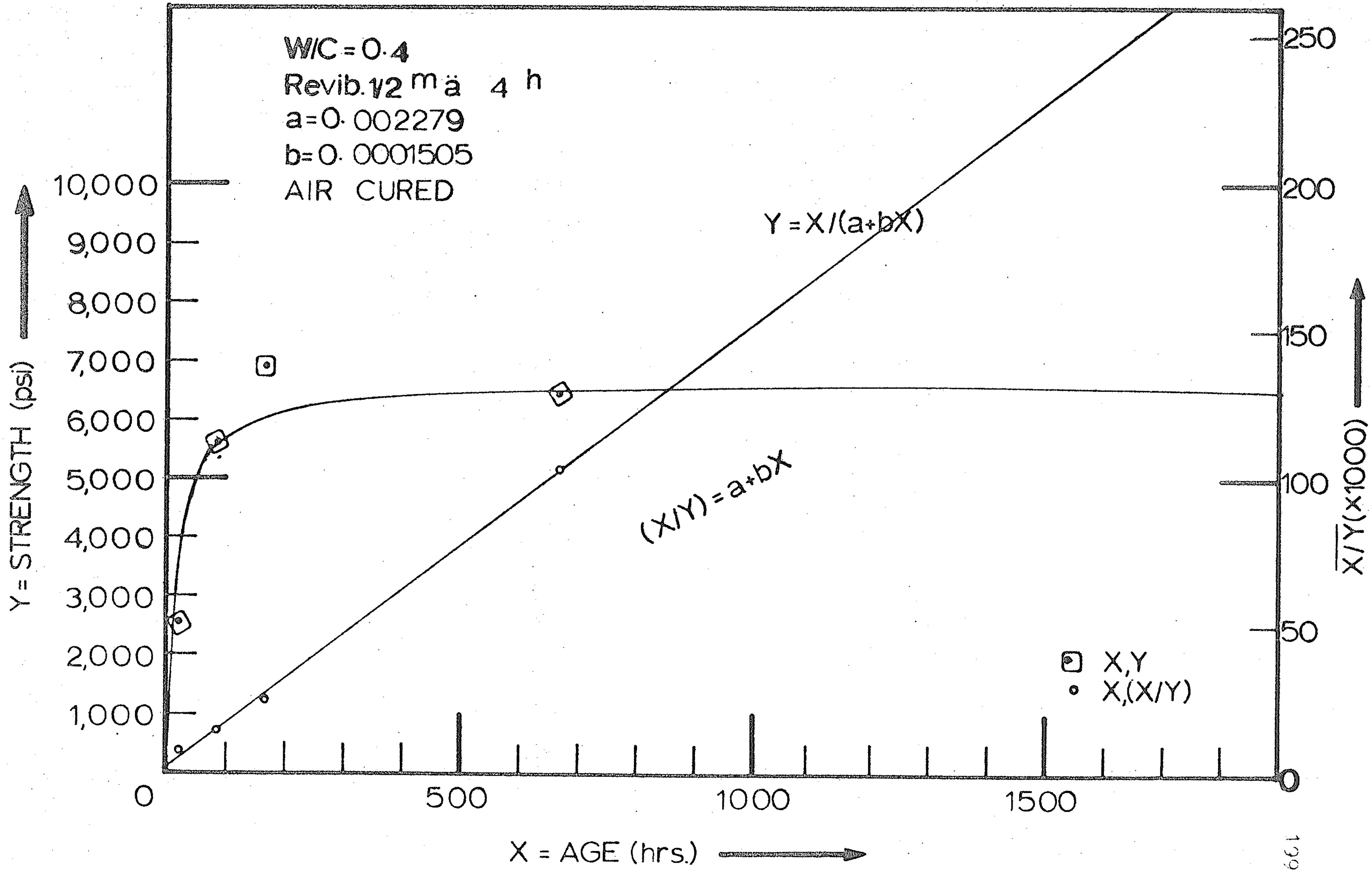

W/C = 0.4
Revib. 1/2 m ä 4 h
a = 0.002279
b = 0.0001505
AIR CURED
Y = X/(a+bX)
(X/Y) = a+bX
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
0
X/Y (×1000)
X,Y
X,(X/Y)

Fig. 4

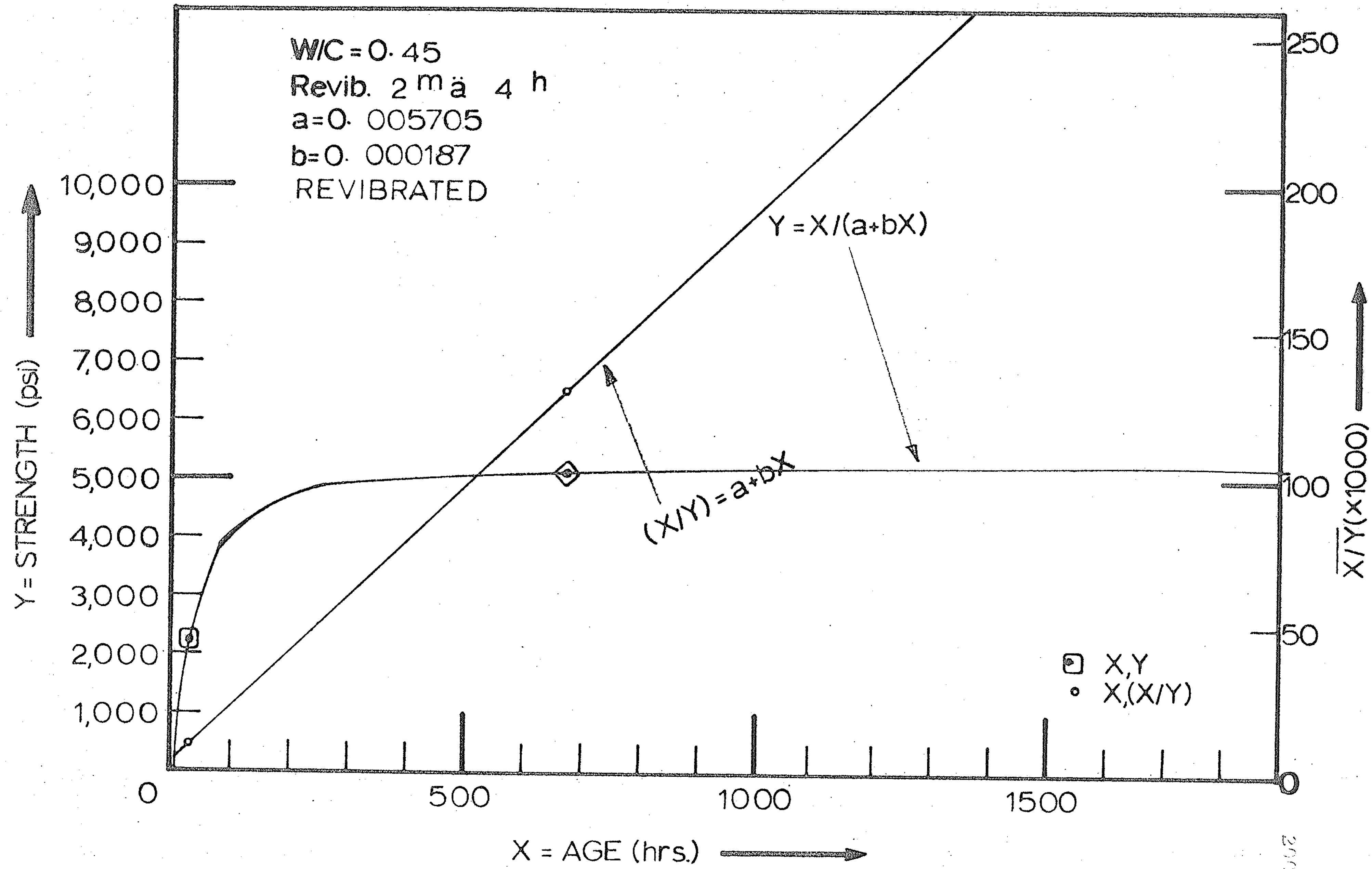
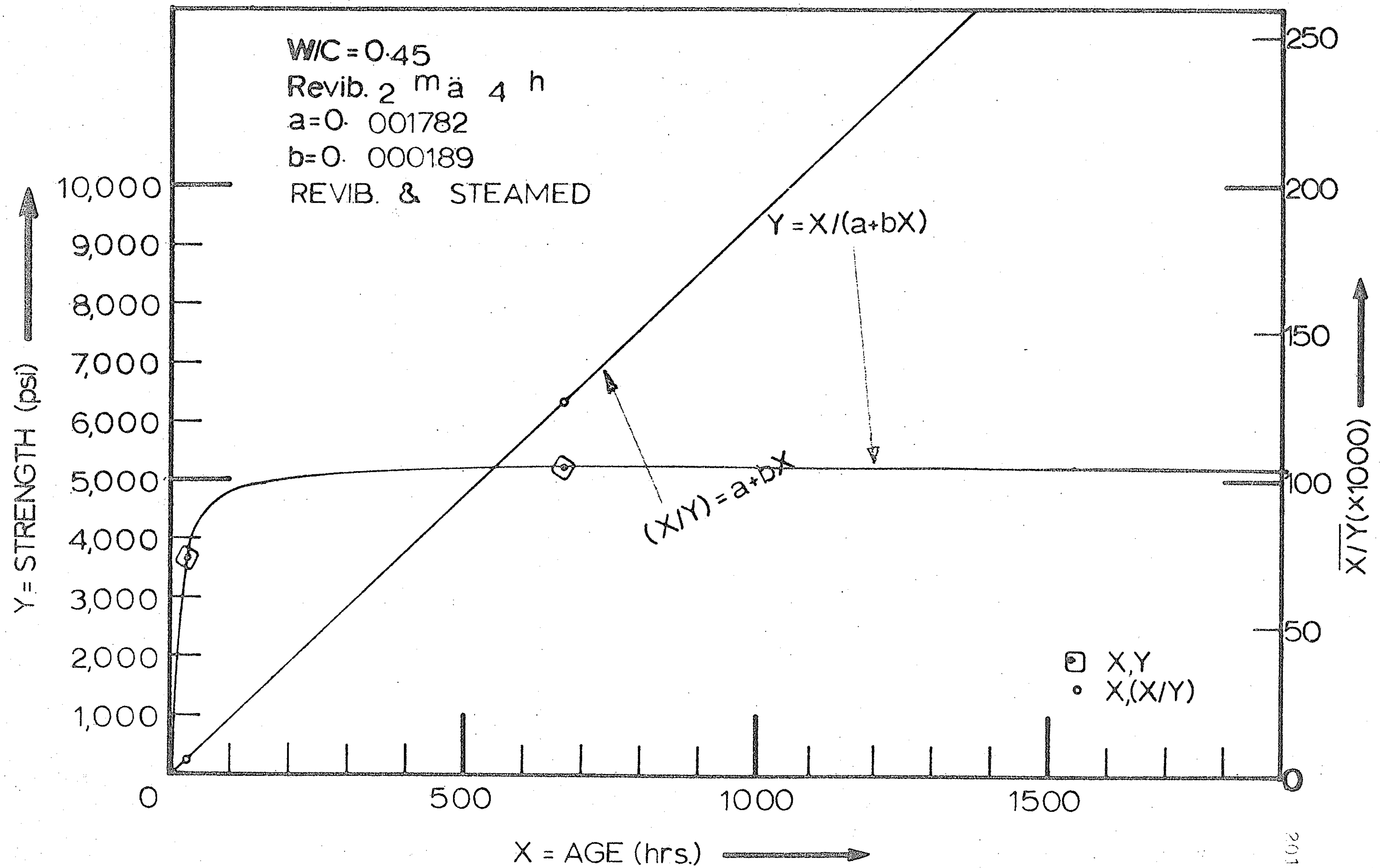

W/C = 0.45
Revib. 2 m ä 4 h
a=0. 005705
b=0. 000187
REVIBRATED
Y = X/(a+bX)
(X/Y) = a+bX
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
0
X/Y(x1000)
X,Y
X,(X/Y)

Fig. 43



W/C = 0·45
Revib. 2 mä 4 h
a=0· 001782
b=0· 000189
REVIB. & STEAMED
Y = X/(a+bX)
(X/Y) = a+bX
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
0
X/Y(×1000)
X,Y
X,(X/Y)

Fig. 44

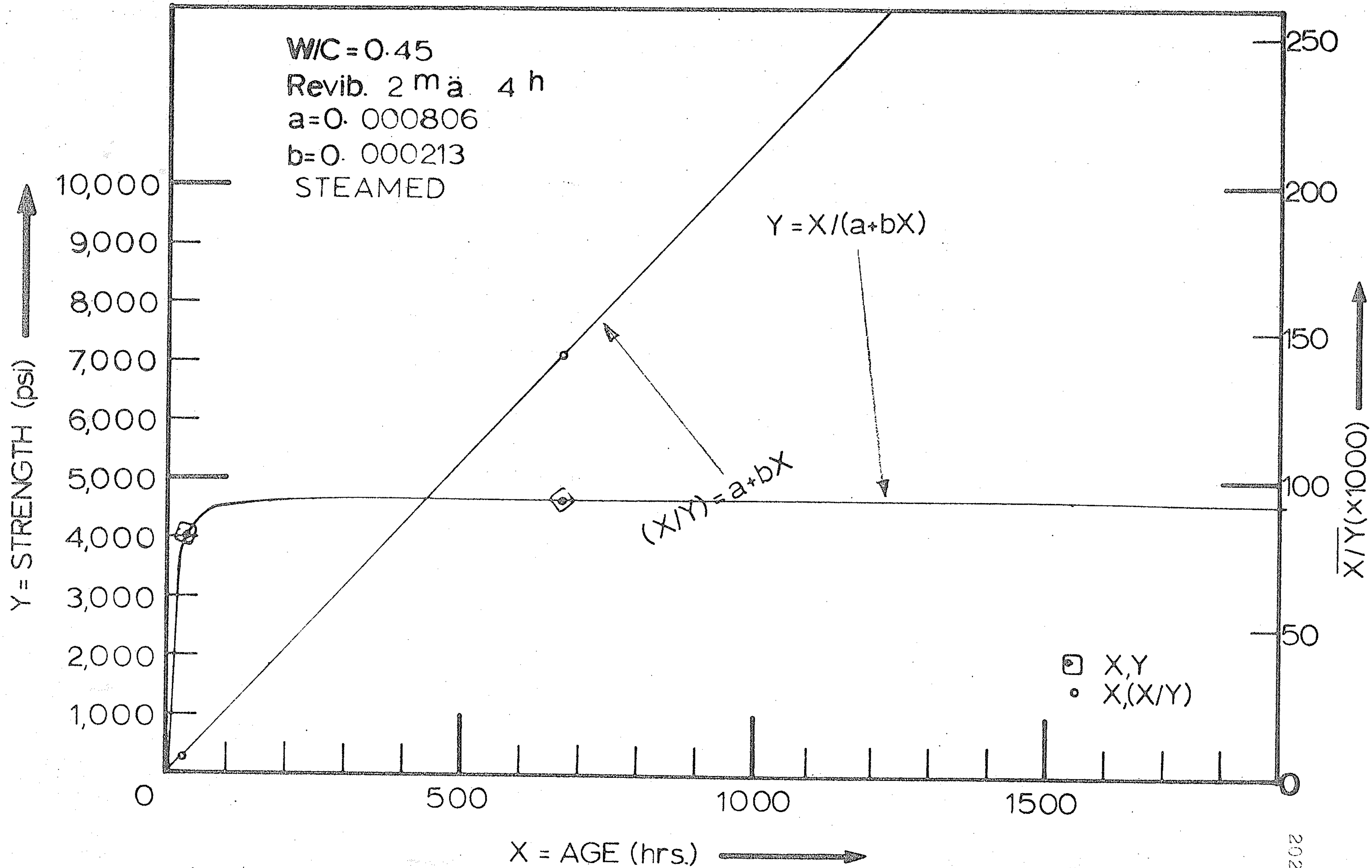

W/C = 0.45
Revib. 2 mä 4 h
a=0. 000806
b=0. 000213
STEAMED
Y = X/(a+bX)
(X/Y) = a+bX
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
X/Y(x1000)
X,Y
X,(X/Y)

Fig. 45

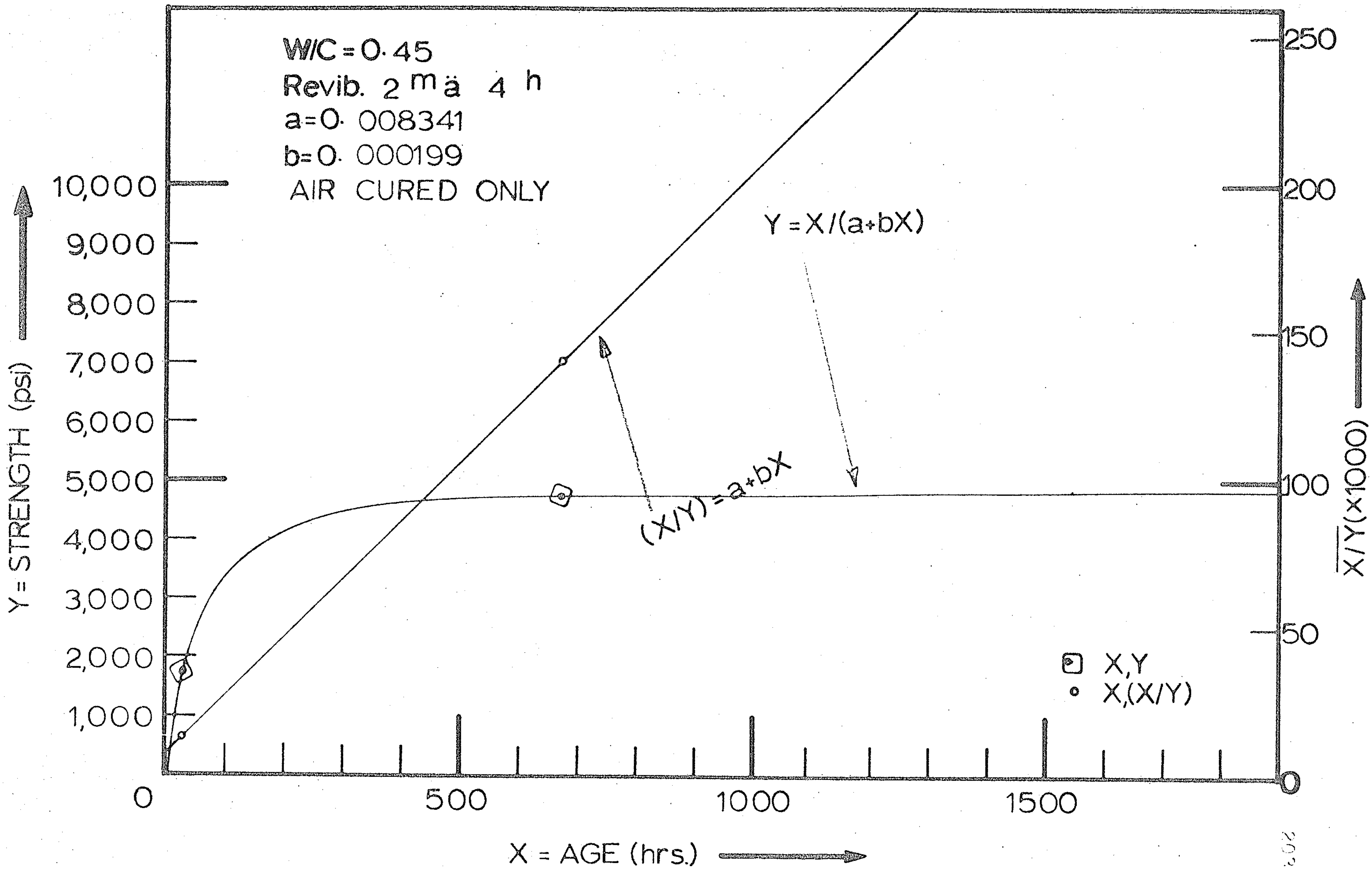
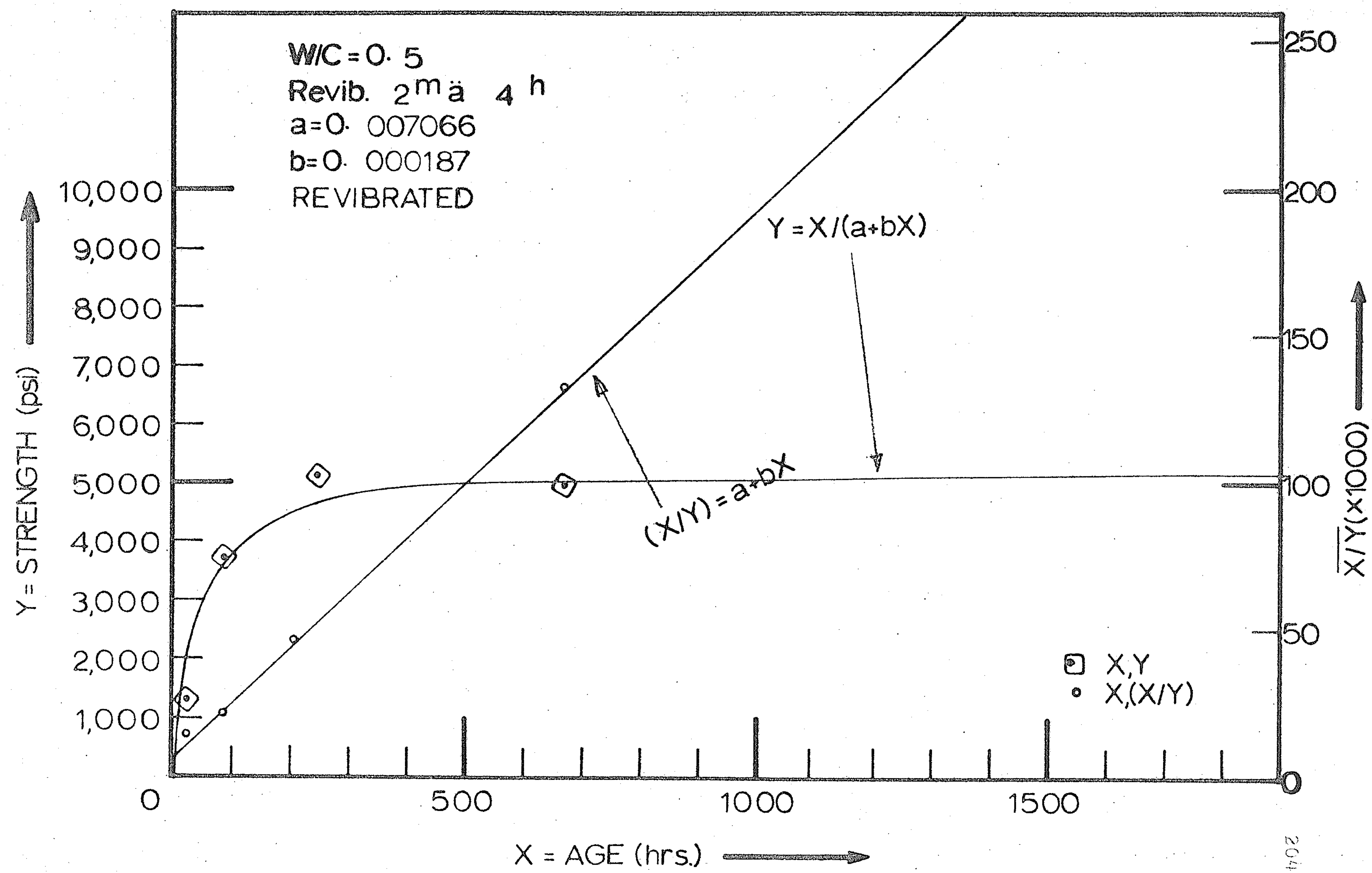

W/C = 0.45
Revib. 2 m ä 4 h
a=0. 008341
b=0. 000199
AIR CURED ONLY
Y = X/(a+bX)
(X/Y) = a+bX
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
250
200
150
100
50
0
Y = STRENGTH (psi)
X = AGE (hrs.)
X/Y (x1000)
X,Y
X,(X/Y)

Fig. 46



W/C = 0. 5
Revib. 2 m ä 4 h
a = 0. 007066
b = 0. 000187
REVIBRATED
Y = X/(a+bX)
(X/Y) = a+bX
X,Y
X,(X/Y)
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
0
X/Y(x1000)

Fig. 47

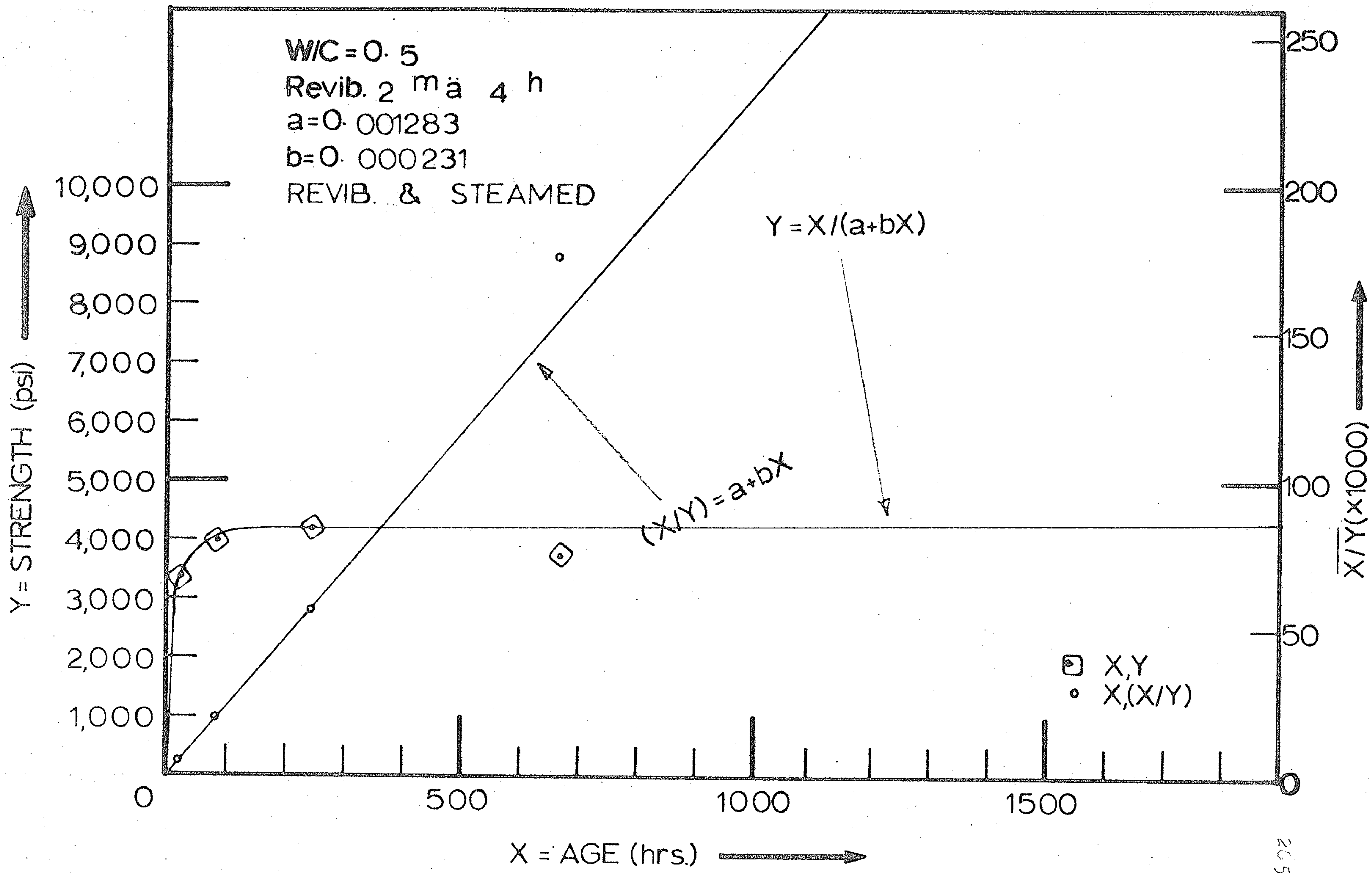

W/C = 0. 5
Revib. 2 m ä 4 h
a=0. 001283
b=0. 000231
REVIB. & STEAMED
Y = X/(a+bX)
(X/Y) = a+bX
X,Y
X,(X/Y)
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
0
X/Y(×1000)

Fig. 48

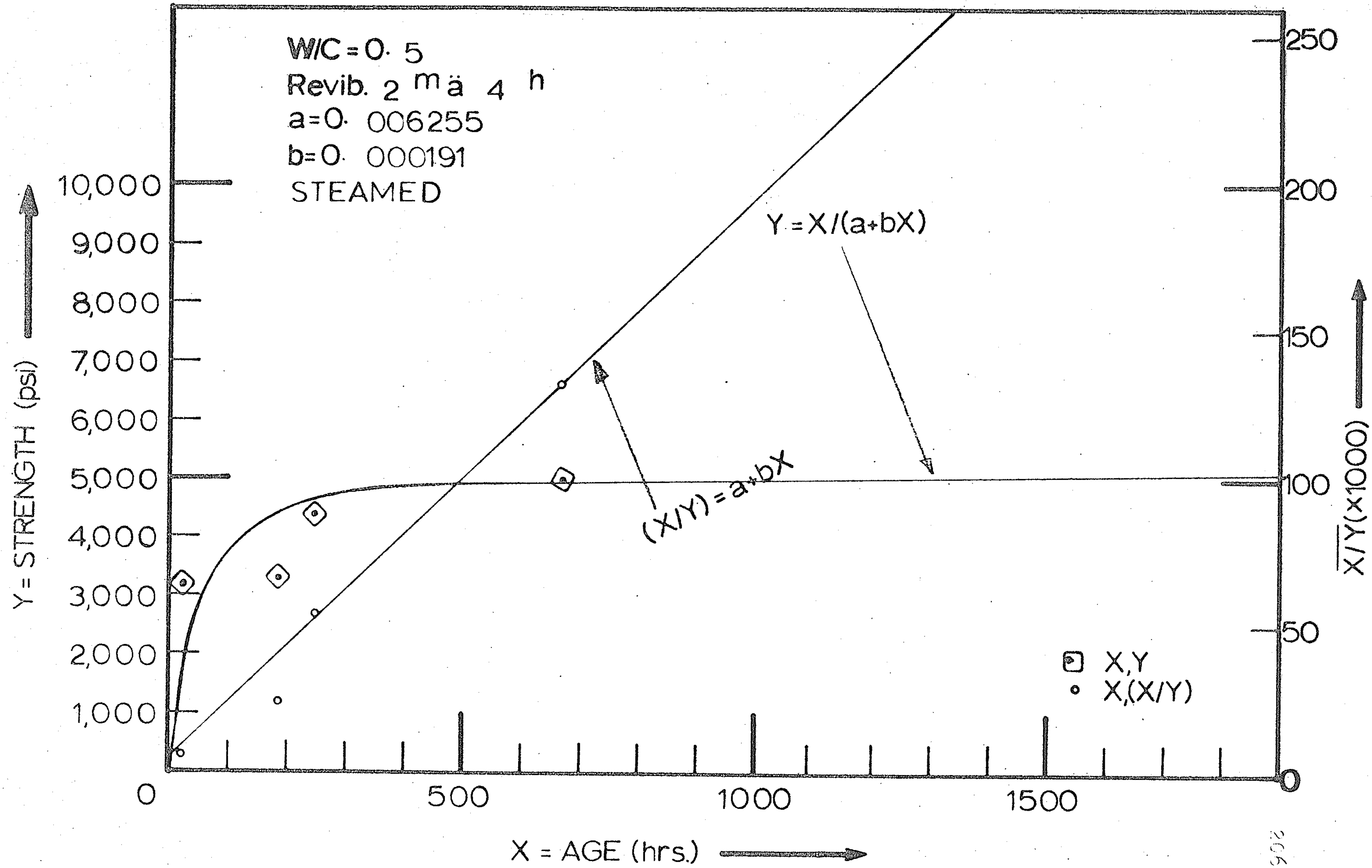
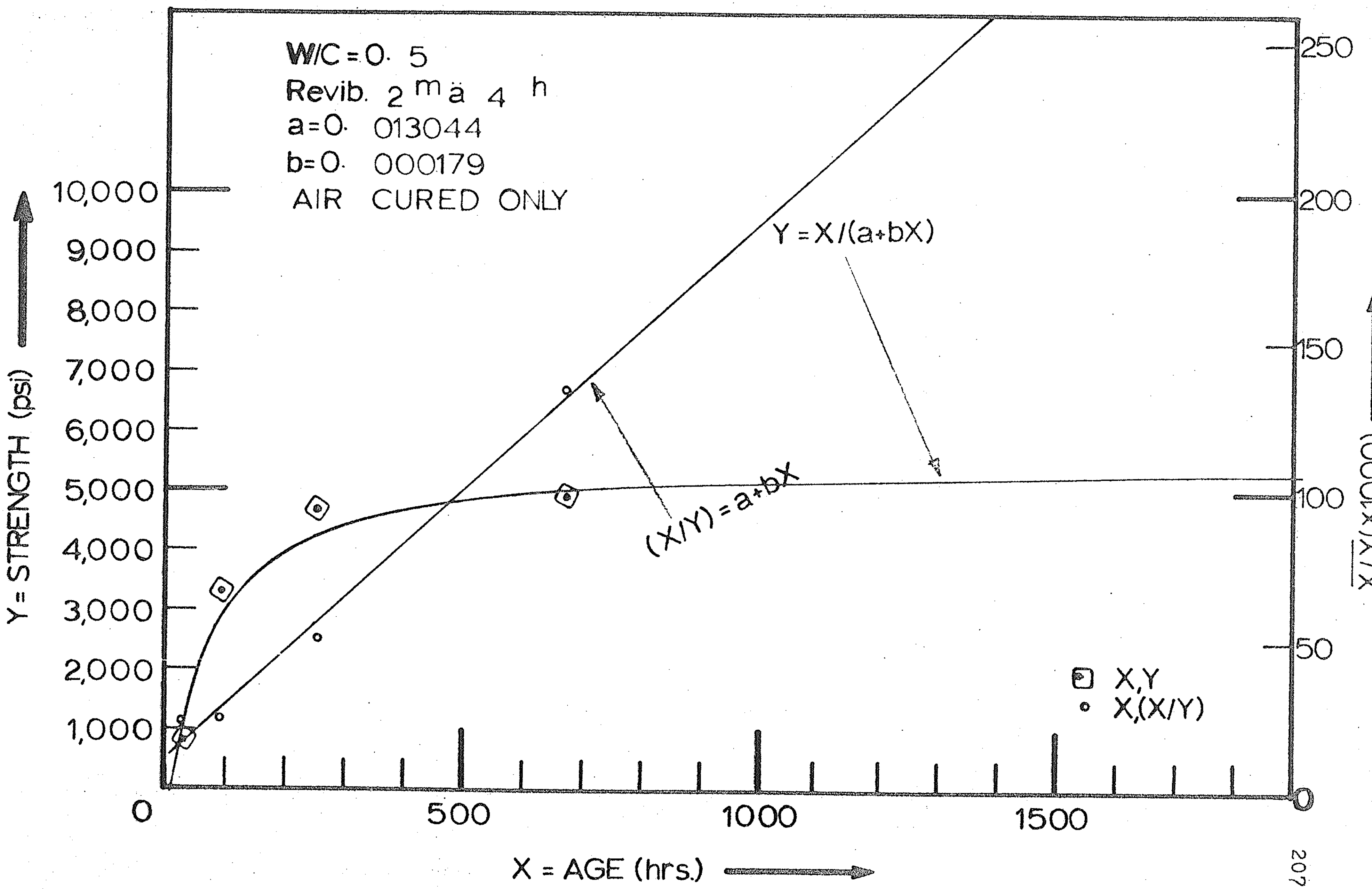
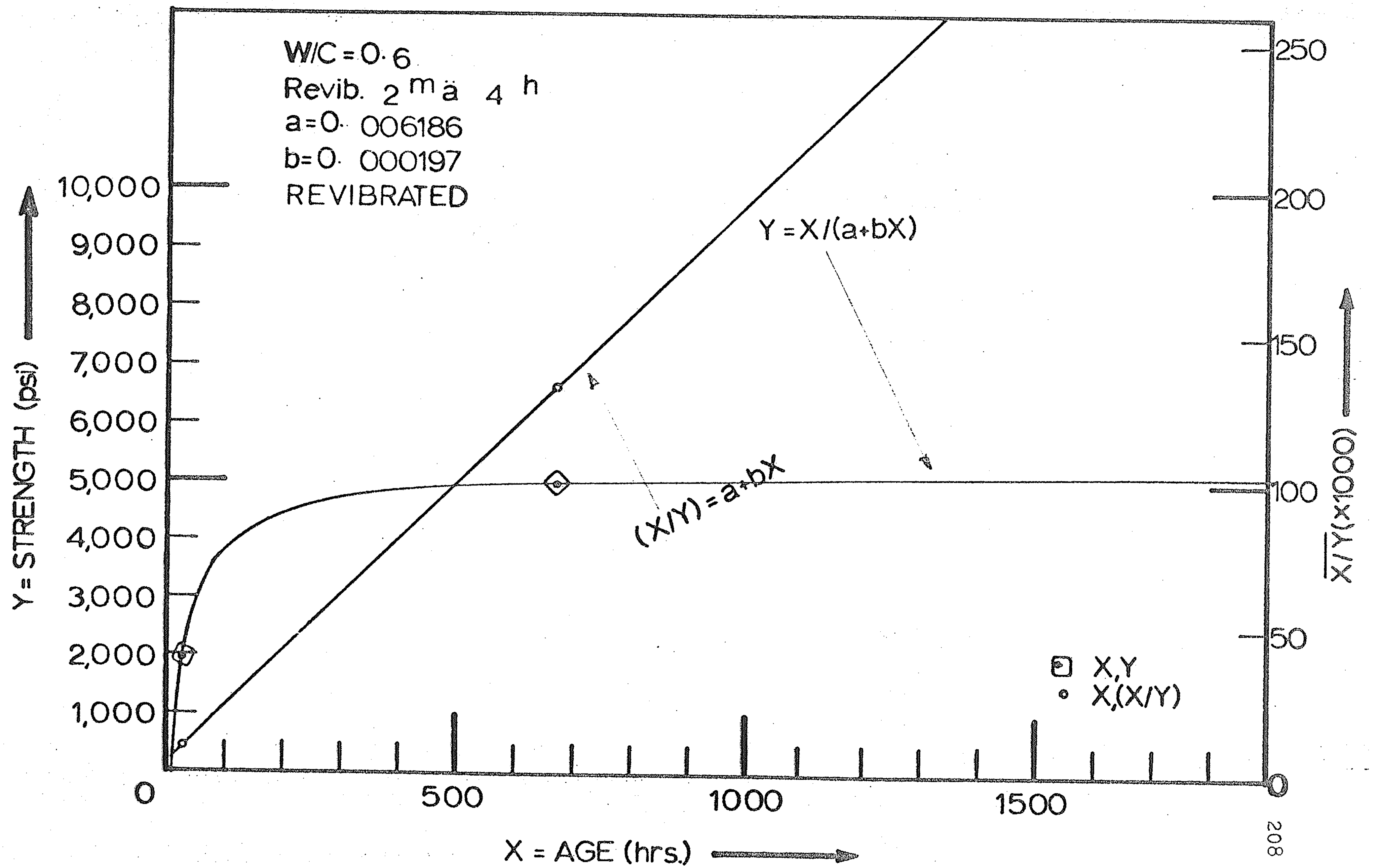

W/C = 0. 5
Revib. 2 m ä 4 h
a = 0. 006255
b = 0. 000191
STEAMED
Y = X/(a+bX)
(X/Y) = a+bX
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
0
X/Y(×1000)
X,Y
X,(X/Y)

Fig. 49



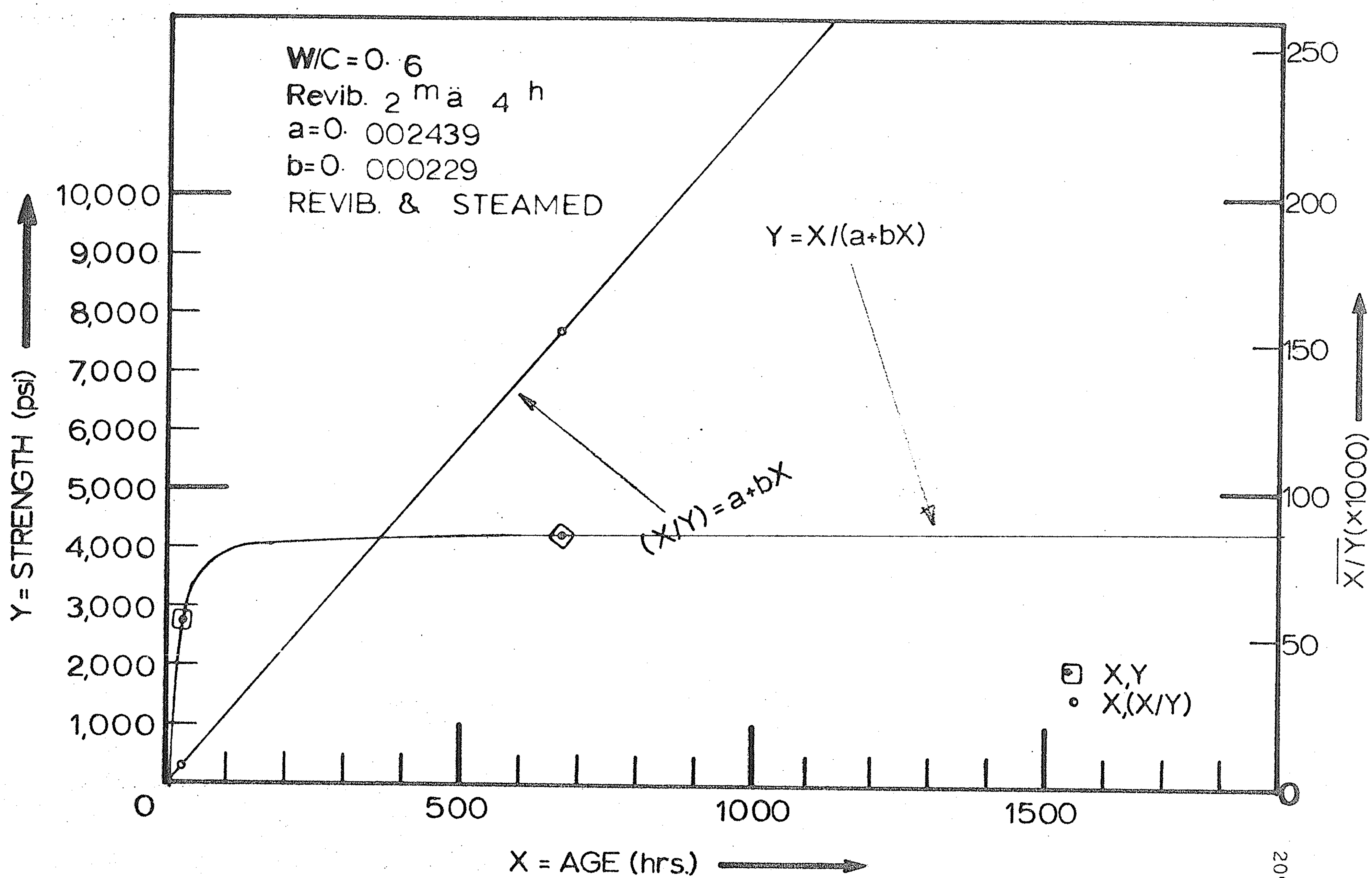
W/C = 0. 5
Revib. 2 m ä 4 h
a=0. 013044
b=0. 000179
AIR CURED ONLY
Y = X/(a+bX)
(X/Y) = a+bX
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
0
X/Y(x1000)
X,Y
X,(X/Y)

Fig. 50



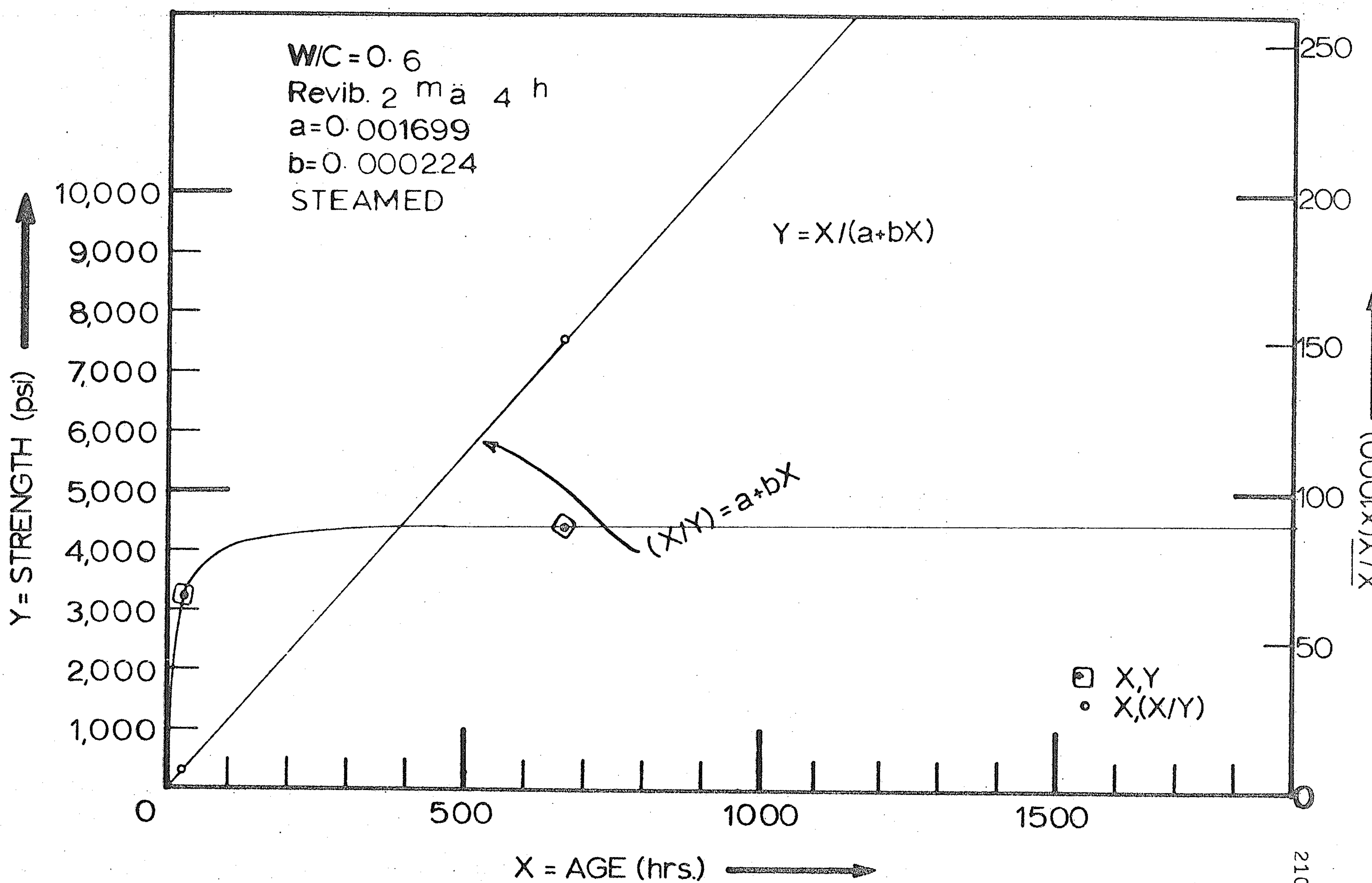
W/C = 0.6
Revib. 2 m ä 4 h
a=0. 006186
b=0. 000197
REVIBRATED
Y = X/(a+bX)
(X/Y) = a+bX
X,Y
X,(X/Y)
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
0
X/Y(x1000)

Fig. 51



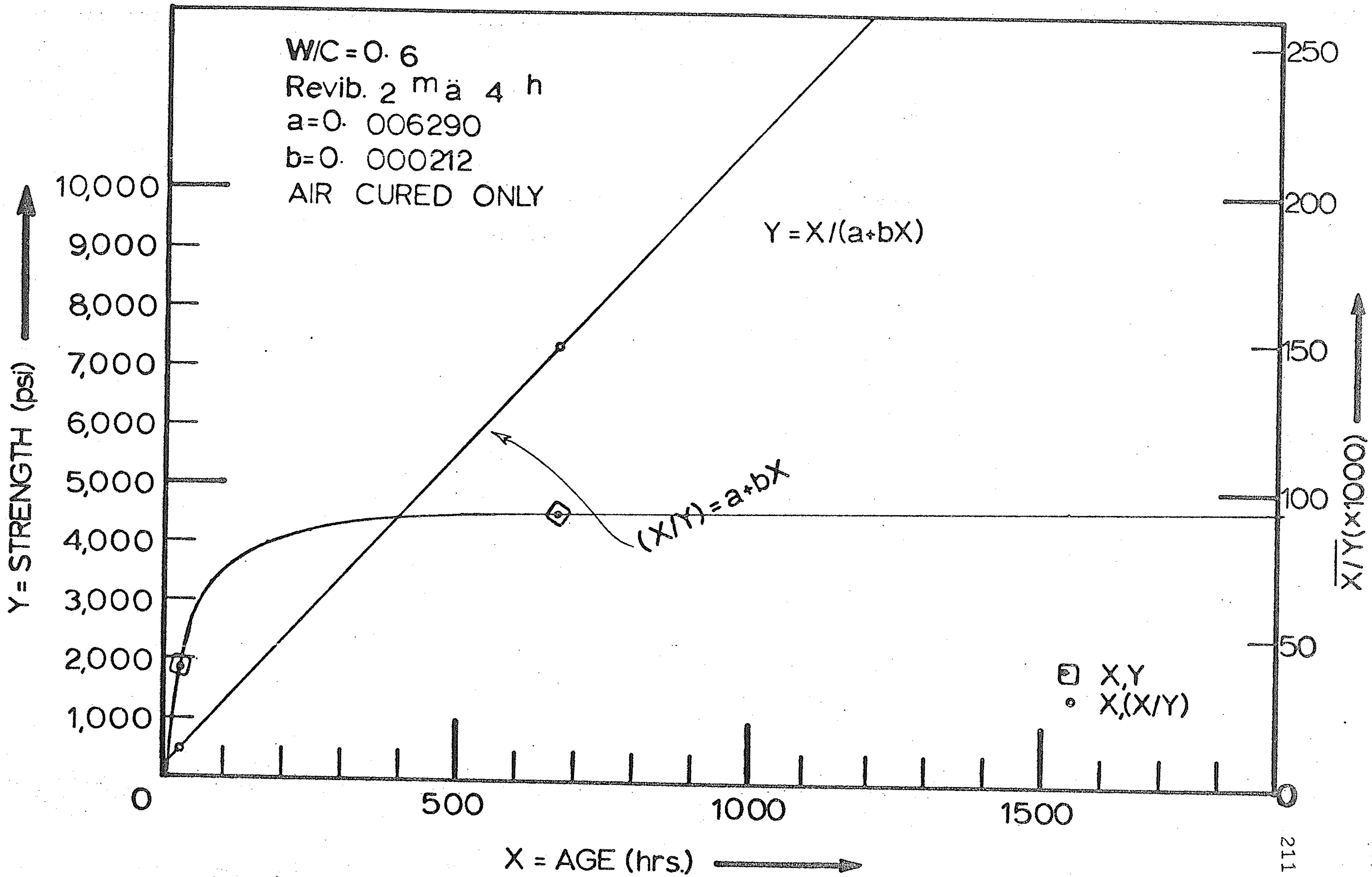
W/C = 0.6
Revib. 2 m ä 4 h
a = 0. 002439
b = 0. 000229
REVIB. & STEAMED
Y = X/(a+bX)
(X/Y) = a+bX
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
0
X/Y (x1000)
X,Y
X,(X/Y)

Fig. 52



W/C = 0.6
Revib. 2 m à 4 h
a=0.001699
b=0.000224
STEAMED
Y = X/(a+bX)
(X/Y) = a+bX
X,Y
X,(X/Y)
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
X/Y(×1000)

Fig. 53



W/C = 0.6
Revib. 2 m ä 4 h
a=0. 006290
b=0. 000212
AIR CURED ONLY
Y = X/(a+bX)
(X/Y)=a+bX
X,Y
X,(X/Y)
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
0
X/Y(x1000)

Fig. 54

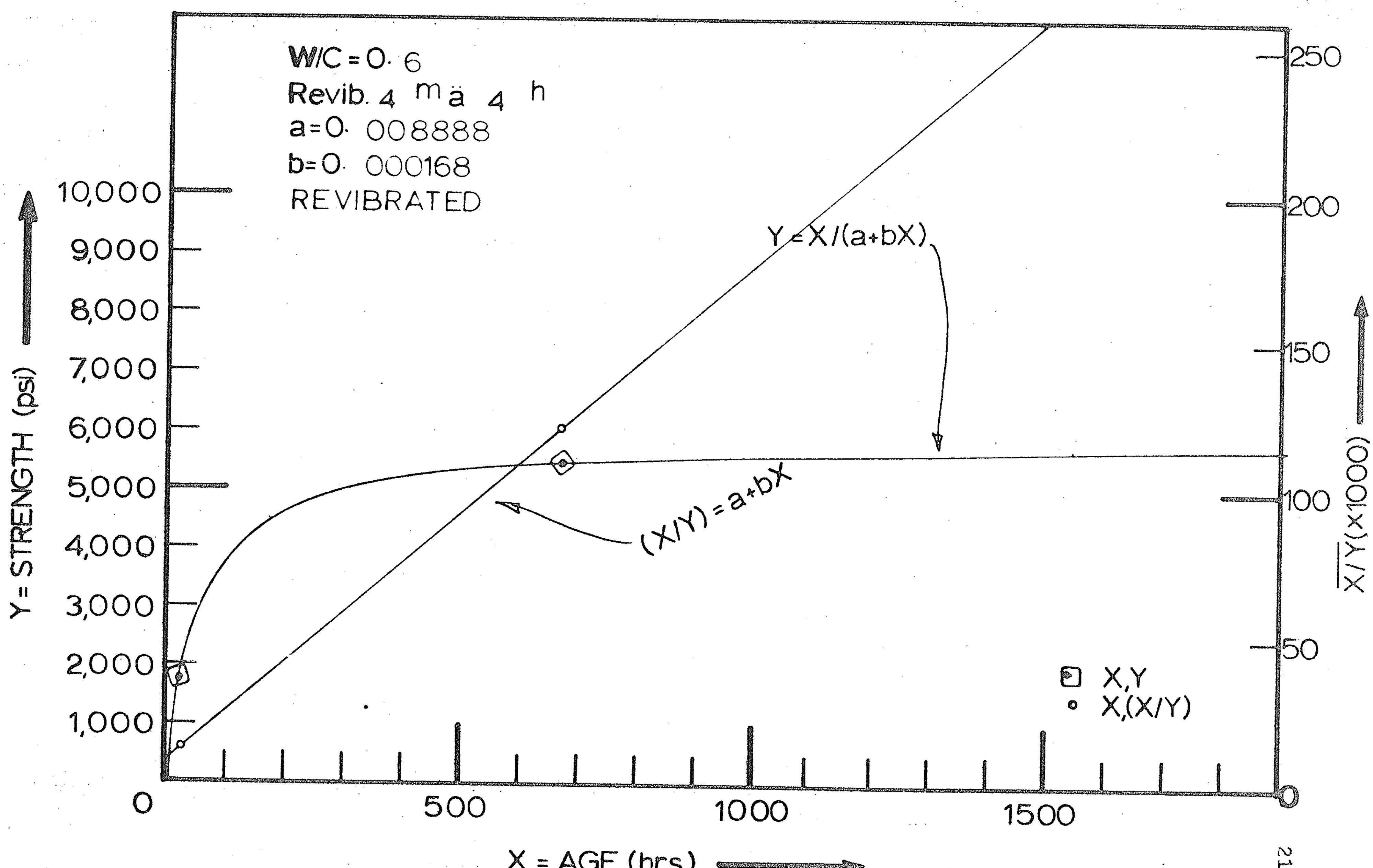

W/C = 0. 6
Revib. 4 m ä 4 h
a = 0. 008888
b = 0. 000168
REVIBRATED
Y = X/(a+bX)
(X/Y) = a+bX
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
X/Y(x1000)
X,Y
X,(X/Y)

Fig. 55

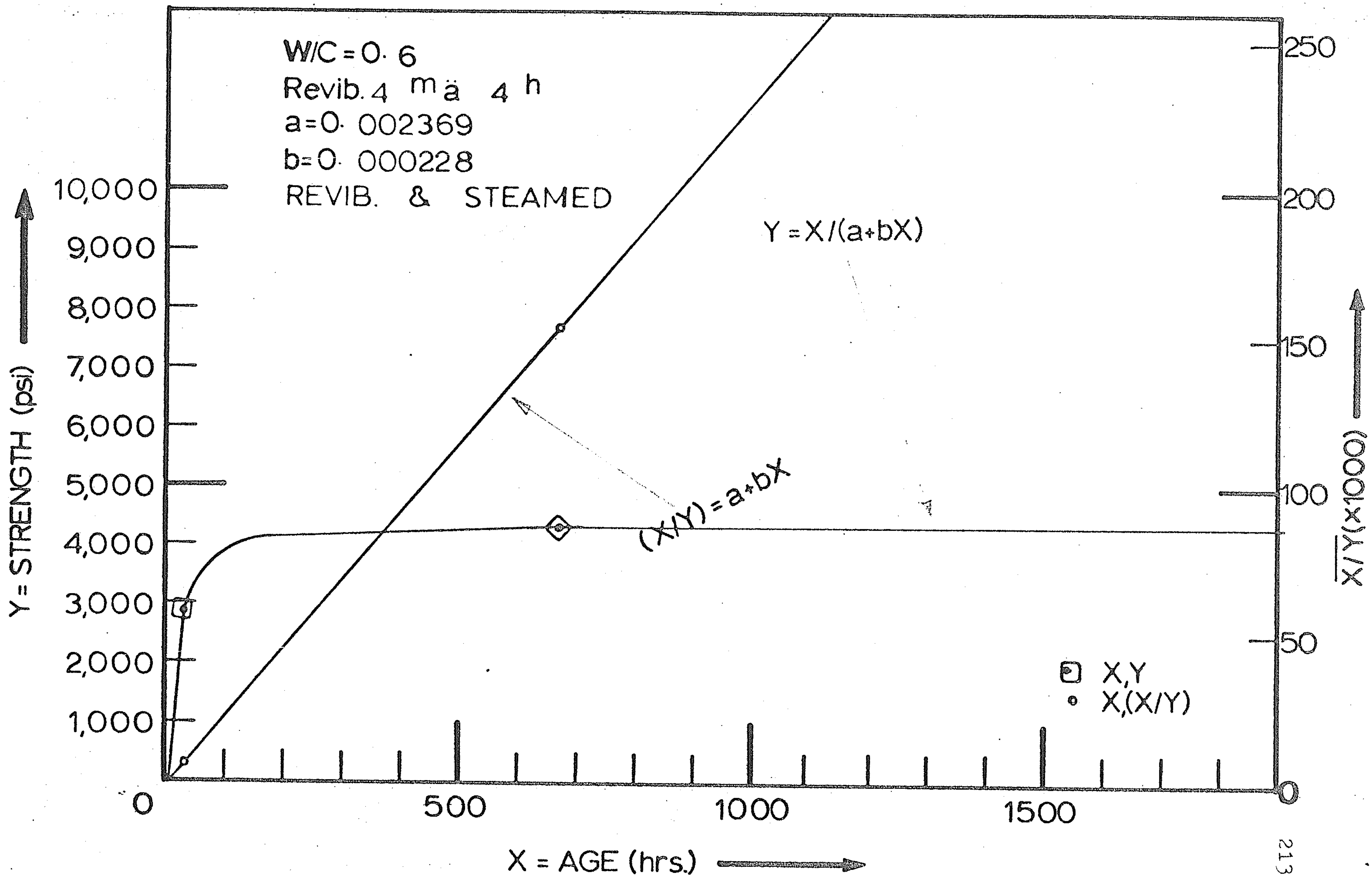
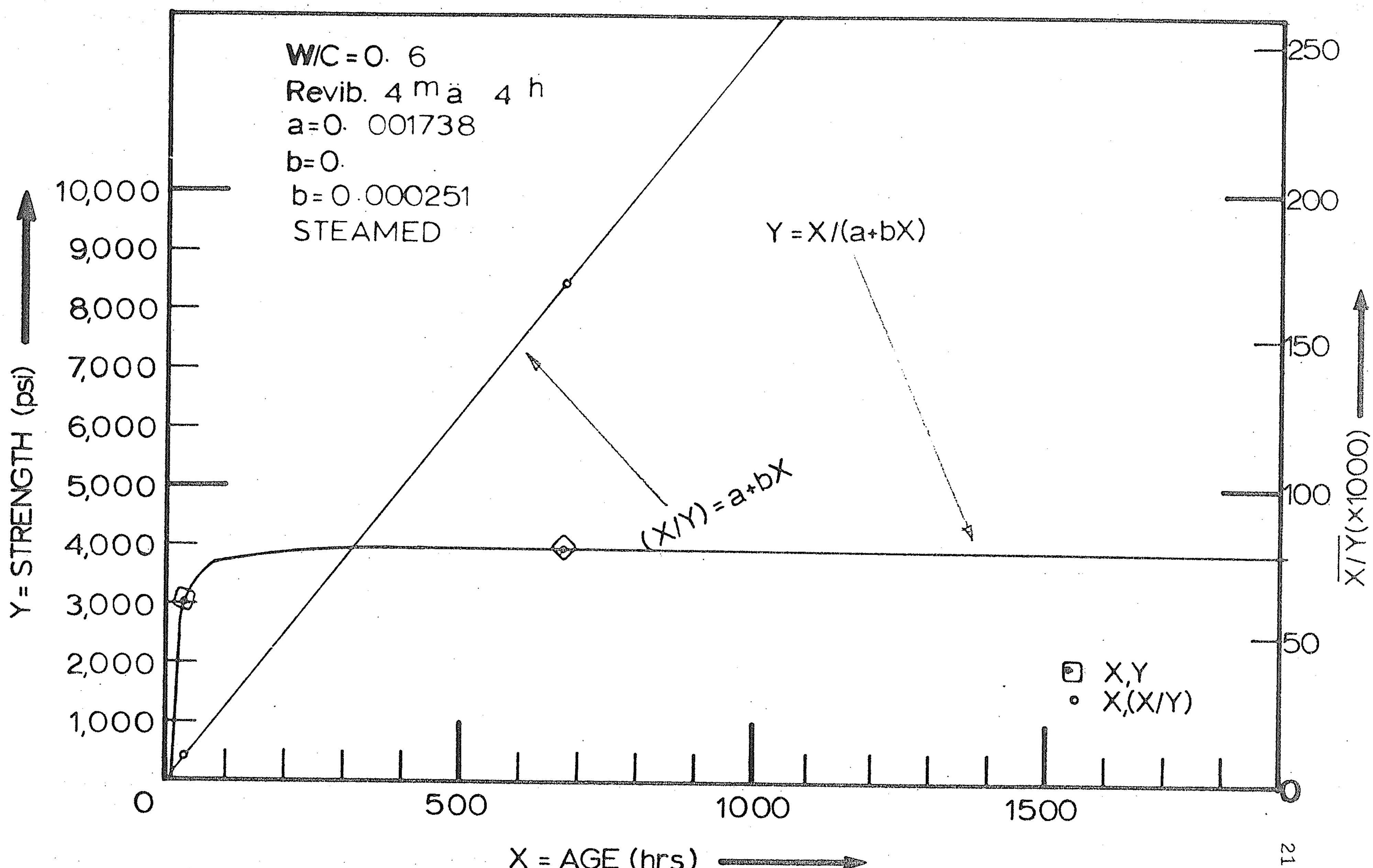

W/C = 0.6
Revib. 4 m ä 4 h
a=0. 002369
b=0. 000228
REVIB. & STEAMED
Y = X/(a+bX)
(X/Y) = a+bX
X,Y
X,(X/Y)
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
0
X/Y(×1000)

Fig. 56



W/C = 0. 6
Revib. 4 m à 4 h
a = 0. 001738
b = 0.
b = 0. 000251
STEAMED
Y = X/(a+bX)
(X/Y) = a+bX
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
X/Y(×1000)
X,Y
X,(X/Y)

Fig. 57

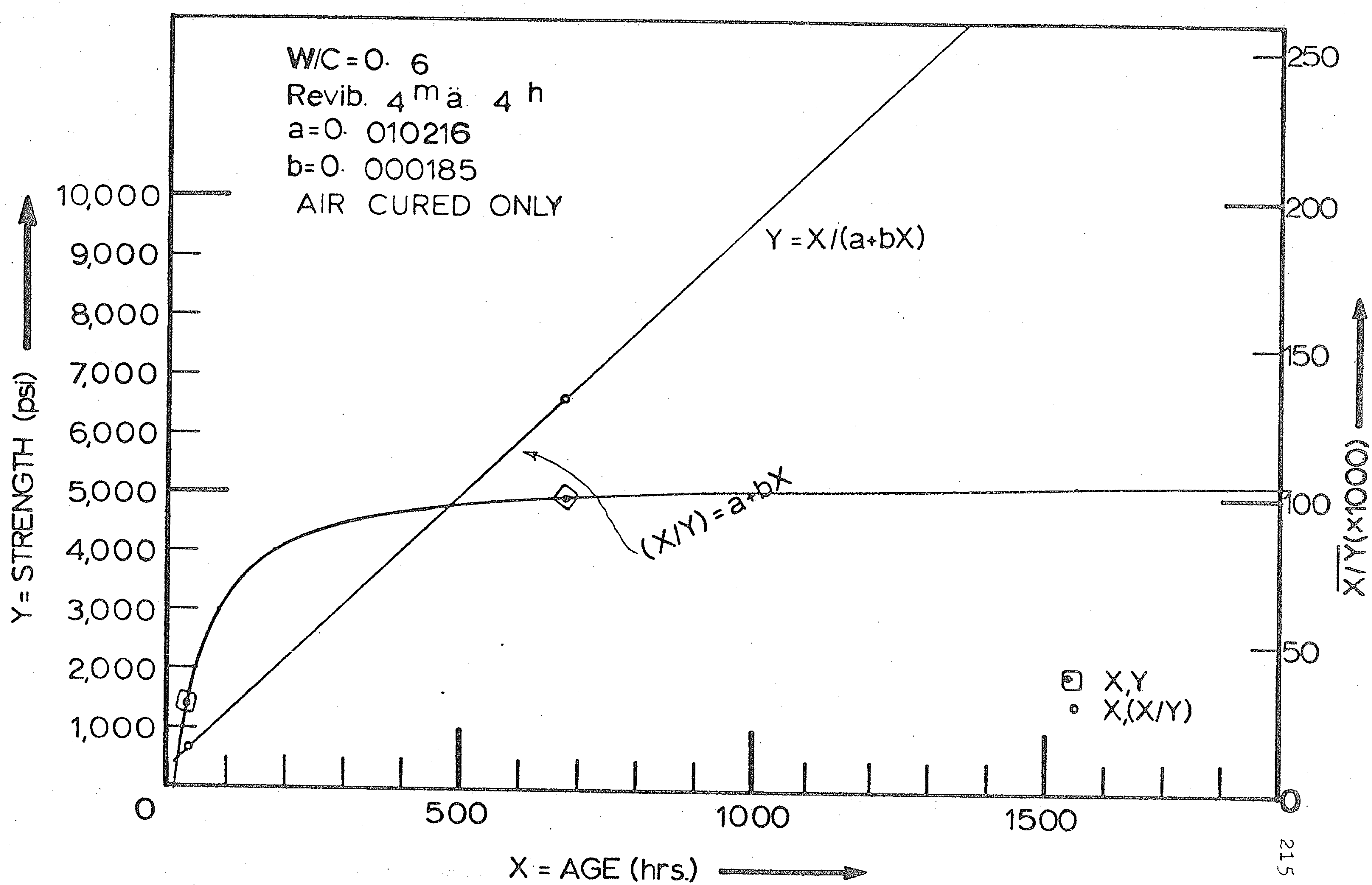
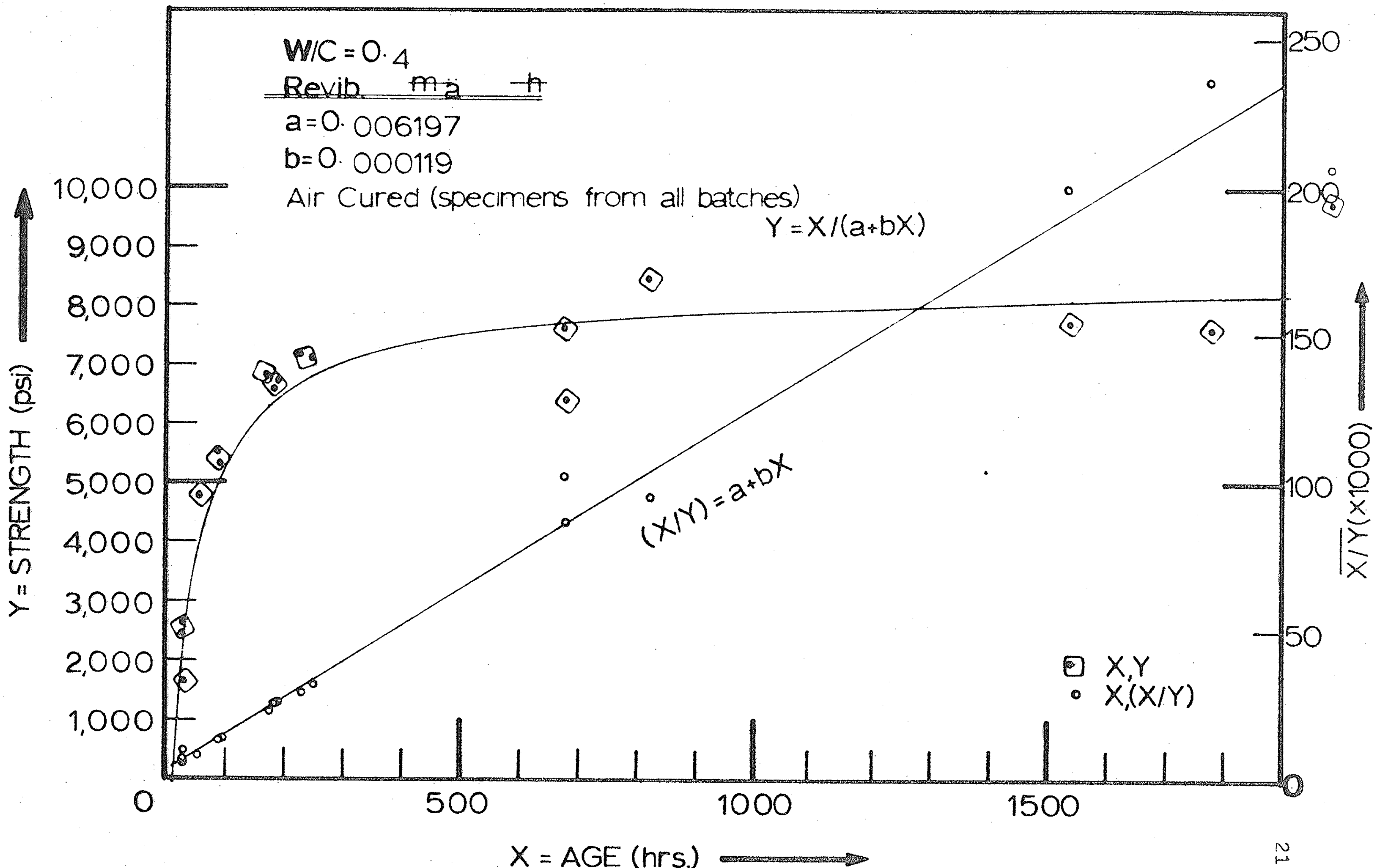

W/C = 0. 6
Revib. 4 m ä 4 h
a = 0. 010216
b = 0. 000185
AIR CURED ONLY
Y = X/(a+bX)
(X/Y) = a+bX
X,Y
X,(X/Y)
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
0
X/Y(x1000)

Fig. 58



W/C = 0.4
Revib m a h
a=0.006197
b=0.000119
Air Cured (specimens from all batches)
Y = X/(a+bX)
(X/Y) = a+bX
X,Y
X,(X/Y)
Y = STRENGTH (psi)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
500
1000
1500
X = AGE (hrs.)
250
200
150
100
50
0
X/Y(x1000)

Fig. 59