ACCELERATED CURING OF CEMENT CONCRETE

A
Dissertation
Submitted in partial fulfilment of
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MASTER OF ENGINEERING
in
Structural Engineering including concrete technology

By
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CERTIFICATE

CERTIFIED that the dissertation entitled "ACCELERATED CURING OF CEMENT CONCRETE" which is being submitted by Sri VIPIN SANKALCHAND SHAH in partial fulfilment for the award of Degree of Master of Engineering in Structural Engineering including Concrete Technology of University of Roorkee is a record of student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree or Diploma.

This is further to certify that he has worked for a period of 4½ months from May 1962 to May 1963 for preparing dissertation for Master of Engineering Degree at the University.

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SYNOPSIS

The concept of maturity of concrete has given rise to methods of accelerated curing which hasten the curing process. These methods can also be used to predict the 28-day strength of a concrete mix. within a short period of time. Much work has been done on various methods of accelerated curing and some relations between accelerated strength and 28-day strength has also been found out. A study of the accelerated methods of curing was made by the author with a view to find out the relative ease and efficiency of one method over the other. It has been observed that steam curing is the most advantageous method of accelerated curing because of it's relative cheapness, simplicity and comparatively higher efficiency.

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CHAPTER I

INTRODUCTION.

The importance of the quality of concrete is now realised on account of the resultant savings in materials due to higher strength. The present or conventional method is to specify the strength of concrete at the end of 28-day normal curing. The advancements made in the construction and increasing popularity of precast reinforced concrete, and prestressed concrete products, have brought a demand for effective and economical methods of production in a short duration. These methods are designed to reduce the time required for concrete, to set and harden, and thereby to attain the required strength, so as to reduce the charges for the storage facilities and other overhead expenses. The unnecessary delay in waiting for 28-days while designing the mixes is also obviated. This gave rise to the need for such tests to specify the strength in general rather than the conventional one. This means the results of 28-day strength should be available quickly and with sufficient accuracy so that the unsatisfactory quality can be rejected, before so much of it has been placed and set, which makes its removal a costly and time consuming operation. The normal strength of concrete is designed for a particular type of cement and W/c ratio. The site adjustment of basic mix proportions is frequently necessary (due to change in aggregate and cement during construction) and can only be tentative until its validity is confirmed by actual test results. If the accelerated tests were not adopted the work has to stop for atleast 28-days.

In 1949 Jacob[27] had tried to correlate the 3-days and 7-days strength with 28-days strength. He used to estimate the 28-day strength by applying the method of least squares to develop the general formulas. But the strength of concrete is a function of many variables such as type of mix, cement, aggregates and size of cubes, hence this formula is not expected to give results with sufficient accuracy.

In 1956 Plowman[28] correlated the normal strength of concrete and maturity of concrete and found a general relation which can be applied to any concrete and the strength will be same if the same maturity by any combination of time and temperature is given. But the concrete strength cannot be predicted until it has gained 2000°F-hr maturity or 2 days of normal curing.

Several chemical accelerators are also existing but these do not give results in short time and 28-day strength of concrete by adding chemical accelerators can be obtained in 7 to 14 days depending upon type and proportion of accelerators.

Maturity of concrete gave a possibility of using the heat treatment to hasten the curing process of concrete. The probable reason for heat treatment was due to two well-known facts.

(1) When the mixing water is added to dry ingredients of a concrete mix, a fairly complicated chemical

reaction between the water and the cement starts, which results in hardening of the concrete.

2) If heat is added to almost any chemical reaction, the rate of the reaction is accelerated.

In 1956 the Port of London Authority sponsored a programme under guidance of Prof. King[10,11] at Queen Mary College of London. Prof. King cured cubes for 6 hours in oven and published the results on it, which showed that the 28-day strength of concrete can be predicted with 90% certainty. In 1959 the work was done on oven curing at by Bondre and Ordman[6] at a curing temperature of 180°F. In 1961 T.N.W. Akroyd[1] published the results for 6 hrs. oven curing which were encouraging. In 1962 Bowen[8] worked at 100°C for 24 hours and concluded that the strength gained by concrete during that period is nearly 7-day normal strength.

In 1960, R.G.Smith-Gander and Akroyd[3] published the results of boiling water curing. The results were similar to those obtained by Prof. King. In 1961 T.N.W. Akroyd[1] published his own results on boiling water curing and modified boiling curing.

In 1962 R.L.Bowen[8] published the results of steam curing at atmospheric pressure for 6 hours and concluded that by equation $y = 0.867x + 2250$. The 28-day normal strength can be predicted.

In 1963 Prof. Govind Rao[9] published the work on electrical curing. He concluded that optimum voltage for compressive strength was 60 volts and after 24 hours the temperature of cube remains same and resistivity of concrete also stabilises to some extent.

In Roorkee University Laboratory, work was carried out to find out the reliability of the results obtained by other workers on accelerated methods of curing. The effect of chemical accelerators, such as Dog Slag, $Cacl_2$, NaCl on compressive strength were studied during investigation. The addition of accelerators revealed that they can be only used to obtain high early strength, but in no case the percentage gained exceeds 65% of 28-day strength by addition of 2/3% of chemical accelerator. The 28-day strength of concrete can be obtained in 8 to 15 days depending upon the percentages and type of accelerators. The $Cacl_2$, takes the least time to obtain 28-day strength. The 28-day strength of concrete was also obtained in 3 day by addition of $2\frac{1}{2}$ % $Cacl_2$ to leaner mix i.e. 1:3:6. The cost of chemical accelerators is also high and it will be economical to use richer mix than adding chemical accelerators to obtain the same increase in strength of concrete.

The cubes were cured in an oven at 100°C for 6 hrs, 12 hrs. and 24 hrs. From this result it was possible to develop a maturity relationship between the maturity of concrete and compressive strength for a concrete continuously cured at 100°C This law can be used for predicting strength of concrete for any hours of oven curing at this temperature.

The steam curing at atmospheric pressure for different hours of curing such as 6,12 and 24 hours was done. The similar maturity law for steam curing was also evolved. The high pressure curing for 6 hours in autoclave at different pressures of 50 p.s.i.g, 75 p.s.i.g, and 100 p.s.i.g, were done and from these results it is possible to obtain 28-day strength of normal cured concrete in 6 hours at 100 p.s.i.g.

The electrical curing at 60 volts for a period of 24 hrs. showed that the accelerated strength for leaner mix is approximately equal to 7-day strength and energy consumed in this method is least as compared to other types of curing.

The results have been found to be similar to those established by other workers. The results establish that the 28-day strength of a concrete can be predicted within a short time by these methods with an accuracy of 7 to 10%.

CHAPTER II

MATURITY OF CONCRETE.

2.1. DEFINITION.

The strength of a given concrete mix, at any age, can be expressed by a single valued function, if all other conditions remain unchanged. The maturity of concrete may be defined as its age multiplied by the average temperature above certain datum, which it has maintained. The datum temperature, for the maturity, may be defined as the curing temperature at which the strength of concrete remains constant irrespective of age.

2.2. DATUM TEMPERATURE.

Several attempts have been made to relate the strength of concrete to its age and for that the datum was assumed to be 14°F (-10°C)[23]. The choice of datum has a marked effect on the calculated maturity of concrete cured at temperatures just above freezing. A difference of 2°F in the assumed datum is found to be equivalent to a 10% difference in the maturity of concrete cured at 34°F (11°F datum)[23]. Mcdaniel's, Wiley's, Timmes and Wileys, Prices and Swedish[6] cured the cubes at different temperatures ranging from +46°C to -15°C for different period and concluded that below temperature of -10°C, there is no appreciable change in strength of concrete irrespective of number of days the concrete is cured. Hence, datum should be -10°C (14°F). The results are reproduced in Fig. Nos 1 to 7. They also show that there is definite relationship between

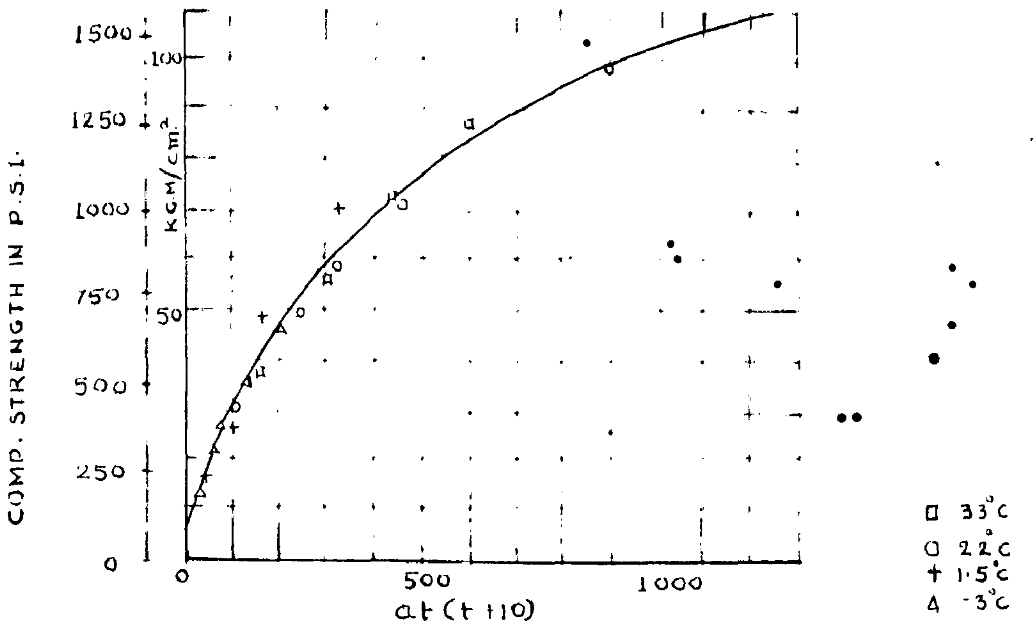


FIG. 1

RESULTS OF MCDANIEL'S TEST ON 8"X16" CYLINDERS HAVING CEMENT CONTENT 240 Kgm/cu.m. (405LB./C.yd) AND W/C = 0·70

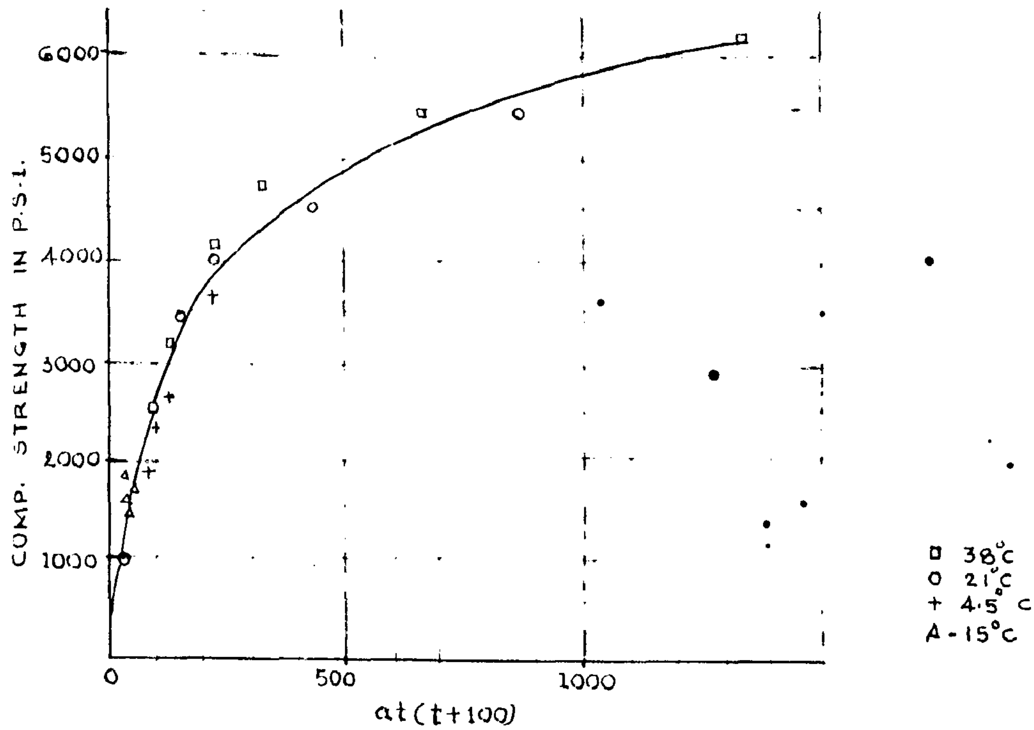


FIG. 2

RESULTS OF WILEY'S TESTS ON 6"x12" ON CYLINDERS HAVING CEMENT CONTENT 390 Kgm/cu.m. (660 LB/C.YD) AND W/C = 0·51

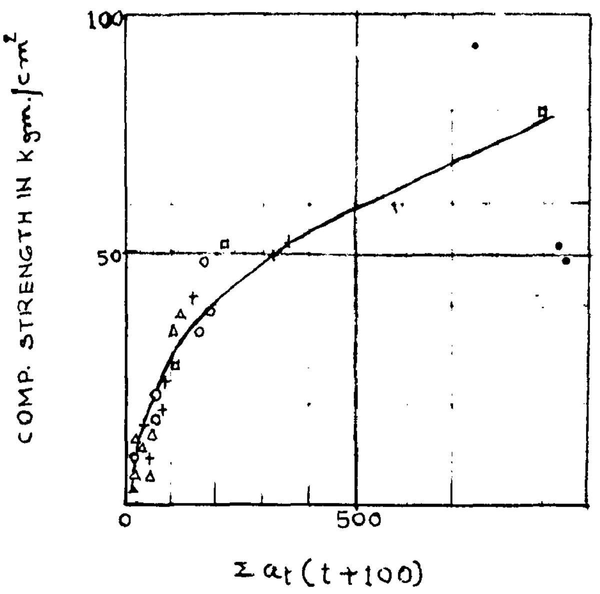


FIG. 3

RESULTS OF TIMMES AND WITHEY'S TESTS ON 3"x6" CYLINDERS HAVING CEMENT CONTENT 225 Kgm/cu.m (350 lbs/c.yd) AND W/C = 0·80

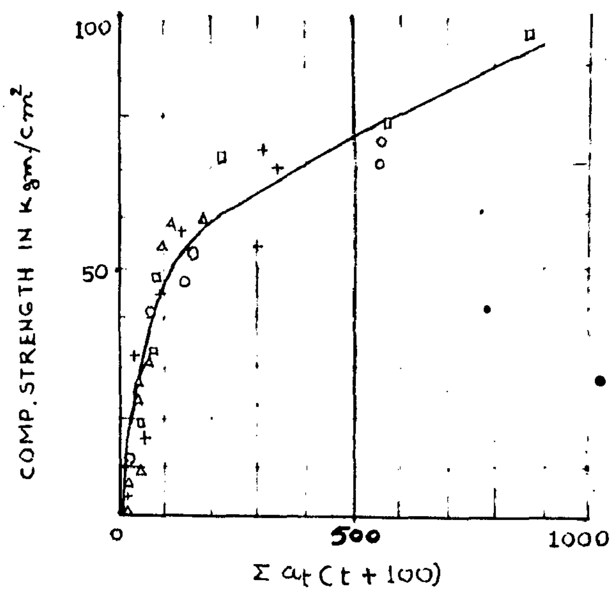


FIG. 4

RESULTS OF TIMMES AND WITHEY'S TESTS ON 3"x6" CYLINDERS HAVING CEMENT CONTENT 320 Kgm/cu.m (540 lbs/c.yd) AND W/C = 0·53

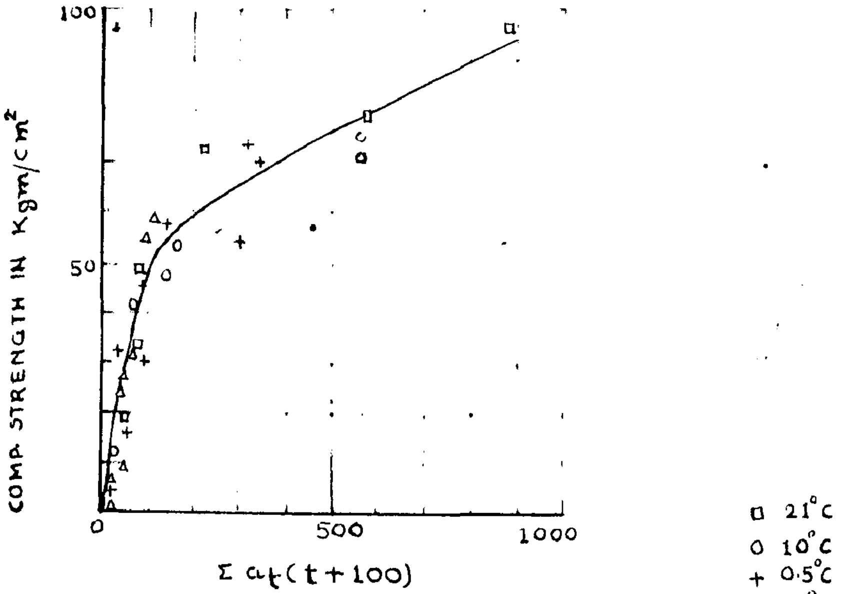


FIG. 5

RESULTS OF TIMMES AND WITHEY'S TESTS ON 3"X6" CYLINDERS HAVING CEMENT CONTENT 430 Kgm./Cu.m (725 lbs/c.yd) AND W/C = 0.40

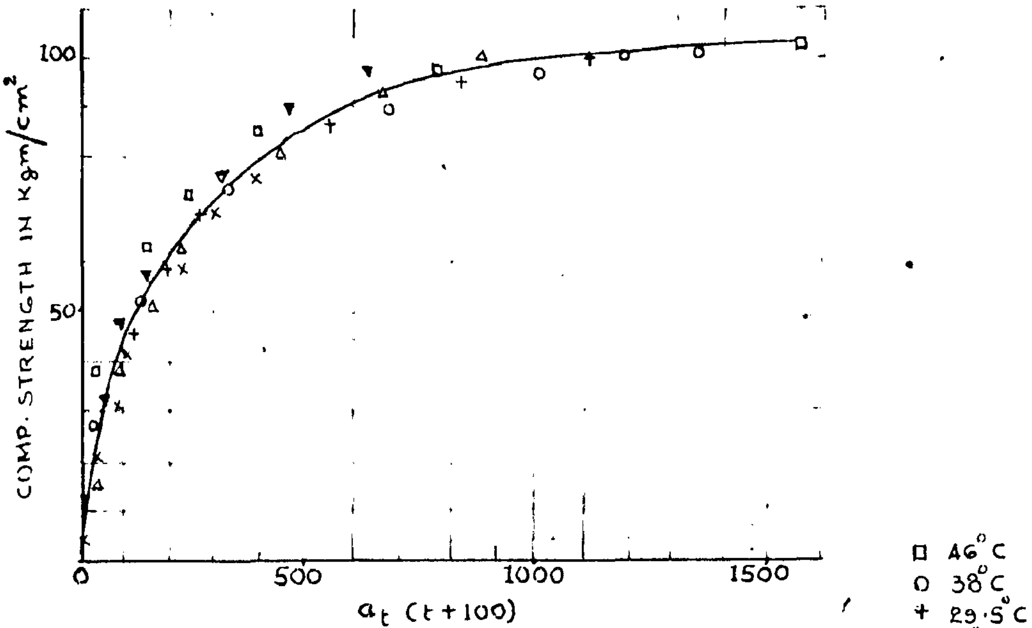


FIG. 6

RESULTS OF PRICE'S TESTS ON 6"x12" CYLINDERS HAVING CEMENT CONTENT 360 Kgm. (610 lbs/c.yd) AND W/C = 0.50

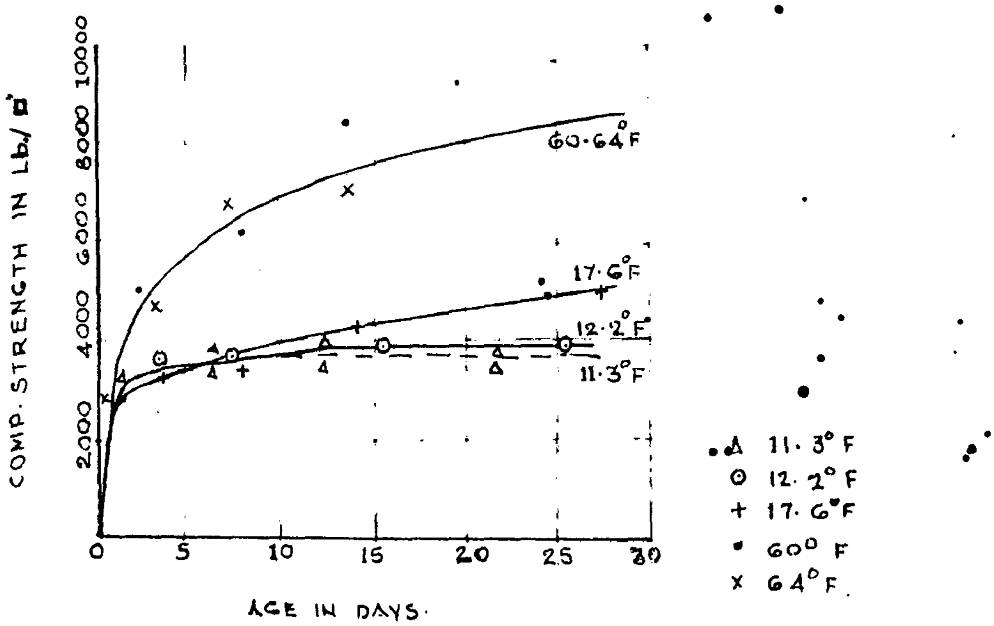


FIG. 7

RESULTS OF PLOWMAN FOR CRUSHING STRENGTH OF CONCRETE CURED AT DIFFERENT TEMPERATURS

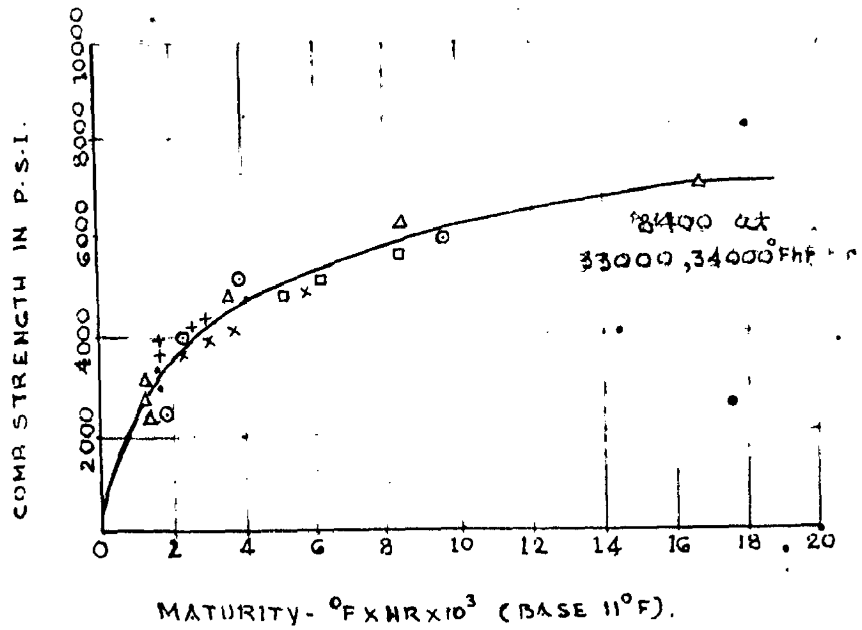


FIG. 8

RESULTS OF PLOWMAN FOR CRUSHING STRENGTH OF CONCRETE WITH RESPECT TO MATURITY AT 11°F TEMP. AS BASE.

the compressive strength of concrete and the temperature at which it is cured though the exact relations have not been found.

2.2. NORMAL CURING.

2.2.1. Law.

It was well known that concrete placed at 32°F or lower will not harden and will have little or no strength. If the concrete is placed at temperatures greater than 32°F and after a few hours, frozen then it will continue to gain in strength. For this reason and because of the need for the cubes to withstand demoulding and handling, the initial curing period at normal temperatures was set arbitrarily at 24 hours. After this initial curing the cubes may be demoulded and cured either in a refrigerator or under water as the case may be at the required temperatures within the limit of ± 3°F.

It was shown by Plowman[20] that the maturities of all points in a block subjected to heating are the same, provided that all return to an initial temperature and therefore, the maturity calculated from the temperature of the concrete of a cube represents that of the whole cube. Figure No. 8 shows the results obtained by Plowman[20] at different temperatures.

Figure No.9 shows the strength plotted against maturity for cubes cured at various temperatures for varying periods of time. It will be seen that they can be represented by a curve. If these strengths are plotted against $\log_{10} \frac{\text{Maturity}}{1000}$ in °F-hr. as shown in Fig. No.9, the relationship is seen to be a straight of the form %age of 28-day strength = $A + B \log_{10} \frac{\text{Maturity}}{1000}$

where values of A and B are given by different authorities can be summarised as given in Table No.1.

Table No.1.

The values of constants A and B at the Exact maturity of 35000°F-hr.

Authority	Constants. A	B
Medaniel	-8.0	72.0
Price	10. 0	53.0
Wiley	17.0	57.5
Davey	0.55	64.5
Nurse	19.0	57.0
Saul	32.0	52.5
Mc Muse	11.8	59.0
Spantoon	18.0	53.0
	9.5	59.5
Plowman.	30.0	45.2

Since the strength at any maturity is proportional to the logarithm of the maturity it is possible to relate the values of the constants A and B to strengths obtained at set maturities of 3,5,7,14,21 and 28 days. For this purpose it is divided into four zones and constants A and B are found for each zone which are shown in Fig. No.10 and Table No.2.

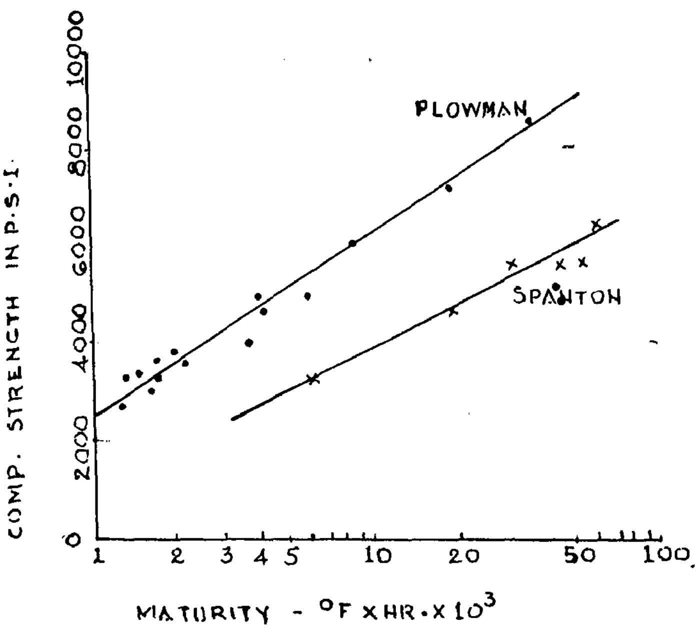


FIG. 9

RESULTS OF PLOWMAN FOR CRUSHING STRENGTHS PLOTTED AGAINST LOG_{10} MATURITY

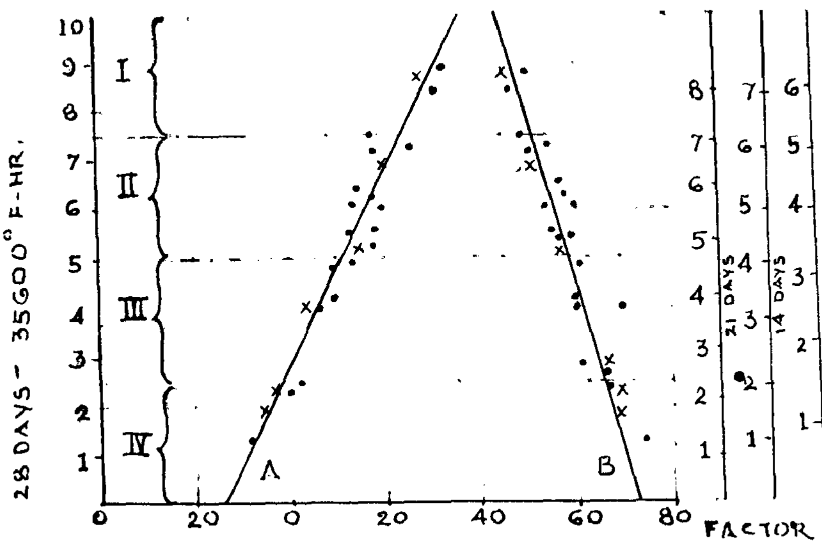


FIG. 10

CONSTANTS A & B FOR DIFFERENT DAYS IN THE EQUATION;

$$\% \text{ OF 28 DAYS STRENGTH} = A + B \log_{10} \frac{\text{MATURITY}}{1000}$$

Table No. 2.

Constants for the four zones. The error involved in using such values instead of the exact values from Fig. No. 18 does not exceed 2%.

Zone	Strength in lbs/sq.in. at 35800°F-hr	26700°F hr.	17800°F-hr.	8900°F-hr.	3800°F-hr.	Value of Constants. A	B
I	0-2500	0-2300	0-2000	0-1600	0-1000	-7	68
II	2500-5000	2300-4800	2000-4000	1600-3200	1000-2200	6	61
III	5000-7500	4800-7100	4000-6300	3200-5200	2200-3800	18	54
IV	7500-10,000	7100-9300	6300-8500	5200-7000	3800-6000	30	46.5

Since the relationship is in terms of a percentage of strength at a given maturity, it may be used to determine the strength of any test specimen irrespective of its geometrical shape, whether cube, prism or cylinder. Cylinder crushing strengths are lower than cube strength for identical concrete. The table prepared may be used with following correction. Multiply the cylinder strength (ht/dia. = 2) by 1/0.85 for obtaining the constants.

2.3.2. Following conclusion can be derived from the work done in this field.

(1) At normal and fixed temperatures concrete gains strength, rapidly at first and later more slowly.

(2) At about freezing point the reaction between the cement and water is dormant and concrete will neit[h]er set nor gain strength at all. At higher temperatur[e] the chemical reaction is stimulated and concrete gains strength more rapidly.

(3) Temperature above freezing, as well as time plays its part in the gain in strength of concrete.

(4) The strength of concrete is proportional to the product of time and temperature.

(5) The maturity can be correlated with the strength by the linear relation as follows

%age of 28-day strength = $A + B \log_{10} \frac{\text{Maturity}}{1000}$

(6) This law is independent of (a) the quality of the cement (b) the w/c ratio ,(c) the A/c ratio, (d) the curing temperature, (e) the shape of the test specimen. Values of the constants for the four zones specified are sufficiently accurate for all normal work.

(7) The values of constants A and B are related linearl[y] to the strength at any age and may be predicted.

(8) Given the strength at any maturity, the strength of the grade of concrete at any other maturity may be calculated.

2.4. OVEN CURING.

2.4.1. Law.

The early workers did not draw any distinction between concrete cured at normal and higher temperature. Their assumption that the same law can be applied was far from correct. The experiments conducted by Mc Intosh[16] have revealed that for same maturity concrete cured at higher temperatures gives strength which is much higher than that of concrete cured at normal temperatures. The higher temperatures curing changes the nature of the reaction products and thus accelerates the strength. The law also varies with the type of cement. Plowman's law can be applied for the concrete cured upto 185°F[16]. A similar law was established by Prof. King, Bondre, Ordman[5] and Narayanan[16]. The law was for concrete cured continuously upto 185°F. The upper limit upto which this law is valid is yet not certain.

The accelerated curing technique used was similar for both the workers. Specimens for curing at elevated temperatures were heated in thermostatically controlled electric ovens. Cube specimens were casted in the normal way in cast iron moulds and the moulds with top and bottom plates were transferred into a cold oven, 30 minutes after water was added to the mix. The heating rate was such as to bring the oven to the maximum temperature in about one hour. The specimens were kept in the oven for varying periods. The Ordman and Bondre's results are expressed as percentages of 28 day strength for five different strengths. The maturity was calculated with 11°F as the datum. The graphs are reproduced in Fig. No.11.

The relation between percentage of 28-day strength and maturity was linear in the form of $A + B \log_{10} \frac{\text{Maturity}}{1000}$. The values of A and B and maturities as calculated by Ordman and Bondre and Narayanan are tabulated in table Nos. 3,4, and 5.

Table No.3.

Maturities.

Heating Cycle: Waiting Time in hrs.	Heating Cycle: Heating Time in hours.	Heating Cycle: Cooling Time in hours.	Maturity in °F-hr.	$\log_{10} \frac{\text{Maturity}}{1000}$
1/2	6	1/2	1005	0.002
1/2	19	1/2	3265	0.514
1/2	23	1/2	3960	0.598

Table No.4.

28-day Strength in p.s.i	%age of 28-day Strength after accelerating curing for 6 hrs.	19 hrs.	23 hrs.	Value of constants. A	B
3800	34.2	53.1	54.2	34.1	35.2
4300	37.2	55.8	58.5	37.2	35.5
5000	40.0	59.0	63.0	39.8	38.2
5770	43.2	62.6	68.5	42.5	42.1
6500	46.1	67.0	74.7	45.5	45.5

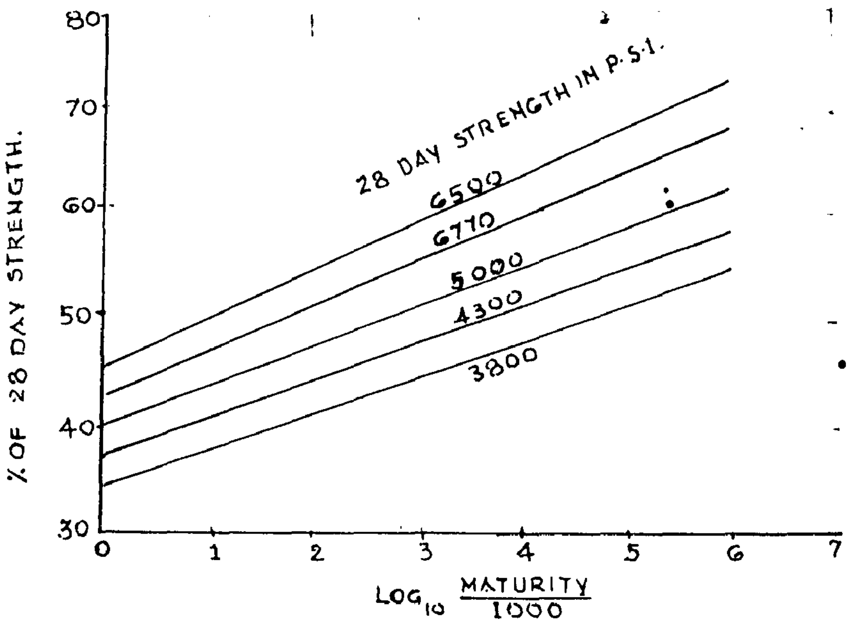


FIG. 11

MATURITY STRENGTH RELATIONSHIP FOR CONCRETE CURED AT 185°F.

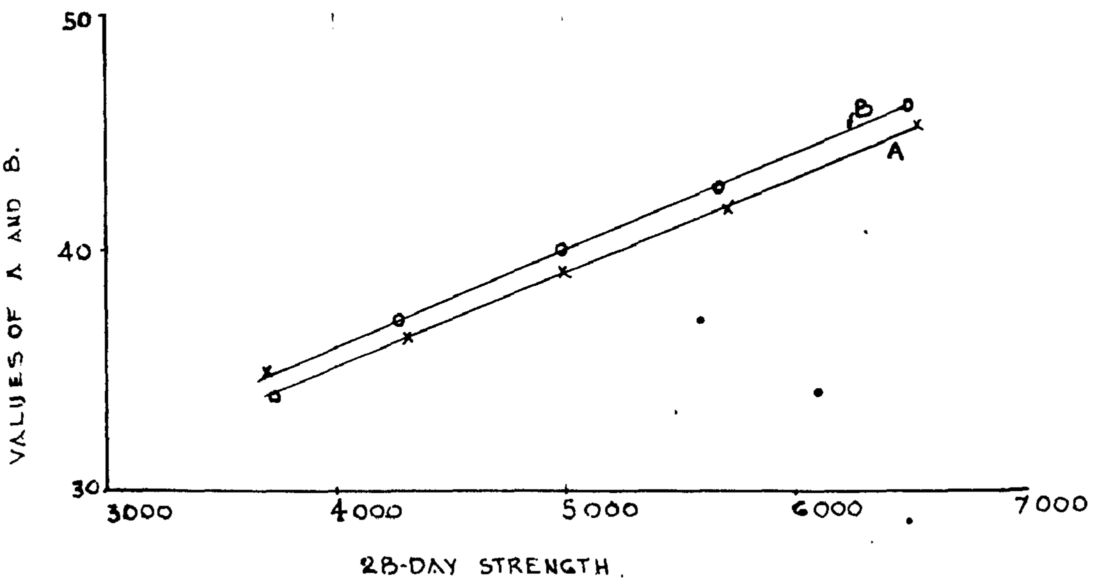


FIG. 12

VALUES OF A AND B IN THE EQUATION, % 28 DAY STRENGTH $= A + B \ LOG_{10} \frac{MATURITY}{1000}$.

TABLE II.4

28-day strength in p.s.i.	A	B
0- 2000	—	—
2000-5000	20.0	50.0
5000-7500	28.0	40.0
7500-10,000	44.0	33.5

2.4.2. Conclusions.

Following conclusions were derived from the work done by both authors.

(1) Plowman's law is applicable to all curing temperatures below 100°F.

(2) At higher temperatures, a different maturity strength relationship corresponds to each curing temperature. Such relationships are also linear.

(3) The linear relation between maturity and strength of concrete can be expressed as

%age of strength at 35000°F-hr is given by

$$A + B \log_{10} \frac{\text{Maturity}}{1000}$$

(4) Variations of A and B are linear.

(5) The values of A and B are different for different types of cement.

(6) The earliest age at which reasonably accurate prediction of long term strengths can be made and may

be taken as that corresponding to a maturity of 2400 °F-hr.

ELECTRICAL CURING.

In case of electrical curing no definite relationship between strength and maturity has been established.(9)

CHAPTER III

CHEMICAL ACCELERATORS

3.1. INTRODUCTION.

The admixtures are substances used in cements, mortars and concrete for the purpose of improving or imparting particular properties to them. Variety of admixtures are used to serve the purpose. They may act as accelerators, or retarders, or air-entraining agents, etc.

Accelerators are used to shorten the time of set as well as to increase the rate of hardening. An accelerator may also serve somewhat as an antifreeze agent by causing a concrete to set before frost damage occurs, as well as by increasing the rate of early heat generations. Accelerators are used to increase the rate of early hardening and thus-

(1) Permit earlier removal of forms,

(2) Shorten the curing period.

(3) Shorten the time of placing a structure into service.

(4) Offset the retarding effects at low temperatures, and

(5) Compensate for the retarding effects of some other admixture.

Chemical materials which accelerate the normal reactions between portland cement and water include calcium chloride, some of the soluble carbonates, silicates (water glass) fluosilicates, aluminous cements and some organic compounds such as triethanolamine.

The effectiveness of an accelerator depends on type and brand of cement, quality and quantity of accelerators, richness of mix, temperature of concrete and curing conditions.

3.2. TYPE OF CEMENT.

Calcium chloride in amount of 1 to 2% by weight of cement increases the early strength of all types of cement. In an investigation[30], it was observed that for any type of cement the 1 1/2 day strength of a concrete, in which 1 to 2% $CaCl_2$ is added, was equal to the 3 day strength of a corresponding type of concrete without $CaCl_2$. It was also found that for high early strength cement the 28-day strength was equal for plain and admixed concrete. To give the rough idea the following table gives the time required to obtain strength of 2000 lbs/sq.in. with different types of cement.

Type of Cement	Time in days for Plain	Admixed 2% $CaCl_2$
Normal	4	1.7
Modified	5	2.0
High Early Strength.	1	0.6
Low Heat	9	4.0
Sulphate resisting.	12	6.0

The higher percentage of calcium chloride can be used at low temperatures than at higher temperatures.

Abram[31] made the tests on the compressive strength of concrete and mortar made of four brands of cement with $CaCl_2$ as an admixture, the percentage of which ranged from 0 to 10%. The results showed that the concrete containing not more than

4% $CaCl_2$ had greater strength than untreated concrete at test periods ranging from 2 days to 3 years, the percentages higher than 4% produced lower strengths at all ages.

3.3. TEMPERATURE.

The temperature at which a concrete mass is placed and cured is an important factor in controling the rate at which concrete develops strength. $CaCl_2$ may be used for promoting accelerated strength development of concrete placed during cold weather. The increase in strength is more at lower temperatures. At 10°F, at all ages, the concrete with $CaCl_2$ has approximately twice the strength of the concrete without $CaCl_2$. But at higher temperatures (50°F) the strength after one year will be the same, 4% $CaCl_2$ produces slightly higher strength than 2% $CaCl_2$.

3.4. CEMENT CONTENT.

The $CaCl_2$ is more effective in increasing the early strength of rich concrete as compared to lean concrete.[30] The strength obtained at the end of one day, by an addition of 2% $CaCl_2$ to a concrete made up of standard cement and high early strength cement was found to be greater than that obtained by an addition of two additional sacks of cement to a cubic yard of concrete containing 5 to 7 sacks of cement. The strength obtained at the end of 7 days with 2% addition of $CaCl_2$ was equal to the strength which can be obtained by addition of 1/2 sack of cement to normally cured concrete[32]. Abram[31] concluded that the increase in strength due to the addition of 2% $CaCl_2$ was practically negligible for a 1:7 mix by volume, and strength increases thereafter upto 1:4 mix (by volume) and for richer mixes it remains constant. The use of $CaCl_2$ above 2 to 3% of the weight of cement has no advantage in strength regardless of mix proportions.

3.5. FLEXURAL STRENGTH.

The $CaCl_2$ has little effect on the transverse strength in early days; then it is slightly reduced. After 28 days and one year the decrease in strength was found to be 10% and 20% for 2% and 4% $CaCl_2$ respectively[22]. At lower temperature the strength is increased and depends on the percentage of $CaCl_2$. The high early strength cement showed no advantage at 40°F over 2% $CaCl_2$[34]

3.6 TENSILE STRENGTH.

Platzmann[25] showed that low percentages of $CaCl_2$ has no effect on strength after 7 and 28 days and reduces it slightly after 2 and 3 months. Levens showed that 2 to 5% $CaCl_2$ increased the 28-day tensile strength of mortar specimens dried after one day, but 2% $CaCl_2$ produced the highest tensile strength. Under moist curing, more than 2% $CaCl_2$ produced lower strengths than specimens without $CaCl_2$.

3.7 HEAT OF HYDRATION.

The $CaCl_2$ increases the heat of hydration of cement during first few hours, but has little effect after one day. The modified cement[26] shows increase of 30% in heat of hydration, by an addition of 1% $CaCl_2$, in one day[25] $CaCl_2$ increase the rate of temperature rise and causes the maximum to occur earlier. For modified cement it was eight hours with 1% of $CaCl_2$ and twelve hours in the normal concrete.

3.8. SULPHATE RESISTANCE.

It contributes to lower resistance to sulphate attack in all cases. The effect will be more in the cement containing low amount of 3CaO. Al_2O_3.

3.9. FREEZING AND THAWING.

Concrete containing not more than 2% $CaCl_2$ gave higher resistance to freezing and thawing than concrete without $CaCl_2$.[28]

3.10 VOLUME CHANGE.

$CaCl_2$ increases the volume change of concrete under moist curing as well as dry curing. Drying shrinkage is generally increased by addition of $CaCl_2$[33]. Yato's[36] however does not agree with this view. 2% $CaCl_2$ increased the shrinkage by 10% for concrete dried for 580 days.[25] The moisture loss was reduced to one-sixth by the addition of $CaCl_2$.

3.11 INITIAL SETTLEMENT.

$CaCl_2$ reduces the initial settlement of concrete. 2% of $CaCl_2$ in concrete reduces the settlement time to half that of concrete without $CaCl_2$.

3.12 TIME OF SET.

$CaCl_2$ in amounts of 0.1, 0.3, 0.5 and 1.0% accelerates the set by 25, 18, 45 and 85 minutes. (25)

3.13. REINFORCING STEEL.

The steel was found to be intact in a concrete containing upto 10% $CaCl_2$ after one year.[37] In high slump concrete (6" to 8") steel showed rusting at early ages. It was less compared to the steel exposed to tap or distilled waters.

3.14. EROSIVE RESISTANCE.

The concrete containing 2% $CaCl_2$ is more resistive to erosive forces, then plain concrete(25), the abrasive resistance would be 10 to 25% greater and cavitation resistance will increase by 100% after 3 months.

3.15 MIX. ADOPTED.

As it is well known that the chemical accelerators help to gain in early and higher strength, the various chemical accelerators are calcium chloride, sodium silicate (water glass), triethanomaline and other substances. The chemical accelerators used were calcium chloride, sodium silicate and sodium hydroxide.

For all these three accelerators the three different proportions of concrete, which are normally used in practice, were used with w/c ratios which gave a constant slump of 2".

Mix No.	Proportions used	w/c ratio.
K	1:1.5:3.0	0.45
V	1:2.0:4.0	0.60
X	1:3.0:6.0	0.70

3.16. CUBES TESTED.

Totally 2013 cubes were cured and tested out of which,

1007 cubes were normally cured and tested at an intervals of 6 hrs, 12 hrs, 24 hrs, 3 days, 7 days and 28 days.

1006 cubes were normally cured with different percentages of various chemical accelerators.

3.17. CUBE PREPARATION.

Though the method of casting cubes have been described in IS:516:1959 " Methods of Tests for Strength of Concrete". The short procedure has been described here so as to make a self-sufficient report.

The cement was thoroughly mixed by hand and stored in a silo so as to give the greatest possible uniformity in the material. The concrete mixer at every mix was rinsed with trial mix so as to prevent the loss of water and cement of the mix. The cement, aggregate and water were mixed for time varying from 6 minutes to 7 minutes depending upon the proportion of coarse aggregate till the resulting concrete was uniform in appearance. Cast iron moulds were used as per specification laid down in IS:516-1959. The moulds were filled in two layers each of 3" thickness and moulds were then vibrated on the standard vibrating table for two minutes.

3.18 CURING.

The test specimens were stored in a room, and to have moist air of atleast 90% relative humidity. The wet gunny bags were wrapped round it for 24 hours. The time was counted from the time of addition of water to the dry ingredients. After this period the specimens were marked and removed from the moulds. They were submerged in clean, fresh water curing tank and kept in water for the required period. Tests were made at an interval of 3,5,7,10,14,21 and 28 days.

3.19. TESTING PROCEDURE.

The cubes were tested under universal 200 ton compression testing machine in wet condition as per IS:516:1959. The cubes were placed in such a way that the load was applied to the opposite sides of the cube at cast, that is not at the top and bottom. The load was applied continuously at the rate of 140 kgm/sq.cm./min. i.e. 2 tons/min for a 6" cube till it could sustain, the reading being ultimate load.

3.20. RESULTS.

3.20.1.(a) Calcium Chloride.

The results are given in table Nos. 6,7 and 8. The graphs of normal strength versus compressive strength for various percentages of $CaCl_2$ have been shown in Fig Nos. 13,14 and 15. Following were the different proportions of $CaCl_2$, which were tried 1/2, 1, 1 1/2, 2 and 2 1/2 expressed as the percentage by weight of cement. By addition of 1/2% $CaCl_2$ to the concrete mixes it was found that the increase in strength varies from 18.2% to 23.7% at the end of 3 days and 6.4% to 7.5% at the end of 28 days. The strength increase decreases as the age increases and between

TABLE NO. 6.

CALCIUM CHLORIDE AS ACCELERATOR

Mix 1:1$^{1}/_{2}$:3 w/c=0.45 by weight. All cubes are 6" size and reading represents the average of 3 cubes.

Sr. No.	% of $CaCl_2$		Normal Strength in p.s.i. 3 days	5 days	7 days	*10 days	14 days	23 days	28 days
K_0	—		2322.0	2800.0	3300.0	3450.0	4000.0	4465.0	4765.0
K_A	0.5%		2893.0	3250.0	3610.0	3915.0	4370.0	4760.0	5070.0
		A	124.7	116.1	108.2	113.2	109.2	106.6	106.4
		B	60.7	68.2	75.8	82.2	91.7	99.9	106.4
K_{A2}	1.0%		3130.0	3535.0	3905.0	4100.0	4545.0	5030.0	5290.0
		A	134.9	126.2	118.2	118.9	113.2	112.8	111.1
		B	65.8	74.3	82.0	86.2	95.5	105.6	111.1
K_{A3}	1.5%		3300.0	3790.0	4070.0	4340.0	4720.0	5185.0	5480.0
		A	142.2	135.5	123.3	126.2	118.2	116.2	115.1
		B	69.4	79.6	85.5	91.7	99.5	109.0	115.1
K_{A4}	2.0%		3660.0	4055.0	4375.0	4600.0	4960.0	5360.0	5680.0
		A	157.7	144.8	132.6	133.3	124.0	120.0	119.2
		B	76.8	85.0	91.9	96.6	104.2	112.5	119.2
K_{A5}	2.5%		3910.0	4230.0	4485.0	4840.0	5100.0	5475.0	5788.0
		A	168.6	151.3	136.0	140.5	127.2	122.8	121.5
		B	82.2	88.6	94.2	101.8	107.2	115.0	121.5

* 4" cubes.

(A) Accelerated Strength as a percentage of corresponding normal cured strength.

(B) Accelerated strength as a percentage of 28 days normal cured strength of plain concrete.

EFFECT OF CALCIUM CHLORIDE ON STRENGTH OF CONCRETE, PROPORTION 1:1·5:3·0 W/C 0·45.

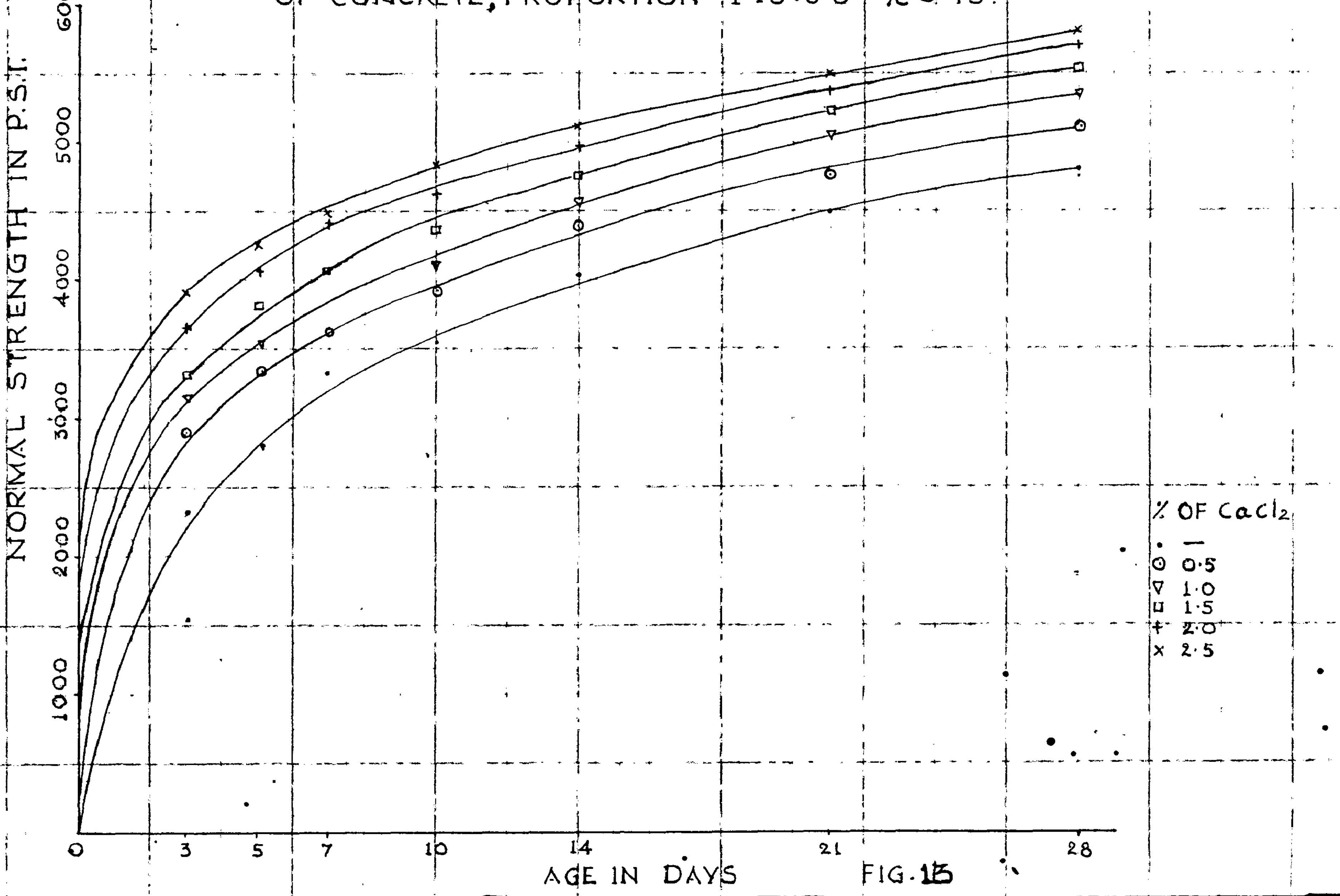


FIG. 15

TABLE NO.7

CALCIUM CHLORIDE AS ACCELERATOR

Mix 1:2:4 w/c = 0.60 by weight All cubes are 6" size and reading represents average of three cubes.

Sr. No.	% of $CaCl_2$		Normal Strength in P.s.i.						
			3days	5days	7days	*10days	14days	21days	28days.
V_o	—		1655.0	2085.0	2430.0	2880.0	3000.0	3260.0	3500.0
V_{A1}	0.5%		1835.0	2325.0	2780.0	3010.0	3275.0	3520.0	3762.0
		A	122.0	111.3	118.4	104.7	109.2	108.0	107.5
		B	52.5	66.5	79.5	86.0	93.6	100.8	107.5
V_{A2}	1.0%		1995.0	2705.0	3070.0	3300.0	3560.0	3910.0	4015.0
		A	132.8	129.8	126.3	114.7	118.7	120.0	114.7
		B	57.0	77.2	87.7	94.4	101.8	111.9	114.7
V_{A3}	1.5%		2375.0	3010.0	3340.0	3560.0	3820.0	4070.0	4210.0
		A	158.0	144.4	137.2	123.5	127.3	125.0	121.0
		B	67.8	86.0	95.5	101.8	109.2	116.2	121.0
V_{A4}	2.0%		2770.0	3360.0	3580.0	3870.0	4070.0	4280.0	4360.0
		A	184.0	161.3	147.3	134.4	135.7	131.2	124.6
		B	79.2	96.0	102.2	110.7	116.2	122.2	124.6
V_{A5}	2.5%		3160.0	3610.0	3900.0	4000.0	4220.0	4410.0	4500.0
		A	210	173.5	160.5	138.9	140.7	135.1	128.5
		B	90.8	103.2	111.5	114.3	120.5	126.0	128.5

*4" cubes.

A) Accelerated Strength as a percentage of corresponding normal cured strength.

B) Accelerated strength as a percentage of 28 days normal cured strength of plain concrete.

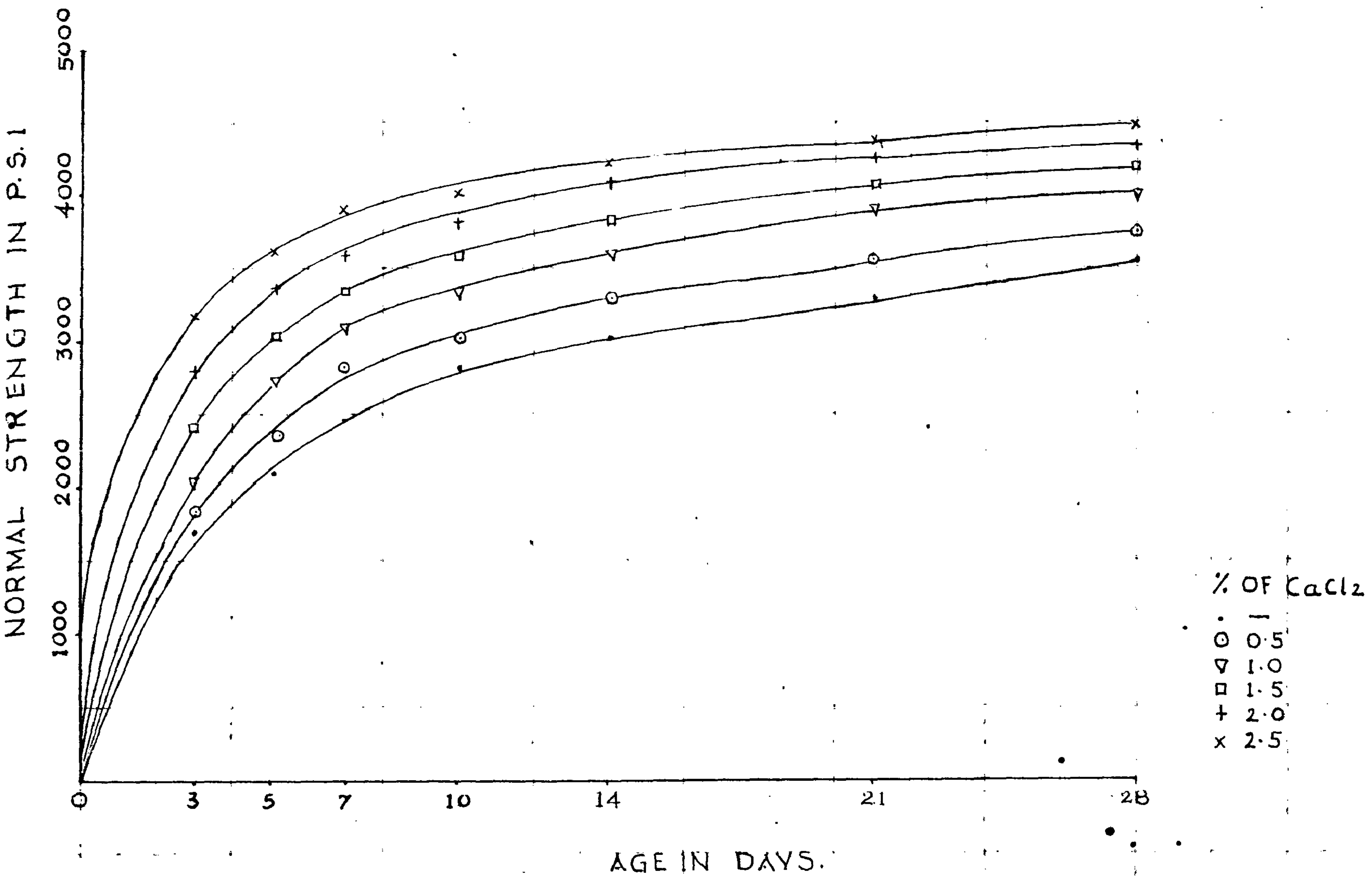


FIG. 14.

EFFECT OF CALCIUM CHLORIDE ON STRENGTH OF CONCRETE, PROPORTION 1:2:4 W/C = .60

TABLE NO. 8

CALCIUM CHLORIDE AS ACCELERATOR

Mix. 1:3:6 W/C = 0.70 by weight All cubes are 6" size and reading represents the average of 3 cubes.

Sr. No.	% of $CaCl_2$		Normal Strength in P.S.I. 3 days	5 days	7 days	*10 days	14 days	21 days	28 days
X_0	——		1060.0	1400.0	1625.0	1720.0	1930.0	2123.0	2013.0
X_{A1}	0.5%		1220.0	1580.0	1850.0	1930.0	2210.0	2395.0	2180.0
		A	115.2	112.9	113.7	113.7	114.3	113.0	107.8
		B	62.7	69.4	80.0	86.0	95.6	103.7	107.8
X_{A2}	1.0%		1410.0	1780.0	2045.0	2201.0	2200.0	2345.0	2320.0
		A	121.2	127.2	125.8	122.2	123.8	110.7	113.2
		B	61.0	70.9	88.4	96.3	103.4	110.7	113.2
X_{A3}	1.5%		1690.0	2000.0	2270.0	2430.0	2600.0	2720.0	2710.0
		A	152.3	142.8	139.6	141.3	131.8	122.2	117.1
		B	69.2	80.6	98.2	105.1	112.7	117.2	117.1
X_{A4}	2.0%		1885.0	2240.0	2480.0	2590.0	2300.0	2820.0	2800.0
		A	179.5	160.0	152.7	150.5	145.0	131.6	121.0
		B	81.5	93.8	107.8	112.0	121.0	121.8	121.0
X_{A5}	2.5%		2020.0	2400.0	2500.0	2706.0	2860.0	2900.0	§ 2850.0
		A	192.3	167.0	150.0	157.2	149.1	133.0	123.0
		B	87.3	101.2	112.2	110.9	121.2	125.2	123.0

*4" cubes.
§ tested at 29 days.

A) Accelerated strength as a percentage of corresponding normal cured strength.

B) Accelerated strength as a percentage of 28 days normal cured strength of plain concrete.

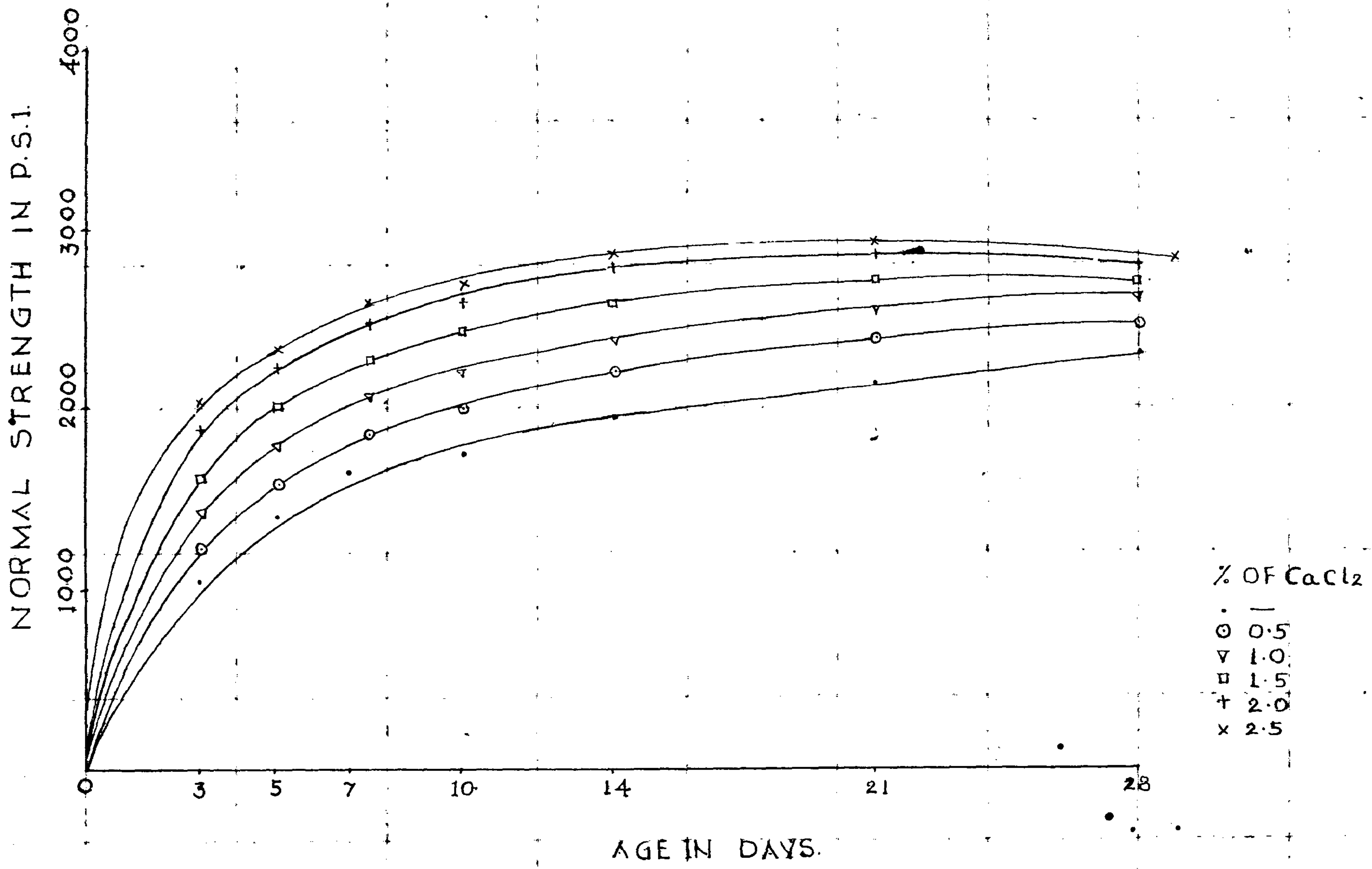


FIG. 15

EFFECT OF CALCIUM CHLORIDE ON STRENGTH OF CONCRETE, PROPORTION 1:3:6 W/C = 0·70

3 and 28 days lies in between those percentages. The higher percentage is for the richer mix. It is also clear from these results that as the days of normal curing goes on increasing the percentage gain in strength over normal cured strength without accelerators goes on decreasing, though the strength at any day and for any percentage of $CaCl_2$ is always more than plain concrete. As the percentage of $CaCl_2$ added to mix goes on increasing the percentage gain in strength increases in the same pattern as for the lower percentage of calcium chloride. Adding 1% $CaCl_2$ the percentage gain in strength over normal cured concrete varies from 32.8% to 31.9% at the end of 3 days and 11.1% to 14.7% at the end of 28-days. Addition of more calcium chloride increases the strength but increase in strength after the addition of 2% $CaCl_2$ goes on decreasing. The optimum percentage of $CaCl_2$ is nearabout 2%. The gain in strength by adding 2% $CaCl_2$ at the end of 3 days varies from 82% to 90% of 28-day strength of plain concrete. 28-day strength of plain concrete will be attained near about 7 days by adding 2% $CaCl_2$ for leaner concrete. The time required is more for richer mix. The relative cost by adding 1/2% $CaCl_2$ is twice that of the richer mix, and also the strength of plain richer mix is more as compared to accelerated concrete.

3.20.2 (b) <u>Sodium Silicate.</u>

Sodium silicate ($Na_2 SiO_3$) known as water glass was also used as an accelerator though it is generally used for surface application to impart the hardness. The same percentages

TABLE NO. 9

SODIUM SILICATE AS ACCELERATOR

Mix 1:2½:3 w/c = 0.45 (by weight) All cubes are 6" size and reading represents average of three cubes.

Sr. No.	% of Na_2 dose		Normal strength in p.s.i.						
			3days	6days	7days	*10days	14days	21days	28days
K0	—		2023.0	2300.0	3200.0	3520.0	4030.0	4605.0	4766.0
KB1	0.5%		2225.0	2975.0	3310.0	3750.0	4198.0	4670.0	4902.0
		A	110.0	129.3	101.2	106.5	103.0	103.7	102.9
		B	46.6	62.4	69.5	78.6	87.9	98.0	102.0
KB2	1.0%		2330.0	3190.0	3460.0	3863.0	4303.0	4773.0	5018.0
		A	117.0	110.7	108.4	109.7	107.0	103.2	105.2
		B	50.0	65.0	72.6	81.0	90.4	100.3	105.2
KB3	1.5%		2520.0	3190.0	3536.0	4004.0	4380.0	4870.0	5120.0
		A	124.7	114.0	103.8	114.1	103.8	108.2	107.3
		B	52.9	67.0	74.2	84.1	92.0	102.2	107.3
KB4	2.0%		2550.0	3305.0	3554.0	4118.0	4500.0	4975.0	5233.0
		A	133.0	118.0	111.3	117.2	111.7	108.5	109.7
		B	53.5	69.4	74.6	86.5	94.6	104.6	109.7
KB5	2.5%		2834.0	3420.0	3820.0	4268.0	4630.0	5070.0	5372.0
			140.3	122.2	116.3	121.0	114.7	112.8	112.7
			59.5	71.8	80.2	89.7	97.2	105.7	112.7

* 4" cubes.

(A) Accelerated strength as a percentage of corresponding normal cured strength.

(B) Accelerated strength as a percentage of 28 days normal cured strength of plain concrete.

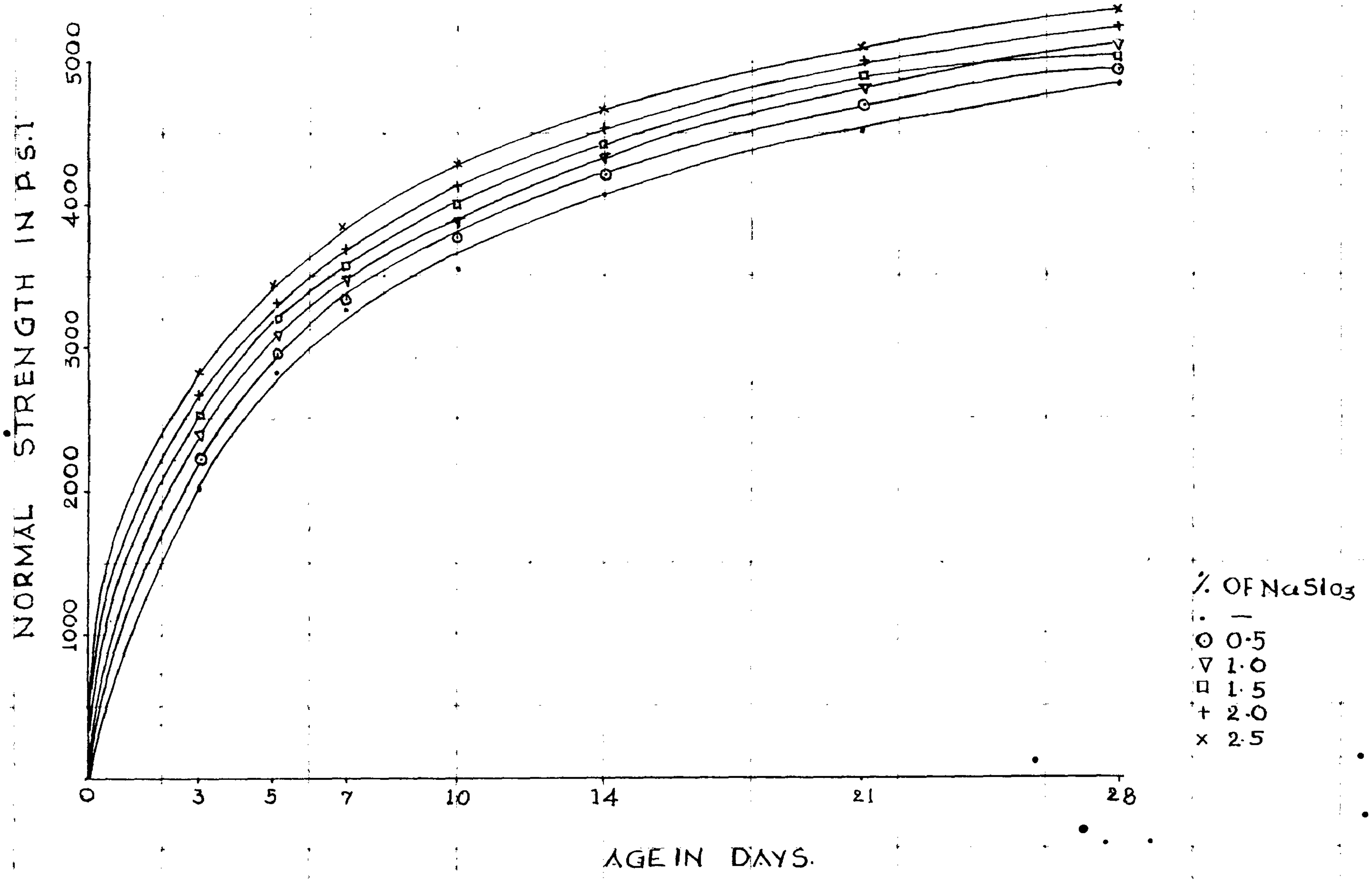


FIG. 16

EFFECT OF SODIUM SILICATE ON STRENGTH OF CONCRETE, PROPORTION 1:1½:3 W/c = 0·45

TABLE NO. 20

SODIUM SILICATE AS ACCELERATOR

Mix 1:2:4 w/c ?0.00 by weight. All cubes are 6" size and reading represents average of three cubes.

Sr. No.	% of sodium silicate.		Normal Strength P.s.i.						
			3days	6days	7days	°10days	14days	21days	28days.
V_0	——		1655.0	2085.0	2130.0	2310.0	3020.0	3220.0	3500.0
V_{B1}	0.5%		1820.0	2260.0	2300.0	2515.0	3200.0	3420.0	3612.0
		A	110.0	108.7	107.0	109.0	106.0	104.0	103.0
		B	51.0	64.4	74.1	83.0	90.6	97.4	103.0
V_{B2}	1.0%		1943.0	236.0	2705.0	2040.0	3310.0	3506.0	3620.0
		A	117.2	114.0	111.2	103.3	110.3	107.5	104.0
		B	55.3	67.0	77.0	85.6	94.4	99.0	104.0
V_{B3}	1.5%		2116.0	2519.0	2862.0	3146.0	3418.0	3600.0	3750.0
		A	127.7	120.6	117.3	112.0	113.0	110.8	107.2
		B	60.2	71.6	81.2	89.6	97.3	102.8	107.2
V_{B4}	2.0%		2300.0	2723.0	3006.0	3310.0	3512.0	3750.0	3843.0
		A	133.0	131.0	123.0	117.0	117.0	115.0	109.0
		B	65.6	77.8	86.4	94.4	100.2	107.0	109.8
V_{B5}	2.5%		2461.0	2800.0	3140.0	3412.0	3623.0	3861.0	3941.0
		A	149.8	139.0	129.3	121.6	120.8	119.3	112.8
		B	70.0	79.4	89.4	97.2	103.2	110.0	112.3

° 4" cubes.

A) Accelerated strength as a percentage of corresponding normal cured strength.

B) Accelerated strength as a percentage of 28 days normal cured strength of plain concrete.

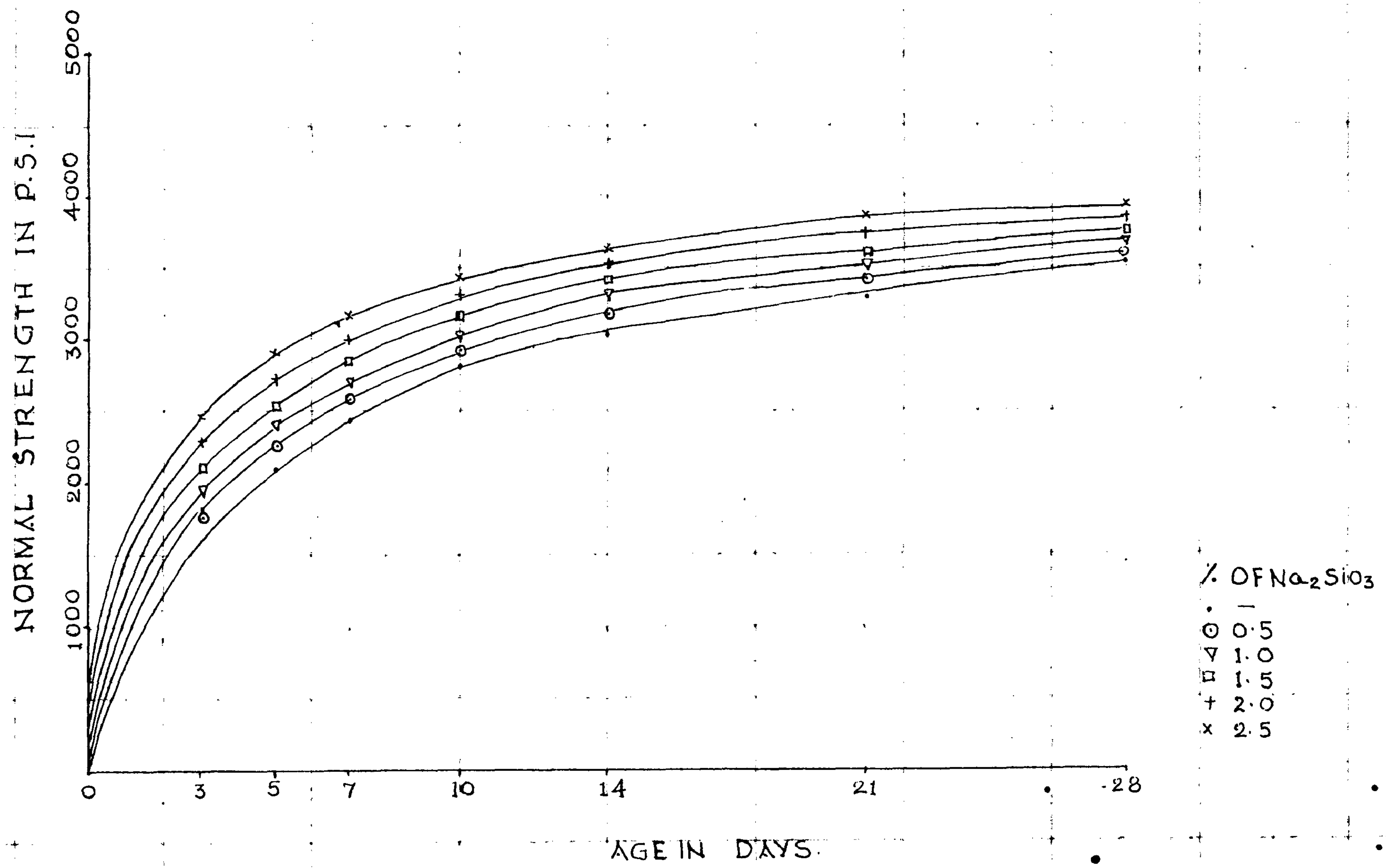


FIG. 17

EFFECT OF SODIUM SILICATE ON STRENGTH OF CONCRETE, PROPORTION 1:2:4 W/C = 0·60

TABLE NO.11

SODIUM SILICATE AS ACCELERATOR.

Mix 1:3:6 w/c =0.70 by weight   All cubes are 6" size and reading represents average of three cubes.

Sr. No.	% of Na_2SiO_3		Normal Strength in P.s.i. 3days	5days	7days	*10days	14days	21 days	28days
X_0	—		1050.0	1400.0	1625.0	1760.0	2020.0	2170.0	2313.0
X_{B1}	0.5%		1140.0	1492.0	1710.0	1916.0	2120.0	2238.0	2380.0
		A	108.0	106.6	105.2	108.8	105.3	103.2	102.8
		B	49.2	64.5	73.8	82.6	91.6	96.8	102.8
X_{B2}	1.0%		1268.0	1580.0	1812.0	2026.0	2212.0	2330.0	2380.0
		A	110.8	112.8	111.4	115.0	110.0	110.2	100.0
		B	54.3	68.2	78.2	87.4	95.6	102.3	103.0
X_{B3}	1.5%		1370.0	1642.0	1900.0	2120.0	2304.0	2478.0	2390.0
		A	130.5	117.3	117.1	120.3	114.7	114.0	103.3
		B	59.2	70.9	82.2	91.6	99.6	109.8	103.3
X_{B4}	2.0%		1481.0	1786.0	1981.0	2205.0	2380.0	2555.0	2530.0
		A	140.0	127.6	121.8	125.2	118.4	117.8	109.6
		B	63.9	77.1	85.4	95.1	102.8	110.2	109.5
X_{B5}	2.5%		1562.0	1870.0	2028.0	2300.0	2416.0	2610.0	2635.0
		A	148.8	131.1	124.4	130.7	120.2	120.1	114.0
		B	67.5	81.0	87.4	99.2	104.2	113.0	114.0

* 4" cubes.

A) Accelerated strength as a percentage of corresponding normal cured strength.

B) Accelerated strength as a percentage of 28 days normal cured strength of plain concrete.

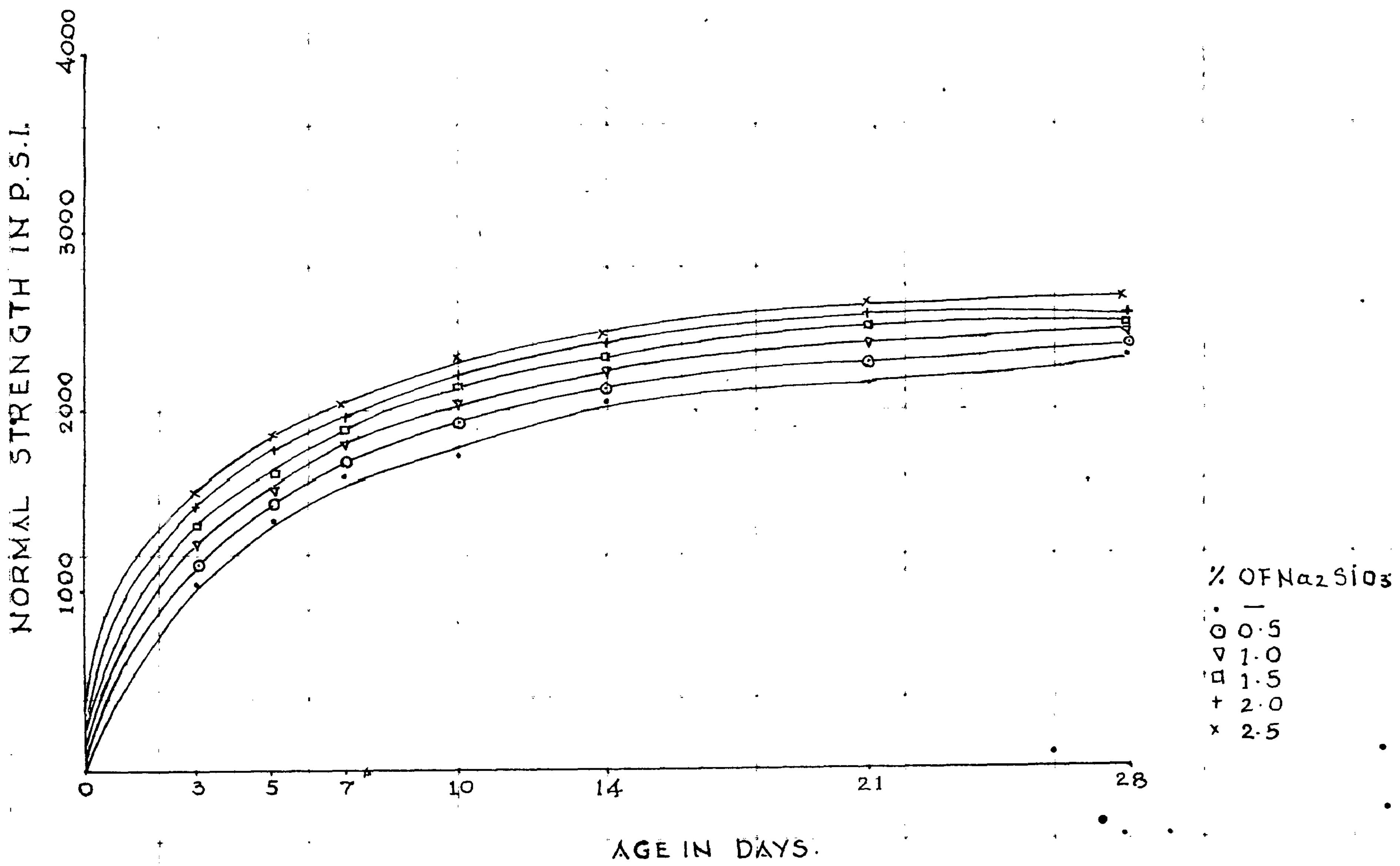


FIG. 18

EFFECT OF SODIUM SILICATE ON STRENGTH OF CONCRETE, PROPORTION 1:3:6 W/C = 0·70 were tried to find out the increase in strength of concrete. The results are tabulated in table nos. 9, 10, and 11 and shown in Figure Nos. 16, 17 and 18.

It was found that by addition of 1/2% Na_2SiO_3, the strength increases varies from 8.8%to 10% at the end of 3 days and 2.8% to 3% at the end of 28-days. The strength increase for any day between 3 and 28 days is between these percentages. The richer or leaner mix has got negligible effect on the percentage gain in strength for any day. As the percentage of Na_2SiO_3 goes on increasing the percentage strength also increases; by adding 1% Na_2SiO_3 strength increases from 17.2% to 19.8% at the end of 28-days. By the addition of 2.5% of Na_2SiO_3 there is a gain in strength of about 46% at the end of 3 days. The age increases the percentage increase in strength decreases, and strength at 28 days for low percentages is approximately same as that of plain concrete. The 28 day strength of plain concrete by adding 2% Na_2SiO_3 is attained in days ranging from 11.6 to 18.0. The lower figure for leaner mix and higher for richer mix.

2.20.3 (c) <u>Sodium Hydroxide.</u>

The addition of 1 to 2% Sodium Hydroxide in cement concrete at the time of casting reduces the setting time to great extent (2% $NaOH$ reduces it to 6 minutes). The effects of Sodium hydroxide on compressive strength of concrete for the same mixes were studied. Three percentages of 1/2,3/4 and 1 were selected for our purpose because more than 1% rendered the casting of cubes practically impossible. The results are tabulated in table nos. 12,13, and 14, and graphs of compressive strength versus age in days are shown in fig. nos. 19,20 and 21.

Addition of 1/2% of NaoH gave increase in strength of 6.6% to 12.2% depending upon the mix at 3 days and 3.7% to 4.7% at the end of 28 days. Higher % increase is for leaner mix. The % gain in strength decreases as the age in days increases. For low percentages strength can be taken equal to that of plain concrete at the end of 28 days. As the addition of NaoH goes on increasing the strength goes on increasing upto its optimum limit and if it is further added, then the strength goes on decreasing. The optimum percentage can be taken as 3/4. Addition of 1% NaoH gave an increase in strength from 16.7% to 32.0% at 3 days and 5.7% to 16.6% at 28days. Addition of 1% gives an increase strength upto 7 days After this it is found that the strength attained is less than that of concrete having 3/4% NaoH. The 28-day strength of plain concrete was attained by addition of 3/4% NaoH in days ranging from 13.5 to 19.5, the lower value is for leaner mix.

It was observed that leaner the mix greater the % gain in strength for all percentages and at all ages.

TABLE NO.12.

SODIUM HYDROXIDE AS CHEMICAL ACCELERATOR

Mix 1:1½:3 w/c = 0.45(by weight) All cubes are 6" size and reading represents average of three cubes.

Sr. No.	% of sodium Hydroxide.		Normal Strength in lbs./sq.in.						
			3 days	5days	7days	10days	*14days	21days	28days
K_o	—		2460.0	2850.0	3150.0	3375.0	4000.0	4465.0	4765.0
K_{c1}	0.50%		2625.0	3068.0	3398.0	3755.0	4140.0	4730.0	4940.0
		A	106.6	107.5	107.8	111.1	103.5	105.8	103.7
		B	55.1	64.4	71.4	78.8	87.0	99.4	103.7
K_{c2}	0.75%		2750.0	3185.0	3500.0	3910.0	4280.0	4875.0	5100.0
		A	111.8	111.8	111.1	1157	106.5	109.2	107.0
		B	57.7	66.8	73.5	82.0	89.5	102.3	107.0
K_{c3}	1.00%		2770.0	3255.0	3575.0	3940.0	4370.0	4840.0	5030.0
		A	116.7	114.2	113.5	116.7	109.3	108.5	105.7
		B	58.2	68.4	75.0	82.7	91.7	101.7	105.7

* 4" cubes.

(A) Accelerated strength as a percentage of corresponding normal cured strength.

(B) Accelerated strength as a percentage of 28 days normal cured strength of plain concrete.

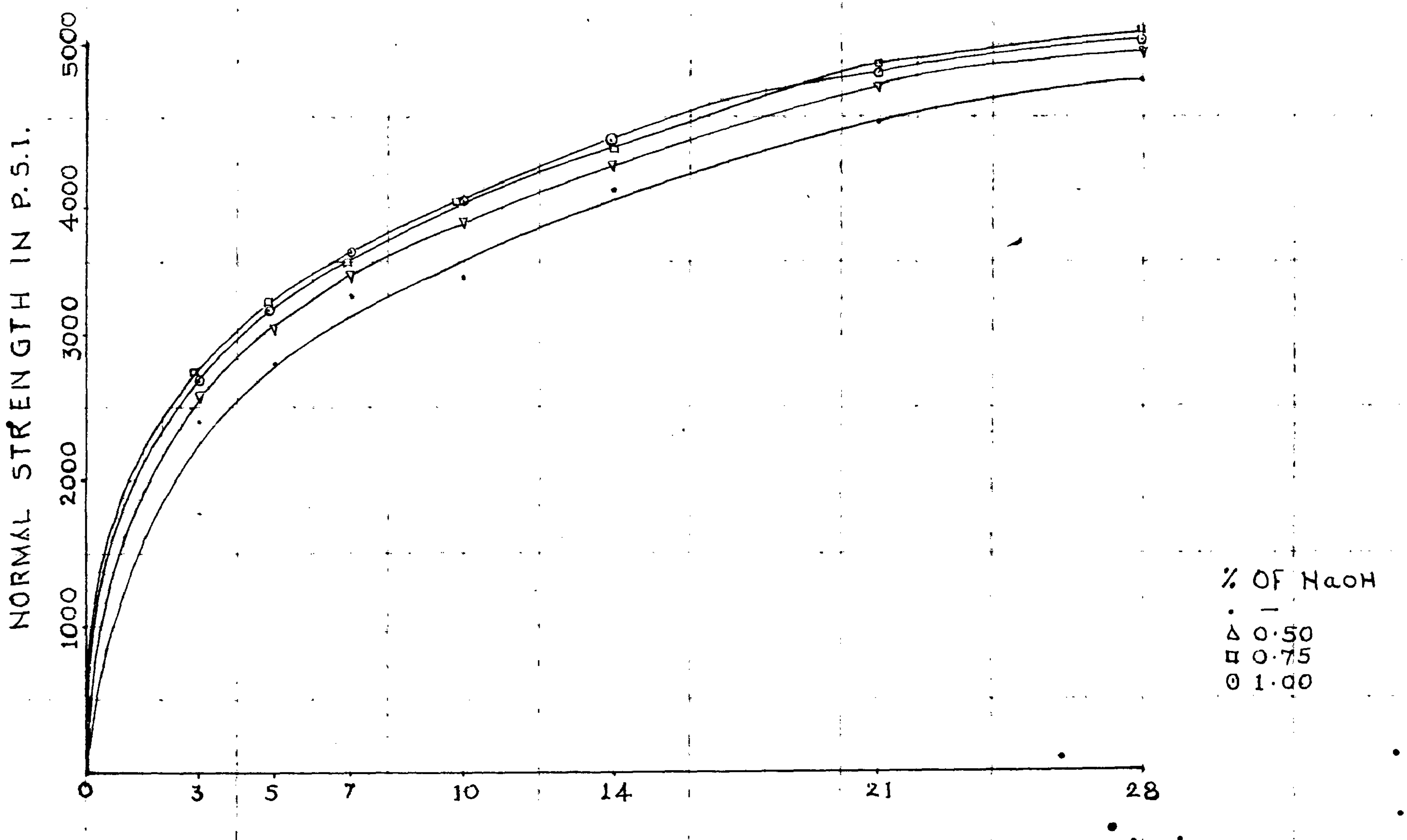


FIG. 19

EFFECT OF CAUSTIC SODA (SODIUM HYDROXIDE) ON STRENGTH OF CONCRETE, PROPORTION 1:1½:3 W/c = 0.45.

TABLE NO. 13

SODIUM HYDROXIDE AS ACCELERATOR

Mix 1:2:4 w/c = 0.60 (by weight) All cubes are 6" size and reading represents average of three cubes.

S.No.	% of $NaOH$		Normal Strength in lbs./sq.in.						
			3days	5days	7days	*10days	14days	21days	28days
V_o	—		1680.0	2120.0	2430.0	2880.0	3000.0	3260.0	3488.0
V_{c1}	0.50%		1875.0	2360.0	2600.0	3125.0	3260.0	3530.0	3640.0
		A	111.7	111.2	107.0	108.8	108.7	108.3	104.3
		B	53.7	67.6	74.5	86.6	93.4	101.1	104.3
V_{c2}	0.75%		2100.0	2500.0	2810.0	3280.0	3540.0	3870.0	3860.0
		A	125.0	117.8	115.7	117.8	118.0	118.8	110.7
		B	60.2	71.6	80.5	94.0	101.5	111.0	110.7
V_{c3}	1.00%		2146.0	2560.0	2897.0	3190.0	3640.0	3730.0	3778.0
		A	127.8	120.8	119.0	114.8	121.3	114.3	108.2
		B	61.6	73.6	83.2	91.6	104.5	106.9	108.2

*4" cubes.

(A) Accelerated Strength as a percentage of corresponding normal cured strength.

(B) Accelerated strength as a percentage of 28-days normal cured strength of plain concrete.

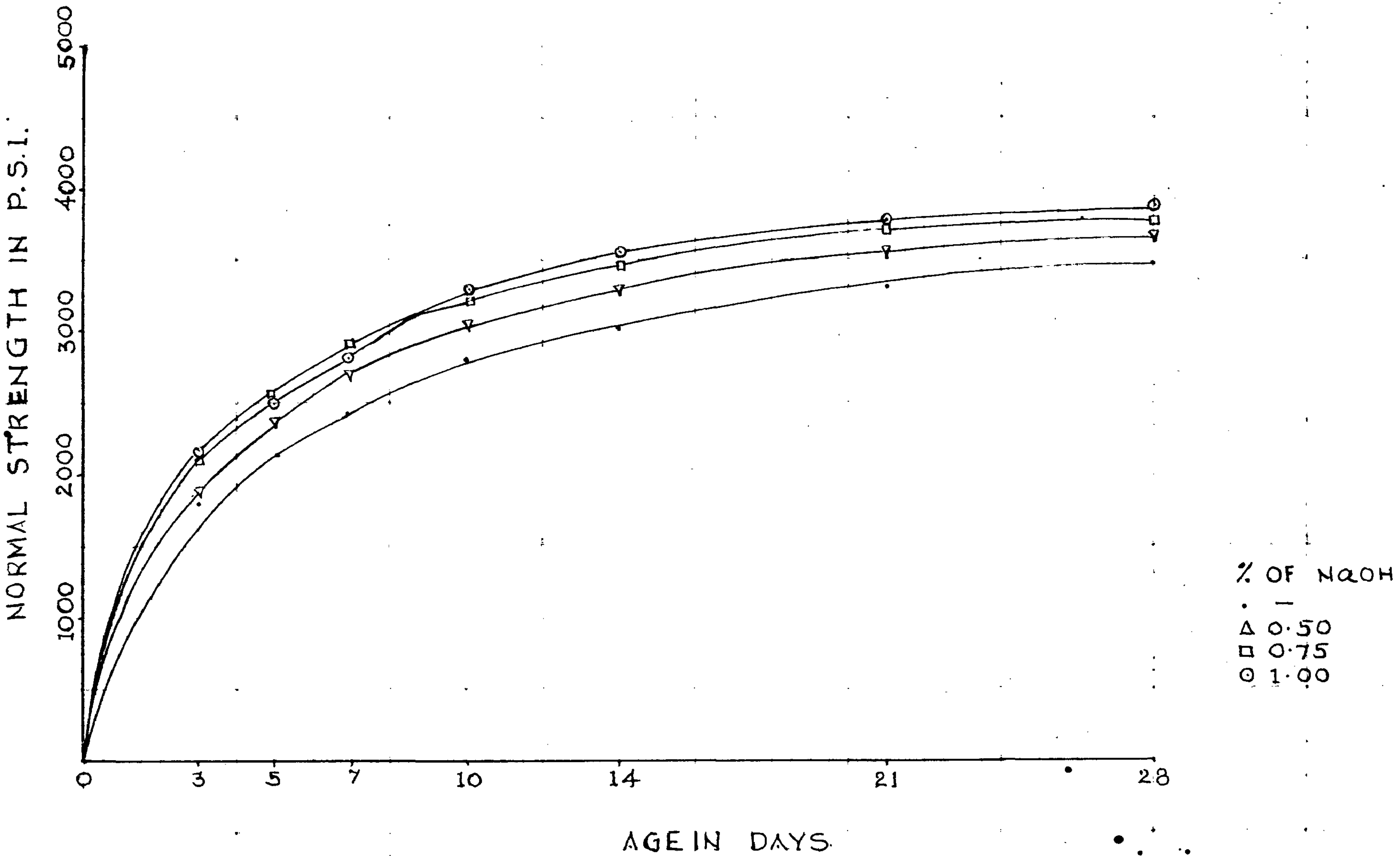


FIG. 20

EFFECT OF CAUSTIC SODA (SODIUM HYDROXIDE) ON STRENGTH OF CONCRETE, PROPORTION 1:2:4 W/c = 0·60.

TABLE NO.14

SODIUM HYDROXIDE AS ACCELERATOR

Mix 1:3:6 w/c =0.70 by weight All cubes are 6" size and reading represents average of three cubes.

Sr. No.	% of NaOH		Normal Strength in p.s.i.						
			3 days	5days	7days	*10days	14days	21 days	28days
X_0	—		1050.0	1400.0	1625.0	1720.0	1930.0	2128.0	2313.0
X_{c1}	0.50%		1180.0	1565.0	1770.0	2000.0	2090.0	2400.0	2492.0
		A	112.2	111.2	108.2	116.2	108.8	113.0	107.7
		B	50.9	67.2	76.4	86.4	90.2	103.7	107.7
X_{x2}	0.75%		1270.0	1620.0	1878.0	2100.0	2280.0	2480.0	2607.0
		A	120.9	116.1	115.3	121.8	118.2	116.8	112.7
		B	54.7	70.4	81.2	90.6	98.5	107.0	112.7
X_{c3}	1.00%		1388.0	1700.0	1965.0	2180.0	2320.0	2565.0	2690.0
		A	132.0	121.6	120.8	126.2	1202	120.6	116.6
		B	59.9	73.4	84.8	94.2	100.2	111.0	116.6

*4" cubes.

(A) Accelerated strength as a percentage of corresponding normal cured strength.

(B) Accelerated strength as a percentage of 28-days normal cured strength of plain concrete.

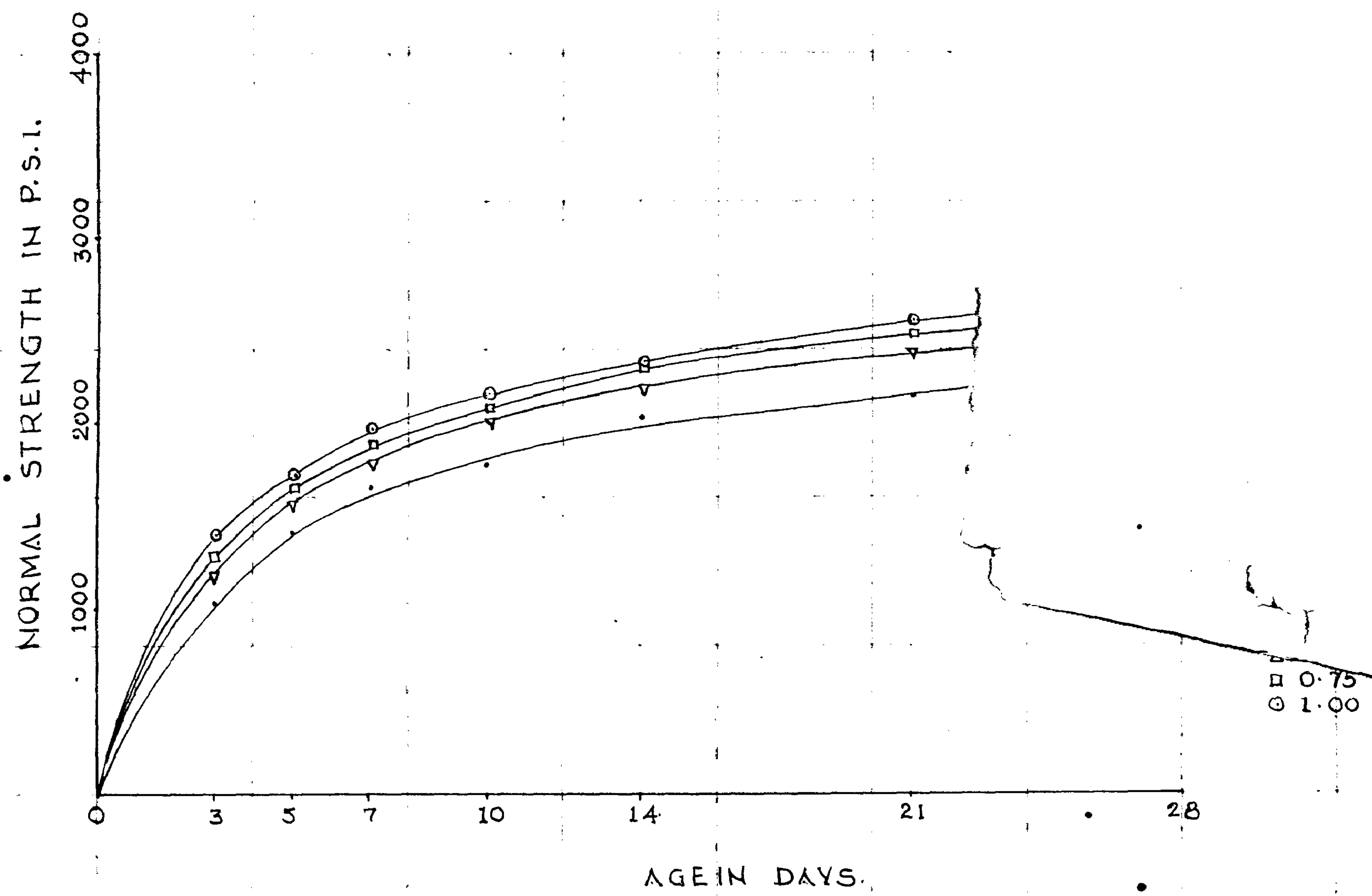


FIG. 21

EFFECT OF CAUSTIC SODA (SODIUM HYDROXIDE) ON STRENGTH OF CONCRETE, PROPORTION 1:3:6 W/C=0·70.

CHAPTER IV

OVEN CURING

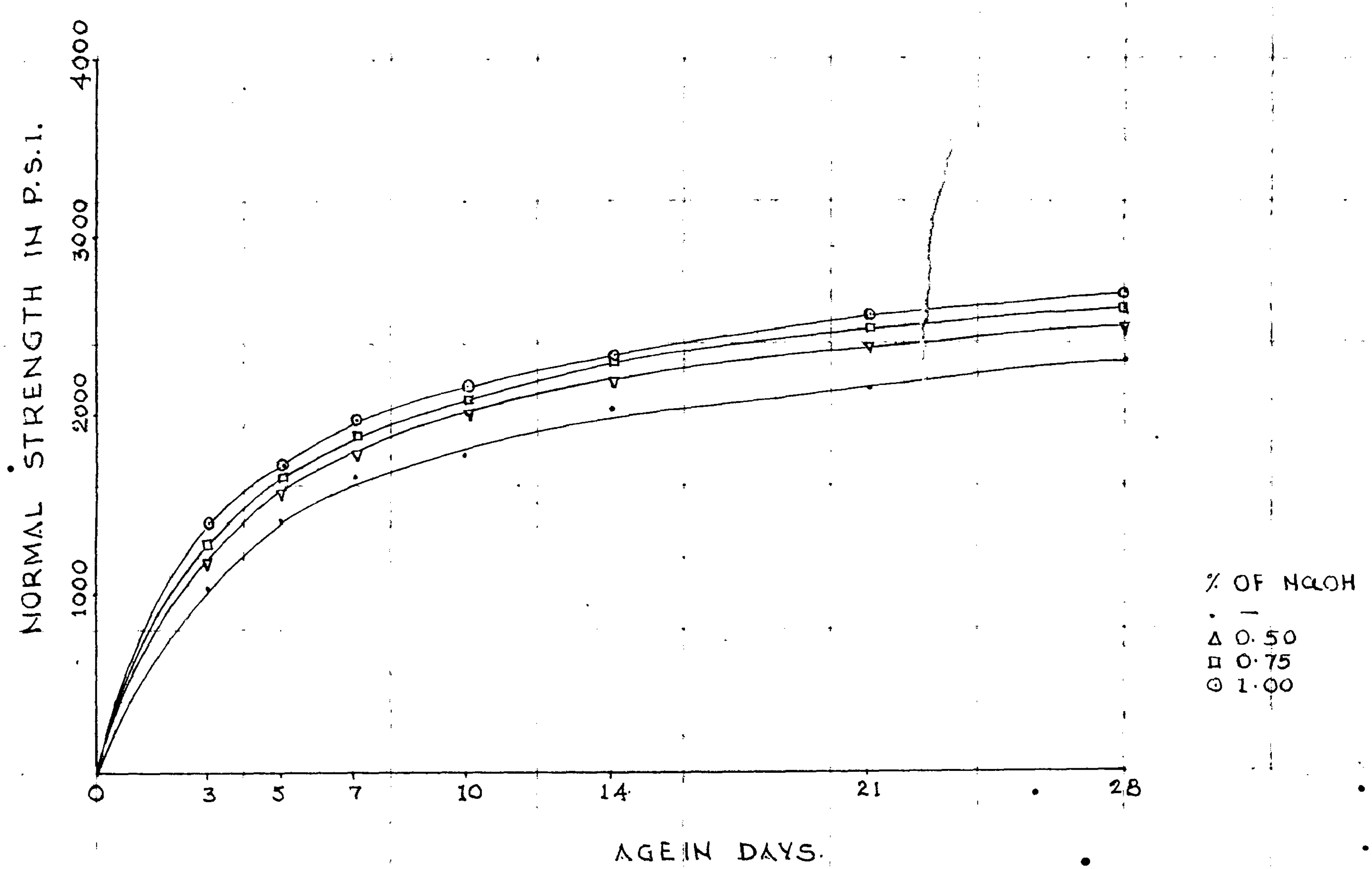


FIG. 21

EFFECT OF CAUSTIC SODA (SODIUM HYDROXIDE) ON STRENGTH OF CONCRETE, PROPORTION 1:3:6 W/c = 0.70.

4.1. INTRODUCTION.

The oven curing of the concrete cubes falls into the category of the accelerating methods. This method is suitable for predicting the strength of the normally cured concrete, few hours after mixing. Even though other methods like steam curing, electric curing are equally effective, they are time consuming and thus comparatively uneconomical.

4.2.
4.2.1. Review.

In 1958 Prof. J.W.H.King worked on this problem, at Queen Mary College of London. He published results for 6 hours of curing and modified curing for 10 hours. In 1960, H.G.Bondre published his thesis on the short term tests under guidance of Prof. King. He also used this technique, however, the curing was done at different temperature. They(10) (8) concluded that the 28-day strength can be predicted within 90.% certainty or within ± 200 lbs./sq.in. by this method. In 1961 Akroyd confirmed the conclusion reached by Prof. King.

The published information on the curing method differs as regards the maximum temperature to which the cubes can be subjected. Prof. King(12) used 200°F for his work though he stated that 185°F can also be used as an alternative temperature. Subsequently Ordman, Bondre(8) and Akroyd(1) used 185°F as the maximum temperature. Thorose Dovan(9) has worked with a maximum temp. of 200°C. The reason for keeping the temperature of 100°F may be that the blue cement has got an optimum temperature of 100°F.

It has been found that the temperature of the oven measured by a single thermometer at top would not be the correct one, because the temperature difference in the oven between the thermometer and the narrow horizontal space between cubes stacked above one another could be quite large in the early stages of heating, as the heated air tends to rise on the top. So, the temperature should be measured at atleast four points. To correct for this, the temperature time graph supplied by the oven manufacturers should be used.

The results given by Prof. King, Ordman, Akroyd and other tally with each other and are reproduced in Figure Nos. 22 to 23. The small difference in the results may be due to several reasons some of them are:-

(1) The temperatures in some cases were different.

(2) Difference in waiting time.

(3) The cubes were also of different sizes.

The concrete cubes cured at 200°C in an air oven for 24 hours gave approximately 7-day normal cured strength[8]. The strength can be further accelerated by addition of calcium chloride. It was found that the cubes containing 2.6% $CaCl_2$ required 10 hours to achieve the 7-day normal cured strength of plain cement concrete.[8]

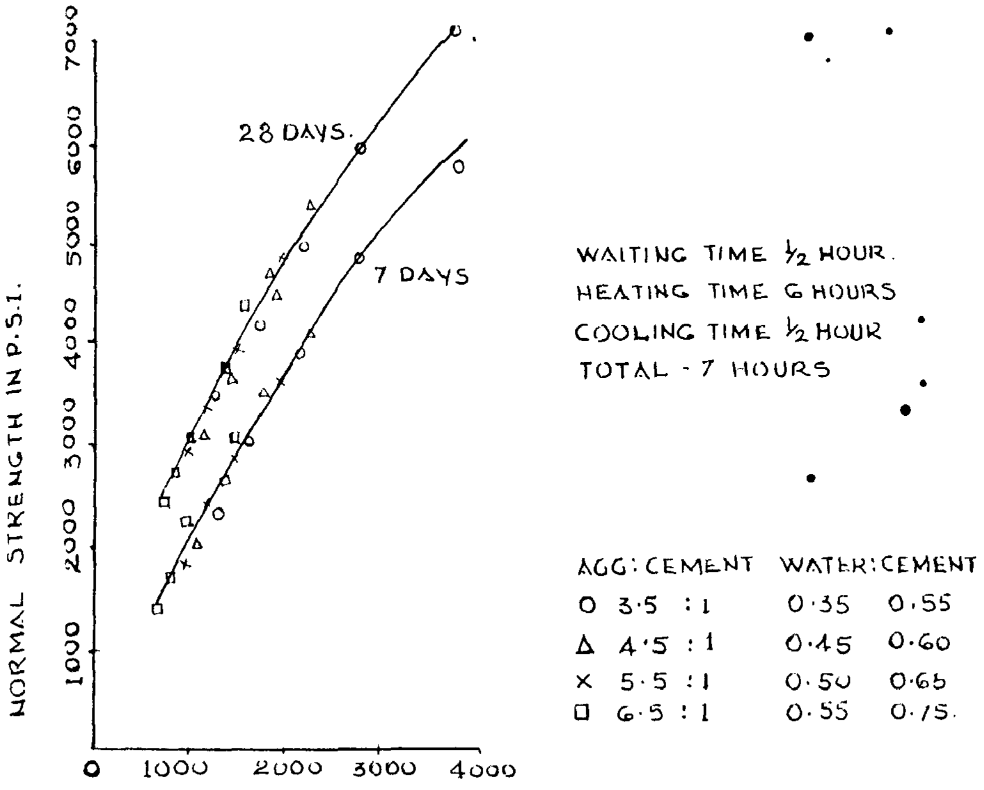


FIG. 22

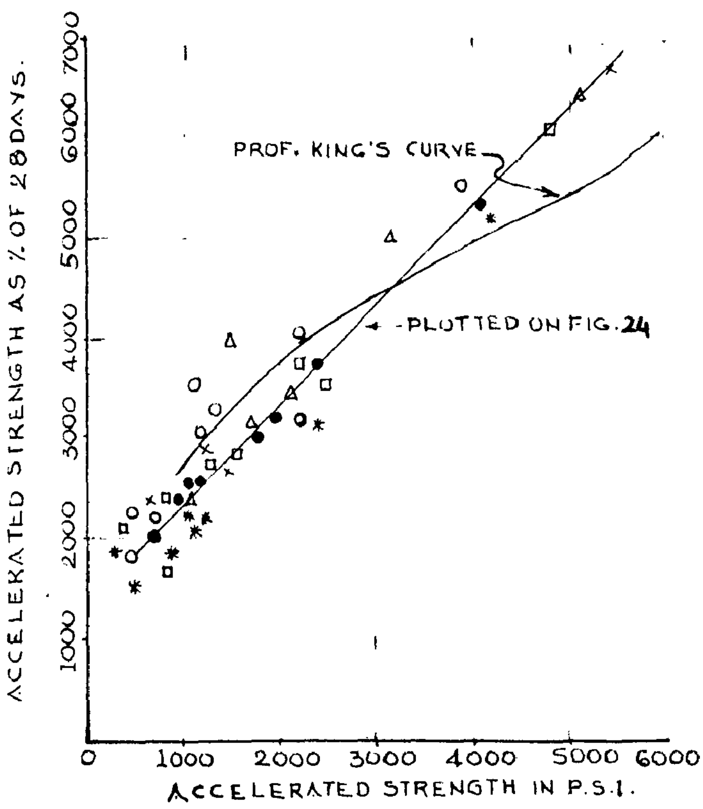


FIG. 23
OVEN METHOD RESULTS.

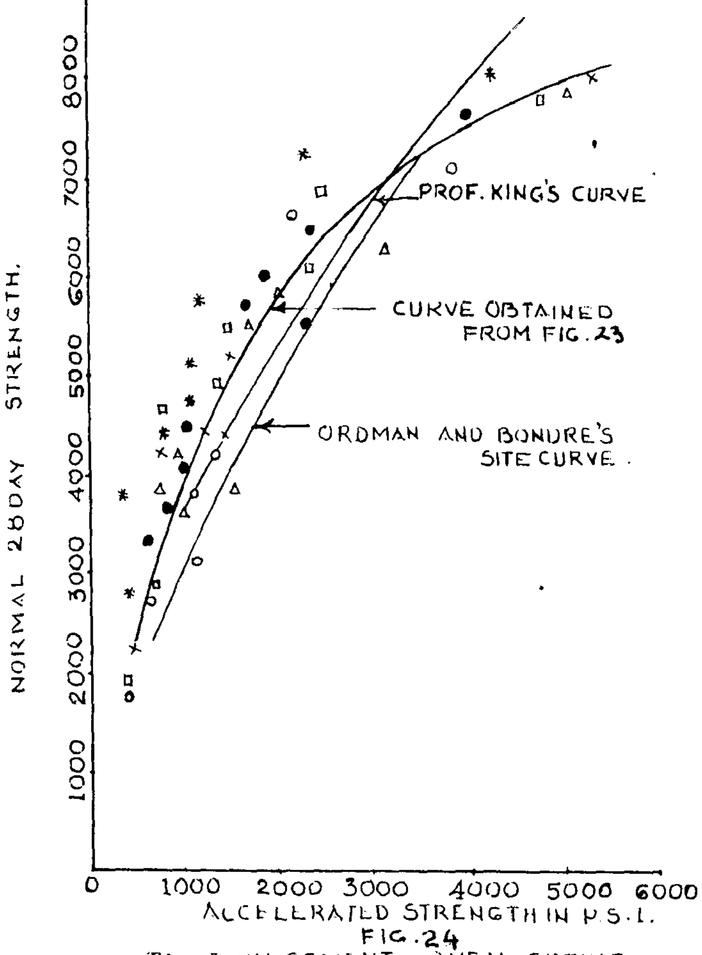


FIG. 24
TEST ON CEMENT OVEN CURING

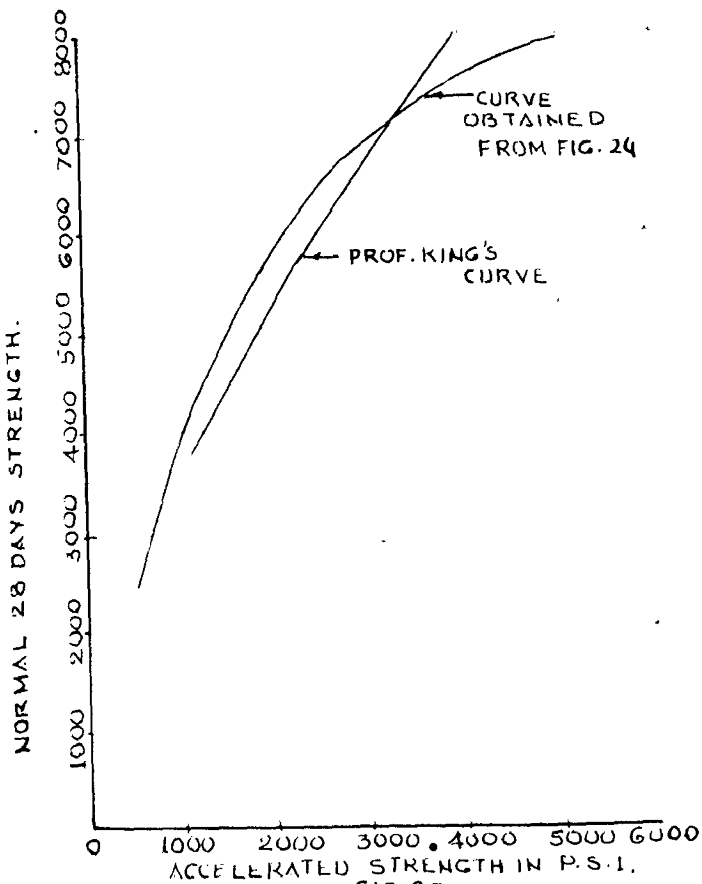


FIG. 25
TESTS ON AGGREGATES' OVEN CURING METHOD.

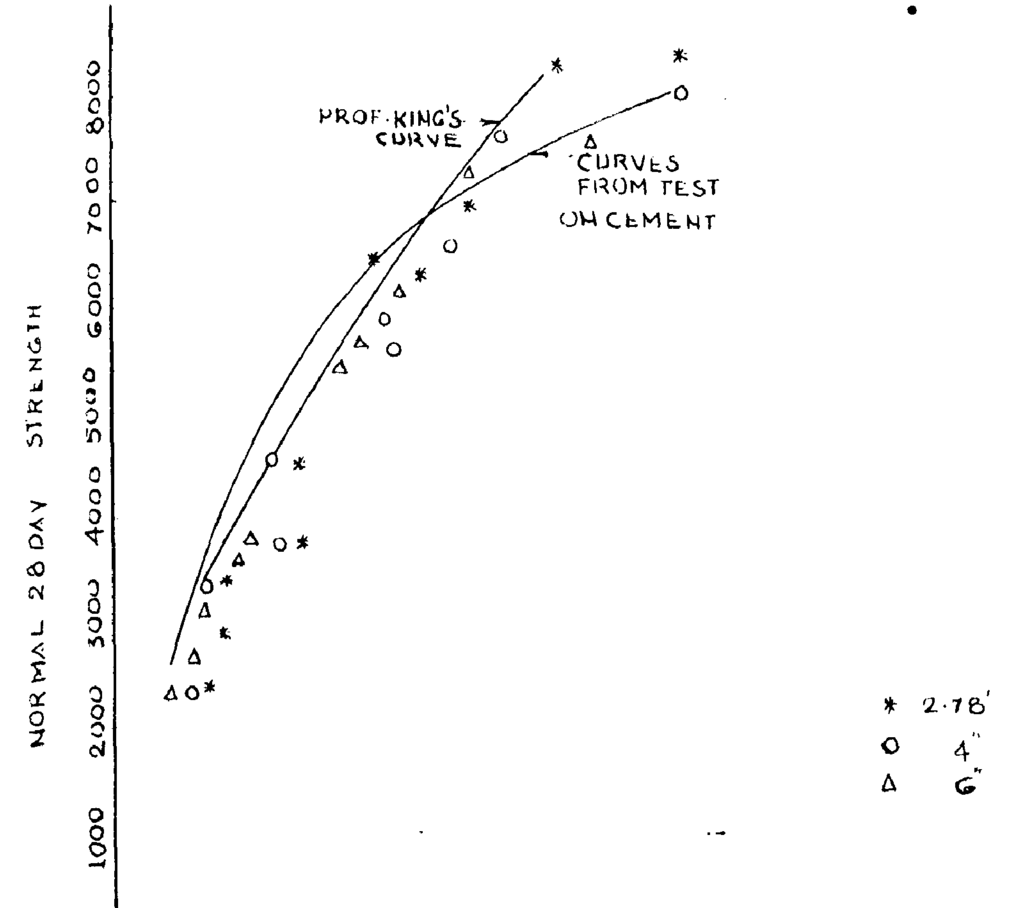


FIG.26

TESTS ON CUBE SIZES: OVEN CURING METHOD.

4.2.2. Effect of Aggregates.

The aggregates will not have effect on the strength of stronger concretes. A 28-day cube might fail by aggregate fracture, while the corresponding low strength accelerated cube might fail through the mortar. Any test of this nature can only be predicted on the basis that mortar failure was predominant in both tests. When it was stronger than the aggregate its effect on strength was greatly diminished, [illegible] could conceive that the two tests would give nearly the same strength for a concrete having a weak aggregate.

The ratios of 7-day strength to accelerated strength, and 28-day strength to accelerated strength for gravel and crushed granite was practically same for strengths below 4500 to 5000 lbs./sq.in.(5). For higher strengths the granite being stronger can withstand more stresses and give higher results.

4.2.3. Effect of Size of Cube.

For this method of curing there is a slight increase in the overall dispersion of the results compared with the other methods. Though the dispersion at 28-days is little less than at 7-days the same curve can be used for any size of specimens provided the specimens used for both tests are identical. The normal cured strength of a 4" cube at 28-days can be predicted from a 4" accelerated cured cube, but the accelerated cube strength of a 4" cube cannot be used to predict the 28-day strength of 6" cube.

4.2.4. Effect of Cement.

The blue cement has got optimum temperature for 180°F (85°C) whereas the high alumina cement gives low results at higher temperatures.

4.2.5. Conclusions.

Following conclusions can be derived from the investigations carried out by other workers.

(1) The normal strength of concrete can be predicted from accelerated strength with 80% certainty.[20]

(2) The 6 hours of oven curing gives the maximum curing condition.[5]

(3) The cubes cured at 100°C for 24 hours gives approximately 7-day normal strength.[8]

(4) Cement has no appreciable effect on 28-day strength prediction. For 7-day the effect will be due to different strength growth in early days.[1]

(5) Size of the cube has no effect on strength upto 6000 lbs./sq [1] [11].

4.3. MIX ADOPTED.

For this work totally 23 different types of mixes were adopted. The workability has got the effect on the compressive strength, so it was necessary to keep it same throughout the experiment. This was achieved by keeping a slump of 2". The proportion of fine to coarse aggregates and w/c ratios were changed

TABLE NO. 16

7 and 28 day Results of the Mix Adopted.

Sl. No.	Mix No.	W/C (Weight)	Proportion (Weight)	A/C (Weight)	7-day Normal Strength p.s.i.	kgm/cm2	28-day Normal Strength p.s.i.	kgm/cm2
1	U	0.40	1:1:2:5	3.50	4200	300.7	5030	354.7
2	Y	0.40	1:1.1:2.2	3.30	4046	285.0	5100	359.5
3	Z	0.40	1:1:1.6	2.60	4430	312.2	5070	357.4
4	D	0.45	1:1.3:2.6	3.90	3660	257.5	4730	333.3
5	O	0.45	1:1.2:3.0	4.20	3270	231.2	4601	324.3
6	A′	0.45	1:1.3:1.75	3.05	3300	233.0	4631	326.0
7	J	0.50	1:1.6:3.2	4.80	3206	232.6	4034	236.3
8	P	0.50	1:1.63:4.09	5.72	2702	190.1	4200	295.0
9	B′	0.50	1:1.53:2.24	3.80	2980	209.3	4070	283.0
10	E	0.55	1:1.9:3.6	5.70	2678	188.7	3706	267.4
11	Q	0.55	1:2.0:5.0	7.00	2464	173.2	3932	275.0
12	C′	0.55	1:1.84:2.76	4.60	2277	160.6	3704	260.5
13	K	0.60	1:2.05:4.10	6.15	2203	155.0	3472	245.4
14	R	0.60	1:2.29:5.73	8.02	2571	181.2	3338	253.7
15	D′	0.60	1:2.12:3.18	5.30	2370	168.1	3406	240.2
16	F	0.65	1:2.16:4.32	6.48	2451	172.9	3578	252.8
17	S	0.65	1:2.5:6.25	8.75	2210	150.0	3416	241.5
18	E′	0.65	1:2.70:4.00	6.70	1917	135.2	3353	236.7
19	L	0.70	1:2.6:6.0	7.80	2413	200.1	3037	212.6
20	T	0.70	1:2.75:6.88	9.63	2072	146.2	3217	226.9
21	D′	0.70	1:3.2:4.8	8.00	1917	135.2	2753	194.8
22	I	0.75	1:3.2:6.4	9.60	1811	127.1	2837	200.1
23	U	0.75	1:3.0:7.6	10.50	1906	134.4	2880	203.1

to get the mixes with wide range of compressive strength. The w/c ratios were varied from 0.40 to 0.75 by weight so as to cover all possible type of mixes used in Engineering construction. The proportion of fine to coarse aggregates was varied from 1.5 to 2.5. The different types of mixes adopted are given in Table No. [illegible]. The 7 and 28-day strength of such mixes in both the units are also given in the same table.

4.4. CUBES TESTED.

360 cubes were oven cured at 100°C for periods of 6 hrs, 12 hrs and 24 hrs. and some of them were cured in water after it had attained the room temperature.

4.5. DESCRIPTION OF OVEN.

A hot air oven manufactured by American Instrument Co. U.S.A. was used. The oven is shown in Fig. No.4.1, the specifications of the oven are as given below.

Voltage	230 volts.
Wattage	2000
Capacity	6.0 c.ft.
Temp.range	40°C to 200°C

4.6. CURING PROCEDURE.

Half an hour after mixing, the cubes were placed in an oven previously brought to a temperature of 60°C. Each cube was covered with an additional plate at the top. The sides

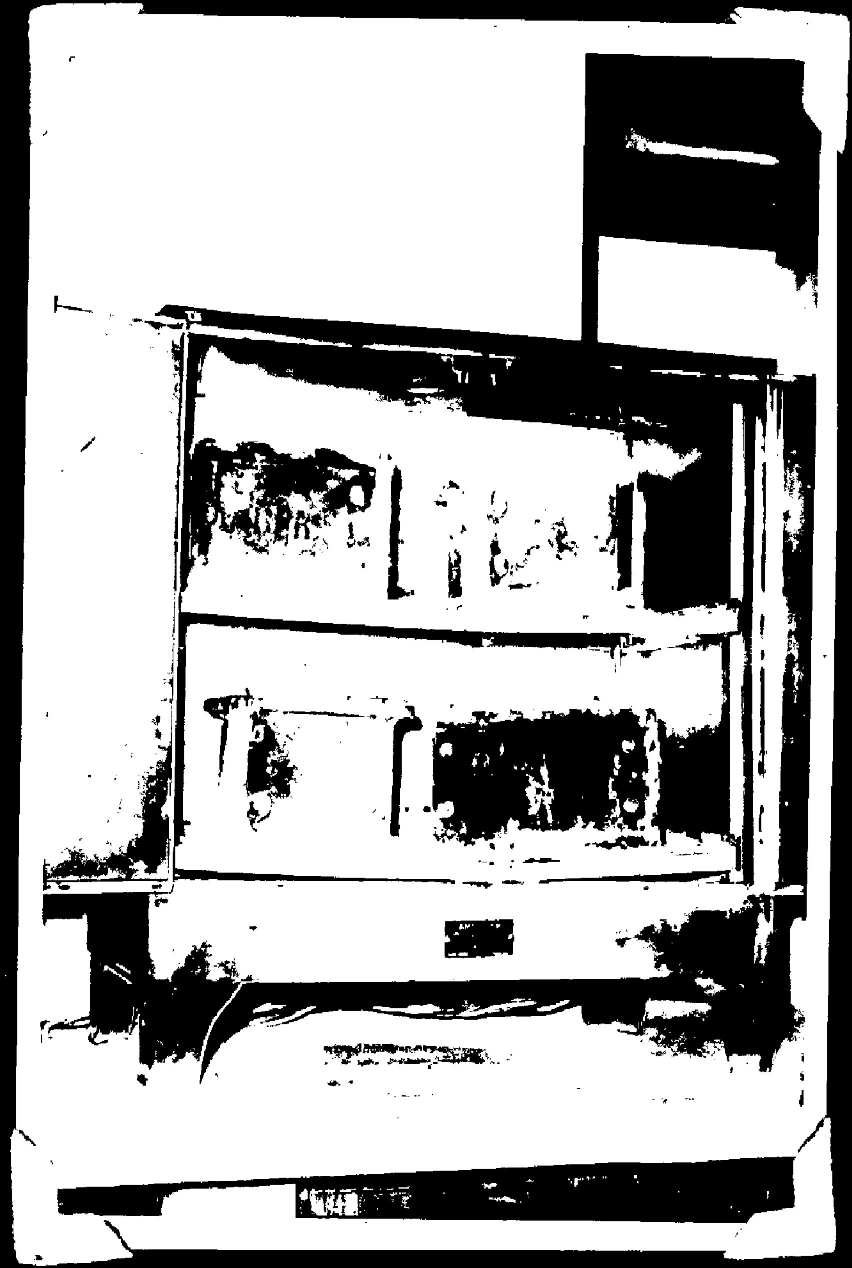


FIG. NO. 4.1 ELECTRIC OVEN

and joints were sealed with yellow soil to reduce the evaporation of moisture to a minimum. The doors and ventilators of the oven were closed and fans near by oven were switched off as it was reported by Bendre and Ordman[6] that it tries to extract the moisture from the cube. The oven was brought to a temperature of 100°C with a period ranging from 2 hours to 2 hours and 20 minutes, at a such rate that 80°C temperature was attained in first hour and the final temperature of 100°C in second hour i.e. the rate of rise of temperature was 2°C per three minutes. The general temperature time pattern is shown in Figure No.27. The temperature was kept constant for the remaining curing period. The cubes were removed at the intervals of 6 hours, 12 hours and 24 hours and stripped. The cubes were allowed to cool under a fan for a period of 1/2 hr. which will lower down the temperature of the cube to room temperature. Then cubes were tested for their compressive strength. The period of 6 hours curing was chosen so as to be well within the working shift of 8 hours. The total heating cycle was 7 hours, as Bendre and Ordman[6] showed that 6 hour curing gives the optimum condition. 24 hours curing period was selected as R.L.Bowen[8] showed that accelerated strength gives 7-day normal cured strength. If 7-day strength is found the 28-day strength can be obtained by using the standard curve plotted by Cement and Concrete Association. The period of 12 hours was selected to find the relation between the maturity and strength of the oven cured concrete at this temperature.

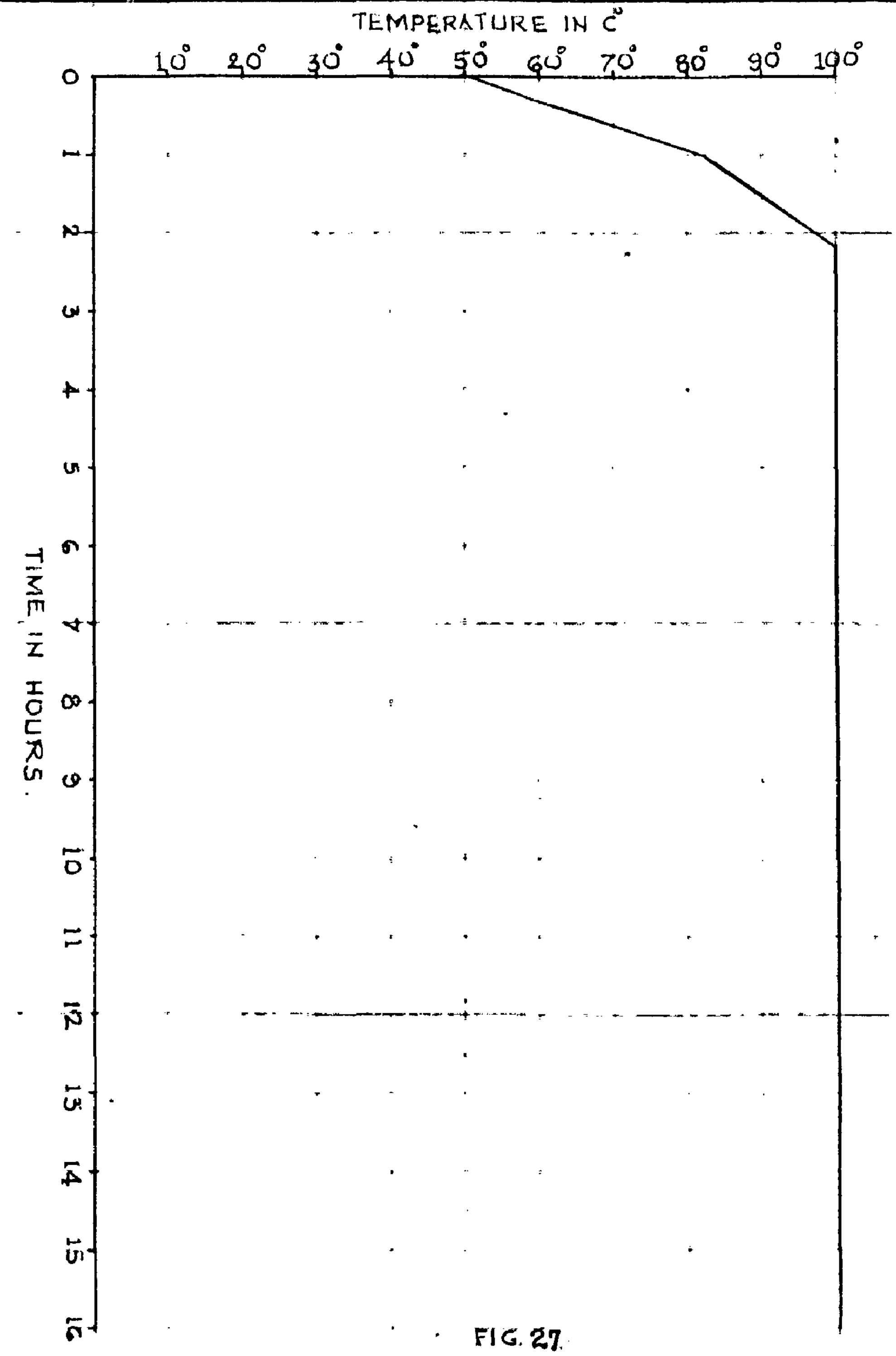


FIG. 27.
GENERAL PATTERN OF TEMPERATURE RISE FOR OVEN.

4.7. TESTING PROCEDURE.

The cubes were tested under Universal 200 Ton Compression Testing Machine in dry condition after it had attained the room temperature. The cubes were placed in such a way that the load was applied to the opposite sides of the cubes at cast, that is not at the top and bottom at a continuous rate of 140 kg/sq. cm/min. till it could sustain.

4.8 RESULTS.

As already explained in curing procedure three different periods of curing were adopted, namely standard 6 hr. cycle, 18 hr and 24 hr. cycle. The results are given in Table Nos. 16, 17, and 18 and plotted in Figure Nos. 28, 29 and 32.

4.8.1. For 6 hour curing the accelerated strength bears a relation $y = 145.[illegible]x^{0.4[illegible]}$ with the normal cured strength. Where x is the 6-hr accelerated strength in p.s.i. and y is the 28-day strength in p.s.i. The relation $y = 200\,x^{1/2}$ also fits the data sufficiently well and can be used as it is more convenient than first.

From Figure No. 28 it is clear that as the normal strength increases accelerated strength expressed as percentage of normal strength increases. The proportion varying in a wide range of 20% to 62% for 28-days and 49.0 to 69% for the 7-day strength. The lower value is for the leaner mix. The graph of accelerated strength versus normal strength is a straight line for low

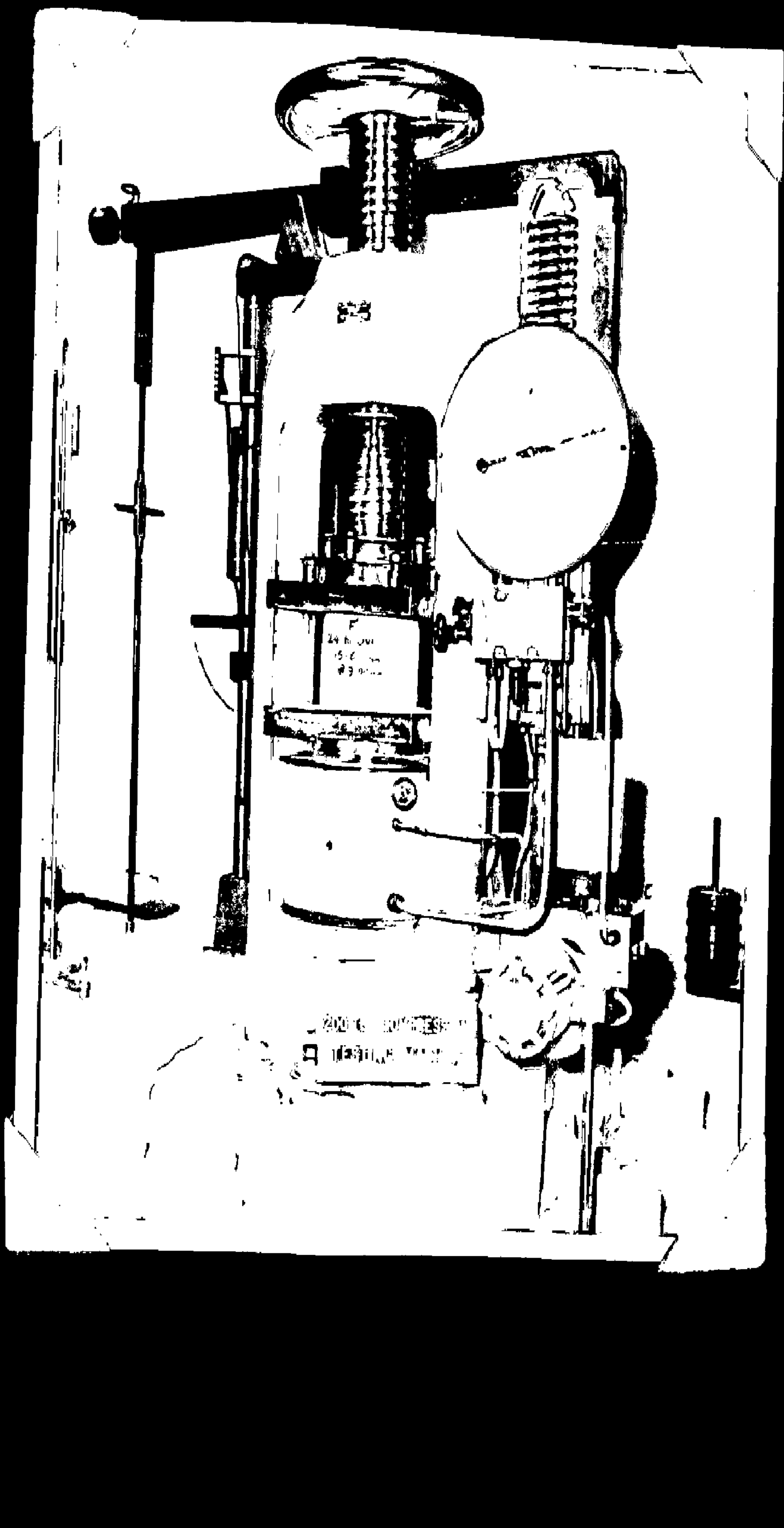


FIG. NO. 4·2 200 TON COMPRESSION TESTING MACHINE

TABLE No. 10. [illegible]

Results of 6 hrs. Oven Curing at 100°C [illegible]

Heating Cycle

Waiting Time	1/2 hr.	
Heating Time.	6	hrs.
Cooling time.	1/2 hr.	

Sr. No.	Mix. No.	Accelerated Strength p.s.i.	Accelerated Strength kg/cm²	7 day Normal [illegible] Strength p.s.i.	7 day Normal Strength kg/cm²	27 day Normal Strength p.s.i.	27 day Normal Strength kg/cm²	Accelerated Strength as % age of p.s.i.	Accelerated Strength as % age of kg/cm²
1	U	2602	182.0	4265	300.7	5030	354.7	60.7	51.6
2	Y	2542	178.5	4046	200.0	5100	350.5	63.0	50.0
3	Z	2631	184.5	4430	312.2	5070	357.4	53.5	51.9
4	D	1882	132.0	3230	227.5	4730	333.3	58.0	39.8
5	O	1552	109.0	3279	231.2	4641	326.3	47.3	33.3
6	A'	1851	130.0	3300	233.0	4611	325.0	56.1	40.2
7	J	1563	110.0	3296	232.6	4064	286.3	47.6	38.0
8	P	1293	90.7	2702	190.1	4200	295.9	46.4	30.8
9	D'	1601	112.8	2963	209.3	4070	288.0	53.9	40.7
10	E	1497	106.1	2378	168.7	3793	267.4	66.9	30.4
11	Q	1120.	78.7	2164	173.8	3932	278.0	46.6	28.5
12	C'	1053	74.2	2277	160.4	3704	263.5	46.5	27.0
13	K	1120	78.7	2193	165.0.	3472	246.4	50.0	32.3
14	R	1045	73.6	2511	181.2	3333	253.7	40.7	28.8
15	D'	1053	74.2	2670	188.1	3486	246.2	39.6	30.3
16	F	1064	74.7	2101	172.0	3378	232.8	48.5	31.5
17	S	922	64.7	2240	158.0	3416	241.5	41.1	27.0
18	B'	900	63.2	1917	136.2	3033	235.7	46.8	27.0
19	L	713	50.2	1413	100.1	2937	213.6	50.5	23.5
20	T	959	64.7	2072	146.1	3217	226.9	46.3	29.0
21	F'	860.	59.7	1917	135.2	2766	194.8	44.3	30.8
22	I	892	63.3	1811	127.1	2837	200.1	49.7	31.6
23	H	763	52.0	1906	134.4	2958	209.1	39.5	25.1

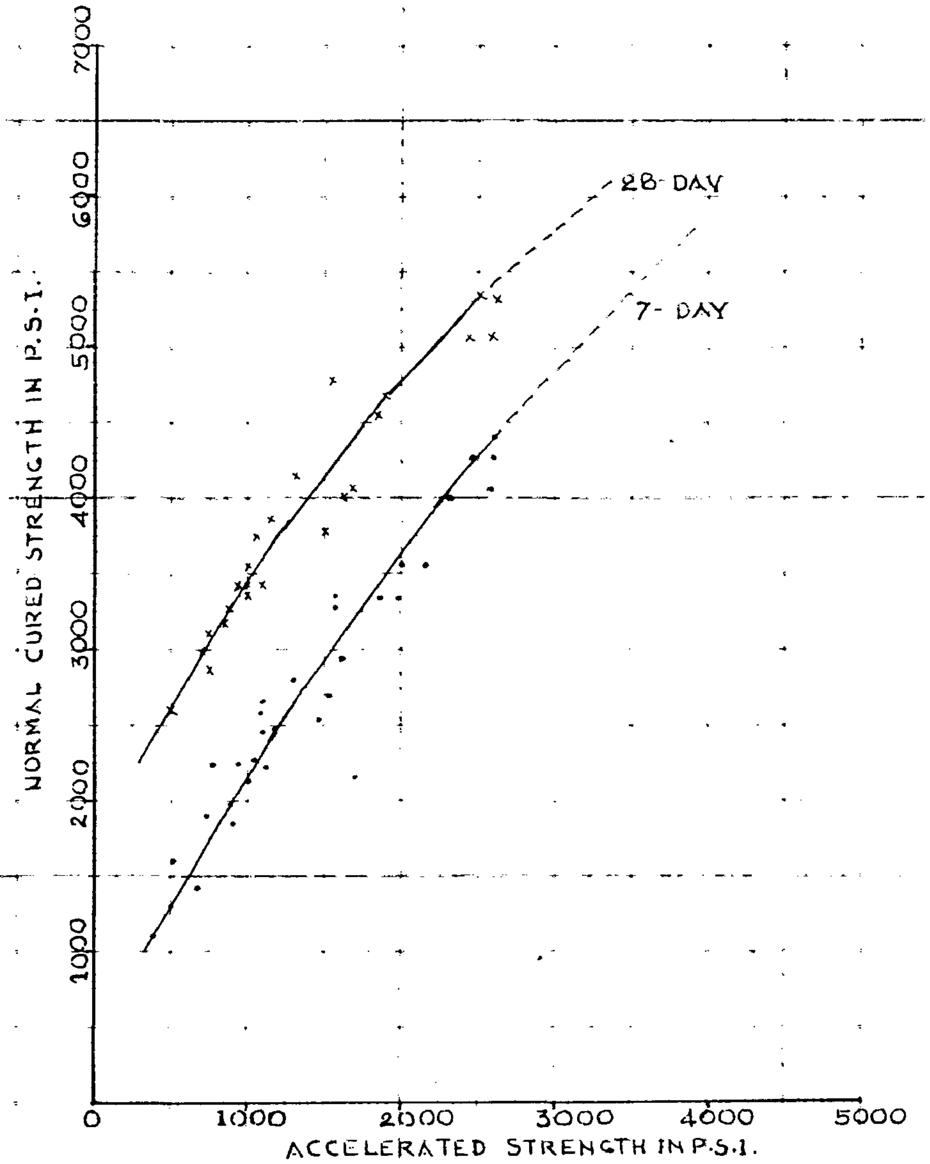


FIG. 28

RESULTS OF 6 HOURS OVEN CURING AGAINST NORMAL CURED STRENGTHS.

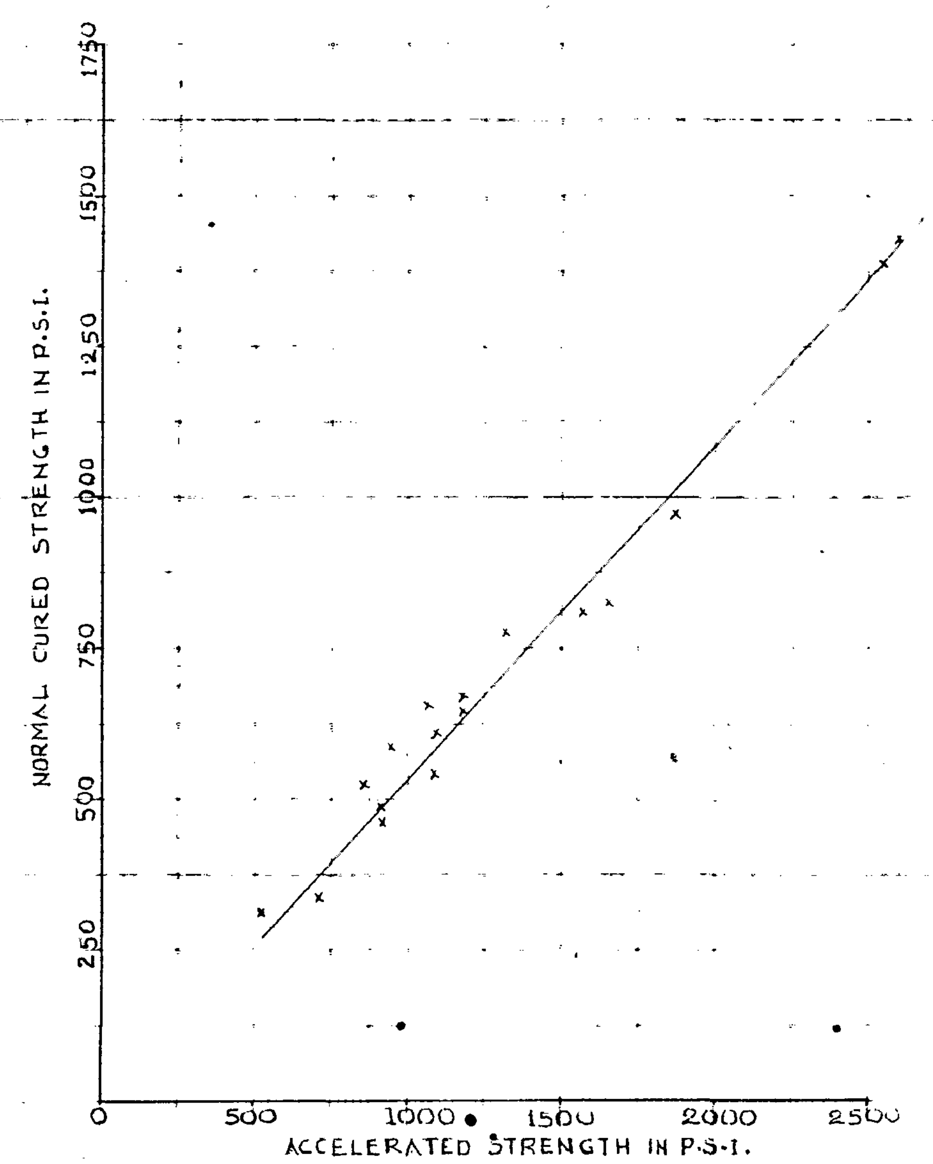


FIG 29

RESULTS OF 6 HOURS OVEN CURING COMPARED WITH 6 HOURS OF NORMAL CURING AFTER 20 HOURS IN MOULD.

strengths upto 2500 p.s.i. From this graph it is possible to predict the strength with an accuracy of ± 300 lbs./sq.in.

To find out the increase in strength as compared to normal curing for the same period of 6 hours it was not possible. So the cubes were tested after 6 hours of water curing. The results are given in Table No.19 and plotted in Figure No.29. The relation between the normal cured strength and accelerated strength is a st. line. The accelerated strength expressed as percentage of normal strength was found to be increasing as the normal strength increases, the variation being from 153.8% to 308.8%. The higher value for higher accelerated strength i.e. richer mix.

To find out the effect of gain in strength after oven curing the cubes were further cured in water after it had attained the room temperature for 7 days in water. The results are given in Table No.22. The graph of accelerated strength versus normal cured strength is shown in Fig. No.35, and also the graph of accelerated curing plus 7-days normal cured strength against 7-days normal cured strength is given in Figure No.48. The percentage gain in strength in 7-days as compared to accelerated strength was varying from 153.8% to 210.0%. The higher value being for the richer mix. while the accelerated strength + normal cured strength was less than that of 7-day normal cured for all mixes and is approximately equal to 7-days strength for richer mix.

4.8.2. In the results of 12-hr oven curing it was found that the strength increases in the same order as it does in 6-hour

TABLE NO. 17

Results of 12 Hrs. Oven Curing at 100°C

Waiting Time. 1/2 hrs.
Heating Time 12 hrs.
Cooling Time. 1/2 hrs.

Sr. No.	Mix No.	Accelerated Strength		7-day Strength		28-day Strength		Acc. Strength as %age of	
		P.s.i.	kgm/cm²	P.s.i.	kgm/cm²	P.s.i.	kgm/cm²	P.s.i.	kgm/cm²
1	U	3550	249.5	4266	300.7	5030	354.7	83.2	70.7
2	Y	3305	232.0	4045	285.0	5100	358.6	81.8	64.8
3	Z	3605	253.0	4430	312.2	5070	357.4	79.2	69.2
4	D	2682	188.5	3380	237.5	4740	333.3	79.9	56.6
5	O	2280	161.0	3270	231.2	4631	326.3	69.8	49.1
6	A'	2360	166.0	3300	233.9	4621	325.0	77.3	53.3
7	J	2270	159.5	3295	232.6	4064	285.9	68.7	55.9
8	P	1880	132.3	2762	196.1	4200	295.9	68.0	46.1
9	B'	2320	163.0	2969	209.3	4070	286.0	78.2	57.0
10	E	2033	143.0	2678	188.7	3790	267.4	76.0	53.6
11	Q	1700	119.5	2464	173.8	3932	276.0	69.0	43.2
12	C'	1620	113.8	2277	160.6	3764	266.5	71.1	42.7
13	K	1692	119.0	2198	155.0	3472	244.4	77.0	48.7
14	R	1800	126.6	2571	181.2	3633	256.7	70.2	49.6
15	D'	1642	115.4	2670	188.1	3486	246.2	61.5	47.2
16	F	1633	114.8	2461	172.9	3378	237.8	67.6	48.4
17	S	1452	102.0	2240	158.0	3410	239.6	64.8	42.5
18	E'	1453	102.1	1917	135.2	3333	236.7	76.0	43.6
19	L	850	59.7	1473	103.1	3037	213.6	57.6	28.1
20	T	1375	96.6	2072	146.2	3217	226.9	66.2	41.5
21	F'	1250	87.9	1917	135.2	2763	194.8	65.2	45.3
22	I	1152	81.0	1811	127.10	2837	200.1	63.6	40.6
23	U	1206	84.6	1905	134.4	2980	209.1	63.3	41.0

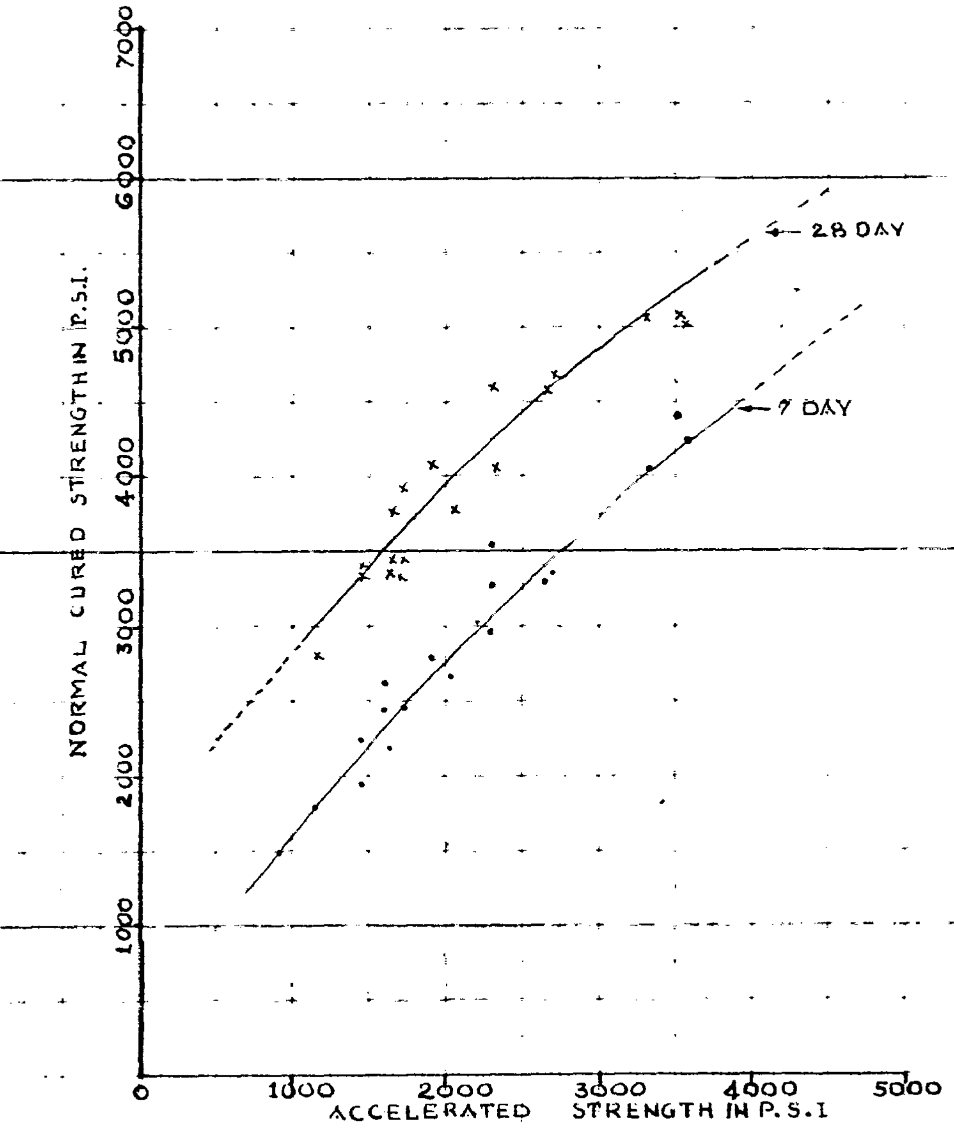


FIG.30
RESULTS OF 12 HOURS OVEN CURING AT 100°C AGAINST NORMAL CURED STRENGTH.

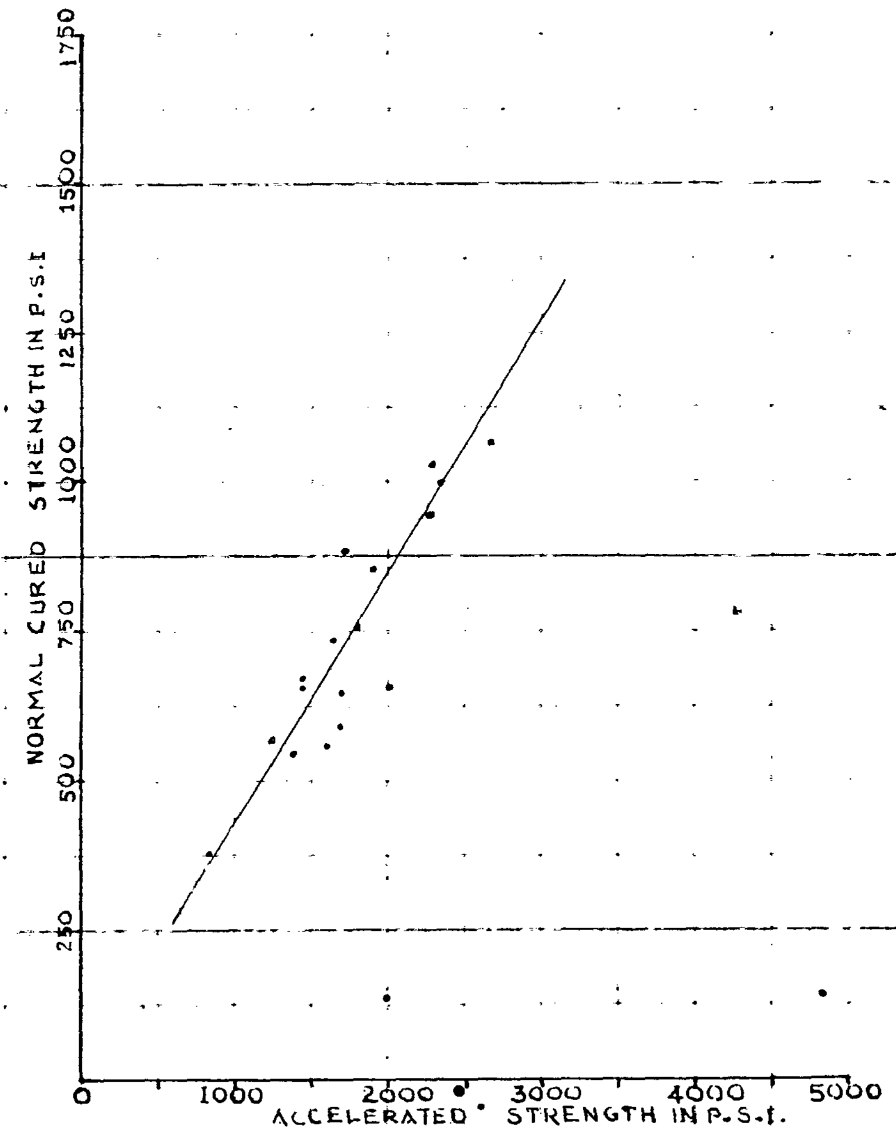


FIG. 31
RESULTS OF 12 HOURS OVEN CURING COMPARED WITH 12 HOURS OF NORMAL CURING AFTER 20 HOURS IN MOULD.

curing. The results are given in Table No. 17. The results of accelerated strength versus 7 and 28-day normal strength was plotted as in Figure No. 42. The relation between the 12-hour accelerated strength and 28-day strength is found to be

$$y = 84.6\, x^{0.4805}$$

where x = 12 hr. accelerated strength in p.s.i.

The accelerated strength when expressed as percentage of normal strength varied from 60.2% to 83.2% of 7-day and 41.1 to 70.7% of 28-day curing. The increase is not much as compared to 0 hour curing.

The results of 12-hours oven curing when compared with 12-hours of normal curing after 20 hours in mould indicates that the relation between these values is a linear as shown in Fig. No. 32. The strength gained varies from type of mixes in a range of 200.0% to 207.0% and is always more than twice its normal strength.

The cubes were normal cured in water for 7 days after it had had attained the room temperature. The results are given in Table No. 23. The graph of accelerated strength against normal cured strength after accelerated curing is shown in Fig. No. 37. The relation is a straight line showing that as the accelerated strength increases the percentage strength gained in normal curing after oven curing goes on varying from 31.8% to 46%. The strength when expressed as percentage of 7-day normal cured strength gave an variation from 60.7% to 93.7% but in no case it is more than the 7-day normal cured strength.

4.8.3. The results of 24 hours oven cured cubes are given in table No.18. The graph of accelerated strength against normal strength was plotted as shown in Figure No.32. The strength increase is not much as compared to 12-hour oven curing. The oven cured strength was found to be approximately equal to 7-day normal cured strength, and 53.7 to 59.0% of the 28-day strength. The higher value for the richer mix.

The results of 24-hours oven curing was compared with the 24-hours normal cured strength after 20-hours in moulds. The gain in strength as it is clear from table No.21 varies from 272% to 336% of the normal strength. The results are also plotted as in Fig. No.45 which is a straight line.

4.8.4. <u>Maturity.</u>

The maturity as defined is the product of the age and temperature above certain datum. For comparison of the results with the other existing the same datum of $-8\frac{1}{3}$°C (17°F) was selected. The maturities for 6 hrs, and 12 hrs and 24 hrs. of oven curing were calculated and are tabulated in table No.24. Table No.25 shows the accelerated strengths obtain from Figure No.29, 30 and 32 for selected 28-day normal strength. For zoning the strength was considered at an interval of 500 p.s.i. The accelerated strength was expressed as percentage of 28-day strength and plotted against $\log_{10} \frac{\text{maturity}}{1000}$ as shown in Fig. No.38. The relation is a straight line one and give separate straight line for each strength. This relation can be expressed as in the form of equation $y = mx + c$ i.e.

TABLE NO.18

Results of 24 hrs. Oven Curing at 100°C

Waiting Time- 1/2 hr.
Heating Time- 24 hrs.
Cooling Time- 1/2 hr.

Sr. No.	Mix No.	Acc. Strength p.s.i.	Acc. Strength kgm/cm²	7-day Strength P.s.i.	7-day Strength kgm/cm²	28day Strength p.s.i.	28day Strength kgm/cm²	Acc. Strength as %age of 7-day	Acc. Strength as %age of 28 day
1	W	4475	314.0	4265	300.7	5030	354.7	105.0	89.0
2	Y	3890	274.0	4045	285.0	5100	359.5	96.2	76.2
3	Z	4505	317.5	4430	312.2	5070	351.4	101.5	88.2
4	D	3434	242.7	3360	237.5	4730	333.3	102.5	73.0
5	O	3133	221.4	3279	231.2	4661	326.3	95.6	67.3
6	A'	3485	246.2	3300	233.9	4611	315.0	105.5	75.6
7	J	3220	227.5	3295	232.6	4064	286.3	97.5	79.2
8	P	2576	181.6	2782	196.1	4200	295.9	92.5	61.2
9	B'	3064	216.7	2968	209.3	4070	288.0	102.5	74.9
10	H	2598	183.1	2678	188.7	3796	267.4	97.2	68.4
11	Q	2146	157.5	2464	173.8	3932	275.0	87.0	54.6
12	C'	2029	143.0	2277	160.6	3784	266.5	89.2	53.7
13	K	2203	155.5	2198	155.0	3472	245.4	100.1	63.5
14	R	2550	179.5	2571	181.2	3633	256.7	99.3	70.2
15	D'	2489	175.3	2670	188.1	3485	246.2	93.3	71.5
16	F	2249	159.1	2451	172.9	3378	252.8	91.8	66.6
17	S	2178	153.7	2240	158.0	3416	241.5	97.3	63.7
18	E'	2013	141.2	1917	135.2	3338	235.7	104.7	60.7
19	L	1537	107.8	1413	106.1	3037	213.6	108.8	50.6
20	T	2100	147.8	2072	146.2	3217	226.9	101.6	65.5
21	F'	1905	134.0	1917	135.2	2756	194.8	99.5	69.1
22	I	1586	111.4	1811	127.1	2837	200.1	87.5	55.8
23	U	1912	134.7	1905	134.4	2880.	203.1	100.1	66.3

TABLE NO.19

**Results of 6 hrs. Oven Curing
Compared with 6 hrs. of Normal Curing.**

Sr. No.	Mix No.	Accelerated Strength		Normal Strength		Acc. Strength as % of N. Strength.
		P.s.i.	kgm/cm²	P.s.i.	kgm/cm²	
1	E	1497	105.1	532.0	37.4	281.0
2	F	1064	74.7	560.0	39.4	190.0
3	I	902	63.3	455.0	32.0	198.0
4	J	1568	110.0	508.0	35.7	308.5
5	K	1120	78.7	550.0	38.6	203.5
6	L	713	50.2	342.0	24.1	208.5
7	O	1552	109.0	810.0	56.9	191.5
8	P	1293	90.7	785.0	55.2	165.0
9	Q	1120	78.7	652.0	45.8	172.2
10	R	1045	73.6	656.0	46.1	159.5
11	S	922	64.7	600.0	42.2	153.5
12	T	950	66.7	420.0	29.5	226.0
13	A'	1851	130.0	975.0	68.6	190.0
14	B'	1661	116.8	825.0	58.0	201.5
15	E'	900	63.2	474.0	33.4	189.8
16	F'	850	59.7	529.0	37.2	160.2

TABLE NO.20.

**Results of 12 hours. Oven Curing
Compared with 12 hrs.of Normal Curing.**

Sr. No.	Mix No.	Acc. Strength Lbs./sq.in.	Acc. Strength kgm/cm2	Normal Strength Lbs./sq.in.	Normal Strength kgm/cm^2	Acc.Strength as % of Normal Strength
1	E	2034	143.0	663.0	46.6	307.0
2	F	1633	114.8	560.0	40.0	288.0
3	I	1152	81.0	536.0	37.5	214.5
4	J	2270	159.6	945.0	66.5	240.0
5	K	1692	119.0	890.0	62.6	190.0
6	L	850	59.7	373.0	26.3	228.0
7	O	2288	161.0	1030.0	72.5	222.4
8	P	1890	132.8	857.0	60.3	220.5
9	Q	1700	119.5	650.0	45.7	261.5
10	R	1800	126.5	756.0	53.2	238.0
11	S	1452	102.1	666.0	46.8	218.0
12	T	1375	96.5	548.0	38.6	251.0
13	A'	2650	186.0	1062.0	74.8	249.5
14	B'	2320	163.0	1000.0	70.3	232.0
15	D'	1642	115.4	739.0	52.0	222.0
16	E'	1466	102.1	680.0	47.8	213.5
17	F'	1280	87.9	57[illegible].0	40.3	218.5

TABLE NO. 21

Results of 24 hrs. Oven Curing Compared with 24 hrs. of Normal Curing.

Sr. No.	Mix No.	Acc. Strength p.s.i.	Acc. Strength kgm/cm^2	Normal Strength p.s.i.	Normal Strength kgm/cm^2	Acc. Strength as % of N. Strength.
1	E	2598	183.1	893.0	62.7	291.5
2	F	2249	159.1	732.0	51.5	307.5
3	I	1586	114.4	602.0	42.3	263.0
4	J	3220	227.6	1072.0	75.5	300.5
5	K	2203	155.5	656.0	46.2	336.0
6	L	1537	107.8	404.5	28.4	380.0
7	O	3133	221.4	1129.0	79.4	277.5
8	P	2576	181.6	1088.0	76.4	236.5
9	Q	2146	151.5	848.0	59.6	254.0
10	R	2550	179.5	882.0	62.0	289.0
11	S	2178	153.7	796.0	56.0	272.0
12	T	2100	147.8	652.0	45.9	322.0
13	A'	3485	245.2	1150.0	80.8	303.0
14	B'	3054	216.7	1030.0	72.4	296.5
15	D'	2489	175.3	816.0	57.4	305.0
16	E'	2013	141.2	549.0	38.6	365.0
17	F'	1905	134.0	678.5	47.6	282.2

TABLE NO.22

Results of 7-days Normal Curing After 6 hrs. in Oven at 100°C

Sr. No.	Acc. Strength		Acc. Strength +7days Normal		7-day Strength		Acc. Strength +7day as % of	Acc. Strength +7day as % of 7day.
	lbs/ sq. in.	kgm/ cm2	lbs/ sq. in.	kgm/ cm2	lbs/ sq. in.	kgm/ cm2		
1	1342	94.2	2780	195.0	3010	211.5	207.0	92.4
2	1120	78.6	2360	165.8	2782	195.5	208.5	84.9
3	715	50.2	1318	92.5	1865	131.0	184.7	70.7
4	1615	113.5	2860	210.0	2920	205.0	177.2	98.0
5	890	62.5	1368	96.0	1690	118.7	153.8	81.0
6	933	65.5	1585	111.2	1753	123.2	170.0	90.5
7	945	66.3	1530	107.4	1747	122.8	162.0	87.5
8	1660	116.5	2735	192.1	2965	208.5	165.0	92.4
9	1055	74.1	2050	144.0	2150	151.0	194.5	95.5
10	1200	83.8	2395	168.3	2670	187.5	200.0	89.8
11	672	47.2	925	65.0	1620	113.8	137.5	57.2
12	833	58.8	1765	124.0	1915	134.5	210.0	92.3

TABLE NO. 23.

Results of 7-days Normal Curing After 12 hrs. in Oven at 100°C.

Sr. No.	Acc. Strength		Acc. Strength + 7-day Cured.		7day Strength		Acc. Strength + 7-day Strength as % of	
	p.s.i.	kgm/cm^2	p.s.i.	kgm/cm^2	p.s.i.	kgm/cm^2	Acc.	7-day
1	2070	145.5	2725	191.5	3360	236.0	131.6	81.2
2	1692	119.0	2220	156.0	3660	257.0	131.2	60.7
3	1265	89.0	1735	122.0	2390	168.0	137.0	72.5
4	2635	185.5	3200	225.0	3540	250.0	121.2	90.4
5	1860	130.7	2715	191.0	3060	215.0	146.0	88.7
6	1070	75.2	1615	113.5	2300	161.5	157.0	70.4
7	2540	178.5	3450	242.5	3950	278.0	136.0	87.5
8	1910	134.2	2490	175.0	2900	204.0	130.5	86.0
9	1452	102.2	2100	147.5	2240	158.0	144.5	93.7

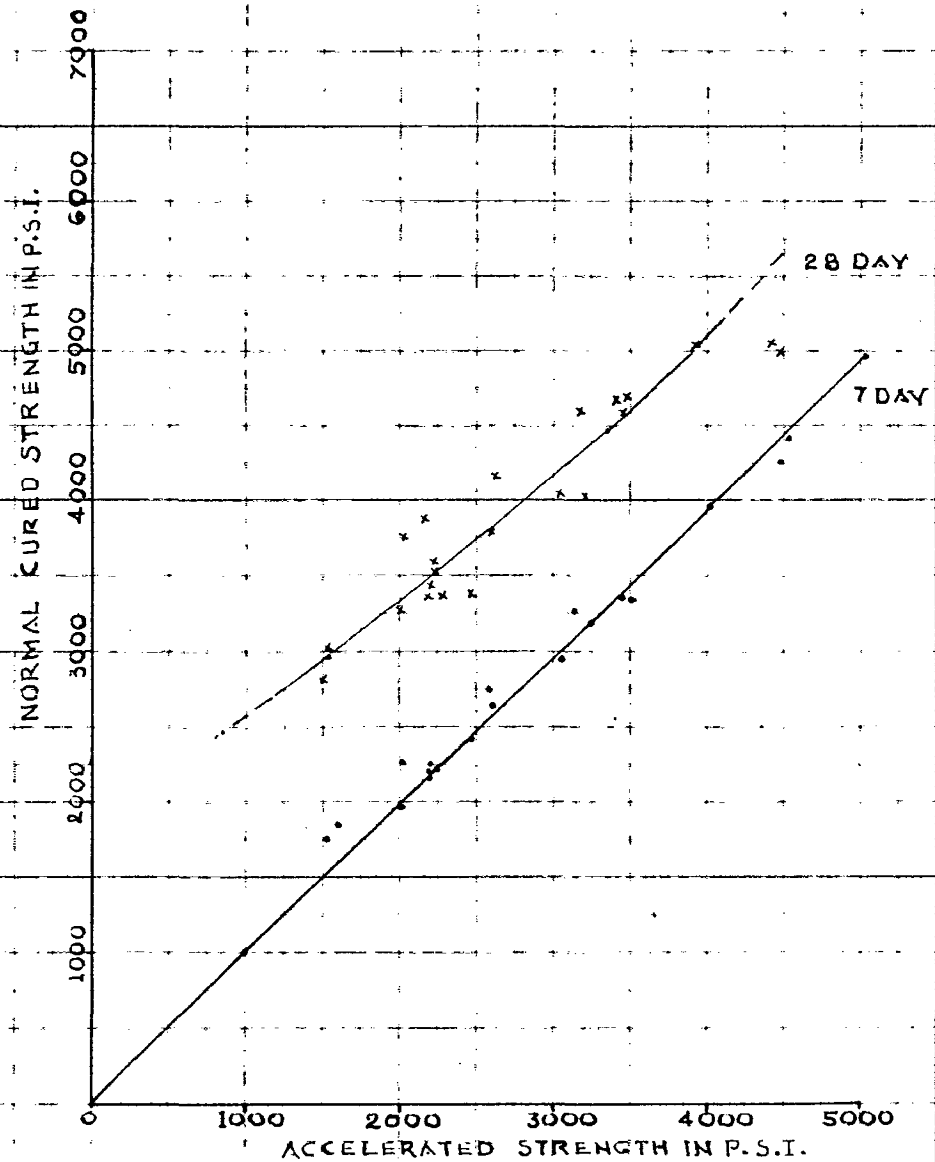


FIG. 32

RESULTS OF 24 HOURS OVEN CURING AT 100°C AGAINST NORMAL CURED STRENGTHS. IT WAS OBSERVED THAT IT GIVES 7 DAY STRENGTH.

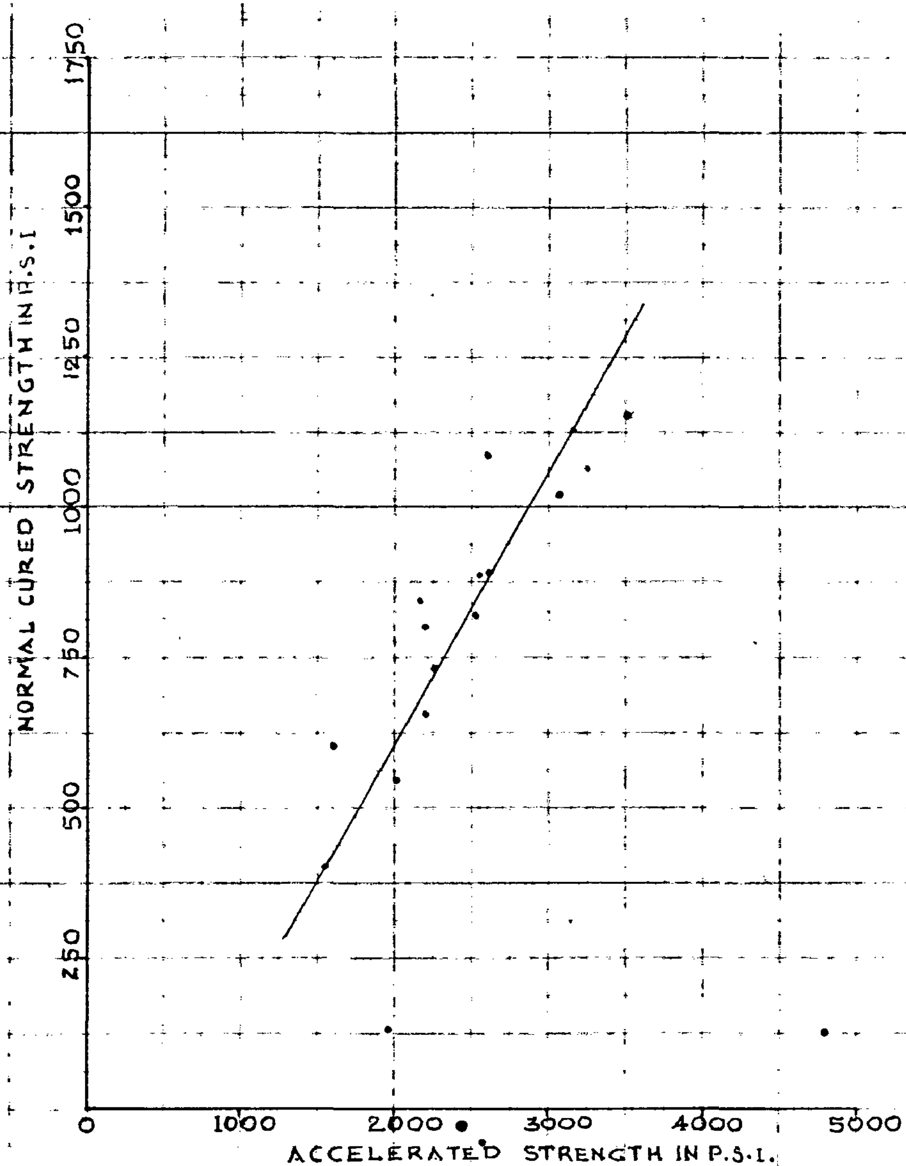


FIG 33

RESULTS OF 24 HOURS OVEN CURING COMPARED WITH 24 HOURS OF NORMAL CURING AFTER 20 HOURS IN MOULD.

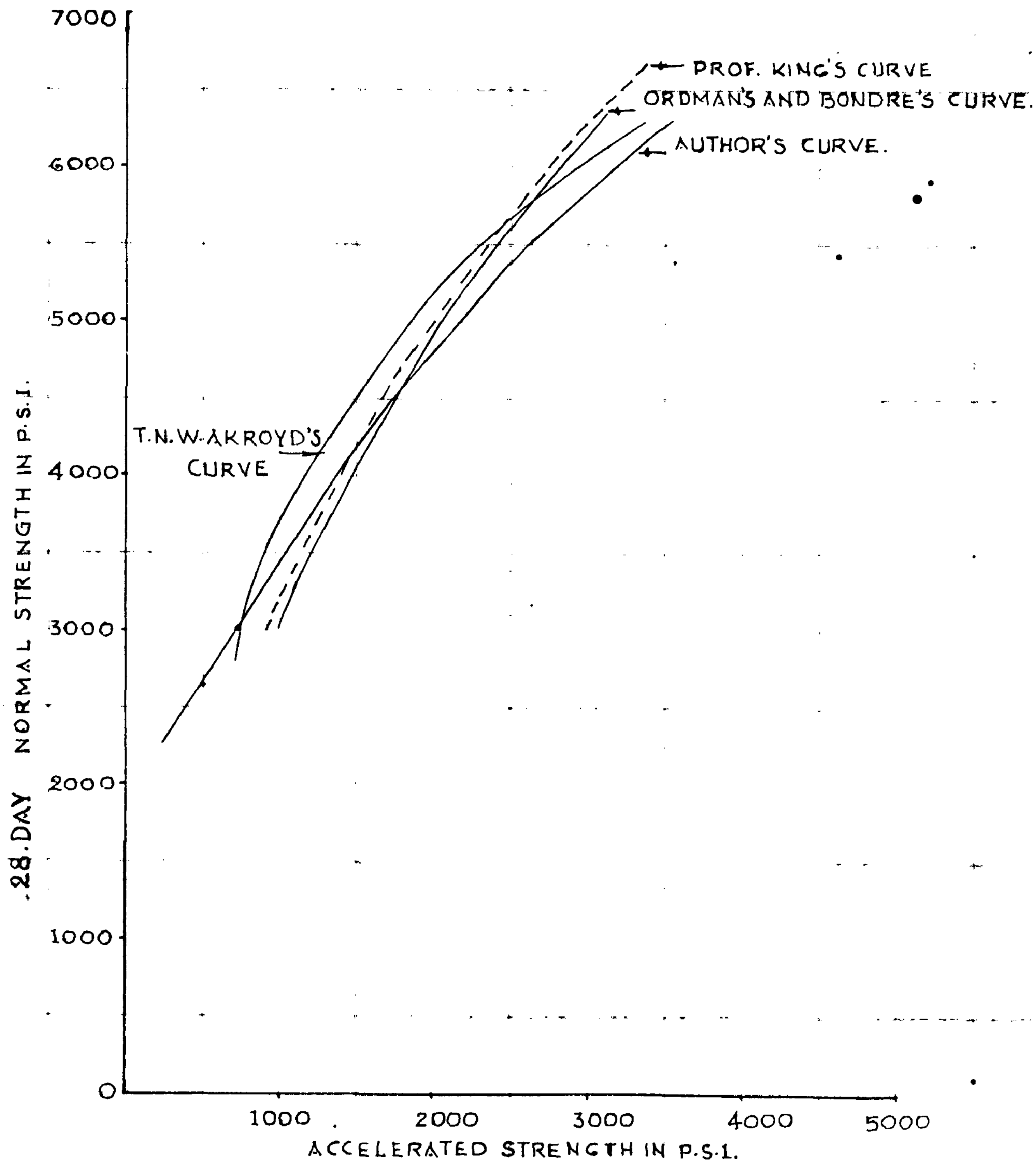


FIG. 34

COMPARISON OF RESULTS OBTAINED BY 6 HOURS OVEN CURING WITH THAT OBTAINED BY DIFFERENT AUTHORITIES, SHOWS THAT RESULTS TALLY WITH ONE OTHER.

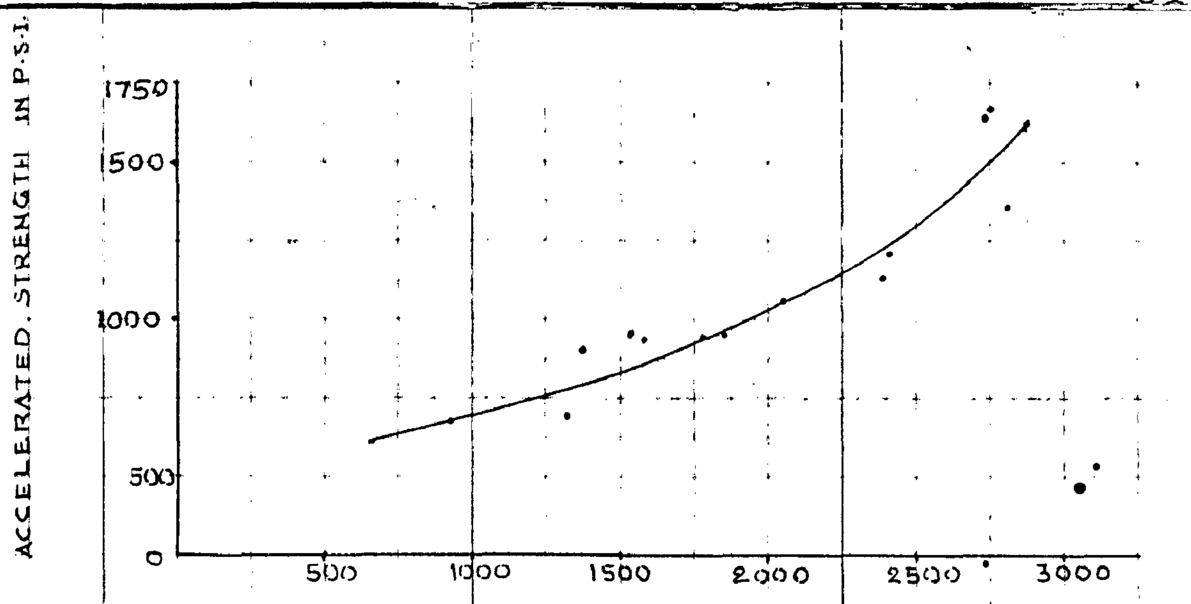


FIG. 35

RESULTS OF 6 HOURS OVEN ACCELERATED STRENGTH PLOTTED AGAINST 7 DAYS NORMAL CURING AFTER 6 HOURS OF OVEN CURING

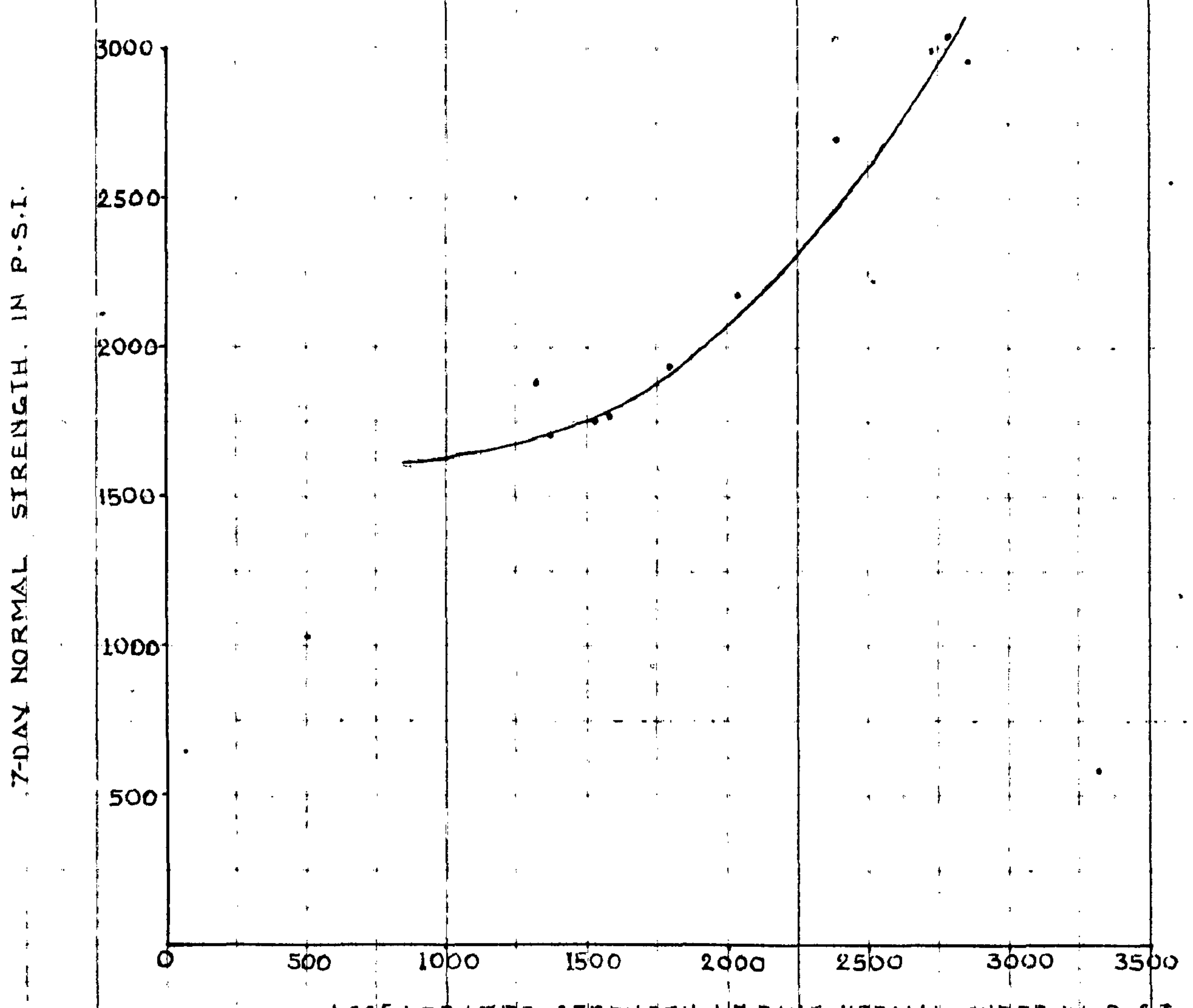


FIG. 36

RESULTS OF 7 DAYS NORMAL CURING AFTER 6 HOURS IN OVEN SHOWS THAT THE STRENGTH GAINED IS LESS THAN THAT OF NORMAL CURED CUBES.

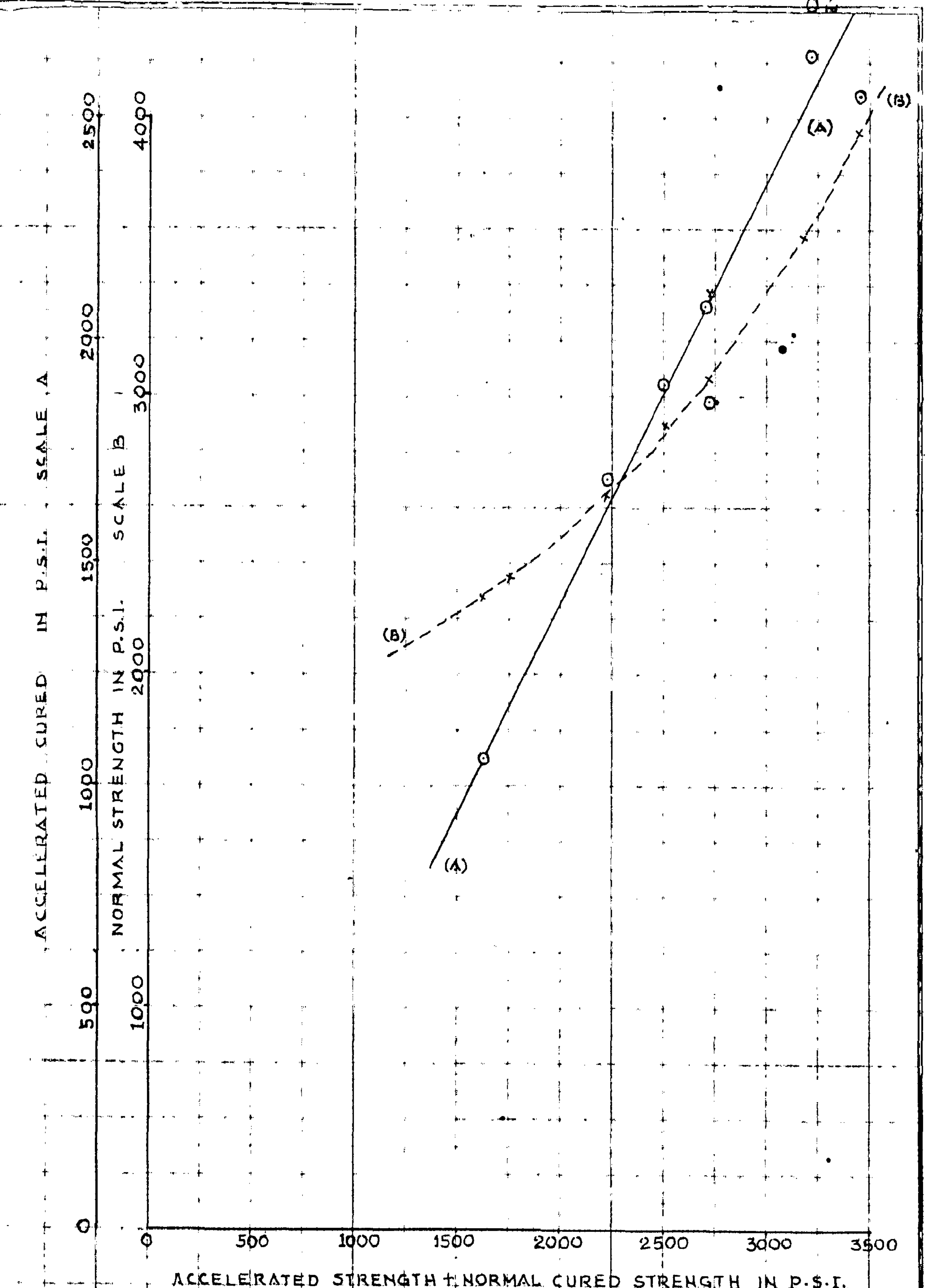


FIG. 37

(A) RESULTS OF 12 HOURS OVEN ACCELERATED STRENGTH PLOTTED AGAINST 7 DAYS OF NORMAL CURING AFTER 12 HOURS IN OVEN.

(B) RESULTS OF 7 DAYS NORMAL CURING AFTER 12 HOURS IN OVEN SHOWS THAT THE STRENGTH GAINED IS LESS THAN THAT OF 7 DAY NORMAL STRENGTH.

percentage of 28-day strength $= A + B \log_{10} \frac{\text{maturity}}{1000}$

The values of constant A and B are given in Table No.26 and for each zone a separate constants are designated. The value of A increases as the strength increases and B remains almost constant for any strength. The increase of A and B with strength is linear. To find the relation exact the values of A and B should be obtained from Fig. No.39 for the known value of accelerated strength.

TABLE NO.24

Maturities for Oven Curing.

Waiting Time.	Heating Time.	Cooling Time.	Total	Maturity °F-hr.	$\log_{10}\frac{\text{Maturity}}{1000}$
1/2	6	1/2	7	1170	0.0682
1/2	12	1/2	13	2370	0.3747
1/2	24	1/2	25	3770	0.6785

TABLE No.25

Oven Curing Strength at Various Selected Intervals

Sl. No.	Accelerated Strength 6 hrs. p.s.i.	12hrs. p.s.i.	24hrs. p.s.i.	28day Normal Strength	6hrs. as% of 28day	12 hrs. as % of 28-day.	24 hrs. as % of 28 day
1	425	700	850	2500	17.00	28.00	34.00
2	725	1120	1525	3000	24.17	37.33	50.80
3	1025	1550	2150	3500	29.30	44.44	61.44
4	1350	2000	2750	4000	37.75	50.00	68.75
5	1700	2550	3325	4500	39.10	56.57	73.90
6	2125	3100	3825	5000	42.50	62.00	76.50
7	2600	3800	4300	5500	47.26	69.02	79.02

TABLE NO.26

Values of Constants A and B in the Equation
% of 28-day = A + B $\log_{10}$ Maturity/1000

Sr.No.	28-day Strength	A	B
1	3000	20.8	50.0
2	3500	25.5	52.5
3	4000	33.5	57.0
4	4500	36.0	55.0
5	5000	39.0	55.0
6	5500	43.5	53.0

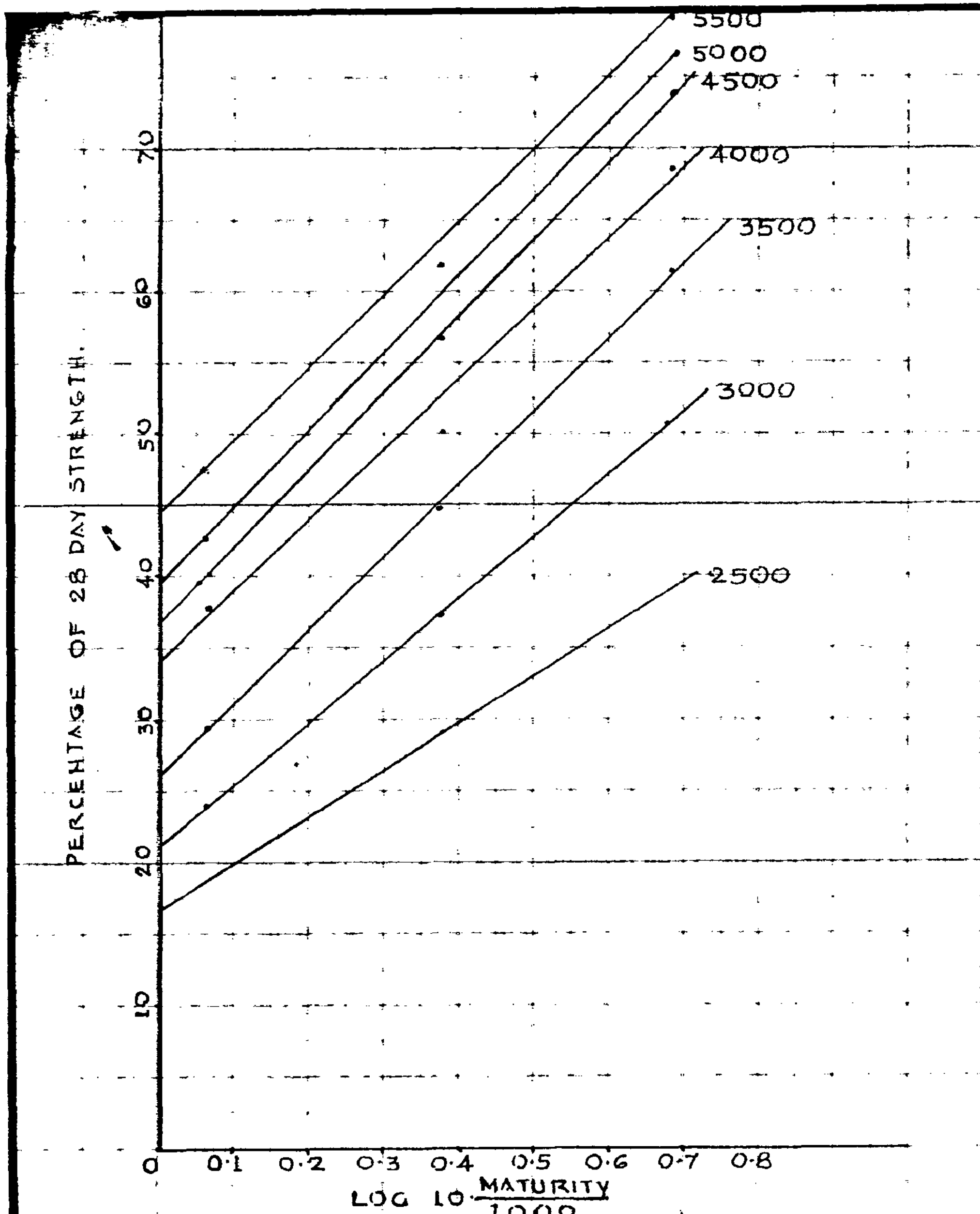


FIG 38

RESULTS OF OVEN CURING PLOTTED AGAINST LOG 10 $\frac{\text{MATURITY}}{1000}$ SHOWING THAT THE RELATION IS A ST. LINE.

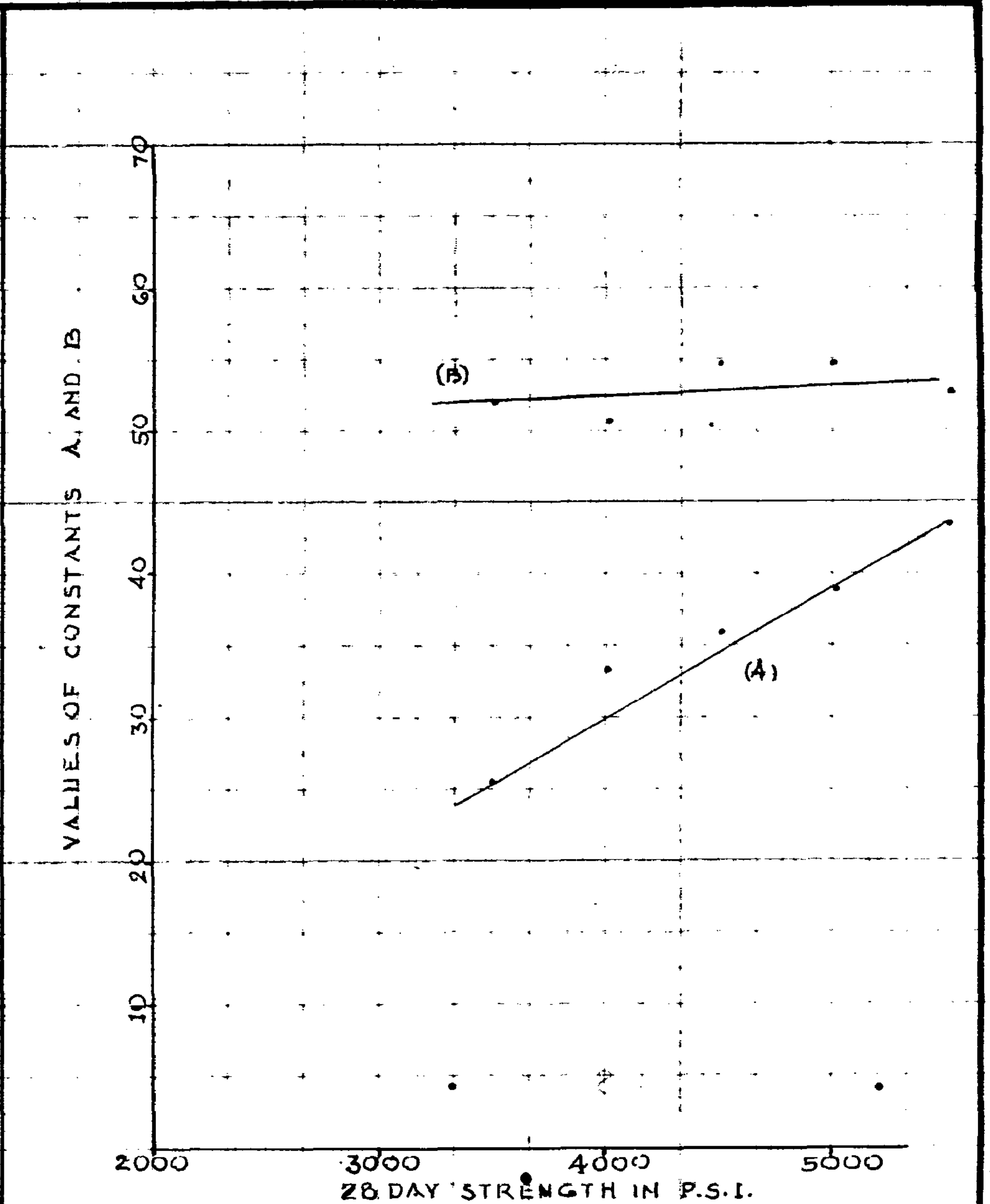


FIG 39

VALUES OF CONSTANTS A AND B OF THE EQUATION.
% STRENGTH OF 28 DAY = A + B $\log_{10} \frac{\text{MATURITY}}{10000}$ PLOTTED AGAINST 28 DAY STRENGTH.

CHAPTER V

STEAM CURING

8.1. INTRODUCTION.

For a large scale production of precast concrete, it is frequently desirable to hasten the curing process, mainly for two reasons.

(1) The moulds can be released as early as possible, so as to facilitate their frequent usage. This way the capital cost can be reduced considerably.

(2) To avoid extensive storage. The finished articles can be delivered to the market as early as possible.

Some accelerating and rapid hardening chemicals were tried to achieve the above said purpose, but the efforts were futile. It was concluded that steam curing can be more effectively used to obtain the desired strength in a small time.

The steam curing process can be divided into two parts (1) Steam curing at atmospheric pressure and (2) Steam curing at high pressure.

The steam curing at atmospheric pressure is quite easy, because not only the steam can be prepared easily, but no controls are required for temperature, and pressure. No special equipment is required, even a small dustbin and stove or any heating device will serve the purpose.

The steam curing at a particular pressure can be subdivided into three parts (1) Continuous low pressure, (2) Intermittent low Pressure and (3) High Pressure.

Continuous low pressure curing is perhaps the most economical method for achieving uniform curing of concrete under controlled temperature and humidity conditions. Thus, it will be best suited for mass production. The concrete units are conveyed to a long tunnel for curing. The tunnel doors are kept close to conserve heat. In order to achieve maximum efficiency with this process a day and night shift is recommended[21]. If this is not possible the work is so arranged that the charge consisting of special units is kept during night time. This way it may be advantageous to have a longer curing period to obtain maximum strength.

The Intermittent low pressure curing is carried out in batteries (compartments) of curing chambers. The batteries are usually designed to take a days output. Steaming is commenced at the end of day's work and often cut off at night. Curing chamber is unloaded in next morning. This is an ideal method if curing is done in one shift only, as the products prepared during day can be cured at night. It does not give good efficiency. The curing chambers for the low pressures can be built of concrete blocks.

The high pressure curing speeds up the curing process by maintaining higher temperatures in the curing chambers and complete humid condition. In this type of curing the maintenance of humidity is of importance as the high temperature has a tendency to flash out the cement which will result in low compressive strength.[21] By keeping pressure as high as 125 lbs./sq.in. the blocks can be sufficiently cured within 4 to 6 hours and within 8 hours it attains approximately the 28-day strength(17). Hence in a day it can work for three shifts. The equipment should consist of thick cylinder or autoclave to withstand high pressures.

With the increase in pressure the strength goes on increasing upto certain pressure. Menzel(7) carried out work on small specimens and concluded the optimum pressure as 136 lbs/sq.in. corresponding to a temperature of 177°C. He worked for a period ranging from 8 hours to 72 hours. Clarkson(7) found that the optimum pressure varies between 110 p.s.i. to 140 p.s.i. depending upon several other factors.

5.2. CURING CHAMBER.

The curing chamber(17) generally consists of 6'-3" long and 3' concrete pipes laid horizontally (for low pressure curing) with air tight doors fitted on both sides.

It is desirable that the method of heating employed should produce the required strength with minimum expenditure of energy and that all the units should be at the same temperature. Heat fed to the chambers and generated by chemical action in the concrete is consumed by the heat lost from the curing chambers and that absorbed by the blocks. The losses can be reduced to minimum by proper insulation.

As an alternative the steam produced can be injected in the curing chamber. The heat transfer in this case will be by condensation. Uniform heating is obtained due to condensation which takes place more rapidly on the cooler units. If the steam entering the curing chamber produces over saturation of the air, the losses will be more.

5.3. EFFICIENCY.

Little information is available on the relative efficiencies of the various pressures in terms of heat requirement per cubic foot of concrete, as it depends on many factors. One American firm, in their investigation used curing chamber of 2500 c.ft. capacity, and cubes were cured at 100°C for 18 hours followed by a drying period of 2 hours quotes that 55 c.ft. of concrete can be cured per H.P. per day. The average cost of the fuel is 0.4 cent (3 n.p.) for a standard 8"x8"x16" block marked at about 20 cents (1 Re.) i.e. the cost is 2% of the cost of concrete and for high pressure it was found to be 5% of the cost of concrete.

5.4. OPTIMUM CONDITIONS.

Same results can be obtained at any pressure by changing steaming period if other factors remain unchanged. Other factors such as size, shape of units, aggregates methods of packing units, consistency of the mix, water-cement ratio and dryness fraction of steam have considerable effect on strength, and hence these factors also affect the adjustment of steaming pressure and steaming period. Stage of the moulded units before exposure to steam, rate of increase of temperature and time required for maximum pressure to develop also affects the results.

The desired strength can be obtained by having slow initial temperature rise and higher final temperature. Higher initial temperature rise produce lower strengths. Prolonged steaming may have an adverse effect while curtailed steaming and prolonged cooling is a beneficial one. Delayed treatment may compensate for a rapid temperature rise. All these factors should be balanced to obtain the same maturity. If treatment is started at the end of one hour, or less, after mixing, the higher temperature gradient will cause lower strengths.

When the gain of strength is plotted against the maturity, it is seen that concrete cured by steam, with a slow initial temperature rise, gains strength slightly more rapidly, in the initial stage and slowly in the later stage as compared to normally cured concrete.

The possible cause of an adverse effect of rapid initial temperature was studied by Roy.(17) He heated the cement and water before mixing which might be taken as equivalent to subjecting the specimens to a very rapid initial temperature rise. He concluded that the effect is due to volume change and rateof hydration. If the cement particles when subjected to a rapid temperature rise, were to develop an impermeable coating, it will restrict further hydration. Such a coating is developed if tri-calcium aluminum hydrates or insufficient calcium sulphate is present in solution.

The solubility of calcium sulphate decreases at higher temperature.

6.5. GAIN OF STRENGTH AFTER STEAMING.

The strength of specimens subjected to a slow initial rise of temperature is greater than normally cured concrete after 24 hours due to the extra maturity obtained by it. Therefore, the strength of normally cured concrete goes on increasing at a faster rate, and it becomes equal to that of steam cured concrete after 10-12 days. At the end of 28-days the strength of normally cured concrete slightly exceeds the strength of steam-cured concrete. Steam curing is not advantageous for more than 7 days.

The second type is the initial high rise of temperature after mixing. During the first few hours this method produces higher strength than that obtained by first method, but after one day it drops down and does not recover upto seventh day. After seven days there is a tendency to recover but does not equal the strength obtained by first method.

The strengths of concrete raised in temperature at intermediate rate or rapidly raised to intermediate temperature or to higher temperatures after a delayed start falls between these two extremes at all ages.

6.6. MATURITY AND ITS APPLICATION TO OBTAIN GIVEN STRENGTH.

Concrete of the same mix at the same maturity has approximately the same strength whatever be the combination of temperature and time.[21] Concrete obeys this law provided its temperature has not reached 50°C until 1 1/2 to 2 hours nor 100°C until 5 to 6 hours after mixing. When concrete has been raised in temperature more rapidly than above, it fails to obey this law. Hence, this can be used to obtain the desired strength in the given time having slow temperature rise and adjusting the variables such that the maturity is obtained during that time. This adjustment can be done as follows.

First find out the time required to obtain this strength by normal curing. This time multiplied by the average temperature will give the maturity in °C-hrs required. Now a treatment can be planned to obtain this maturity by adjusting the variables. If time is short the steaming can be increased and cooling time reduced.

8.7. EFFECT OF A/C AND W/C RATIO.

The adverse effect of a rapid early temperature rise is seen to be greater as the w/c and A/C ratio increases. Experiments[21] showed that even slower temperature gradients may be necessary with high ratios, but this may not be of practical importance as the inferior concrete would not normally be steam cured.

8.8. EFFECT OF AGGREGATES.

The aggregates if ground finely enough, would act as pozzolanas. This effect shows up even at comparatively low temperatures. The steam curing has harmful effects when the aggregate is composed wholly or partly of calcium carbonate. The effect is apparent at high pressures than at low or atmospheric pressures.

6.9. EFFECT OF CEMENT.

A rapid-hardening portland cement shows normal increase in strength, when used with non-reactive aggregates. If reactive aggregates and rapid-hardening cement is used it shows a great increase in strength due to a more pronounced lime-silica reaction. The effect of $CaCl_2$ is to further accelerate the hardening, but the proportionate effect is less than that obtained without $CaCl_2$. The high-alumina cement is adversely affected by a rise in temperature as the rate of hydration is sufficiently rapid at normal temperatures.

The effect of steam curing on concrete containing slag varies with the type of cement and their content of granulated slag. It causes staining and harmful effect due to excess sulphur. Portland blast furnace cements show normal increase. Super-sulphated cement is adversely affected by temperature above 40°C and has maximum rate of hydration between 20°C and 40°C.

6.10. EFFECT OF SIZE OF SPECIMEN.

It may be assumed that the rate at which the heat is absorbed at any given instant is proportional to the surface area of the concrete product. The temperature by which specimen is raised will depend on the amount of heat absorbed and weight of concrete. It also depends on the thermal conductivity. However, the main factor is the surface area. In flat slabs if the area of the sides are neglected then the surface area is constant whatever the thickness may be and hence the heating rate should be same for all thicknesses, but that is not the case. The thick slab has got less rate of heat absorption. It depends not only on the surface area but surface area per unit volume of the concrete.

6.11. PREDICTION OF NORMAL STRENGTH.

In 1951 R.L.Down(8) worked out a relation between the accelerated strength and normal strength. The cubes were cured for 6 hours in steam at atmospheric pressure after 24 hours of waiting period. The relations are as follows:

$y = 1.820\,x + 1237$ for 1:2:4
1:3:6 Cement Concrete.

$y = 2.041\,x + 370$ for 1:4:8 Cement concrete

Where x is the accelerated strength in lbs/sq.in. and
y is the 28-day normal cured strength in lbs/sq.in.

6.12. SHRINKAGE AND MOISTURE MOVEMENT.

The low pressure steam curing has little effect on the moisture movement of the concrete. The drying shrinkage is slightly reduced. If the cycle is restricted to that sufficient for demoulding, then yard storage is necessary and drying cycle is disadvantageous. High pressure steam curing reduces both drying shrinkage and moisture movement in all cases.

5.19. CONCLUSIONS.

Following conclusions can be derived

(1) The concrete products should not be subjected to the higher temperature for atleast two hours after mixing.

(2) The maturity law for normal cured concrete can be applied to the concrete having low initial temperature rise.

(3) A reduction in shrinkage and moisture movement is observed.

(4) An increase of resistance to sulphate attack is achieved by this method.

(5) By steam curing, the concrete after 7 days gains in strength at lesser rate than the normal cured concrete.

(6) The concrete products can be delivered to the market on the same day after 6 hrs. of steam curing at 125 p.s.i.

(7) The concrete should be well safe guarded against the thermal shock otherwise it will crack.

(8) The optimum pressure is between 120 p.s.i. to 140 p.s.i. for the maximum strength of the concrete.

(9) Bond strength is adversely affected by steam curing.

(10) Addition of CaCl2 has no appreciable effect on accelerating the strength if the blocks are steam cured.

(11) High early strength of high pressure steam cured concrete units are permanent.

(12) Steam cured products are lighter in colour than that of moist cured units.

6.14. MIXES ADOPTED.

The mixes adopted are given in Table No. 14. The Table No. 14 also gives the 7 and 28-day normal strength of concrete.

6.15. CUBES TESTED.

Totally 516 cubes were cured by these type of curing. Out of this 360 cubes were cured at atmospheric pressures for 6 hrs, 12 hrs. and 24 hrs, and remaining cubes were cured in autoclave for 6 hours at pressures of 40 p.s.i.g., 80 p.s.i.g. and 120 p.s.i.g.

6.16. DESCRIPTION OF INSTRUMENTS USED.

6.16.1 Steam Bath.

For atmospheric curing steam bath manufactured by precision scientific Co. U.S. was used. The steam bath is shown in Fig. No. 6.1 and 6.2. The specifications of the steam bath are as given below.

Voltage	230
Watts.	2000
Amperage	11

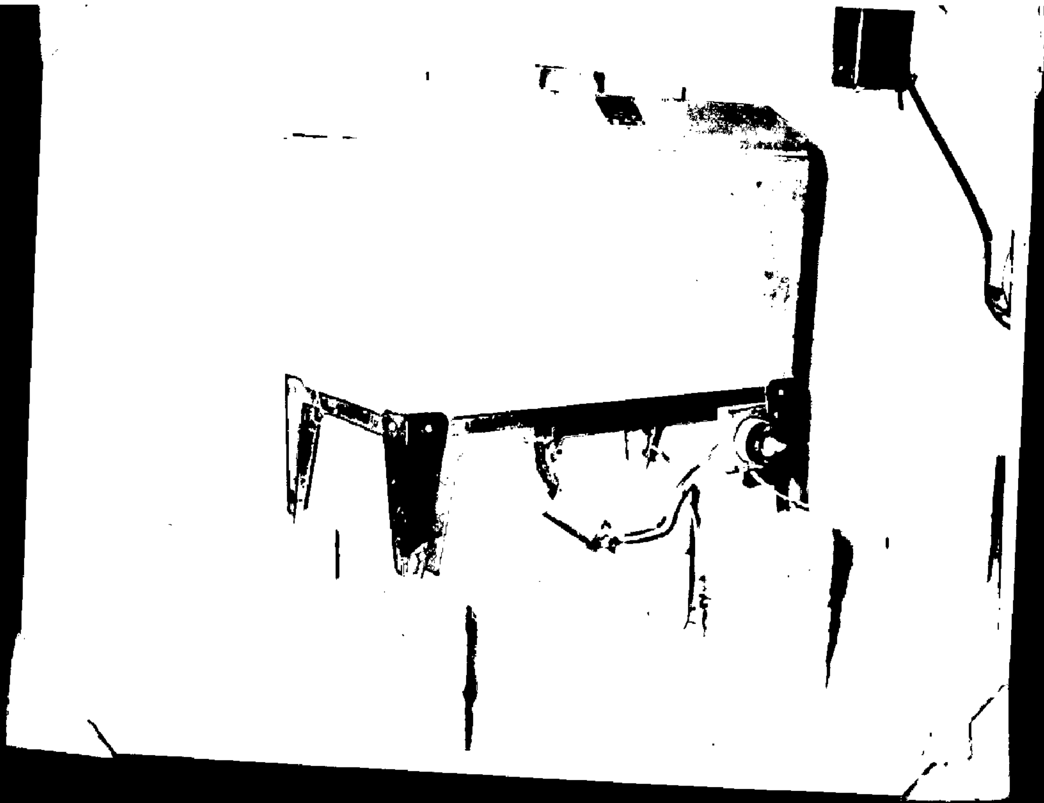


FIG. 5·1 STEAM BATH

FIG. 5·2 ARRANGEMENT OF CUBES IN STEAM BAT

Capacity 4.0 c.ft. (total)
2.5 c.ft. for cubes.
1.5 c.ft. for water.

Temperature range- to 100°C.

5.16.2. Autoclave.

For high pressure curing the autoclave manufactured by Central Scientific Co., U.S.A. was used. The autoclave is shown inFig. No.5.3, the specifications of the autoclave are as given below.

Voltage	110
Watts.	1500
Max. allowable pressure	350 p.s.i.
Healing Surface Area	2.6 sq.ft.
Diam. of autoclave	6 1/2".
Total capacity	0.4 c.ft.

Two heaters with thermostatic control to adjust pressures.

5.17. CURING PROCEDURE.

5.17.1. Curing at Atmospheric Pressure.

The concrete cubes prepared cannot be subjected to steam just after casting as it cannot withstand heat. The cubes were allowed to remain in mould for 20 hours just as in the normal curing i.e. covered with wet gunny bags. Then they were stripped off and put into a steam bath. The water in steam bath was previously brought to temp. 60°C before the cubes were kept. The top of the bath was covered so as to cure all thefaces equally. The top cover was provided with two holes, one for steam

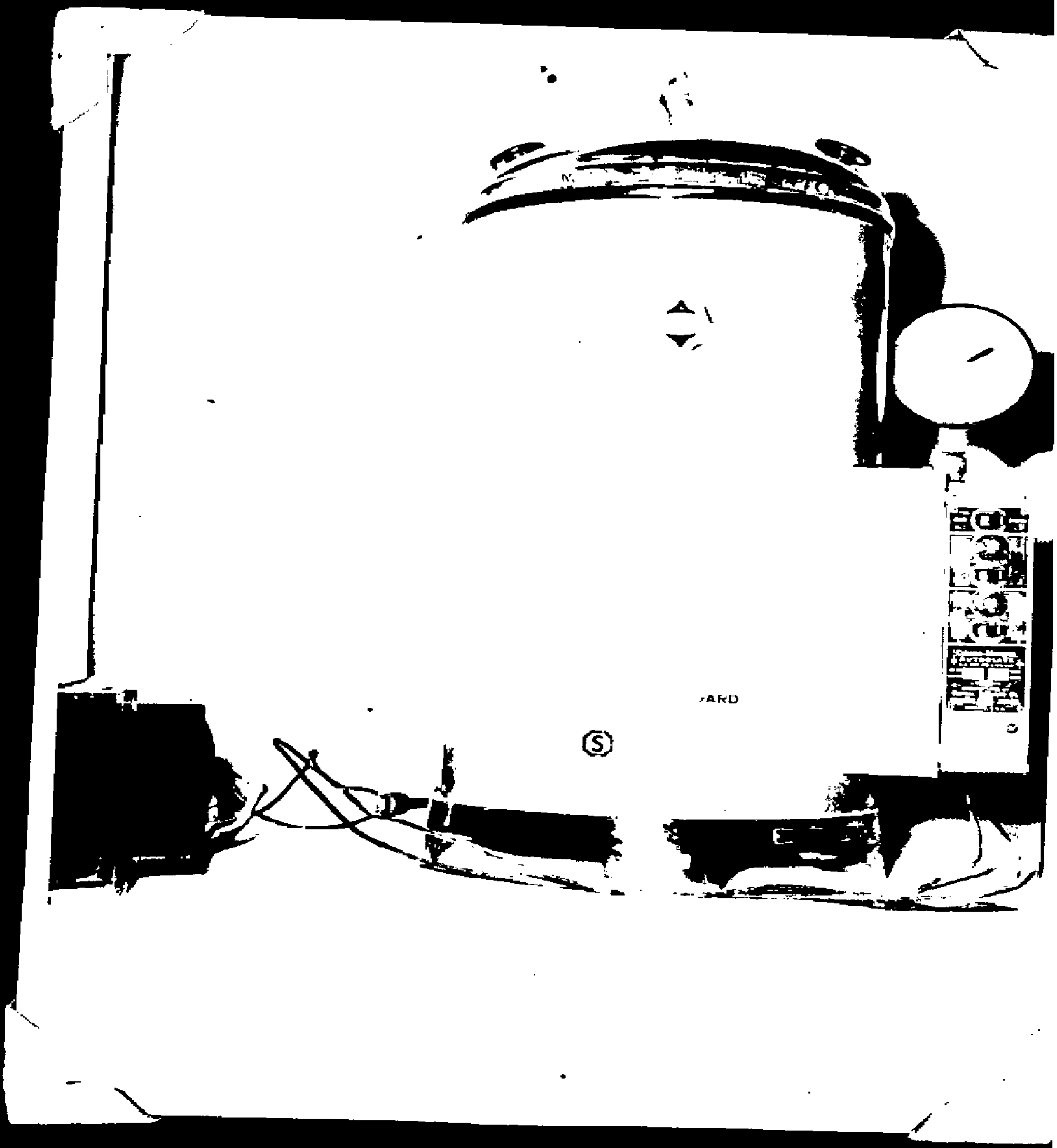


FIG. NO. 5.3 AUTOCLAVE

outlet so as the temperature may not rise above 100°C and other can be used for temperature measurement. The water was heated electrically and its boiling point was reached in approximately 3 hours. The typical time-temperature curve is shown in Fig.No.40. From Fig. No.40 it is clear that the temperature rise for first hour was from 60°C to 80°C while at the end of three hours the water was boiling. The water was kept boiling and cubes were cured for a total period of 6 hrs, 12 hrs and 24 hrs. The cube were removed from the steam bath after expiry of curing period and were allowed to cool under a fan for a period of one hour. They were tested under a Compression Testing Machine.

The curing period of 6, 12, and 24 hours were chosen for the same reasons as given for oven curing and also for relative comparison of strength between two types of curing.

5.17.2 (2) High Pressure Curing.

The rise in pressure gives the higher strength upto certain optimum pressure the reason being higher temperature and more latent heat supplied. Clarkson(47) found that optimum pressure is 140 p.s.i., therefore, three different pressures below this range were selected namely 60 p.s.i. 90 p.s.i. and 120 p.s.i. (all above atmosphere). The 4" cubes were put in autoclave as the capacity of autoclave was limited to hold the number of cubes. The water in autoclave was just at room temperature. The lid was closed and switch was put on. The steam was formed in one hour and the required pressure reached in next three-fourth hour. After

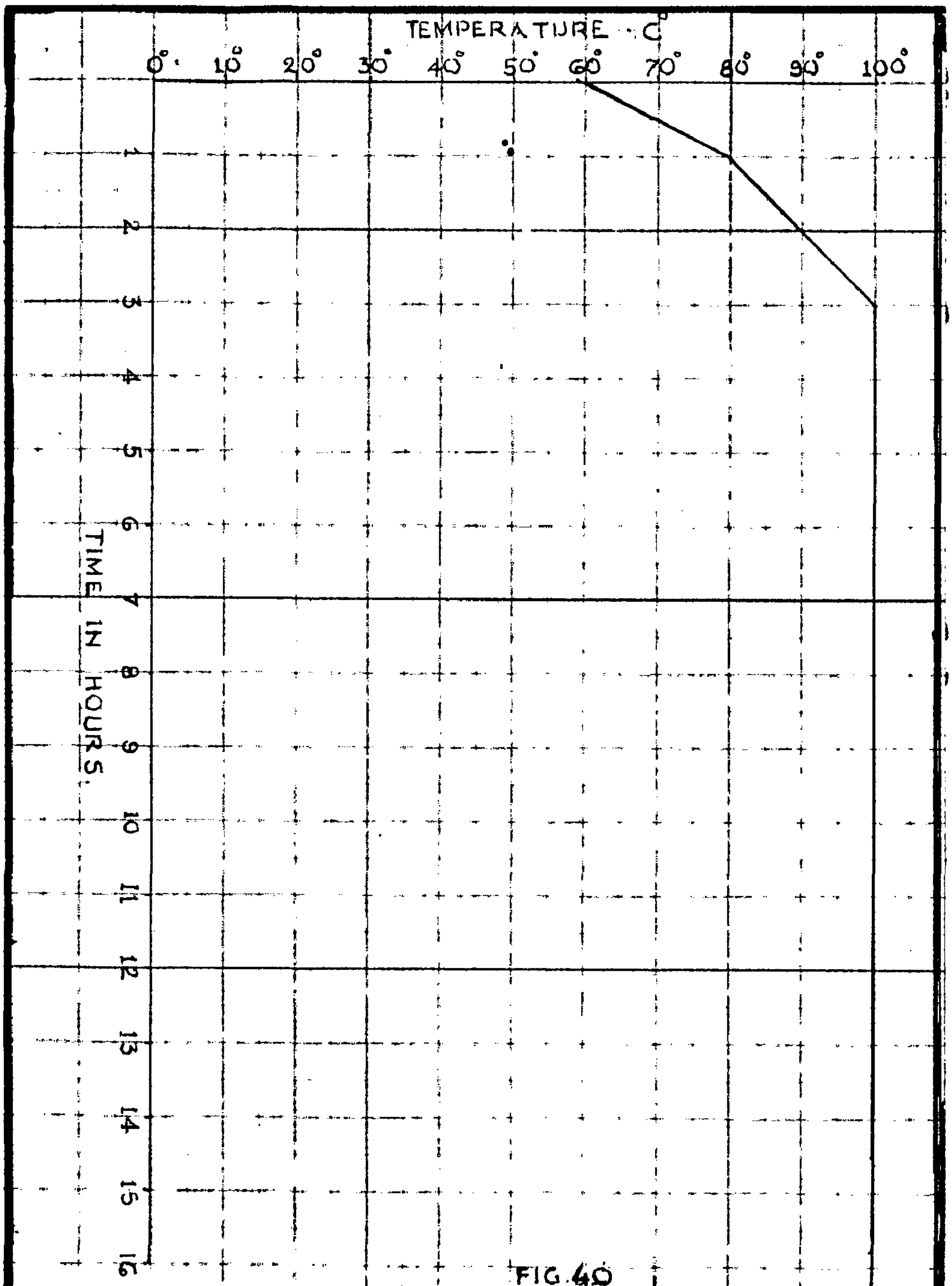


FIG.40

GENERAL PATTERN OF TEMPERATURE RISE FOR STEAM BATH.

the total curing period of 6 hours in autoclave, the cubes were removed from the autoclave, and allowed to cool under fan for 1/8 an hour. They were tested under compression testing machine.

5.18. RESULTS.

5.18.1.(1) Steam Curing At Atmospheric Pressure.

To compare the increase in strength by this method as compared to other methods the same curing periods were chosen. 6 hours was standard cycle as it can be done conveniently in a working shift of 8 hours. The results of 6 hrs, 12 hrs and 24 hrs. steam curing are given in Table Nos. 27,28 and 29, and Fig. Nos.41, 42, and 43 respectively.

5.18.1.1. 6-hr. cycle.

In the 6-hr cycle when results are plotted against 7-day and 28-day normal strength the relation is approximately a straight line. Assuming it to be a straight line, the best fit is given by the equation,

$$y = 1.02x + 2200$$

where x is the 6 hr. accelerated Strength of steam cured concrete in lbs/sq.in.

y is the 28-day normal strength in p.s.i.

As the normal strength increases the accelerated strength expressed as percentage of the normal strength increases mostly in all the cases the variation being from 38.0% to 83.1% of 7-day and 22.4% to 60.2% of the 28-day strength. The higher percentage is for richer mix. As compared to oven curing of same period the

TABLE NO.27

Results of 6 Hrs. Steam Curing at Atmospheric Pressure.

Waiting Time-	20 hrs. (in mould)
Heating Time-	6 hrs.
Cooling Time-	1 hr.
Initial Temp.of water.	60°C

Sr. No.	Mix No.	Accelerated Strength.		7 day Normal Strength		28day Normal Strength.		Accelerated Strength as % of	
		P.s.i.	kgm/cm2	p.s.i.	kgm/cm2	p.s.i.	kgm/cm2	7 day	28 day
1	W	3550	250.0	4265	300.7	5030	354.7	83.1	70.6
2	Y	3205	255.5	4045	285.0	5100	359.5	79.3	62.8
3	Z	3508	247.0	4430	312.2	5070	351.4	79.2	69.2
4	D	2500	176.0	3360	237.5	4730	333.3	74.4	52.8
5	O	2388	168.0	3279	231.2	4661	326.3	72.8	57.3
6	A'	2372	167.0	3300	233.9	4611	315.0	71.8	51.4
7	J	2370	166.9	3295	232.6	4064	286.3	71.8	58.3
8	P	1750	123.2	2782	196.1	4200	295.9	62.9	41.7
9	B'	1920	135.1	2968	209.3	4070	288.0	64.6	47.2
10	E	1400	98.5	2678	188.7	3796	267.4	52.4	36.8
11	Q	1305	91.9	2484	173.8	3932	275.0	52.8	36.8
12	C'	1250	88.0	2277	160.6	3784	266.6	54.9	33.1
13	K	1102	77.5	2198	155.0	3472	245.4	50.2	31.8
14	R	1530	107.8	2571	181.2	3633	256.7	62.4	42.1
15	D'	1421	100.0	2670	188.10	3485	246.2	53.2	40.7
16	F	1300	91.6	2451	172.9	3378	252.8	53.1	38.5
17	S	1050	73.8	2240	158.0	3416	241.5	46.8	30.7
18	E'	788	55.5	1917	135.2	3338	235.7	41.1	23.6
19	T	1068	75.2	2072	146.2	3217	226.9	51.5	33.2
20	F'	1042	73.3	1917	135.2	2756	194.8	54.3	37.9
21	U	644	45.3	1905	134.4	2880	203.1	33.8	22.4

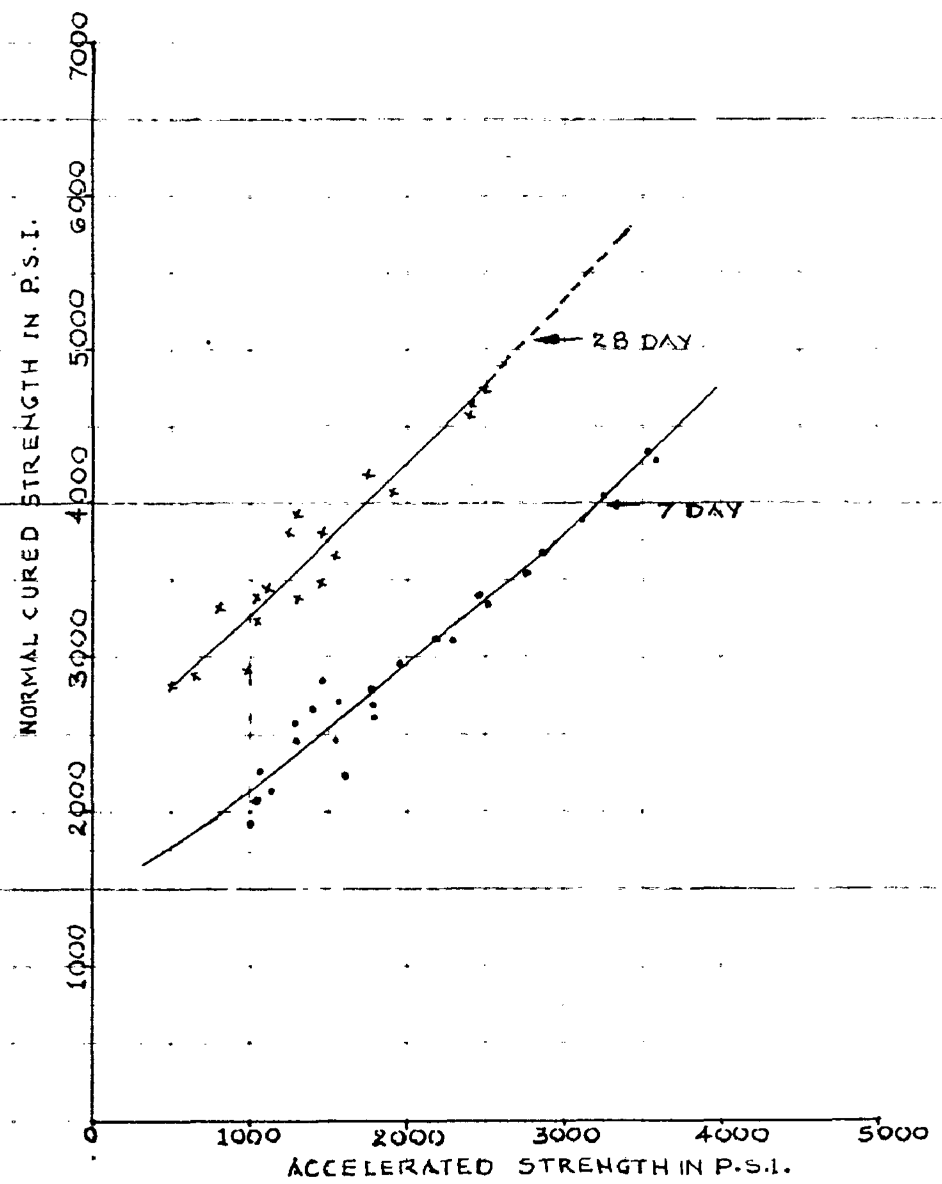


FIG. 41

RESULTS OF 6 HOURS STEAM CURING AT ATMOSPHERIC PRESSURE AGAINST NORMAL CURED STRENGTH.

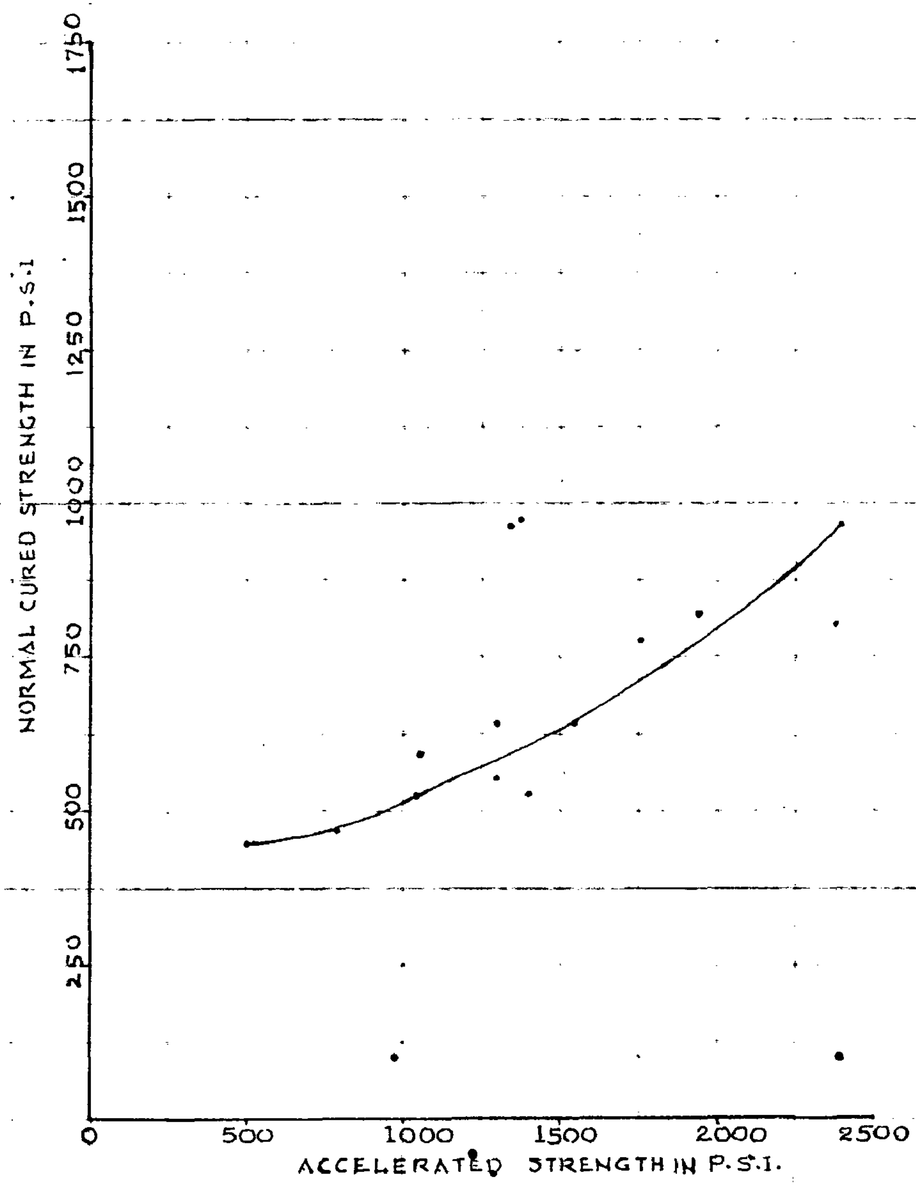


FIG. 42

RESULTS OF 6 HOURS STEAM CURING AT ATMOSPHERIC PRESSURE COMPARED WITH 6 HOURS OF NORMAL CURING AFTER 20 HOURS IN MOULD.

strength is less. It may be due to different chemical reaction.

Results of 6-hours steam cured cubes were compared with the results obtained after the normally cured cubes after 20 hours in the mould. The results are given in Table No.30 and Fig.No.42 The relation is a curve convex upwards. The results cannot be compared as the strength of early ages are not reliable and liable to give wrong results. The increase in strength above normal cured concrete varies from 14.1% to 333%.

Some cubes after they had attained room temperature were immersed in water and further cured for 7-days in normal way. The results are given in Table No.33. The accelerated curing results were compared with the final strength of concrete and found that the relation is nearly parabola as shown in Fig. No.47. The percentage increase in strength in 7-days above accelerated curing varied from 36.5% to 110%. There was no definite trend about its variation with type of mix. The results of normal cured cubes after steam cured were compared with 7-days normal cured. The relation is a straight line. As the normal strength is increased the percentage increase in strength of cubes also increases, the variation being from 66.5% to 96.0% but in no case it has achieved equal to normally cured strength.

5.10.1.2. <u>12 Hr. Cycle.</u>

From the results of 12 hour steam curing at atmospheric pressure it was found that there is increase in strength of the same order as it was in 6-hour steam curing, though the increase

TABLE NO.28

Results of 12 Hrs. Steam Curing at Atmospheric Pressure.

Waiting time-	20 hrs. (in mould)
Heating time-	12 hrs.
Cooling time-	1 hr.
Initial temp. of water.	60°C.

Sr. No.	Mix No.	Accelerated Strength		7 day Normal Strength		28 day Normal Strength.		Accelerated Strength as% of	
		p.s.i.	kgm/cm²	p.s.i.	kgm/cm²	p.s.i.	kgm/cm²	7 day	28 day
1	W	3800	267.5	4265	300.7	5030	354.7	89.0	75.5
2	Y	3650	256.5	4046	285.0	5100	259.5	90.4	71.5
3	Z	3780	266.0	4430	312.2	5070	357.4	85.3	74.6
4	D	2980	209.5	3360	237.5	4730	333.3	88.7	63.0
5	O	2818	198.2	3279	231.2	4661	326.3	85.8	60.4
6	A'	2988	210.4	3300	233.9	4611	325.0	90.5	64.8
7	J	2850	200.2	3295	232.6	4064	286.3	86.3	70.0
8	P	2250	158.2	2782	196.1	4200	295.9	80.9	53.6
9	B'	2311	162.7	2968	209.3	4070	288.0	77.7	56.7
10	E	1904	133.7	2678	188.7	3796	267.4	77.3	50.2
11	Q	1906	133.7	2464	173.8	3932	275.0	77.3	48.5
12	C'	1300	91.4	2277	160.6	3784	266.5	57.2	34.4
13	K	1205	84.7	2198	155.0	3472	245.4	54.7	34.6
14	R	1612	113.0	2571	181.2	3633	256.7	62.7	45.6
15	D'	1930	135.8	2670	188.1	3485	246.2	72.3	55.4
16	F	1886	132.7	2451	172.9	3378	252.8	76.8	55.7
17	S	1182	83.1	2240	158.0	3416	241.5	52.8	34.6
18	E'	1072	75.4	1917	135.2	3338	235.7	56.0	32.2
19	T	1208	85.0	2072	146.2	3217	226.9	58.5	37.7
20	F'	1344	94.5	1917	135.2	3756	194.8	70.2	48.8

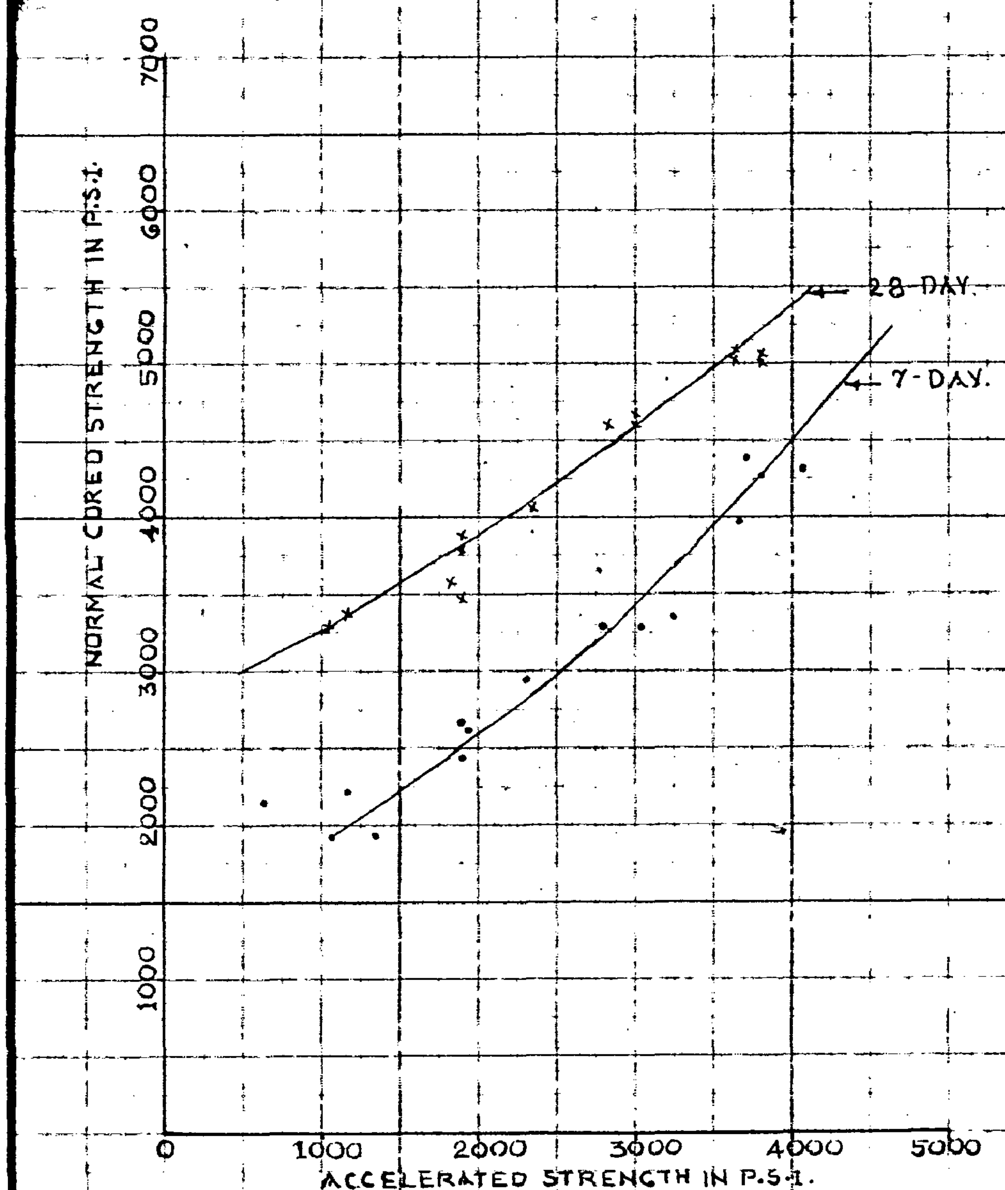


FIG 43

RESULTS OF 12 HOURS STEAM CURING ATMOSPHERIC PRESSURE AGAINST NORMAL CURED STRENGTH.

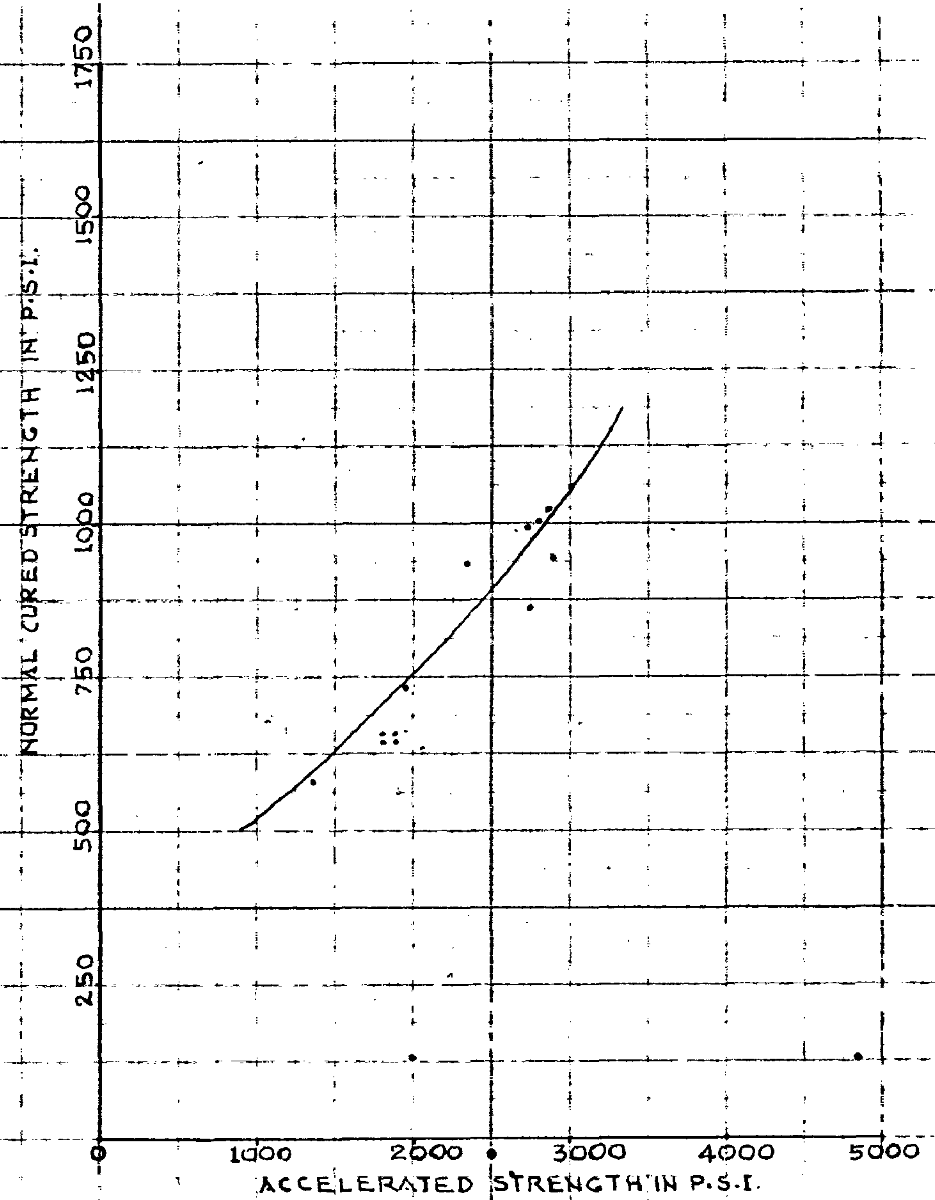


FIG. 44

RESULTS OF 12 HOURS STEAM CURING AT ATMOSPHERIC PRESSURE AGAINST 12 HOURS OF NORMAL CURING AFTER 20 HOURS IN MOULD.

in strength was not much as compared to 6-hour curing. The accelerated strength expressed as percentage of the normal strength increases their variation being from 52.0% to 90.5% of the 7-day strength and 32.2% to 75.6% of the 28-day strength. The increase in strength is more than that of oven curing for the same period. The results were compared with the normal curing of the same period and given in Fig. No.44. It indicates that as the normal strength increases the accelerated strength as percentage of normal curing varies from 140.8% to 332.0%. The higher gain in accelerated strength is for richer mix. The graph is having a slight curvature as indicated in Fig. No.44. The scatter is much more as the strength of normal cured concrete is not reliable upto 2 days.

8.10.1.3. <u>24-Hr.Cycle.</u>

For 24-hours curing it was found that upto lower normal cured strengths (upto 4000 lbs/sq.in.) the accelerated strength is lesser than the 7-day normal cured strength. The variation being of 15% i.e. atleast 85% of the 7-day strength is obtained for any mix. For the higher values of normal strength it gives more than 7-day strength. The accelerated strength gained in 12 hours varies from 22.1% to 36.7 of the 28-day normal cured strength. The results of 24 hour steam curing were compared with those of 24-hour normal curing after 20 hours in the mould. The results are tabulated in Table No.32. The strength when expressed as percentage of normal cured strength was found to be varying from 201.0% to 382%, the higher values were obtained for higher normal cured strength, the relation between normal cured and accelerated strength

TABLE IV.22.

Results of 24 Hrs. Steam-Curing at Atmospheric Pressure.

Waiting Time – 20 hrs. (in mould)
Heating Time – 6 hrs.
Cooling Time – 1 hr.
Initial Temp. of water. 60°C

Sr. No.	Mix No.	Acc. Strength p.s.i.	Acc. Strength kg/cm²	7-day Strength p.s.i.	7-day Strength kg/cm²	28day strength p.s.i.	28day strength kg/cm²	Acc. Strength as % of 7-day	Acc. Strength as % of 28day
1	U	4270	300.3	4265	300.7	5020	351.7	101.0	80.7
2	Y	4300	300.2	4046	286.0	5200	365.6	106.5	84.3
3	Z	4400	310.0	4420	312.3	5070	357.4	99.6	86.8
4	D	3572	240.6	3360	237.6	4730	333.3	106.3	75.5
5	O	3500	246.3	3270	231.2	4661	328.3	106.8	76.0
6	A°	3560	250.2	3300	233.0	4611	325.0	108.0	77.3
7	J	3200	225.2	3295	231.6	4064	286.3	97.0	78.7
8	P	3000	211.0	2782	196.1	4200	296.0	108.0	71.5
9	B°	2794	197.3	2968	209.3	4070	286.0	94.4	68.7
10	E	2506	176.0	2678	188.7	3703	257.4	93.6	68.0
11	Q	2239	157.6	2464	173.3	3923	276.0	90.6	57.0
12	C°	1878	132.5	2277	160.6	3784	266.5	82.5	50.1
13	K	1842	129.6	2293	158.0	3172	223.4	80.3	58.0
14	R	2579	207.6	2971	181.2	3633	254.7	92.5	65.4
15	D°	2120	170.6	2370	166.1	3105	218.2	90.0	69.6
16	F	2579	181.6	2451	172.9	3378	238.0	105.2	76.6
17	S	°1603	112.6	2240	158.0	3416	241.5	71.6	46.9
18	E	∅1403	105.6	1927	135.2	3353	236.7	70.3	46.0
19	T	1719	120.1	2072	146.2	3217	226.9	83.5	53.1
20	F°	1664	117.2	1927	136.3	2764	194.3	86.7	60.4

–° cured for 23 hours.
∅ cured for 20½ hour.

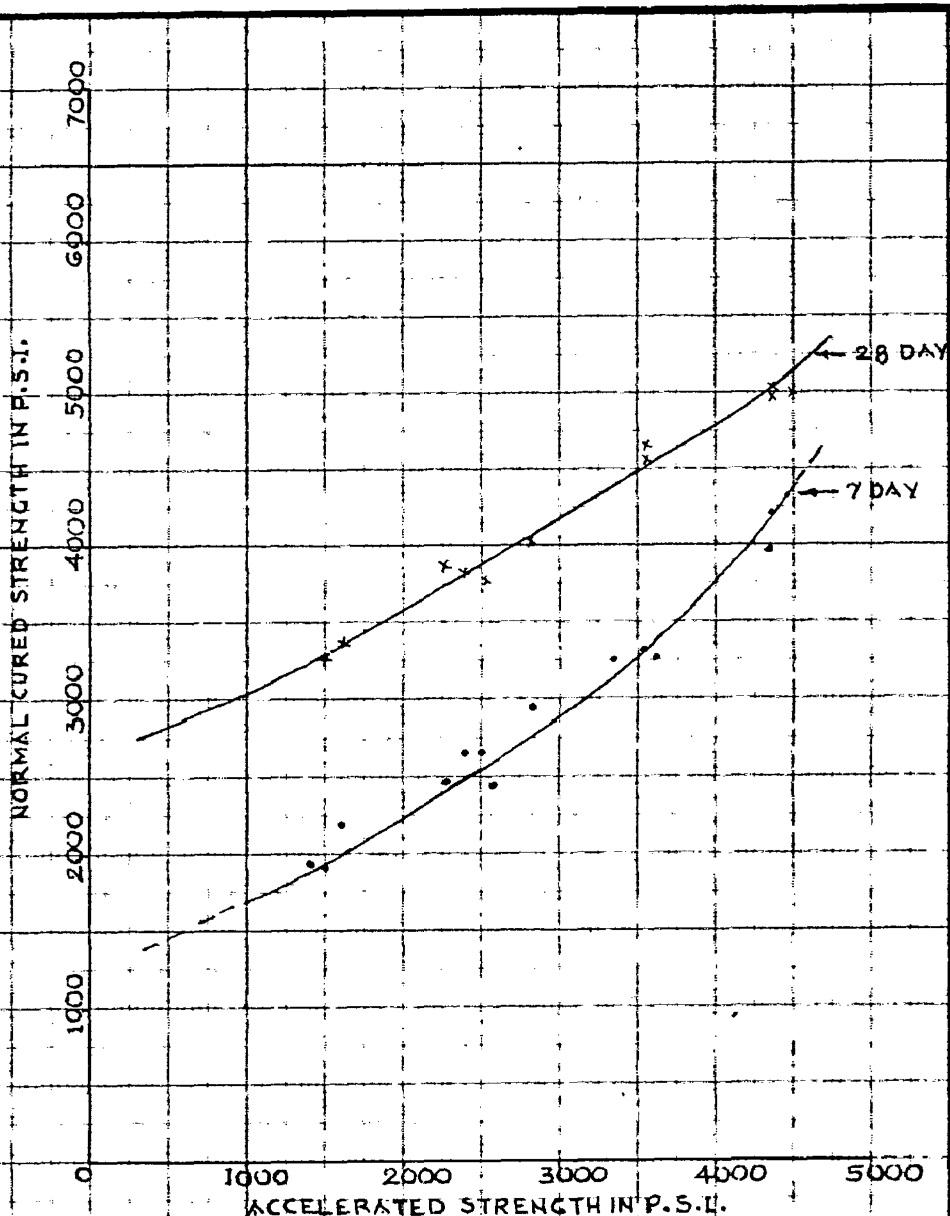


FIG. 45

RESULTS OF 24 HOURS STEAM CURING AT ATMOSPHERIC PRESSURE AGAINST NORMAL CURED STRENGTHS.

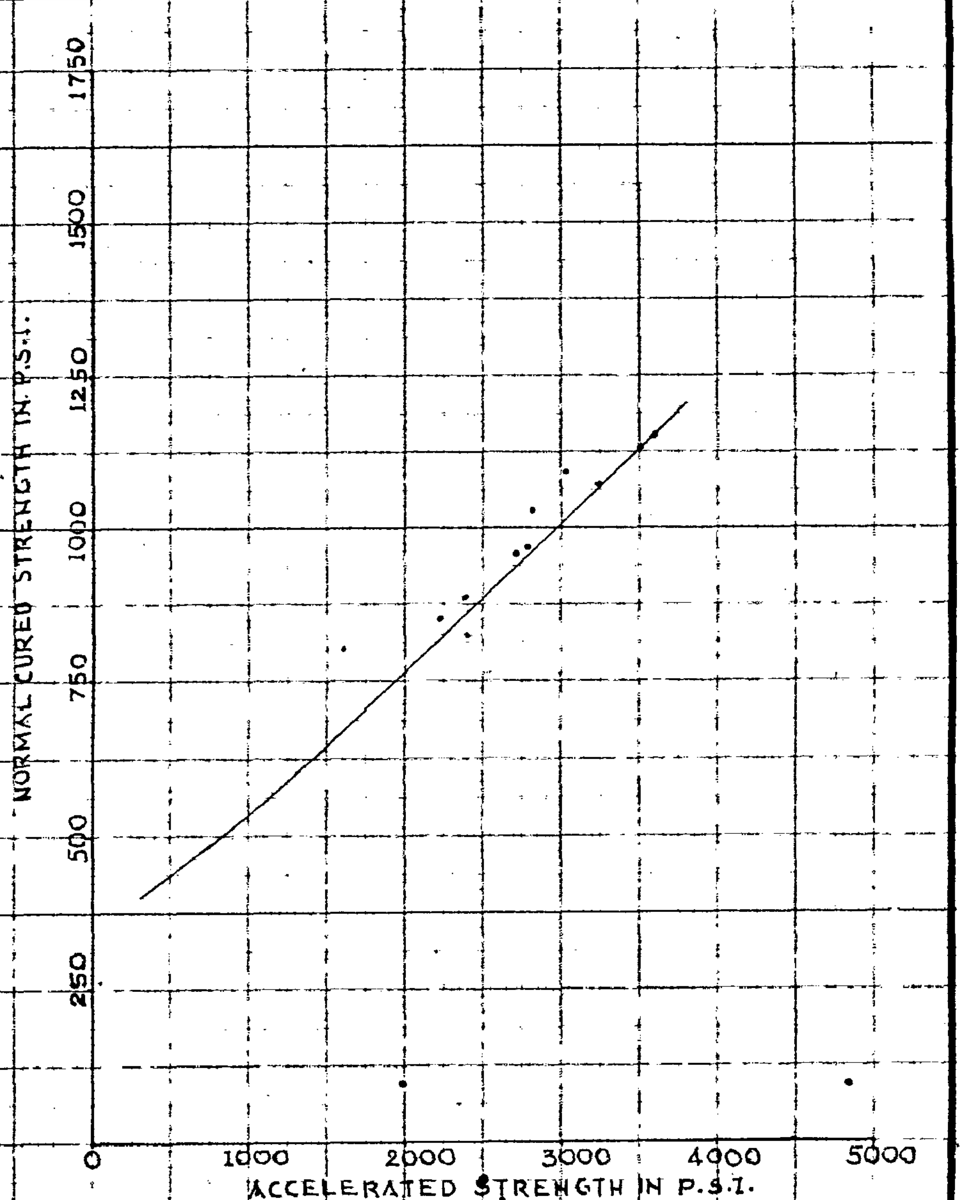


FIG. 46

RESULTS OF 24 HOURS STEAM CURING AT ATMOSPHERIC PRESSURE AGAINST 24 HOURS OF NORMAL CURING AFTER 20 HOURS IN MOULD.

TABLE NO.30.

Results of 6 Hours.Steam Curing Compared with 6 hrs. of Normal Curing.

Sr. No.	Mix. No.	Acc. Strength		Normal Strength		Acc.Strength as % of N.Strength
		P.s.i.	kgm/cm²	R.s.i.	kgm/cm²	
1	E	1400	98.5	532.0	37.4	263.5
2	F	1300	91.5	560.0	39.4	232.0
3	I	500	35.2	455.0	32.0	110.0
4	J	2370	166.9	508.0	35.7	466.0
5	K	1102	77.5	550.0	38.6	200.0
6	L	400	29.3	342.0	24.1	117.0
7	O	2388	168.0	810.0	56.9	295.0
8	P	1750	123.2	785.0	55.2	223.0
9	Q	1305	91.9	652.0	45.8	200.2
10	R	1530	107.8	656.0	46.1	233.0
11	S	1050	73.8	600.0	42.2	175.0
12	T	1068	75.2	420.0	29.5	254.0
13	A'	2372	167.0	975.0	68.6	243.2
14	B'	1920	135.1	825.0	58.0	232.5
15	D'	1421	100.0	1245.0	87.5	114.1
16	E'	788	55.5	474.0	33.4	166.5
17	F'	1042	73.3	529.0	37.2	197.2

TABLE NO.31

Results of 12 Hours Steam Curing at Atmospheric Pressure Compared with 12 Hours of Normal Curing.

Sr. No.	Mix No.	Acc. Strength p.s.i.	Acc. Strength kgs/cm2	Normal Strength p.s.i.	Normal Strength kgs/cm2	Acc. Strength as %age of Normal Strength
1	E	1904	133.7	663.0	46.6	287.0
2	F	1886	132.7	568.0	40.0	332.0
3	J	2850	200.2	945.0	66.5	302.0
4	K	1205	84.7	890.0	62.6	135.5
5	L	560	39.4	372.0	26.3	149.2
6	O	2818	198.2	1030.0	72.5	273.5
7	P	2250	158.2	857.0	60.3	262.8
8	Q	1906	133.7	650.0	45.7	293.0
9	R	1612	113.7	756.0	53.2	213.4
10	S	1182	83.1	666.0	46.8	177.5
11	T	1208	85.0	548.0	38.6	220.0
12	A'	2988	210.4	1062.0	74.8	282.0
13	B'	2311	162.7	1000.0	70.3	231.1
14	D'	1930	135.8	739.0	52.0	261.0
15	E'	1072	75.4	680.0	47.8	158.0
16	F'	1344	94.5	572.0	40.3	235.0

TABLE NO. 32

Results of 24 Hours Steam Curing at Atmospheric Pressure Compared with 24 Hours of Normal Curing.

Sr. No.	Mix No.	Acc. Strength p.s.i.	Acc. Strength kgm/cm²	Normal Strength p.s.i.	Normal Strength kgm/cm²	Acc. Strength as %age of Normal Strength
1	B	2603	170.0	893.0	62.7	281.0
2	F	2570	181.5	732.0	51.5	352.3
3	J	3200	225.2	1072.0	75.5	298.0
4	K	1842	129.5	653.0	46.2	281.0
5	O	3500	240.2	1120.0	79.4	310.0
6	P	3000	211.0	1092.0	76.4	275.8
7	Q	2239	157.5	848.0	60.0	263.5
8	R	2375	167.5	882.0	62.0	269.0
9	S	1603	112.5	780.0	55.0	201.0
10	T	1710	120.1	652.0	45.9	263.0
11	A'	3500	250.2	1150.0	80.8	310.0
12	D'	2784	197.2	1030.0	72.4	272.0
13	D'	2420	170.5	816.0	57.4	297.0
14	E'	1490	105.5	510.0	36.0	273.0
15	F'	1634	117.2	678.5	47.6	242.0

TABLE No. 23

Results of 7-days Normal Curing After 6 Hours in Steam Curing at Atmospheric Pressure.

Sr. No.	Acc. Strength		Acc. Strength 7 day Cured.		7day Strength		Acc. Strength + 7 day Strength as % of	
—	p.s.i.	kgm/cm²	p.s.i.	kgm/cm²	p.s.i.	kgm/cm²	Acc. Strength	7-day Otrength.
1	1600	123.5	2940	206.5	3178	223.0	163.6	93.0
2	1150	81.2	1700	120.5	1960	139.2	155.0	80.7
3	1760	123.6	2960	208.0	3236	228.0	169.2	91.5
4	1460	102.0	2720	191.5	2869	200.5	188.0	95.5
5	1108	77.9	2340	164.5	2540	178.0	211.0	92.0
6	1033	73.0	1755	123.2	1910	136.0	169.0	91.6
7	2130	149.5	3200	226.0	3520	248.0	150.5	91.0
8	1103	77.9	2672	180.5	2602	189.5	232.5	95.6
9	1000	71.0	1370	84.3	1635	120.3	135.6	87.4
10	1232	86.5	1910	134.2	2050	144.5	153.0	93.2
11	1930	135.5	3120	220.0	3640	253.0	162.3	86.0
12	1250	87.5	2700	190.0	3120	219.3	216.0	86.5
13	1505	105.7	2760	194.0	2990	210.5	183.6	92.3
14	1053	74.5	2066	145.0	2290	161.2	197.0	91.0
15	995	70.0	1920	135.0	2120	153.2	193.2	88.3

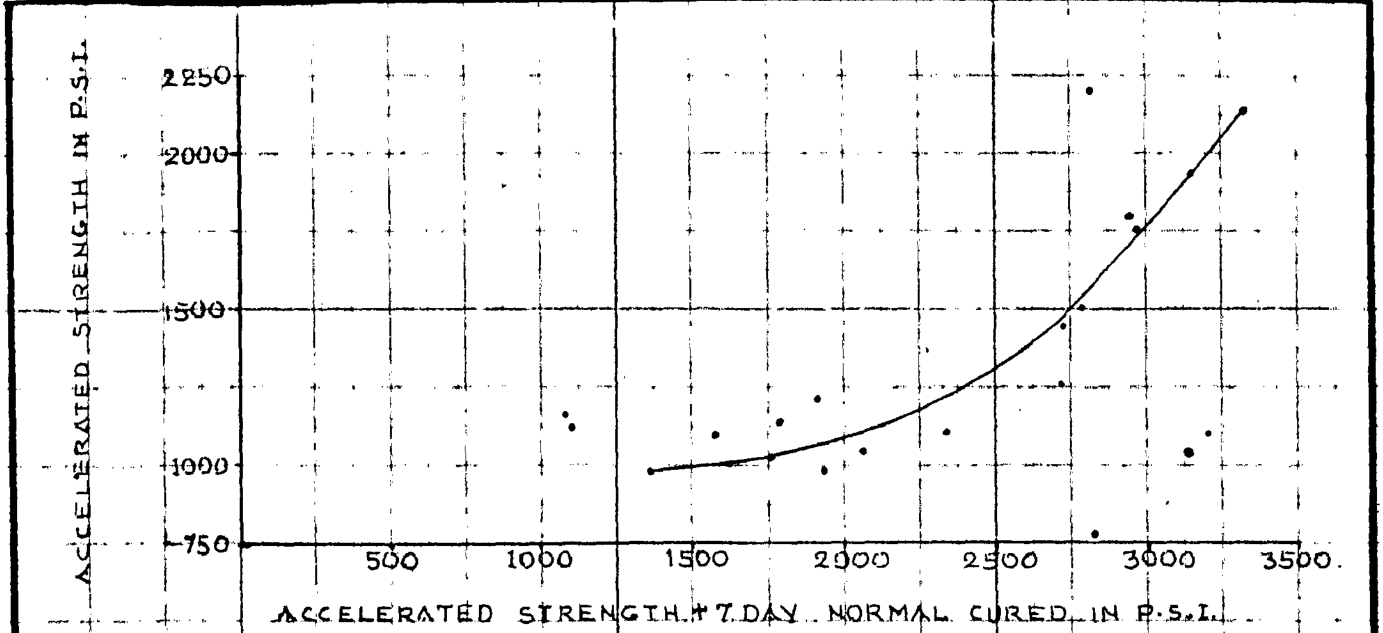


FIG. 47

RESULTS OF 6 HOURS STEAM CURED STRENGTH PLOTTED AGAINST 7 DAYS OF NORMAL CURING AFTER 6 HOURS IN STEAM BATH.

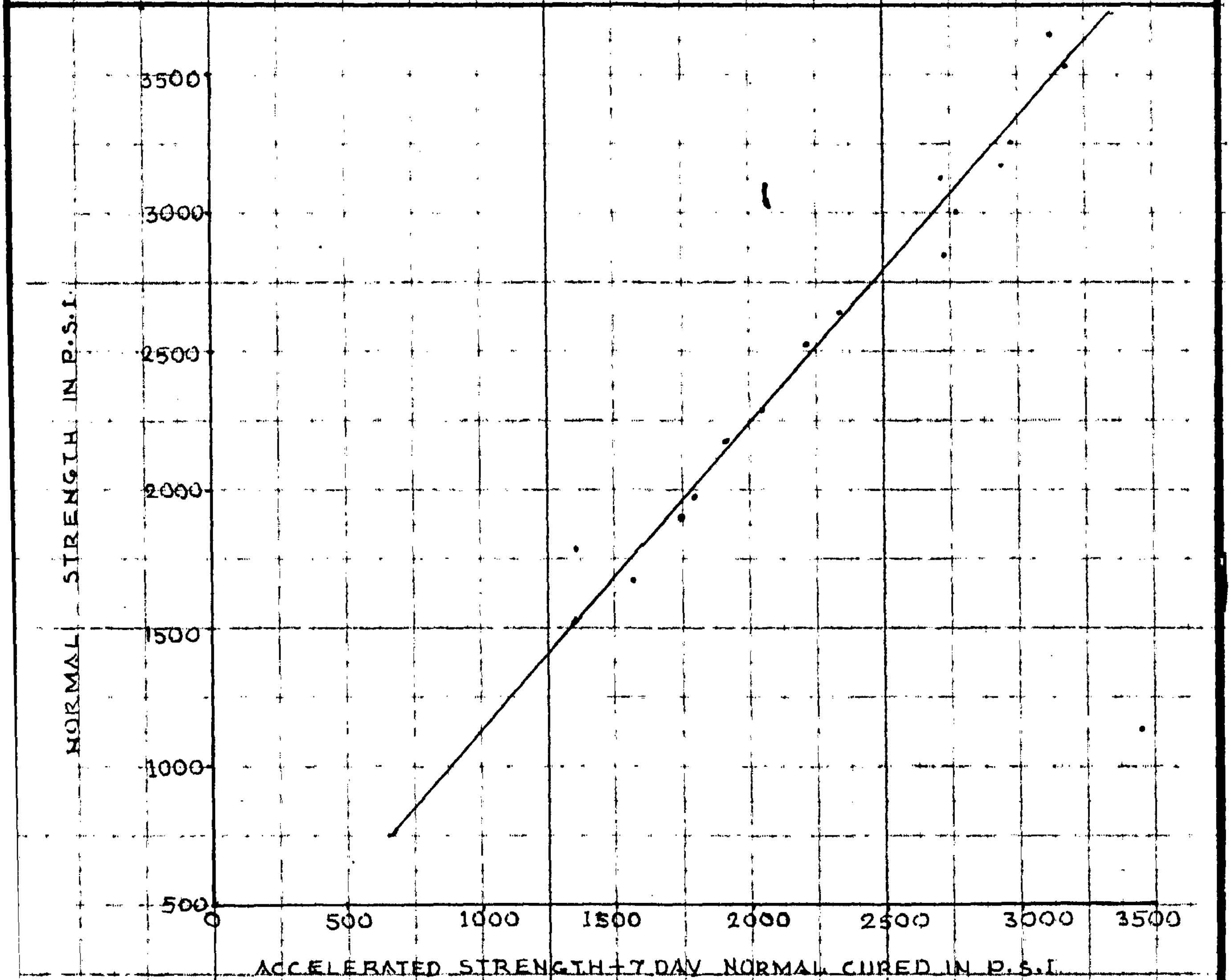


FIG. 48

RESULTS OF 7 DAYS NORMAL CURING AFTER 6 HOURS IN STEAM BATH SHOWS THAT THE STRENGTH GAINED IS LESS THAN THAT OF 7 DAY NORMAL STRENGTH.

is a straight line as shown in Fig. No.48.

6.10.1.4. Maturity.

The maturity is defined as the product of time and temperature above certain datum. For comparison of this relation with oven curing the same datum of 11°F was selected and results are calculated. The maturities for 6 hrs, 12 hrs, and 24 hrs of steam curing were calculated and are tabulated in Table No.24. Table No.25 represents the 6 hours, 12 hours and 24 hours accelerated strength obtained from Fig. Nos.41, 43 and 45 for selected 28-day normal strength. For zoning and comparison of constants the same interval of 800 lbs./sq.in. was selected. The accelerated strength was expressed as percentage of 28-day strength and plotted against $\log_{10} \frac{\text{maturity}}{1000}$ as shown in Fig. No.49. The relation is a straight line and there are as many straight lines as the number of zones selected. The relation can be expressed in the form of

$$\text{Percentage strength of 28-day} = A + B \log_{10} \frac{\text{Maturity}}{1000}$$

The values of constants A and B are given in Table No.26 and also shown in Fig. No.50. The value of B increases as 28-day normal strength increases while the value of A remains approximately constant. The variation of A and B are linear with strength.

6.10.2(2) Steam Curing at High Pressures.

Three different pressures were selected so as to study the effect of strength on high pressure curing. The maximum limit as determined by Clarkson(7) is 123 p.s.i. so three different

TABLE No.34

Maturities for Steam Curing.

Waiting Time.	Heating Time.	Cooling Time.	Total	Maturities °F.hr.	Log 10 $\frac{\text{Maturity}}{1000}$
20	6	1	27	3063	0.48473
20	12	1	33	4267	0.63033
20	24	1	45	6681	0.82485

TABLE NO.35

Steam Curing Strength at Various Selected Intervals.

Sr. No.	Accelerated Strength 6hrs.	12 hrs.	24 hrs.	28day Normal Strength P.s.i.	6hrs. as % of 28 day	12 hrs. as % of 28 day.	24 hrs. as % of 28 day
1	1250	1350	1750	3500	35.5	38.5	50.0
2	1700	2150	2575	4000	42.5	63.7	64.4
3	2225	2650	3350	4500	49.6	63.3	74.4
4	2675	2450	4150	5000	83.5	69.0	83.0

TABLE NO.36

Values of Constants A and B in the Equation:

$$\% \text{ of 28 day} = A + B \log \frac{\text{Maturity}}{1000}$$

Sr. No.	28 day Strength p.si.	Constants. A	B
1	3500	13.0	45.0
2	4000	10.5	67.4
3	4500	12.0	78.5
4	5000	10.5	91.0

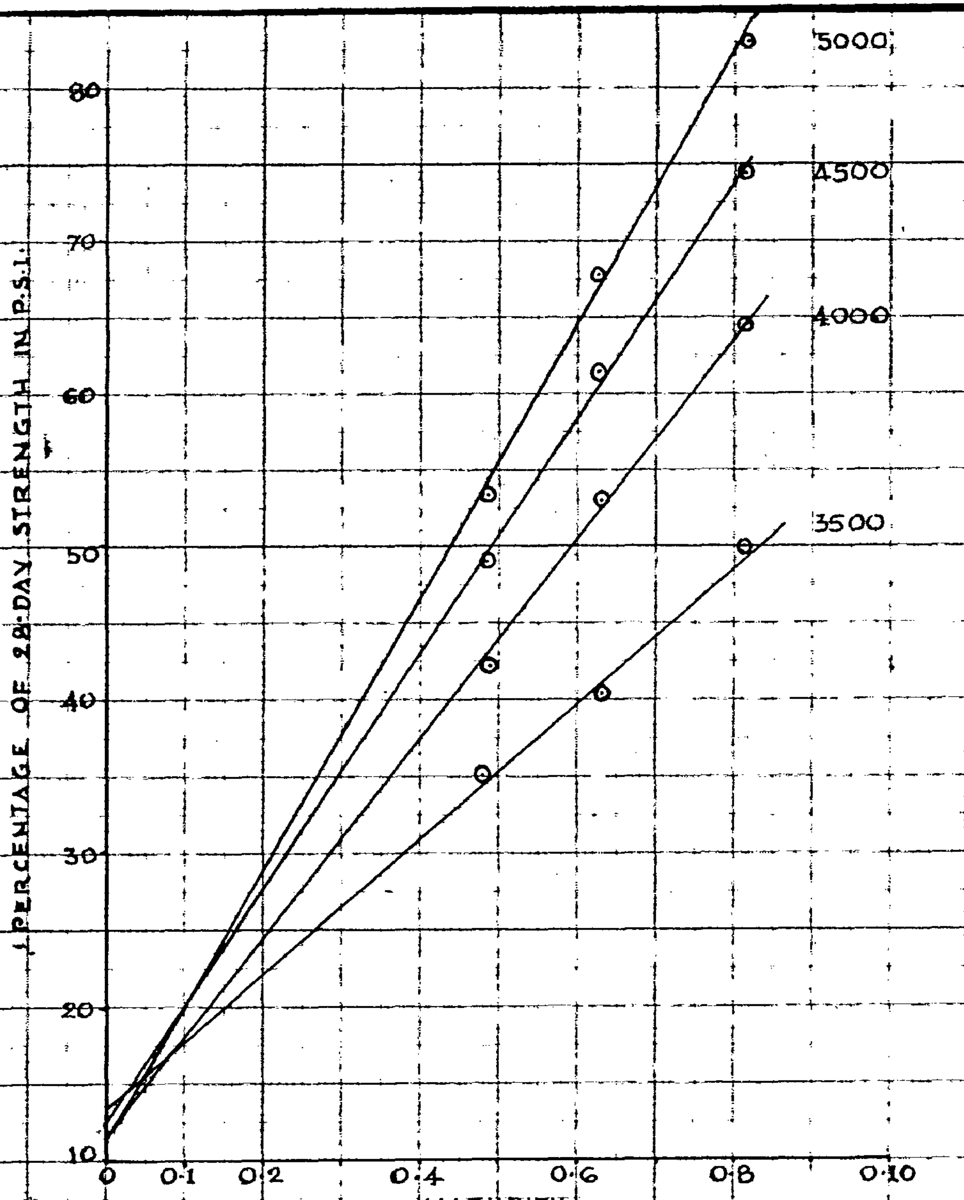


FIG. 49

RESULTS OF STEAM CURING AT ATMOSPHERIC PRESSURE PLOTTED AGAINST $\log_{10} \frac{\text{MATURITY}}{1000}$ SHOWING THAT THE RELATION IS A ST. LINE.

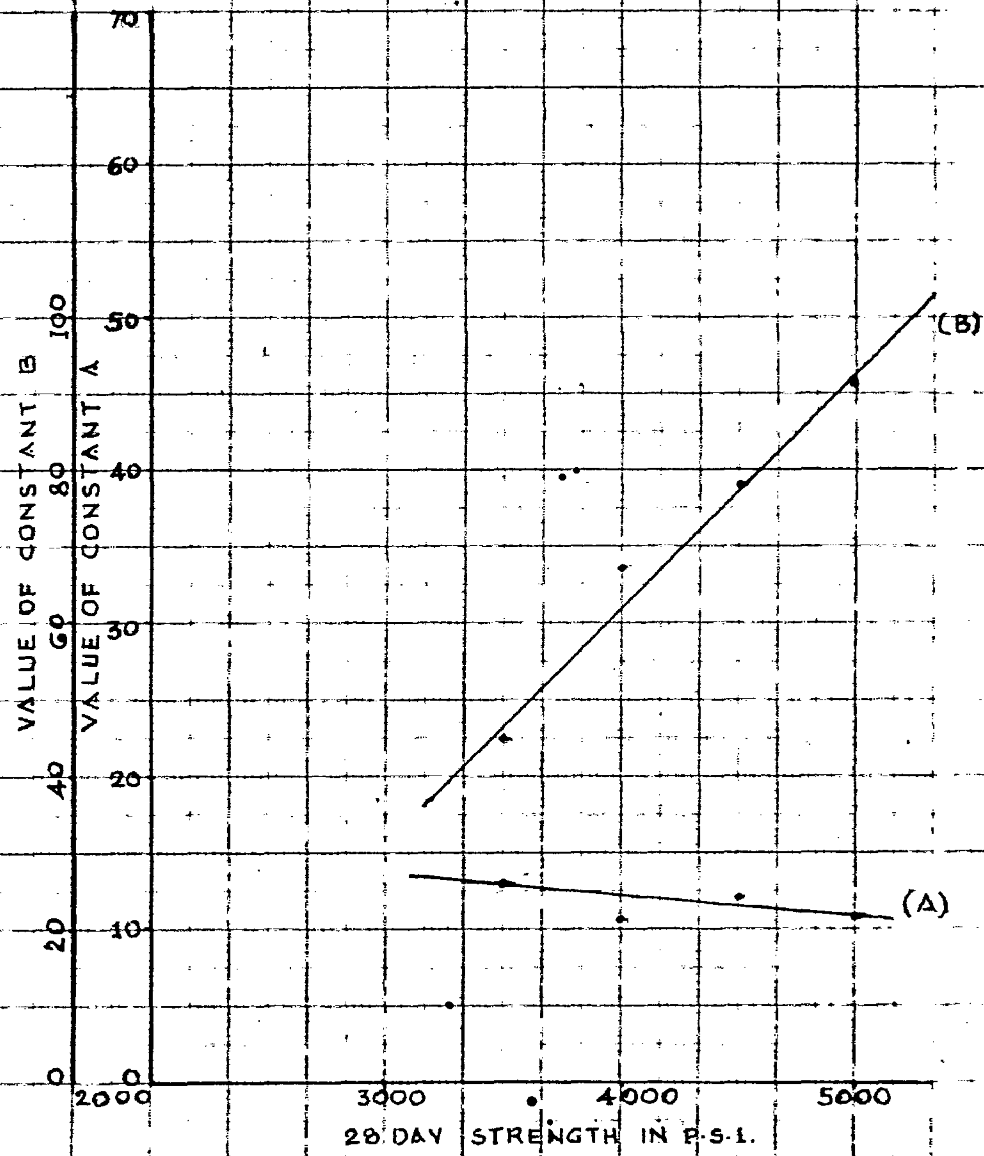


FIG. 50

VALUES OF CONSTANTS A AND B OF THE EQUATION, % STRENGTH OF 28 DAY $= A + B \log_{10} \frac{\text{MATURITY}}{1000}$ PLOTTED AGAINST 28-DAY STRENGTH.

pressures 60 p.s.i., 90 p.s.i. and 120 p.s.i. above atmospheres were selected for study. The results are tabulated in Table Nos. 37, 39, and 41 and plotted in Fig. Nos. 51 to 56.

5.10.2.1. Results of steam curing at 60. p.s.i. show that it gives approximately 34.7 to 81 % of the 7-day strength and 28.4% to 64.4% of 28-day strength. As the normal strength is increased the accelerated strength expressed as percentage of the normal strength increases. The gain 6-hour curing is more than by oven and steam curing at atmospheric method. Results of accelerated curing were compared with the normal curing of the same period. The results are given in Table No.38 and Figure No.52. The accelerated strength increases as the normal strength increases. The accelerated strength obtained were expressed as percentage of normal curing found varying in a range of 131% to 474% the large range is due to uncertainty of normal strength at early ages.

5.10.2.2. Results of steam curing at 90 p.s.i. show that it gives approximately 46.0% to 114.0% of the 7-day strength and 23.8% to 81.0% of 28-day strength, the higher percentage for the richer mix. For 28-day strength above 4000 p.s.i. it was found that in 6 hours the attained more than 7-day strength. The accelerated strength was compared with the normal strength of the same period the results are given in Table No.40 and Fig. No.54. As the normal strength increases accelerated strength also increases its variation being from 210.6% to [illegible]. The higher percentage is for higher normal strength.

TABLE NO.37

Results of 6 hrs. Steam Curing at 60. p.s.i. above atmosphere.

Waiting time- 20 hrs.
Heating time- 6 hrs.
Cooling time- 1 hr.
Cube size- 4"
Temp. of water- 144.8°C

Sr. No.	Mix No.	Acc. Strength		7-day Strength		28-day Strength		Acc. strength as percentage of	
		p.s.i.	kgm/cm²	p.s.i.	kgm/cm²	lbs./sq.in.	kgm/cm²	7 day	28day
1	W	3387	238.5	4265	300.7	5030	354.7	79.6	67.4
2	Y	3280	231.0	4045	285.1	5100	359.5	81.0	64.4
3	J	2405	169.1	3295	232.6	4064	286.3	72.9	59.2
4	K	1000	70.3	2198	155.0	3472	245.4	45.5	28.8
5	P	1762	124.0	2782	196.1	4200	295.9	63.4	41.9
6	R	1545	108.7	2571	181.2	3633	256.7	60.2	42.6
7	T	720	50.7	2072	146.2	3217	226.9	34.7	23.4
8	B'	2078	146.2	2968	209.3	4070	288.0	70.0	57.2
9	D'	1630	114.8	2670	188.1	3485	246.2	61.0	46.8
10	E	1650	116.2	2678	188.7	3796	267.4	61.6	43.4
11	F	1375	96.8	2451	172.9	3378	252.8	56.2	40.7
12	Q	2400	169.0	2464	173.8	3932	275.0	97.6	62.6
13	O	2450	172.5	3279	231.2	4661	326.3	74.7	52.7
14	Q	1540	107.5	2464	173.8	3932	275.0	62.5	39.2
15	S	1120	79.0	2240	158.0	3416	241.5	50.0	32.8
16	A'	2650	186.8	3300	233.9	4611	3250	80.4	57.5

TABLE NO.33

Results of 6 hrs. Steam Curing at 60 p.s.i. above Atmosphere compared with 6 hrs. of Normal Curing.
(4" cube used)

Sr. No.	Mix. No.	Acc. Strength p.s.i.	Acc. Strength kgm/cm²	Normal Strength P.s.i.	Normal Strength kgm/cm²	Acc. as %age of 28 day.
1	E	1650	116.2	532	37.4	310.0
2	F	1375	96.8	560	39.4	246.0
3	J	2405	169.1	508	35.7	474.0
4	K	1000	70.3	550	38.6	181.8
5	O	2450	172.5	810	56.9	302.5
6	P	1762	124.0	785	55.2	224.5
7	Q	2400	169.0	652	46.0	368.0
8	R	1615	113.7	655	46.1	235.2
9	S	1120	79.0	600	42.2	186.6
10	T	720	50.7	420	29.5	171.6
11	A'	2660	186.8	975	68.6	272.0
12	B'	2078	146.2	825	58.0	252.0
13	D'	1630	114.6	1245	87.5	131.0

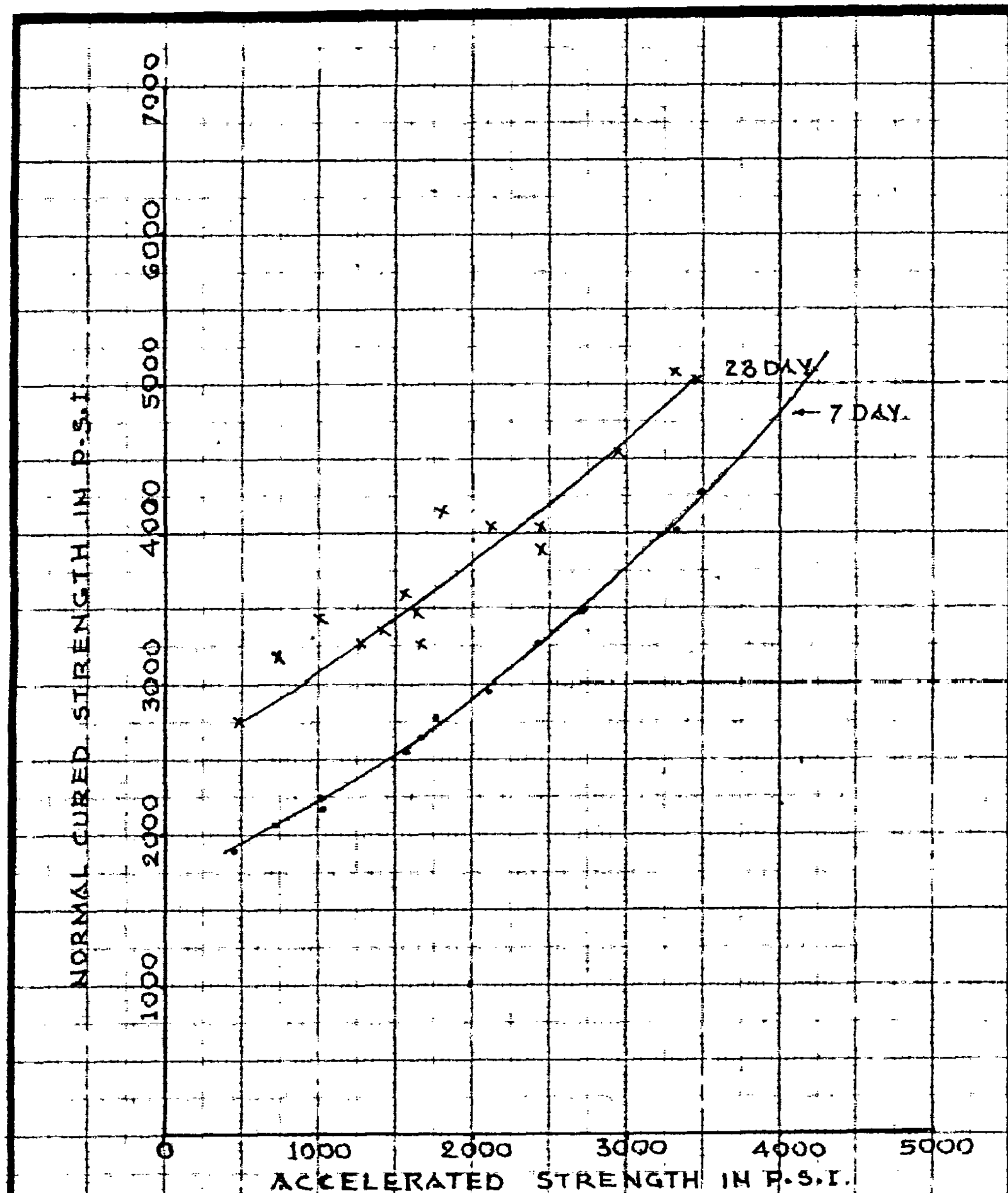


FIG. 51.

RESULTS OF 6 HOURS STEAM CURING AT 60 P.S.I. AGAINST NORMAL CURED STRENGTHS.

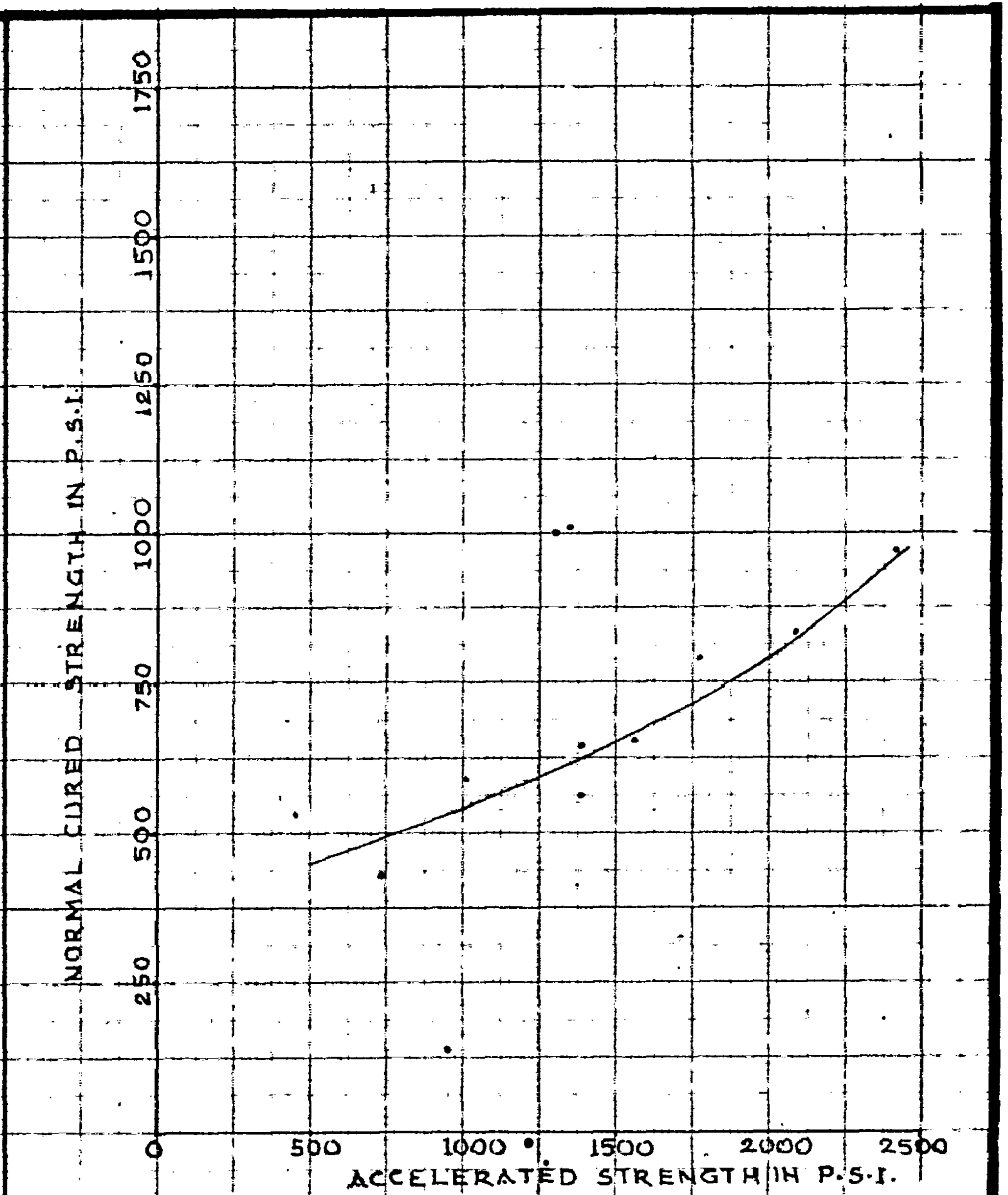


FIG. 52

RESULTS OF 6 HOURS STEAM CURING AT 60 P.S.I. AGAINST 6 HOURS OF NORMAL CURING AFTER 20 HOURS IN MOULD.

TABLE No.39

Results of 6 hrs. Steam Curing at 80 P.s.i. above Atmosphere.

Waiting time- 20 hrs.
Heating time- 6 hrs.
Cooling time- 1 hr.

Cubic size- 4"
Temp.of water- 160.1°C

Sr. No.	Mix No.	Acc.Strength		7-day Strength		28-day Strength		Acc.Strength as %age of	
		p.s.i.	kgm/cm²	p.s.i.	kgm/cm²	p.s.i.	kgm/cm²	7day	28day
1	D	3827	269.0	3360	237.5	4730	333.3	114.0	81.0
2	O	3550	249.6	3279	231.2	4661	326.3	108.2	74.6
3	E	2625	184.5	2678	188.7	3796	267.4	97.8	69.2
4	Q	2345	165.0	2464	173.8	3932	275	94.7	59.6
5	F	2264	159.2	2451	172.9	3378	252.8	92.5	67.0
6	S	1720	121.0	2240	158.0	3416	241.5	76.8	50.3
7	E'	900	63.3	1917	135.2	3338	235.7	46.9	26.8
8	F'	1100	77.4	1917	135.2	2756	194.8	57.2	39.9
9	P	2825	198.6	2782	196.1	4200	295.9	100.2	67.2
10	J	3700	260.0	3295	232.6	4064	286.3	112.1	90.5
11	B	2380	167.2	2571	181.2	3633	256.7	92.7	65.5
12	B'	3140	221.0	2968	209.3	4070	288.0	105.7	77.2
13	I	885	62.4	1811	127.10	2837	200.1	48.8	31.2
14	K	1736	122.1	2198	155.0	3472	245.4	78.8	50.0
15	T	1355	95.2	2072	146.2	3217	226.9	65.5	42.1
16	A'	3643	256.0	3300	233.9	4611	325.0	110.0	79.0
17	D'	2625	184.2	2670	188.1	3486	246.2	98.5	75.6

TABLE No. 40

Results of 6 Hrs. Steam Curing at 80 p.s.i. above Atmosphere compared with 6 hrs. of Normal Curing.
(4" cube used)

Sr. No.	Mix No.	Acc. Strength P.s.i.	Acc. Strength kgm/cm²	Normal Strength P.s.i.	Normal Strength kgm/cm²	Acc. as %age of Normal Strength.
1	E	2625	184.5	532	37.4	494.0
2	F	2264	159.2	560	39.4	404.5
3	I	886	62.4	455	32.0	194.7
4	J	3700	230.0	508	35.7	750.0
5	K	1736	122.1	550	38.6	316.0
6	O	3550	250.5	820	57.9	433.0
7	P	2826	198.5	786	55.2	360.0
8	Q	2346	165.0	652	45.8	360.0
9	R	2380	167.2	656	46.1	363.5
10	S	1720	121.0	600	42.2	286.8
11	T	1355	95.2	420	29.6	322.5
12	A'	3643	256.0	975	68.6	374.0
13	B'	3140	221.0	825	58.0	381.0
14	D'	2625	184.2	1246	87.6	210.5
15	E'	900	63.3	474	33.4	189.6
16	F'	1100	77.4	529	37.2	208.0

5.18.2.3. Results of steam curing at 120 p.s.i. show that the strength compared to 7-day gives about 30% more than the 7-day normal strength and approximately 28-day normal strength. As the normal strength increases accelerated strength expressed as percentage of the normal strength increases. The accelerated strength was compared with the normal curing of the same period and the results are given in Table No.42 and Fig. No.53. The accelerated strength expressed as percentage of normal strength varies from 334% to 607 %. The higher percentage for the richer mix. This curing period of 6 hours at 120 p.s.i. above atmosphere (i.e. 134.7 p.s.i. absolute) gave the maximum strength.

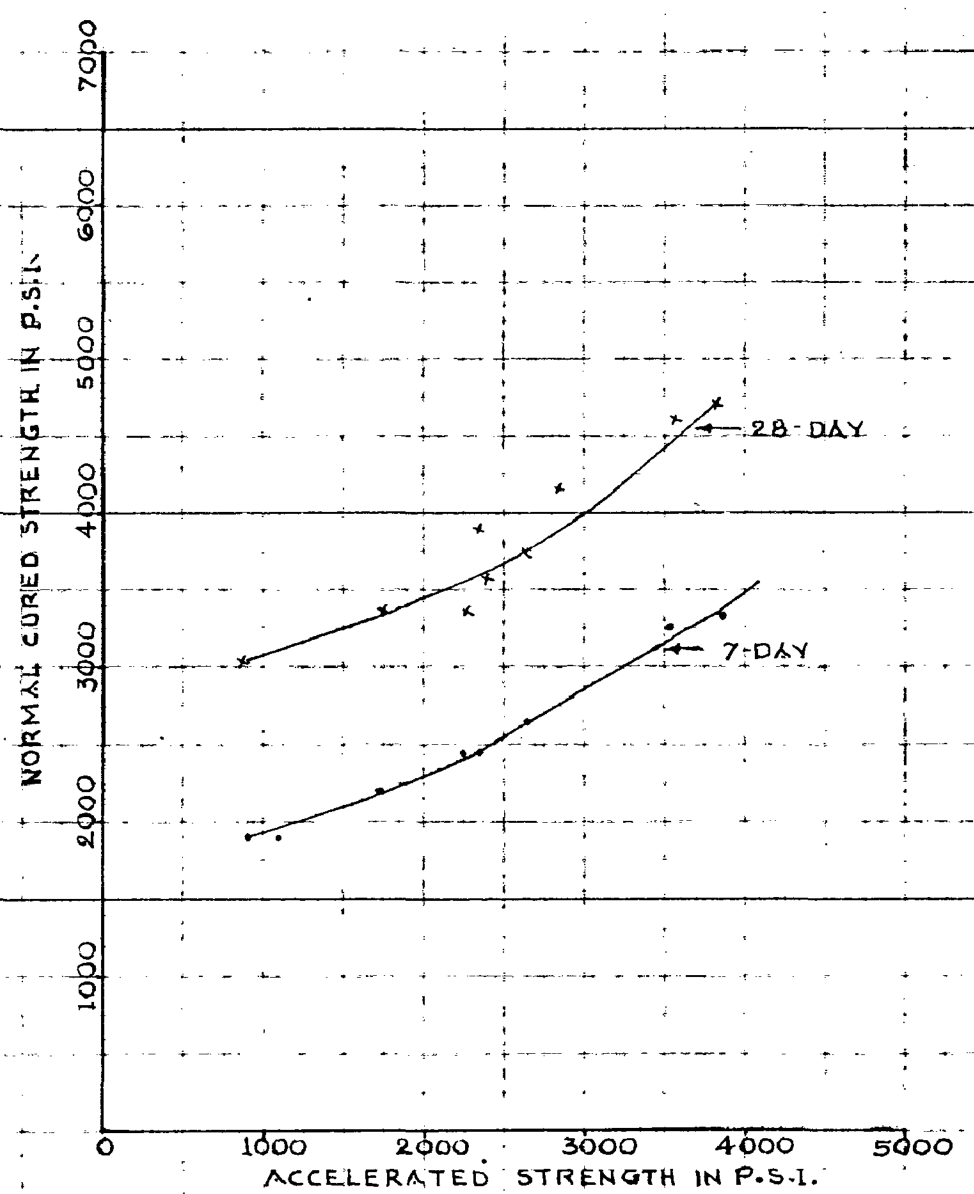


FIG 53

RESULTS OF 6 HOURS STEAM CURING AT 90 P.S.I AGAINST NORMAL CURED STRENGTHS.

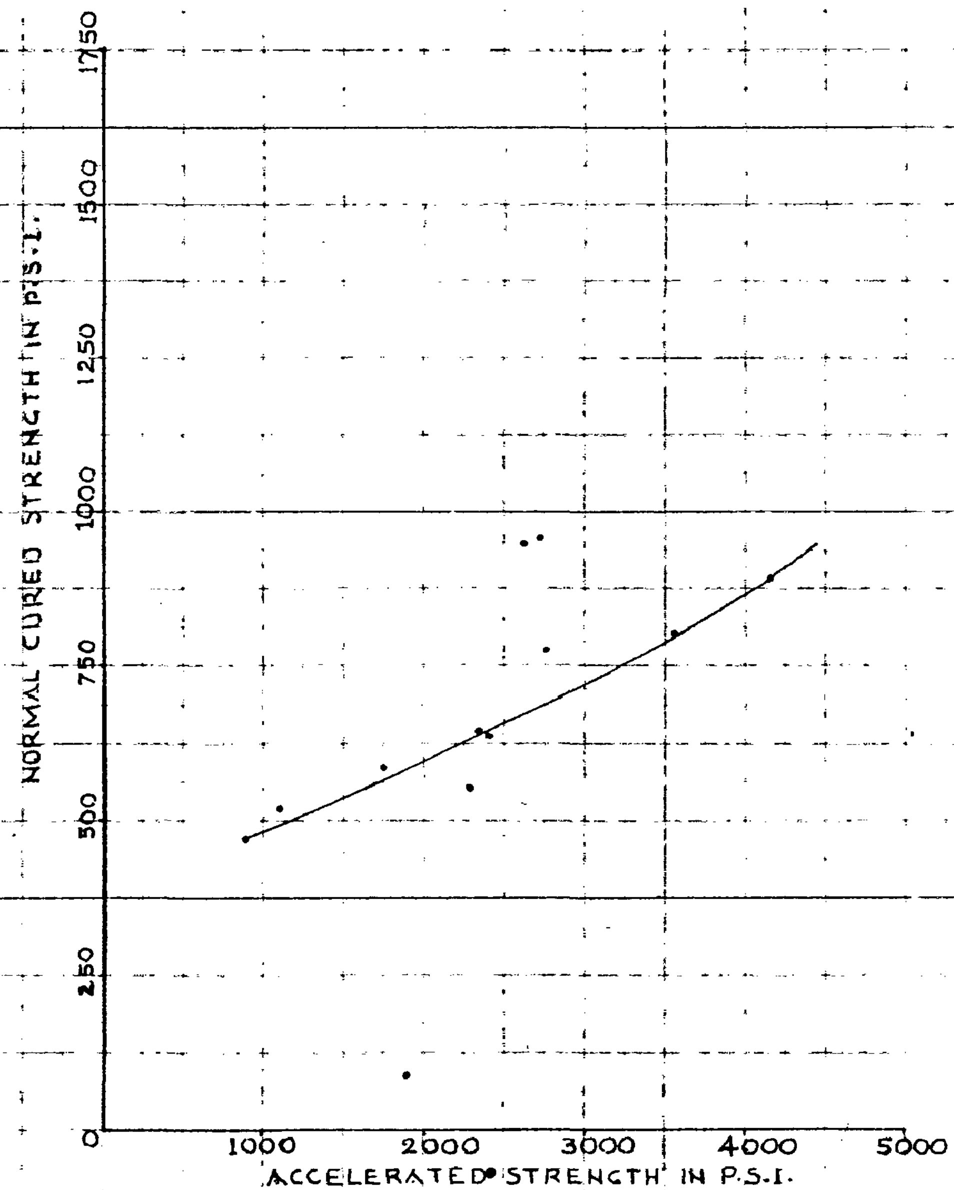


FIG. 54

RESULTS OF 6 HOURS STEAM CURING AT 90 P.S.I. AGAINST 6 HOURS OF NORMAL CURING AFTER 20 HOURS IN MOULD.

5.18.2.3. Results of steam curing at 120 p.s.i. show that the strength compared to 7-day gives about 30% more than the 7-day normal strength and approximately 28-day normal strength. As the normal strength increases accelerated strength expressed as percentage of the normal strength increases. The accelerated strength was compared with the normal curing of the same period and the results are given in Table No.42 and Fig. No.63. The accelerated strength expressed as percentage of normal strength varies from 334% to 687 %. The higher percentage for the richer mix. This curing period of 6 hours at 120 p.s.i. above atmosphere (i.e. 134.7 p.s.i. absolute) gave the maximum strength.

TABLE NO. 43.

Results of 6 hrs. Steam Curing at 120 P.s.i. above Atmosphere.

Waiting time- 20 hrs.
Heating time- 6 hrs.
Cooling time- 1 hr.

Cube size- 4" size.
Temp. of water-171.0°C

Sr. No.	Mix No.	Acc. Strength		7-day Strength		28-day Strength		Acc. Strength as % age of	
		p.s.i.	kgm/cm2	p.s.i.	kgm/cm2	p.s.i.	kgm/cm2	7day	28 day
1	E	3575	251.2	2678	188.7	3790	267.4	130.6	94.3
2	F	3050	214.5	2451	172.0	3570	252.0	124.0	90.2
3	I	2220	156.0	1811	127.1	2857	200.1	122.7	80.0
4	J	4000	281.2	3295	232.0	4061	284.3	121.2	98.3
5	K	2929	206.0	2133	150.0	3472	244.4	133.2	84.5
6	L	1646	115.8	1418	100.1	3037	213.6	116.2	54.2
7	O	4370	308.0	3270	231.2	4631	324.3	133.9	93.5
8	P	3575	251.5	2702	190.1	4200	295.9	132.0	87.5
9	Q	3275	230.0	2461	173.8	3932	275.0	133.0	83.3
10	R	3375	238.0	2571	181.2	3633	255.7	131.3	93.0
11	S	3003	211.5	2290	160.0	3416	241.5	131.1	88.1
12	T	2675	188.0	2073	146.2	3217	226.9	129.2	83.3
13	A'	4263	300.0	3303	232.0	4611	325.0	132.3	91.8
14	B'	3989	283.5	2983	209.0	4070	286.0	132.2	96.6
15	D'	3463	243.5	2670	188.1	3496	246.2	130.0	99.6
16	E'	2660	187.0	1927	136.2	3338	235.7	138.4	79.7
17	F'	2620	184.0	1917	135.2	2754	194.8	136.6	95.3

TABLE NO.42.

Results of 6 hrs. Steam Curing at 120 p.s.i. above Atmosphere compared with 6 hrs. of Normal Curing.
(4" cube used)

Sr. No.	Mix No.	Acc. Strength p.s.i.	Acc. Strength kgm/cm^2	Normal Strength p.s.i.	Normal Strength kgm/cm^2	Acc. Strength as %age of N. Strength.
1	E	3575	251.2	532	37.4	674.0
2	F	3050	214.5	560	39.4	545.0
3	I	2220	156.0	455	32.0	488.0
4	J	4000	281.2	508	35.7	787.0
5	K	2928	206.0	550	38.6	533.0
6	L	1645	115.8	342	24.1	481.0
7	O	4375	308.0	810	56.9	538.0
8	P	3675	258.5	785	55.2	468.0
9	Q	3275	230.0	652	45.8	500.3
10	R	3375	238.0	656	46.1	514.0
11	S	3005	211.5	600	42.2	501.0
12	T	2675	188.0	420	29.5	637.0
13	A'	4235	298.0	975	68.6	434.0
14	B'	3930	286.5	825	58.0	476.0
15	D'	3465	243.5	1245	87.5	278.5
16	E'	2660	187.0	474	33.4	562.0
17	F'	2620	184.0	529	37.2	494.5

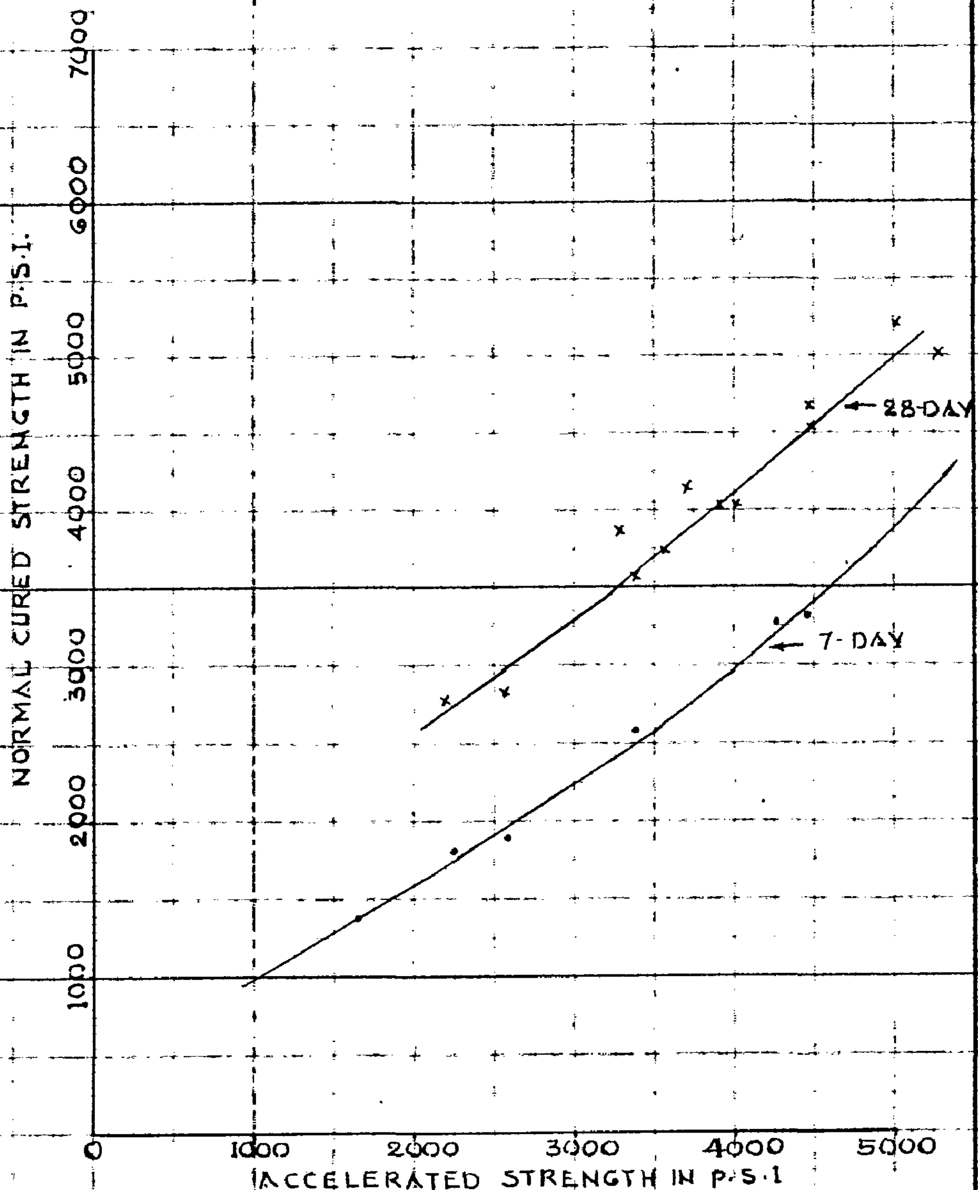


FIG. 55

RESULTS OF 6 HOURS STEAM CURING AT 120 P.S.I. AGAINST NORMAL CURED STRENGTHS.

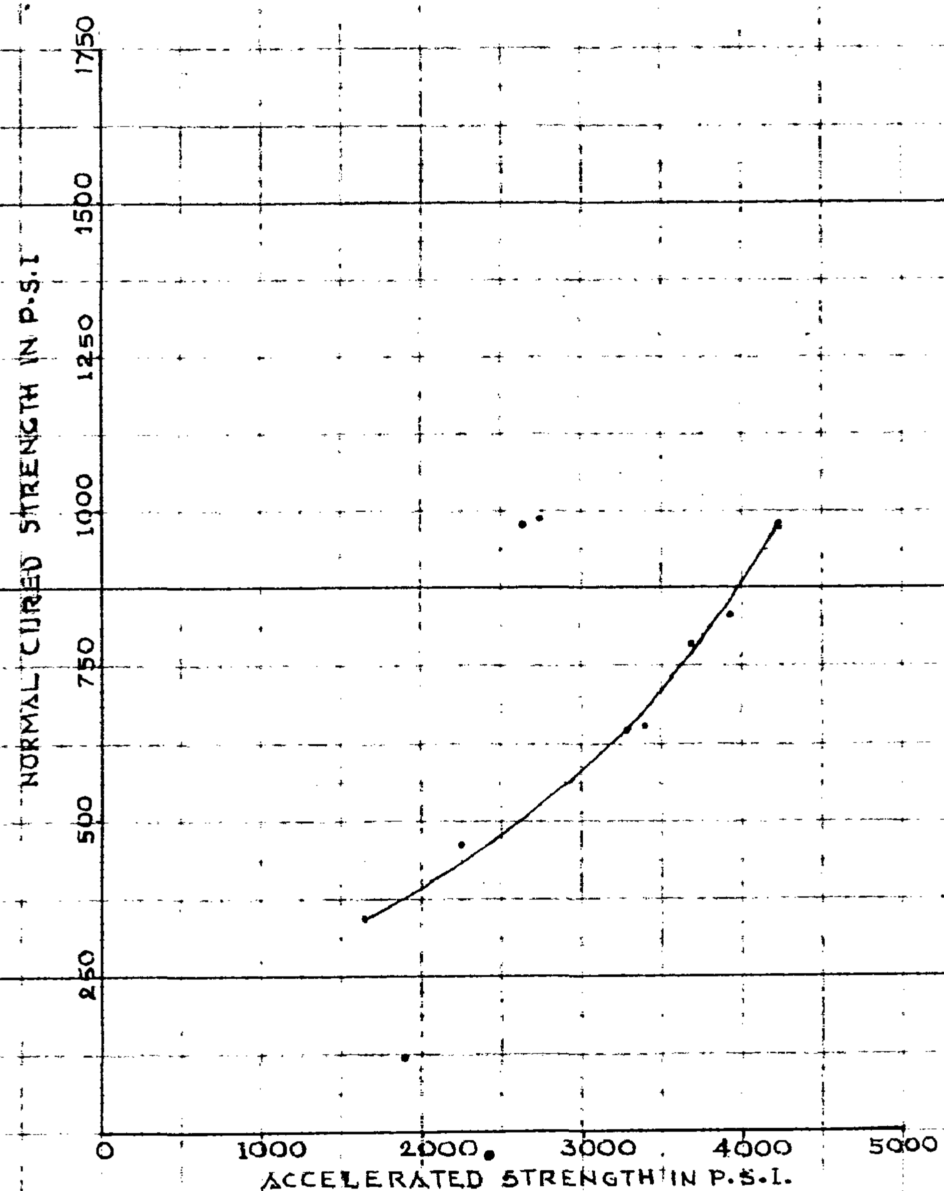


FIG. 56

RESULTS OF 6 HOURS STEAM CURING AT 120 P.S.I AGAINST 6 HOURS OF NORMAL CURING AFTER 20 HOURS IN MOULD.

CHAPTER VI

ELECTRICAL CURING

6.1. In cold countries where the temperature in winter reaches several degrees below zero the concreting is difficult to handle. The concrete will freeze due to the lower temperature and there will not be appreciable gain in strength. To overcome these difficulties either aggregates and water are heated or salt or chemicals are mixed with the concrete. In severe winter conditions, methods like heating the components do not go far in preventing freezing.

The most common practice is the construction of temporary hutting around the projected building. The air inside may be heated by coal or coke braziers. The mixing water is heated to [illegible]°C and concrete mix is conveyed to the site in well insulated containers. This method is economical when the work is concentrated e.g. multi-storeyed buildings, heavy structures etc., where the concrete volume per unit of floor area is small. The structure can be projected by providing double moulds between which hot air or steam is blown as soon as the concrete is casted.

Another method of dealing with wide extensive structures is by precasting. Precast members are preferably manufactured in central shops, using mechanical equipment to accelerate the hardening of the concrete and to improve its quality. Heavy members are cast in horizontal position on the concrete floor near the place of their final position and are protected against frost by small movable tents which are heated by coke braziers. The erection of precast units is independent of temperature conditions, the joints being made by permanent metallic or temporary wooden connections. Reinforced concrete joints are usually casted later when weather conditions are favourable.

Steam or allied methods of curing suffer from the disadvantage of setting up steep temperature gradients during the process of setting and from the difficulty of applying these methods to massive structures like concrete roads, dams etc.

In order to prevent these difficulties electrical curing of concrete was first tried in Sweden in 1922-23 by Brand and Dohl[33] and it was utilised in Russia[14] and Japan[15] to heat the concrete structures. The current was passed in freshly prepared concrete to develop heat and thus accelerating the process of curing.

6.2. PRINCIPLE

Following matter deals with the principle on which the concrete treatment is based. Wet green concrete is to a certain extent electroconductive and current passes through it depending upon the voltage applied. Owing to the inherent resistance of the concrete, the electric power is transformed into heating according to Jule's law and the internal temperature of the cold concrete is raised. This may be supplemented to some extent by heat of hydration. This increase in temperature accelerates the setting and rapid hardening of the concrete. The conductivity of the concrete to the electric current is attributed to the moisture content of the concrete. Current is passed through the green concrete by introducing into it two or more poles, the circuit being closed by the fresh concrete itself. Only alternating current can be used for this purpose, because direct current affects a decomposition of the water by electrolysis.(9)

6.3. ELECTRODES.

6.3.1. Type of Electrodes.

Usually two type of electrodes are used, surface electrodes consisting of strips of galvanised steel, and internal electrodes made up of round steel bars, put into the concrete.

When internal electrodes are used the spacing of stirrups and reinforcement hooks has to be adjusted to prevent short circuits. Longitudinal or cord electrodes are simple in erection and yield an even distribution of temperature. Pin electrodes are inserted into the concrete in the transverse direction. They are small bars, usually made from reinforcement waste.

6.3.2. Design of Electrodes.

The electrodes are designed for the current capacity. It was found that if current passing through the electrodes was beyond the optimum limit, the electrodes got heated excessively and that the concrete immediately in contact with the electrodes got heated first. This shuts of the interior portion of the concrete block to the effects of the current, as the hardened concrete has a poor conductivity and the electrodes are put out of the circuit.[14] Some investigators,[9,14] showed that the current intensity in the surface electrodes should not be more than about one ampere per 10 sq.in. (1.5 ampere per sq.dm.) and that for internal electrodes it should not be more than 1 ampere per 6 sq.in. (3 ampere per sq.dm.).

All calculations in the design of an electrode scheme should be regarded as rough and approximate as they are made with assumed values of the electro-resistivity of the concrete, which is of the order of 1000 to 2000 ohm. per dm. per sq.dm.

6.3.3. Metal For Electrodes.

The electrodes may be used in different forms according to the purpose and type of structures. As regards the metal of the electrodes, any metal will be equally efficient provided it withstands the conditions of curing. As regards copper it was found[9] that as the contact resistance between electrodes and concrete increases, a small direct current passes. Galvanised iron sheets are satisfactory and quite cheap.[9]

6.4. TEMPERATURE PATTERN.

The electric-treatment of the concrete is characterised by the variation of temperature. Temperature regime varies within wide range during the time from switching on the current until the concrete has cooled down. It also depends on the voltages applied. As the voltage applied across the specimen goes on increasing the rate of temperature rise as well as the maximum temperature goes on increasing as shown in Fig. No.57. At low voltage e.g.30V or 40V, the temperature time curves are nearly horizontal. After 12 hours of treatment all curves come to close and at about 24 hours reaches the minimum temperature[9]

According to Russian[30] instructions the highest temperature of the regime should at no time exceed, for massive structures 70°C, during the first 24 hours of heat treatment. The rate of temperature rise should be even and limited to a maximum of 6°C/hour which can be increased to 10°C per hour in a second step, i.e. after 20 hours of heat treatment. The duration of active treatment should not exceed 30 hours. The cooling down process should last for not less than 24 hours. This will give an area mounting to 2500-2600°C-hrs. A portland cement concrete which absorbed this quantity of heat had attained 60% to 70% of the designed 28-day strength.[14]

If the structures are thinner, the maximum temperature limit should be 80°C and the time required will be more. The number of degree-hours required for electro-treatment comprises of two portions.

(1) That absorbed during the active electro-treatment, which may be varied as required by the circumstances within sufficiently wide limits.

(2) That absorbed during the cooling down process which is a function of the thermal emissivity, the shape of the structure and moulding, the insulation

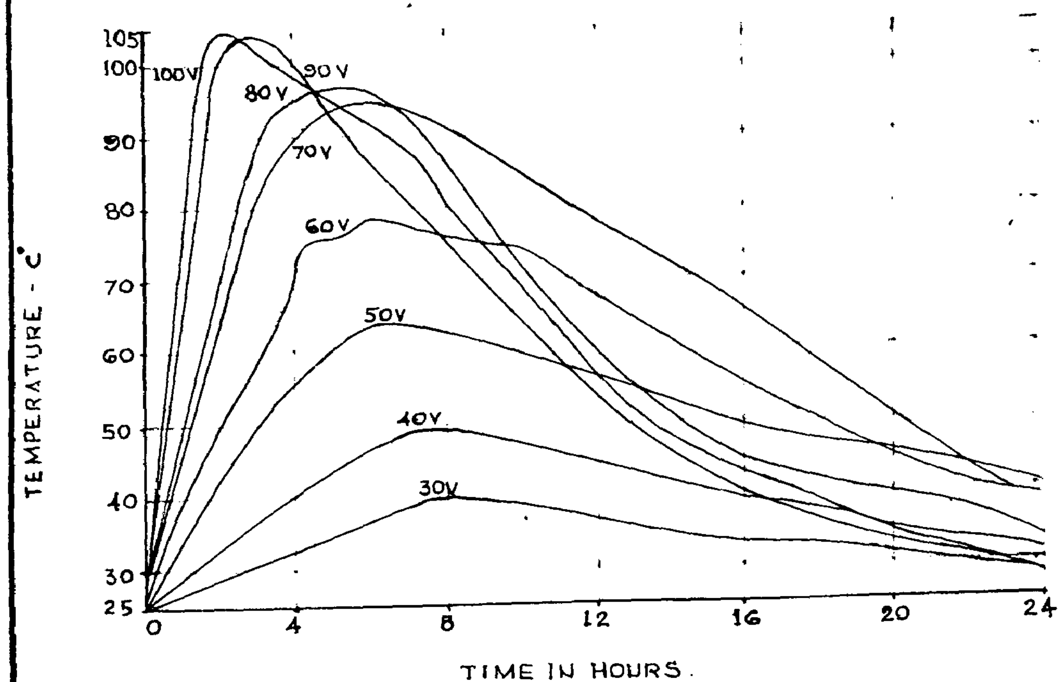


FIG.57.

TEMPERATURE-TIME RELATIONSHIP IN THE ELECTRICAL CURING OF CONCRETE CUBES.

employed, and the temperature of the surrounding air.

6.5. ENERGY CONSUMPTION.

The energy consumption depends on the surface moduli of the structure, voltage and duration of the treatment. As the voltage goes on increasing both the rate as well as the total energy goes on increasing as indicated in Figure No.58. At lower voltages the rate is very low and the variation in the energy consumption is also slight. At higher voltages the curves become very steep. One particular feature was found that the curves are that they ascend for some time, dropping to a certain minimum value and again ascending finally reaching to a minimum value after 24 hours[9] as shown in Figure No.58. The energy consumed also depends upon the structures. It varies from 70 to 160 K.W.H. per cubic meter of concrete treated to 200 K.W.H. per cubic meter depending upon the type of structures.[14] Lower value are for massive structures. It also depends on the surface coefficient of the structure one cubic meter of concrete work with 6 moulds requires approximately 6 kilowatts while the same volume in 16 moulds and 28 moulds requires 10 and 14 kilowatts respectively.

6.6. COST.

The additional cost of electro-concrete varies mainly with the total quantity of concrete to be treated and with the daily output. An average figure is 25 to 30% of the cost of concrete for a regular daily output of 20 cubic meters with a minimum of 2500 cubic meters per year.

6.7. PROPERTIES OF CONCRETE.

6.7.1. Comp. Strength.

It has been found (see Fig. No. 59) that 60 volt is the optimum voltage required for an electro-concrete to attain maximum strength. If the voltage is increased, the strength of the concrete goes on decreasing till a minimum strength is reached at 100 volts. In an investigation[9] the specimens cured for 24 hours, revealed that it gives roughly 7-day normal cured strength.

6.7.2. Tensile Strength.

For tensile strength, the maximum voltage was found to be 80 volts and strength was approximately equal to 1/10 of the compressive strength for almost all voltages applied across control specimens[9] (See Fig. No.60)

6.7.3. BOND STRENGTH.

The effect on bond strength was found by casting 6"x6"x8" blocks with one central mild steel rod (1/2" dia.) inserted along the longitudinal direction, projecting 5" on one side and 2'6" on the other side[9]. They were subjected to pull out test in the tensile testing machine of 10 ton capacity. The load which produces a slip of 0.001" was called the bond

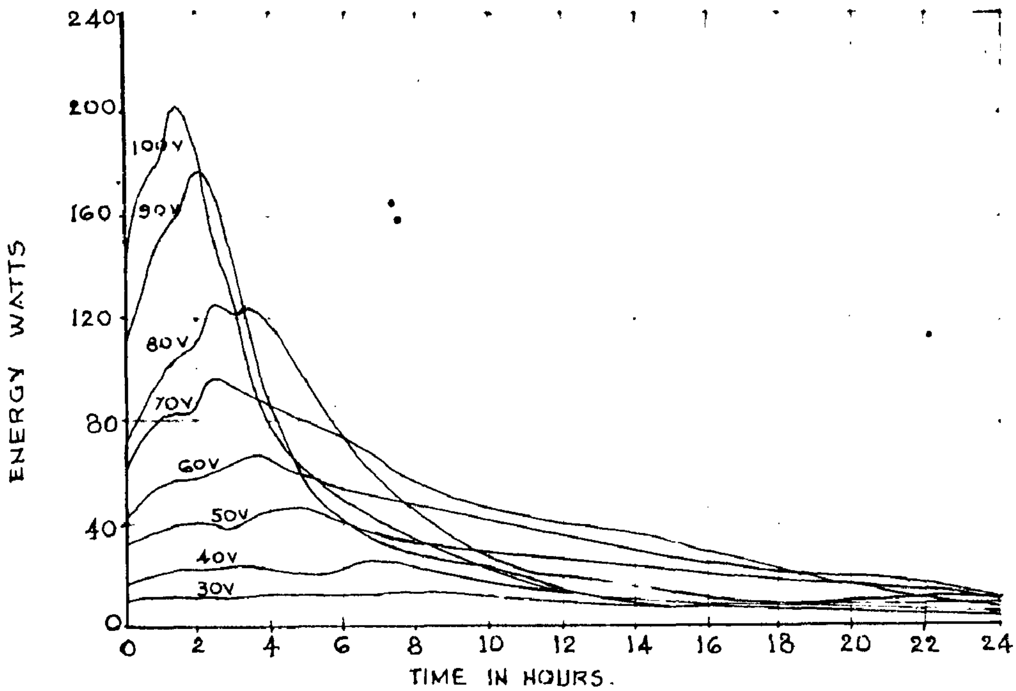


FIG. 58

ENERGY - TIME RELATIONSHIP IN ELECTRICAL CURING OF CONCRETE CUBES.

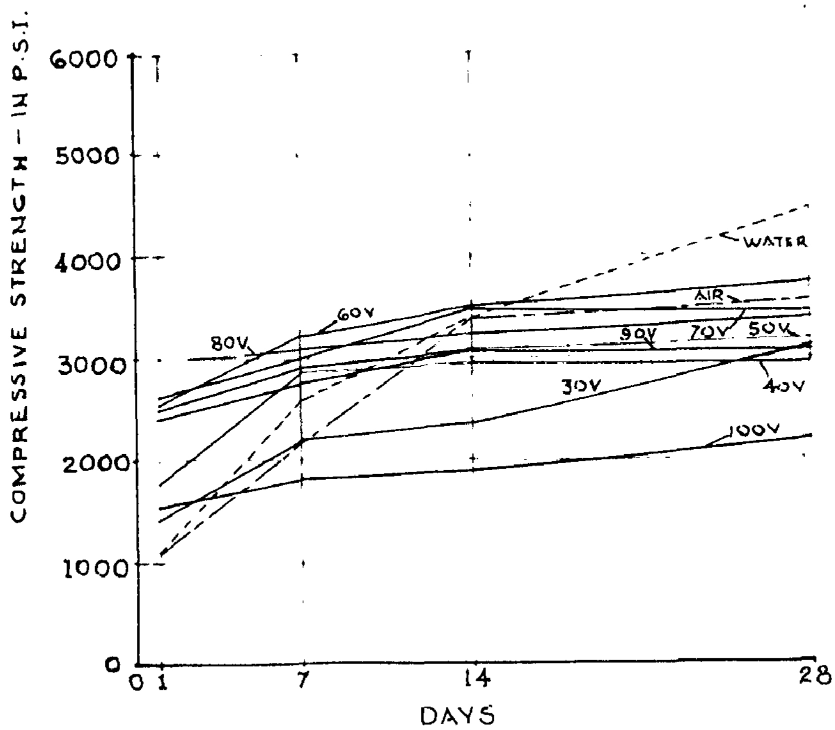


FIG. 59

COMPRESSIVE STRENGTH OF ELECTRICAL CONCRETE CUBES.

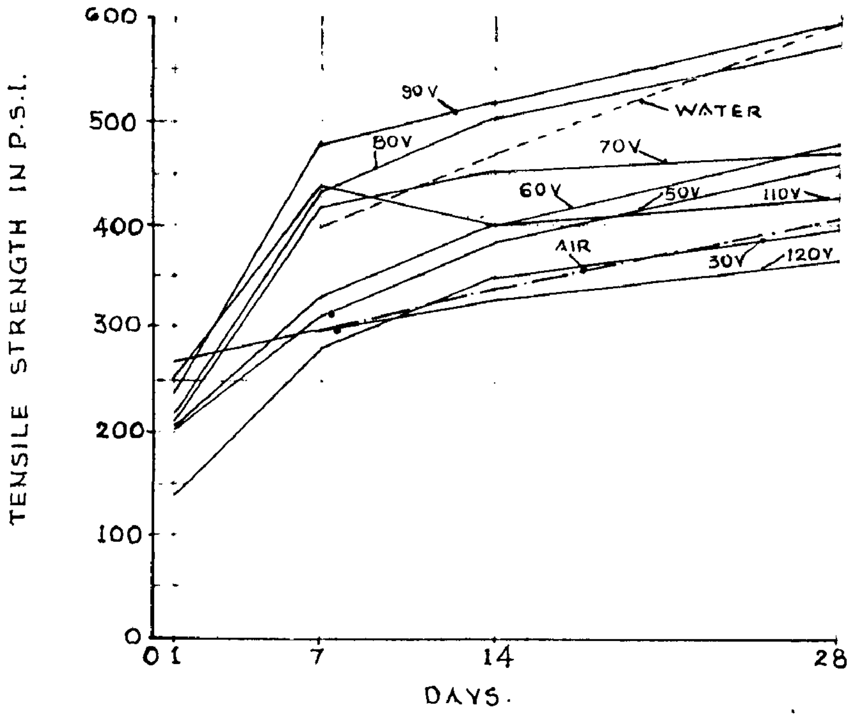


FIG. 60.

TENSILE STRENGTH OF ELECTRICAL CURED CONCRETE.

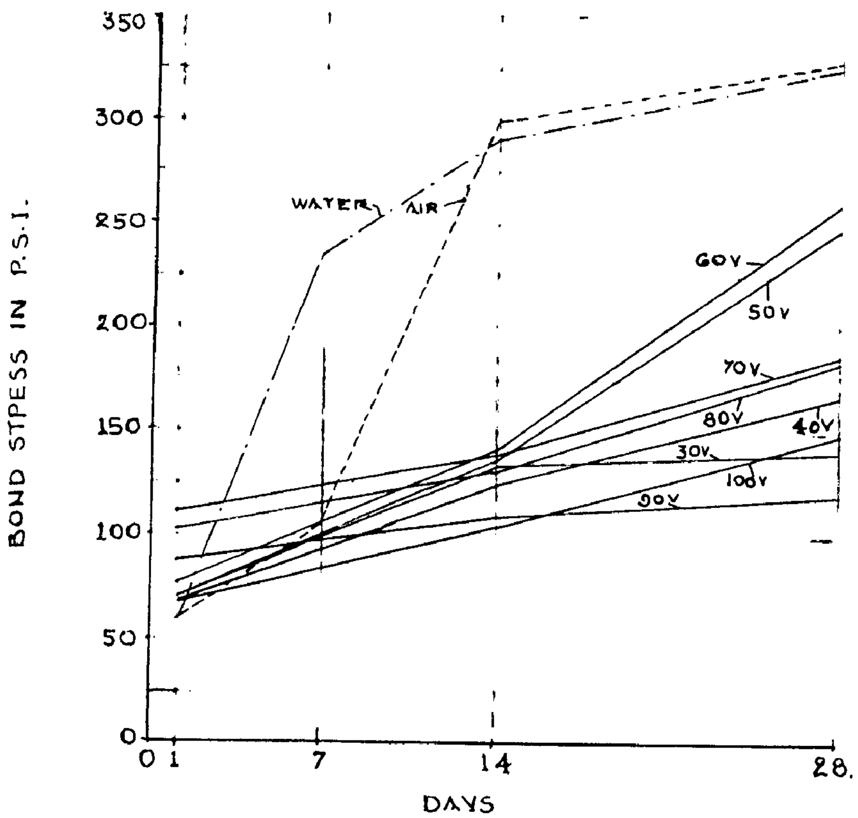


FIG. 61

BOND STRENGTH OF ELECTRICALLY-CURED CONCRETE.

strength of the concrete. This divided by the surface area of the embeded portion of the rod gave the bond stress. Bond strength goes on increasing with voltage, reaches a maximum and then falls having optimum voltage as 60 volts. The results are reproduced in Fig. No.61. The bond strength of concrete was less than the ordinarily cured concrete. Thus, electric curing has got an adverse effect on the bond strength.

6.7.4. Shrinkage.

The drying shrinkage depends on various factors such as type of aggregate, size of the aggregate, w/c ratio etc. The results indicate that the percentage shrinkage goes on decreasing with the rise in voltage. This means, if the concrete specimen is treated at higher and higher temperatures, the percentage shrinkage would be very low.

6.7.5. Miscellaneous.

As w/c ratio rises, the rate as well as the maximum temperature goes on increasing, and may reach the boiling point of water in some cases. The energy consumption also increases in the same order as the temperature.

. . . . Permeability.

It has been found that, permeability goes on decreasing as the voltage goes on increasing , till it reaches an optimum value of at 110 volts, after which it again rises.

6.8. DEFECTS.

The structural design of reinforced concrete buildings to be erected in electro-concrete has to be carefully checked and often requires amendments to the shape, reinforcement and moulds of various members, the types of electrodes to be used and their spacing, can be decided upon only in connection with the detailed reinforcement drawings, in order to avoid interference between the electrodes and reinforcement. As this method is quite expensive in comparison with the usual methods whenever possible, preference should be given to the cheaper methods. This can be advantageously applied to structures which are neither too massive nor too slender.

6.9. CONCLUSIONS.

Conclusions about electric curing of Bohin and Brund[30], Billig Curt[14] and Prof. Govind Rao[9] can be summarised as follows:-

(1) The rate of temperature increase and its maximum value are functions of voltage for a fixed mix, w/c ratio and spacing of electrodes.

(2) The leaner the mix and smaller the proportion of sand to aggregate, the higher the electro-resistivity of the concrete.

(3) Concrete mixed with gravel aggregate has higher

than has concrete mixed with broken stone for any fixed mix, w/c ratio and spacing of electrodes.

(4) The strength of electrically cured concrete, after further storage in air goes on increasing.

(5) There is no definite relation between maturity and strength.

(6) For the same normal mix, and for smaller aggregates, a concrete of dry consistency has a higher resistivity than a concrete of wet consistency.

(7) The electro-resistivity of concrete probably varies in reciprocal proportion to the ratio of the nominal mix i.e. cement (sand + aggregate).

(8) The mild steel bars placed at right angles to the flow of current in the electrically cured concrete has no effect on the heat generation, in the concrete due to the passing of electricity. They behave as redundant members in concrete so far as electrical curing is concerned.

(9) There is an optimum voltage for maximum strength of electrically cured concrete for a particular mix, w/c ratio and electrodes spacing.

(10) The strength of electrically cured concrete rises with the rise in voltage upto optimum and then falls back.

(11) The maximum tensile strength is obtained at 78°C.

(12) The tensile strength of the ai..
specimens lies between 1/8 to 1/10 of the
strength of electrically cured concrete specimens.

(13) The bond strength of electrically cured concrete
after 28 days is less than that of either water
cured or air cured specimens.

(14) The mild steel reinforcing bars placed in the directio
of the flow of current in the electrically cured conc-
rete in the electrically cured concrete help to devel-
op more heat as compared to that developed in a spec-
imen having similar dimensions, with M.S. bars placed
at right angles to the flow of current and cured by
electricity under similar conditions.

(15) Concrete slabs upto 12" length can be cured by means
of generally available 220 volts power with a proper
arrangement of electrodes.

(16) Maximum permeability is obtained at 80°C.

6.10. Mixes adopted.

The mixes adopted for this curing with its normal stre
gth are given in Table No.15.

6.11. Cubes Tested.

Totally 175 cubes were cured at 60 volts.

6.12. CURING.

The cubes were casted in the usual manner but in wooden moulds to prevent short circuit. The optimum voltage as indicated by Prof. Govind Rao[6] was 60 volts for compressive strength and the temperature at the end of 24 hours attained by the cubes were near about room temperature. In present study, cubes were cured for 24 hours at 60 volts. Two thin galvanised plates were used as electrodes. The cubes were connected in parallel as shown in Fig. No.6.1. and a current was passed. The top face was covered with a thin coat of wax to prevent moisture evaporation. The temperature was measured at the centre of the cube at a regular interval of one hour. At the end of the curing period the moulds were stripped and cubes allowed to cool for half an hour. Then, they were tested for their compressive strength. Care was taken to see that the faces in which current was passed were not under machine.

The following heating cycle was adopted

Waiting time-	1/2 hr.
Curing time-	24 hours.
Cooling time-	1/2 hour.
Total	25 hours.

6.13. RESULTS.

6.13.1. The results of the accelerated curing are given in Table No.49 and Graph No.71. The curves are of same nature as given by the steam curing. The strength achieved in this case is less as compared to 24-hour oven and steam curing. As the normal strength was increasing, the accelerated strength approac

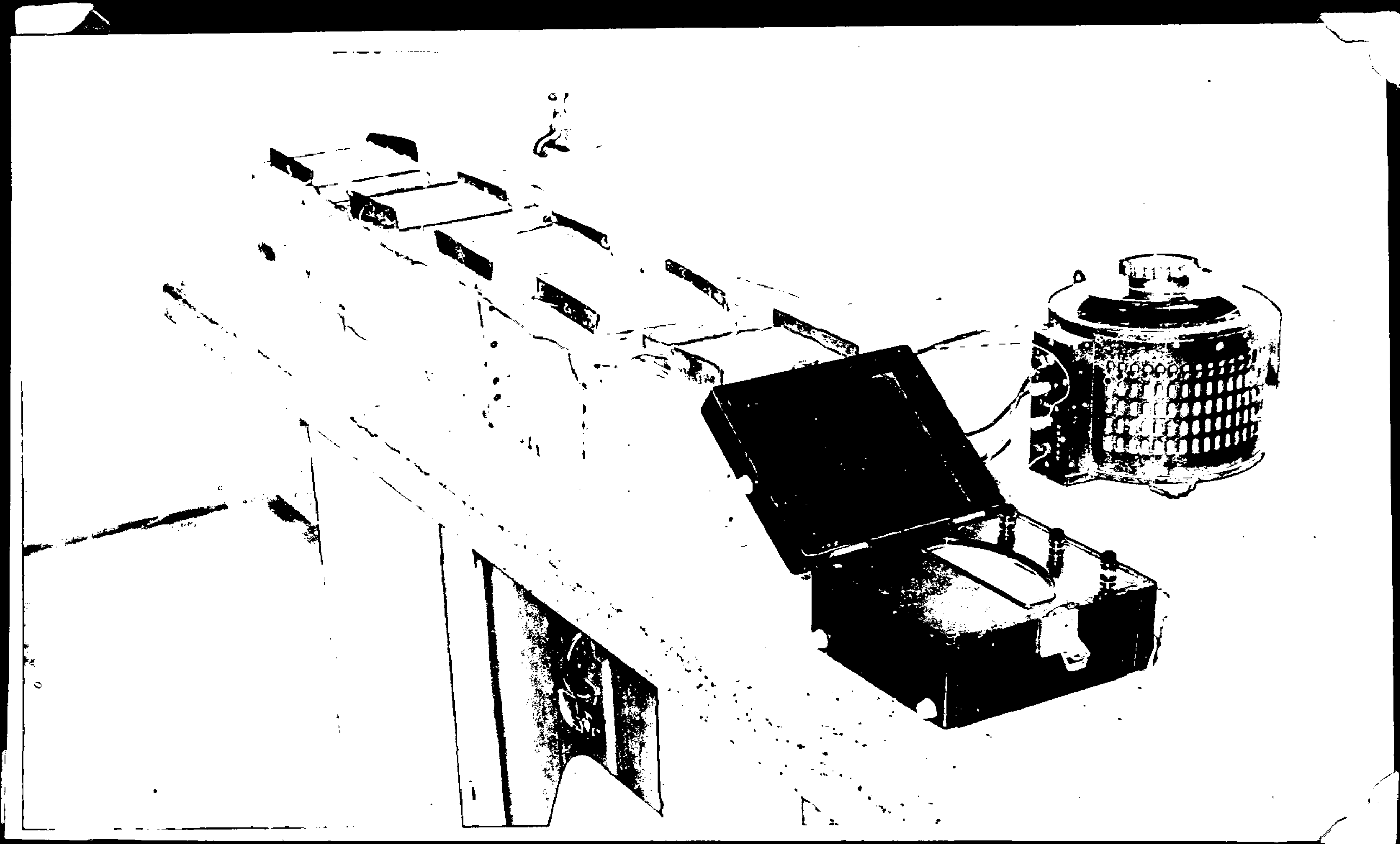


FIG. 6·1 ARRANGEMENT FOR ELECTRICAL CURING

TABLE NO.43

Results of 24 Hours Electrical Curing, at Constant Voltage of 60 Volts.

Sr. No.	Mix No.	Accelerated Strength lbs/sq.in	Accelerated Strength kgm/cm²	7day Normal Strength lbs/sq.in.	7day Normal Strength kgm/cm²	28 day Normal Strength lbs/sq.in.	28 day Normal Strength kgm/cm²	Accelerated Strength as % of 7 day	Accelerated Strength as % of 28 day.
1	W	3800	267.0	4265	300.7	5030	354.7	89.0	75.7
2	Y	3400	239.0	4045	285.0	5700	359.5	84.0	66.6
3	Z	4200	296.5	4430	312.2	5070	357.4	94.7	82.8
4	D	2182	153.5	3360	237.5	4730	333.3	65.0	46.2
5	O	2460	173.0	3279	231.2	4661	326.3	75.0	52.8
6	A'	2587	182.0	3300	233.9	4611	315.0	78.5	56.2
7	J	2763	194.3	3295	232.6	4064	286.3	84.0	68.2
8	P	1850	130.2	2782	196.1	4200	295.9	65.5	44.2
9	B'	2103	148.0	2968	209.3	4070	288.0	70.7	51.5
10	E	1639	115.2	2678	188.7	3796	267.4	61.2	43.2
11	Q	1730	121.8	2464	173.8	3932	275.0	70.2	44.0
12	C'	1418	99.5	2277	160.6	3784	266.5	62.3	37.5
13	K	1500	105.5	2198	155.0	3472	245.4	68.2	43.2
14	R	1850	130.2	2571	161.2	3633	256.7	72.0	50.9
15	D'	1863	131.0	2670	188.1	3485	246.2	69.7	60.3
16	F	1700	119.2	2451	172.9	3378	252.8	69.4	50.9
17	S	1325	93.2	2240	158.0	3416	241.5	59.2	38.8
18	E'	1170	83.2	1917	135.2	3338	235.7	61.0	35.0
19	L	600	42.2	1413	106.1	3037	213.6	42.4	19.8
20	T	880	61.8	2072	146.2	3217	226.9	42.4	27.4
21	F'	1100	77.0	1917	135.2	2756	194.8	57.3	39.9

TABLE NO.44

Results of 24 hours Electrical Curing at Constant Voltage of 60 compared with 24 hours of Normal Curing.

Sr. No.	Mix No.	Acc. Strength p.s.i.	Acc. Strength kgm/cm2	Normal Strength lbs/sq.in.	Normal Strength kgm/cm2	Acc. Strength as %age of N. Strength.
1	E	1639	115.2	892.0	62.7	183.7
2	F	1700	119.5	733.0	51.5	232.5
3	J	2709	190.3	1072.0	75.3	252.0
4	K	1600	112.5	656.0	46.2	229.0
5	L	600	42.2	404.5	28.4	148.0
6	O	2460	173.0	1129.0	79.4	218.0
7	P	1880	132.2	1088.0	76.4	173.0
8	Q	1730	121.8	843.0	59.3	205.0
9	R	1850	130.2	882.0	62.0	210.0
10	S	1325	93.2	794.0	56.0	166.8
11	T	850	61.0	652.0	45.9	135.0
12	A'	2537	182.0	1150.0	80.8	221.7
13	B'	2103	148.0	1030.0	72.4	204.0
14	D'	1863	131.0	816.0	57.4	228.5
15	E'	1270	89.2	580.0	40.6	218.0
16	F'	1100	77.3	673.5	47.3	163.3

as percentage of the normal strength was increasing. The percentage variation is not large as compared to other methods. This gives approximately 42.5% to 94.7% of the 7-day strength depending on the free water and aggregate ratio, and 27.4 % to 82.0% of the 28-day strength. The 28-day curve takes a sharp turn at normal strength of 4600 p.s.i.

6.13.2. The results of electrical curing were compared with the normal curing of the same period. Results are given in Table No. 44 and plotted as shown in Fig. No. 72. The relation is a straight line one. The gain in strength over normal curing is not much as compared to the steam and oven curing. The gain in strength over normal curing varies from 48% to 150%.

6.13.3. <u>Time-Temperature Curves.</u>

To find out the effect of temperature rise with the time, the temperature was measured at an interval of every half an hour for first few hours and then at an interval of three hours. The results are plotted and shown in Fig. Nos. 62 to 69. To compare with the rate and max. temperature reached the graphs are plotted for the constant w/c ratio. It is found that the maximum temperature is generally reached in 3 to 4 hours. The temperature rise depends on w/c ratio of the mix, as the w/c ratio decreases the maximum temperature increases. Also the minimum temperature rise is given between 60° to 70° except in few cases. The maximum temperature for a particular w/c ratio

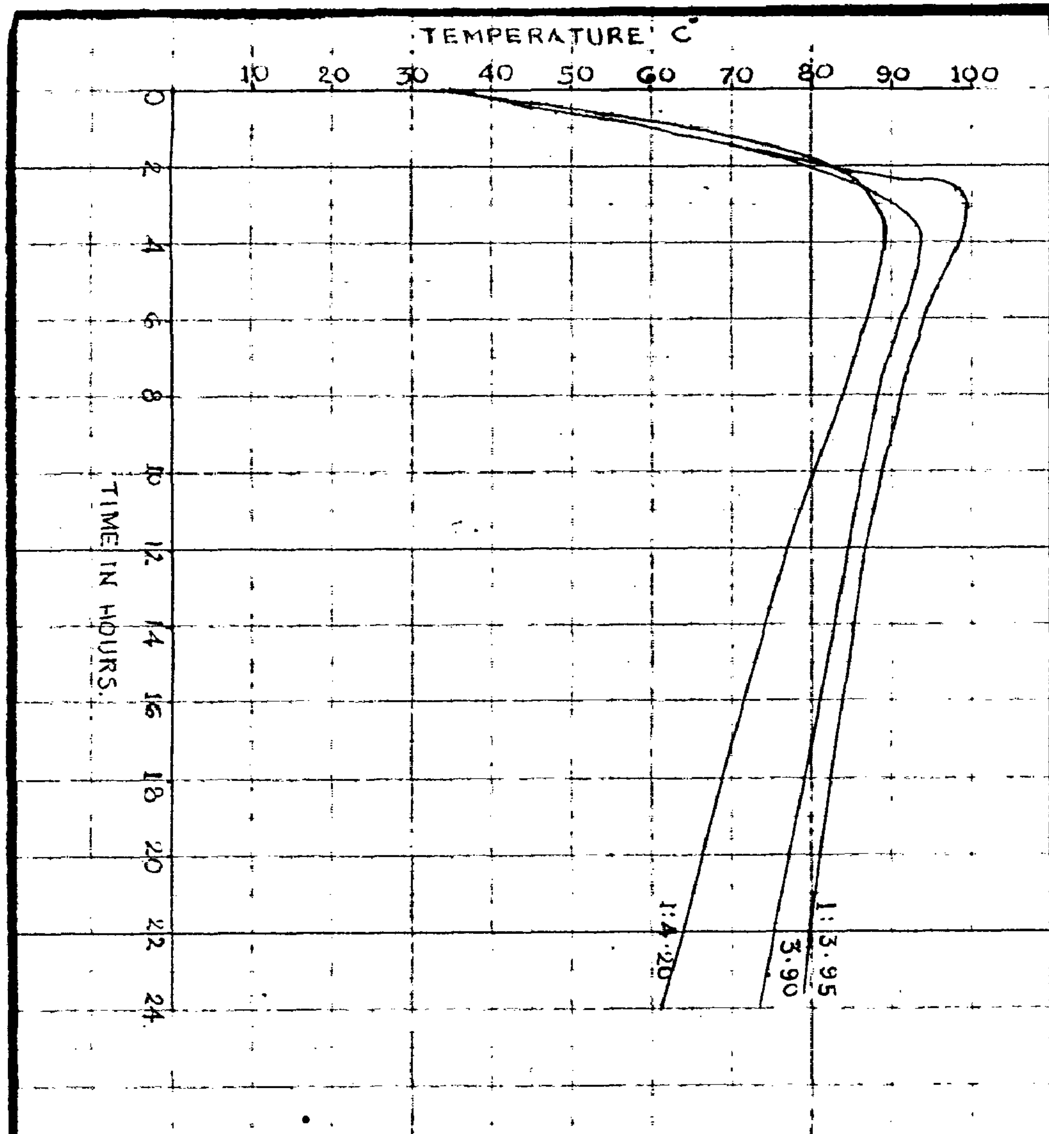


FIG. 62

EFFECT OF TEMPERATURE FOR A CONSTANT W/C RATIO FOR ELECTRICAL CURING OF CONCRETE.
W/C = 0·40 VOLT = 60

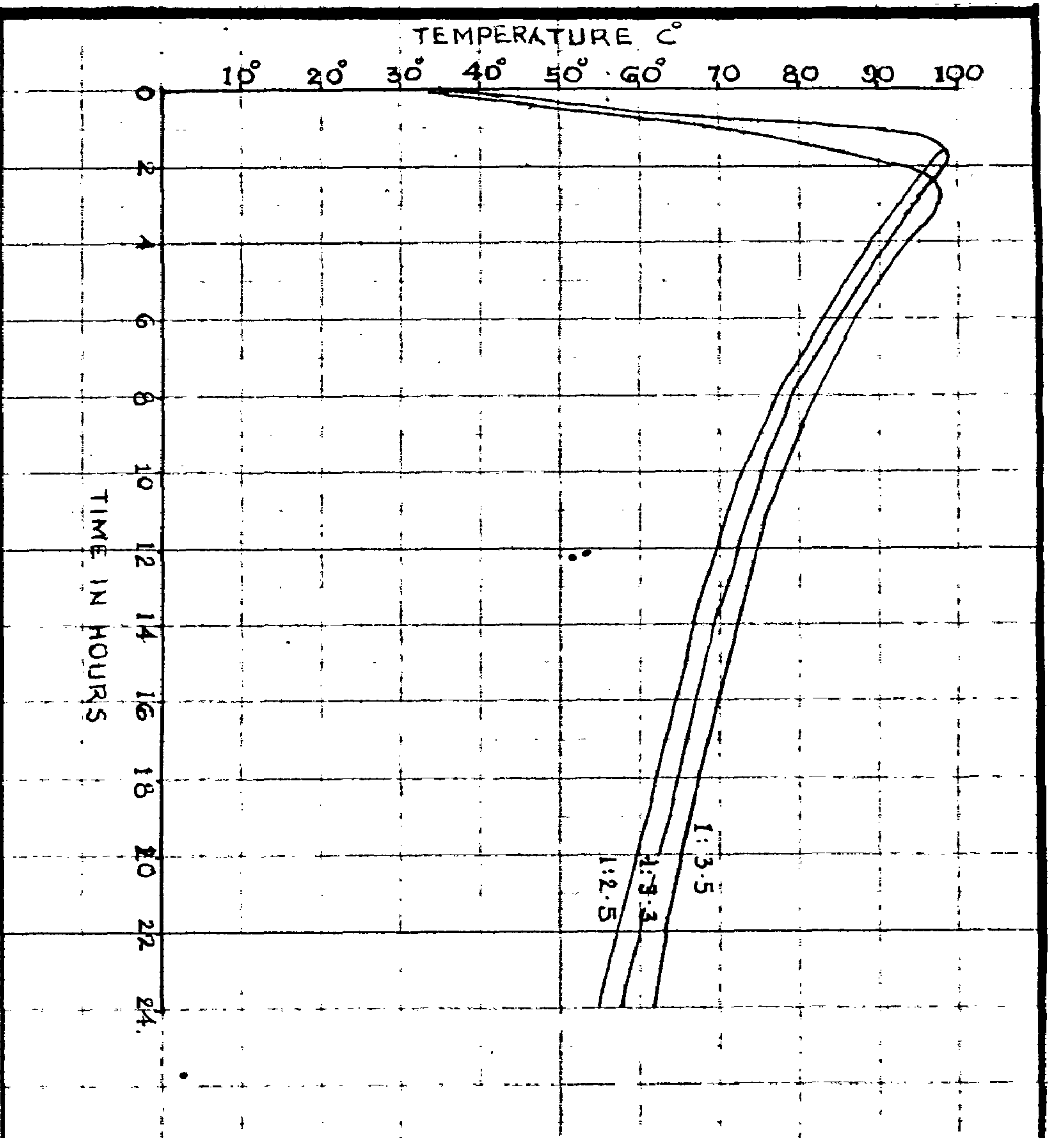


FIG. 63

EFFECT OF TEMPERATURE FOR A CONSTANT W/C RATIO FOR ELECTRICAL CURING OF CONCRETE.
W/C = 0·45 VOLT = 60

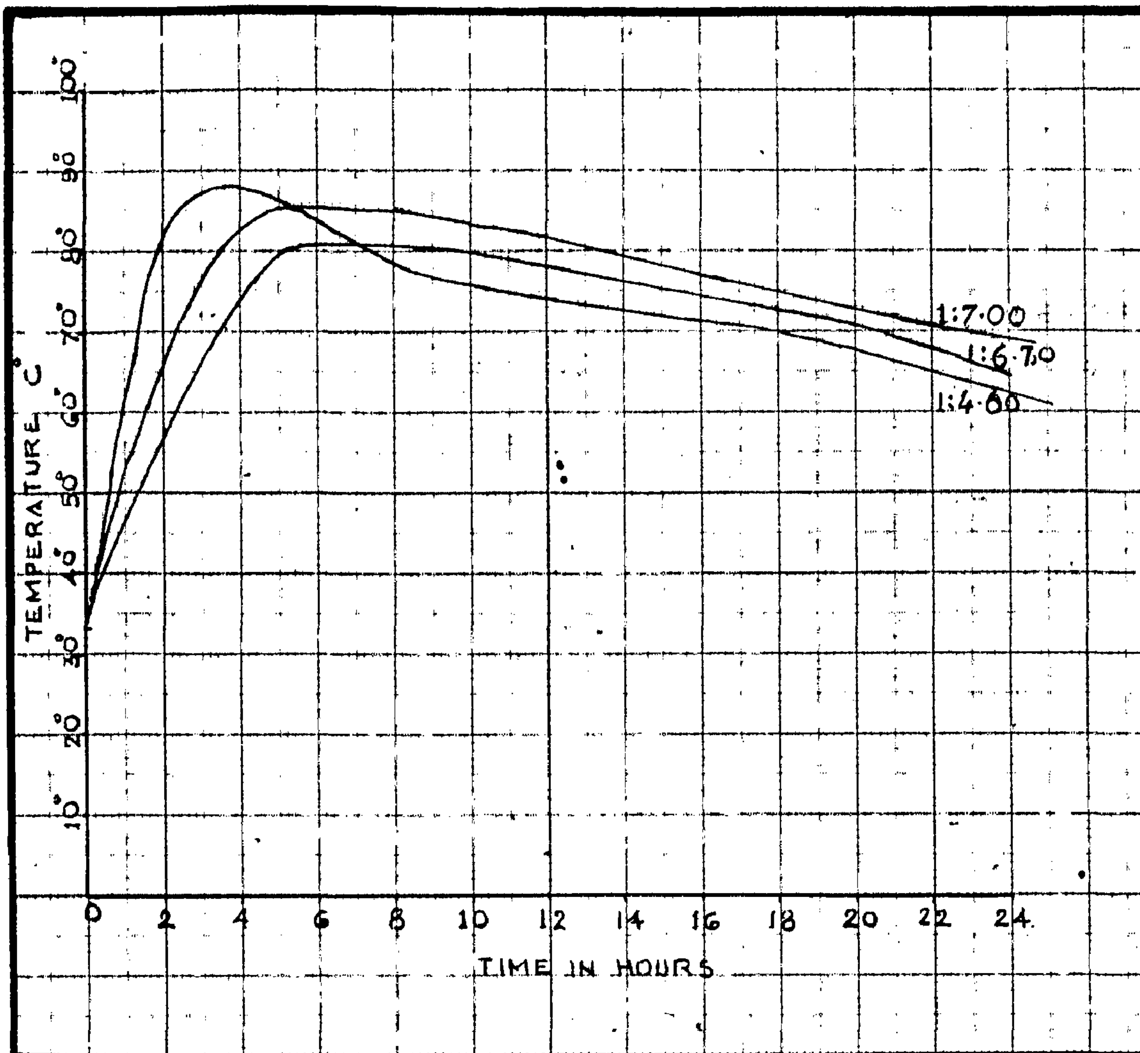


FIG. 65
EFFECT OF TEMPERATURE FOR A CONSTANT W/C RATIO FOR ELECTRICAL CURING OF CONCRETE.
W/C = 0.55 VOLT = 60

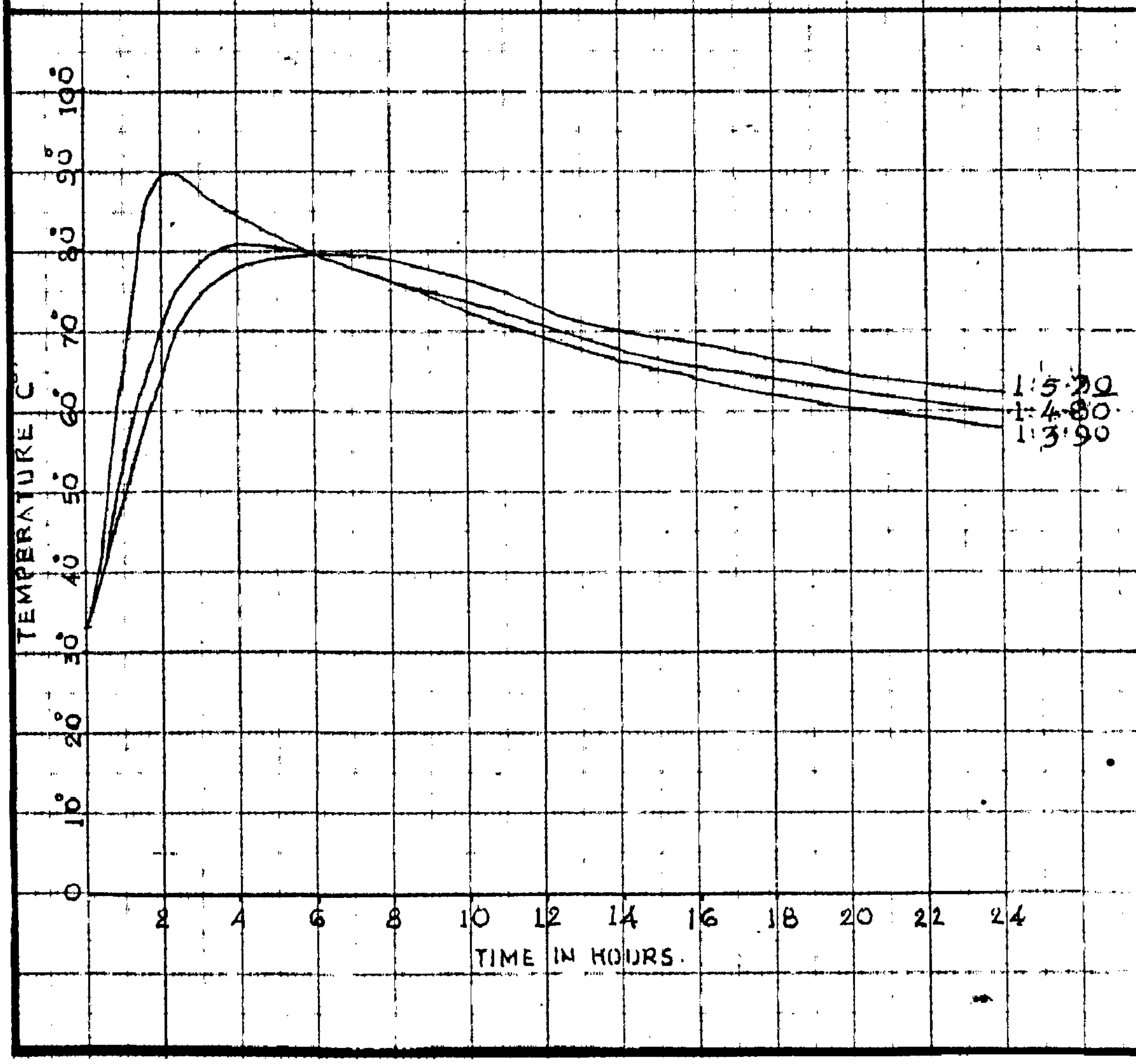
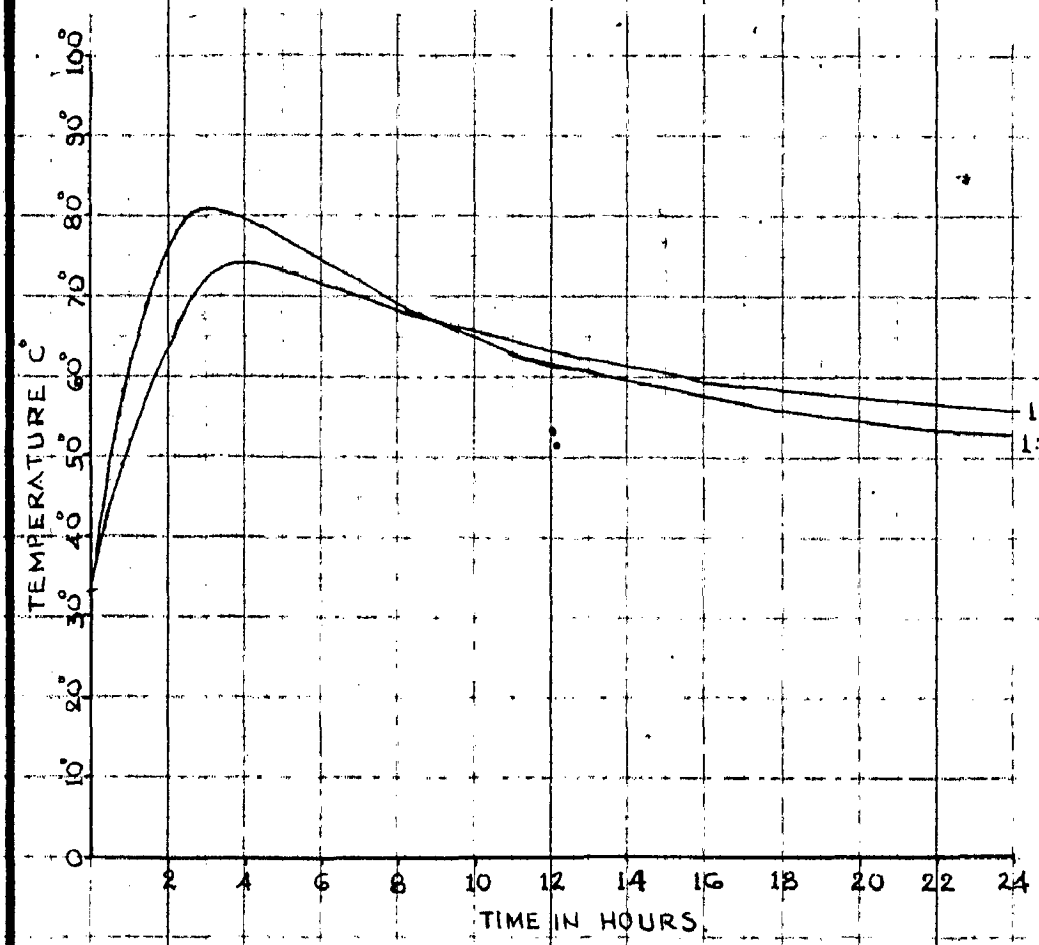


FIG. 64
EFFECT OF TEMPERATURE FOR A CONSTANT W/C RATIO FOR ELECTRICAL CURING OF CONCRETE.
W/C = 0.50 VOLT = 60



EFFECT OF TEMPERATURE FOR A CONSTANT W/C RATIO FOR ELECTRICAL CURING OF CONCRETE.
W/C. = 0.65 VOLT 60.
FIG 67

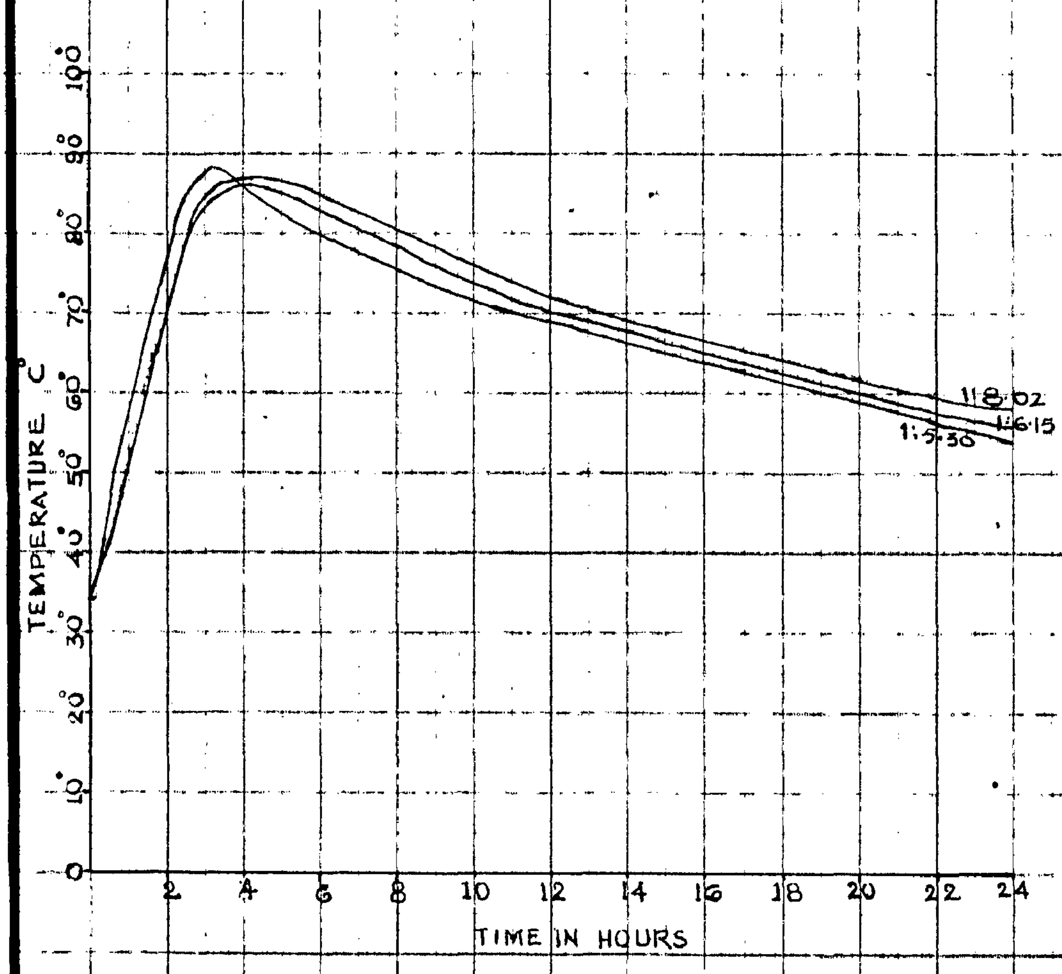


FIG. 66
EFFECT OF TEMPERATURE FOR A CONSTANT W/C RATIO FOR ELECTRICAL CURING OF CONCRETE.
W/C. = 0.60 VOLT 60

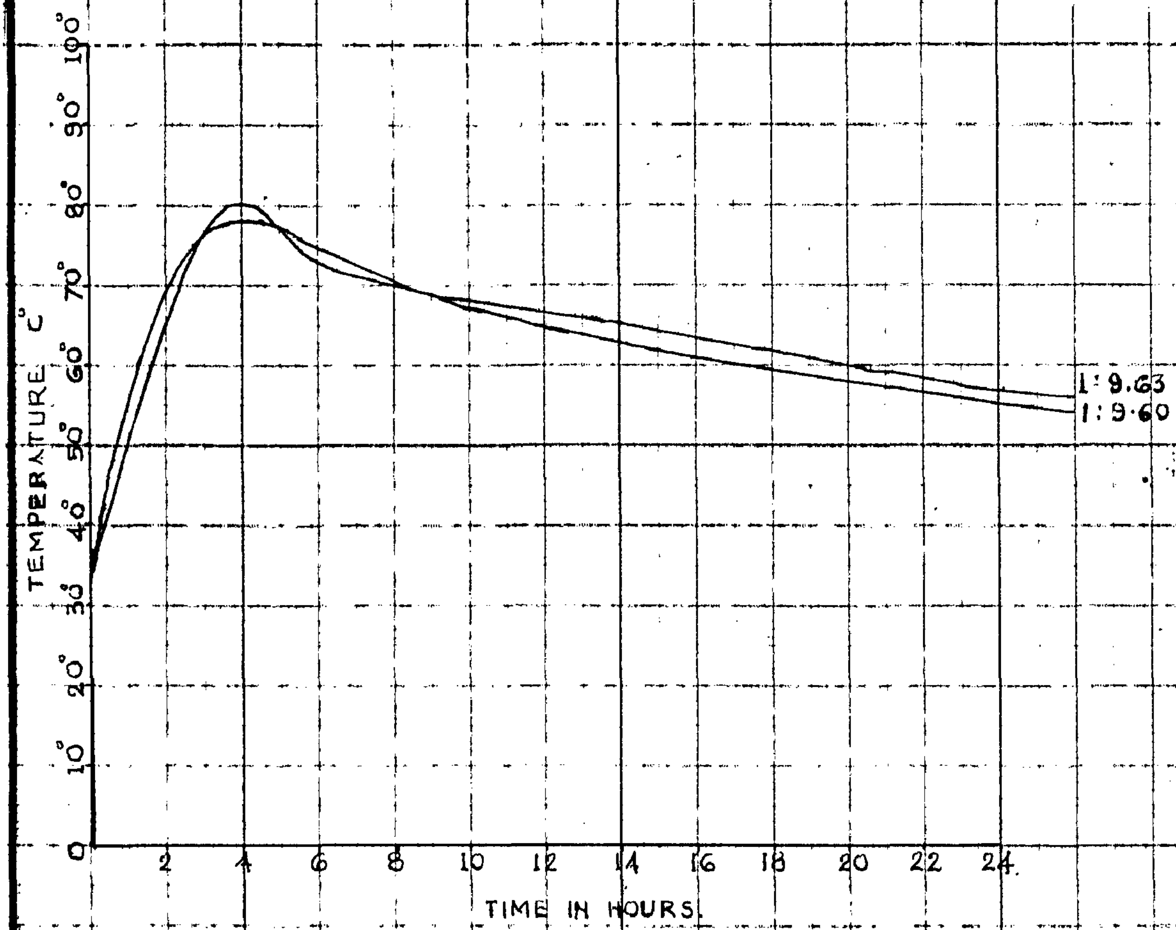


FIG 69

EFFECT OF TEMPERATURE FOR A CONSTANT W/C RATIO FOR ELECTRICAL CURING OF CONCRETE.

W/C = 0·70 VOLT = 60.

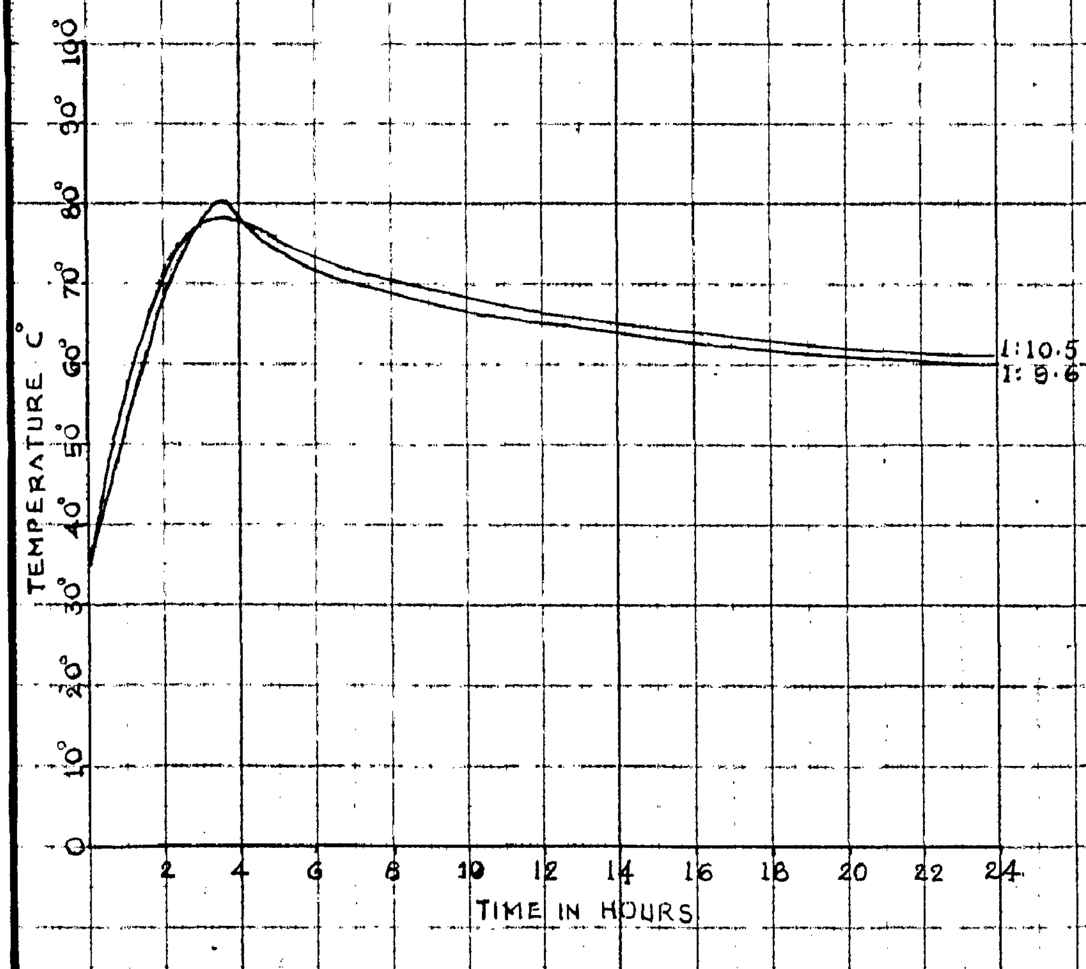


FIG. 68

EFFECT OF TEMPERATURE FOR A CONSTANT W/C RATIO FOR ELECTRICAL CURING OF CONCRETE

W/C RATIO = 0·75 VOLT = 60

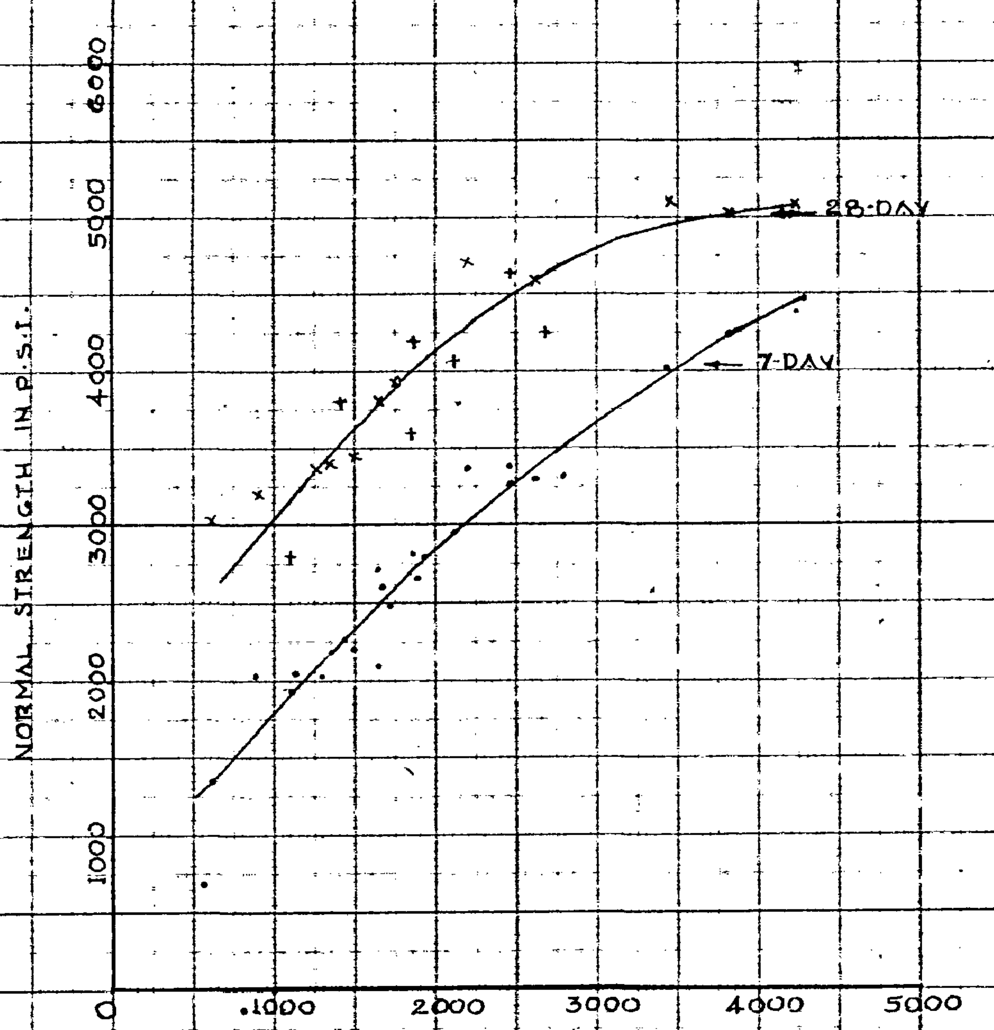


FIG. 71.

RESULTS OF 24 HOURS ELECTRICAL CURING AT 60 VOLTAGE AGAINST NORMAL CURED STRENGTH.

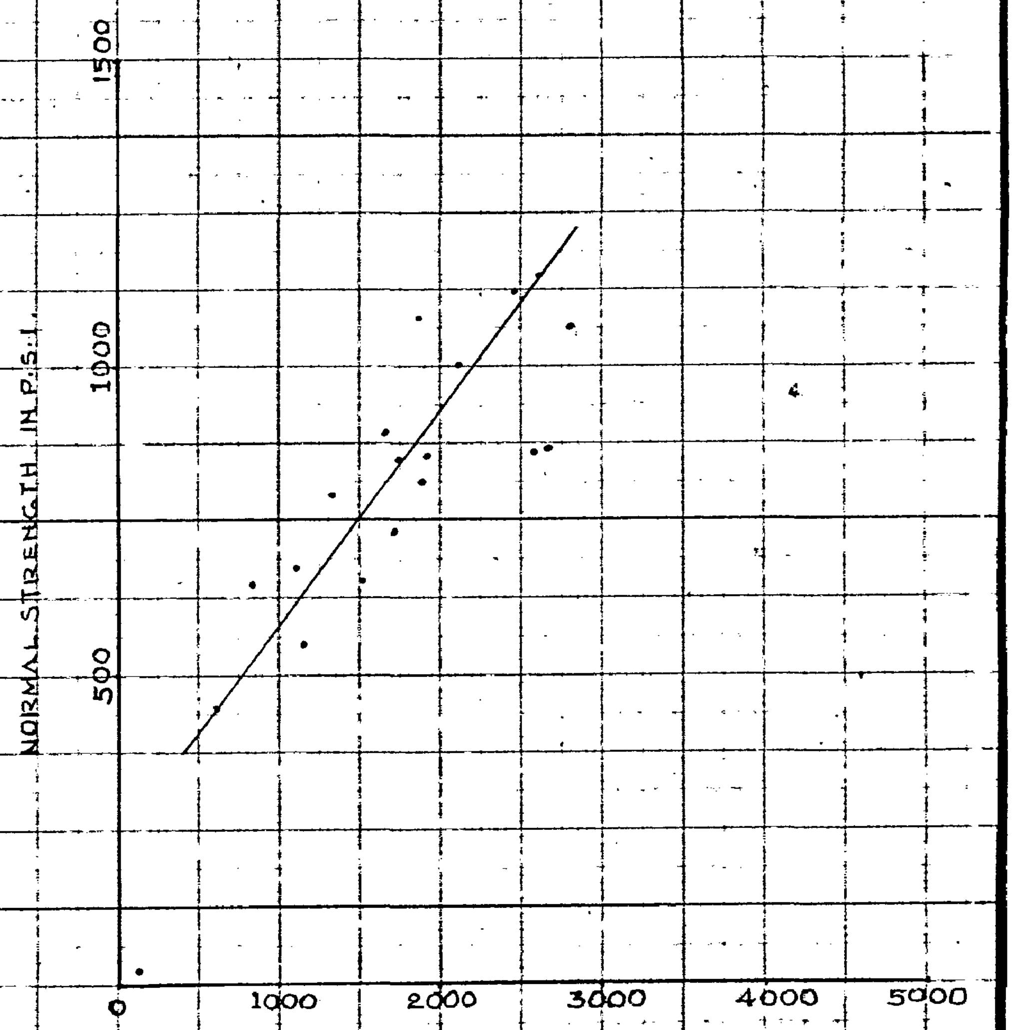


FIG. 72.

RESULTS OF 24 HOURS ELECTRICAL CURING AT 60-VOLTAGE AGAINST 24 HOURS NORMAL CURING AFTER 20 HOURS IN MOULD.

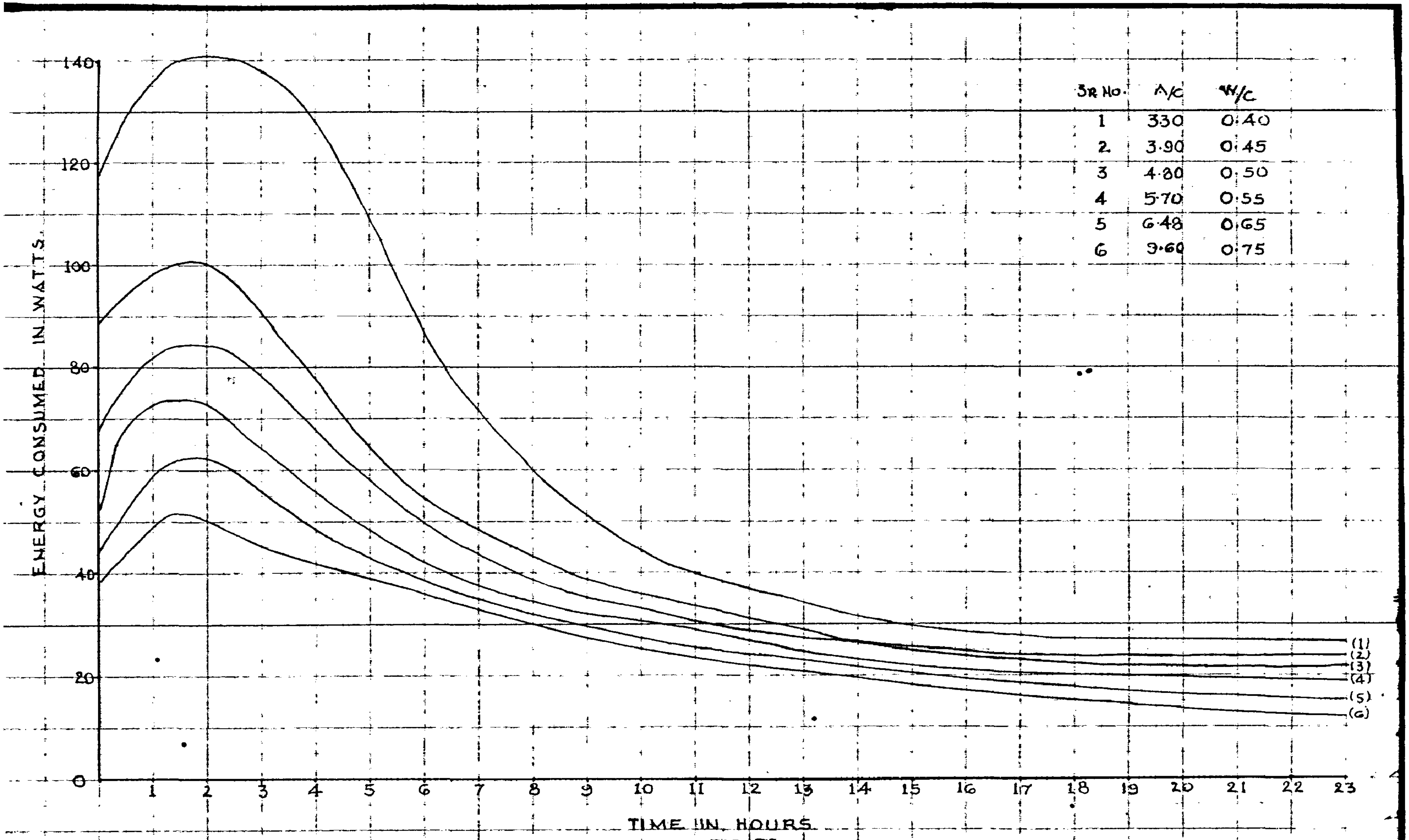


FIG. 70

ENERGY CONSUMED IN WATTS FOR 6" CUBE BY ELECTRICAL CURING AT CONSTANT VOLTAGE VOLT-60

PROPORTION OF F.A. : CA = 1 : 2

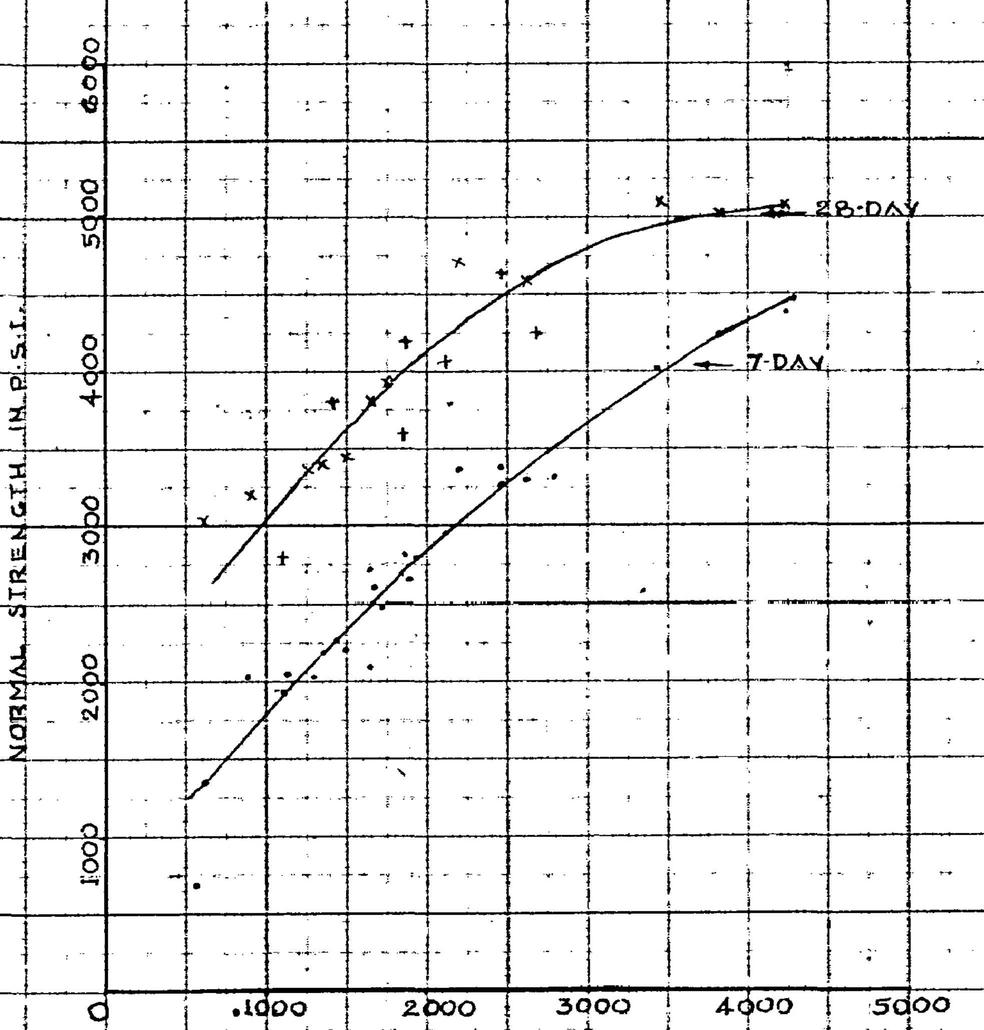


FIG. 71

RESULTS OF 24 HOURS ELECTRICAL CURING AT 60 VOLTAGE AGAINST NORMAL CURED STRENGTH.

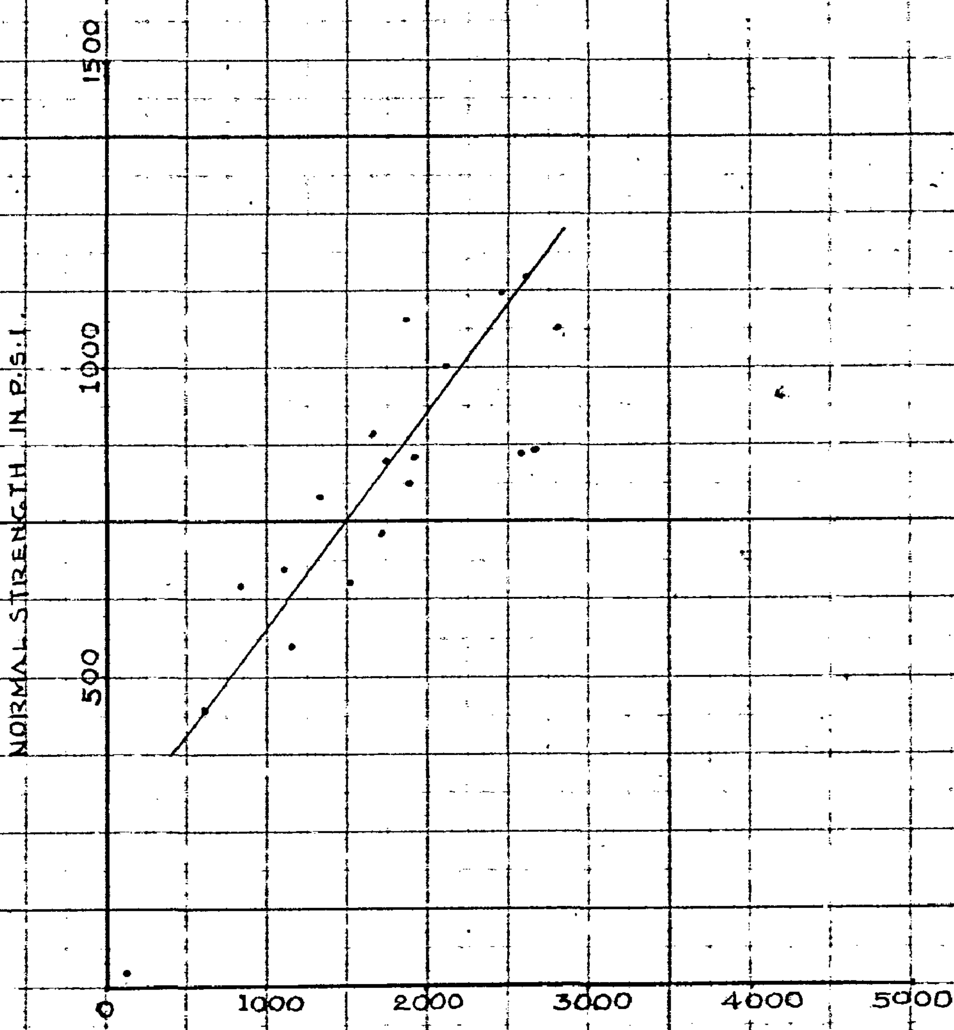


FIG. 72

RESULTS OF 24 HOURS ELECTRICAL CURING AT 60-VOLTAGE AGAINST 24 HOURS NORMAL CURING AFTER 20 HOURS IN MOULD.

depends on the aggregate/cement ratio, also as the aggregate/cement ratio increases the maximum temperature decreases.

6.13.4. Energy Consumed.

To find out the energy consumed an ammeter was connected to the circuit and readings of current were taken at the same interval of time as for temperatures and energy was calculated. The graphs are plotted in Fig. No. 70. Firstly, for few hours the curve rises and it attains the maximum value at about 2 hours. Then curve falls and after 12 hours of curing the energy consumed remains approximately same. The rate as well as maximum energy consumed depends on the w/c ratios, as the w/c ratio decreases the energy consumed increases. The A/c ratio has got negligible effect for a particular w/c ratio and hence average graphs are plotted.

CHAPTER VII

MISCELLANEOUS METHODS

7.1. BOILING WATER CURING.

The cubes can be easily cured by this method without uptodate temperature and humidity controlled curing room. The hot water units are portable. Boiling water can be obtained by an electric heater, or from a steam boiler or heated on a stove. The equipment is a simple one, a dust bin and calor gas or any other heating device. The comparative cost is 1/8th of that of oven curing.

Many methods have been adopted uptill now and mainly they can be divided into two categories (1) keeping the water boiling throughout the period of curing, (2) Leaving the cubes in airtight tank after the water has started boiling. In this case the temperature at the end of curing period will not be same.

In 1933 O.G.Patch[20] adopted the second method in which the cubes were cured for 8 hours at 195°F, the final temperature being 175°F. Variation of cement, w/c ratio, and gravel gradings showed a marked effect on the strength of concrete. For a short range of variation on w/c ratio, the relationship between w/c ratio and strength was found to straight line which tends to become a curve with a wide range of variation in w/c ratio. The average ratio of 28-day strength to 8-hour accelerated strength was found to be 3.6 for all types of cement.

In 1950 T.N.W. Akroyd and R.G.Smith-Gander cured the cubes for 7-hours in water which was kept boiling throughout the curing period. The results of these workers are shown in Figure No.73. It is clear that if accelerated strength is known, 7 or 28-day normal strength can be predicted from this graph.

In 1931 Akroyd published his results separately which are reproduced in Fig. Nos.75 and 76. While plotting this graph he assumed that if the relation between accelerated strength expressed as percentage of normal strength and normal strength is a straight line, then the relation between normal strength and accelerated strength is a straight line.

In 1962 P.Smith and Chojnacki[2] cured the cylinders for 23 hours in boiling water and found that cylinders gained about 60% of 28-day strength. He obtained the following relation.

$$R_{28} = R_a 1.275 + 970$$

where R_a is the 23-hr accelerated strength in lbs./sq.in.

R_{28} is the compressive strength in p.s.i.

7.1.1. Effect of time delay before Curing.

Tests were carried out[3] in which cubes were subjected to delay of upto four hours before being placed in hot water and brought upto boil. There appeared to be no great difference in the results with time.

7.1.2. Effect of Time of Curing.

In a study of the effect of time of curing[3] for various periods varying from 3 3/4 hours to 12 hours. The results

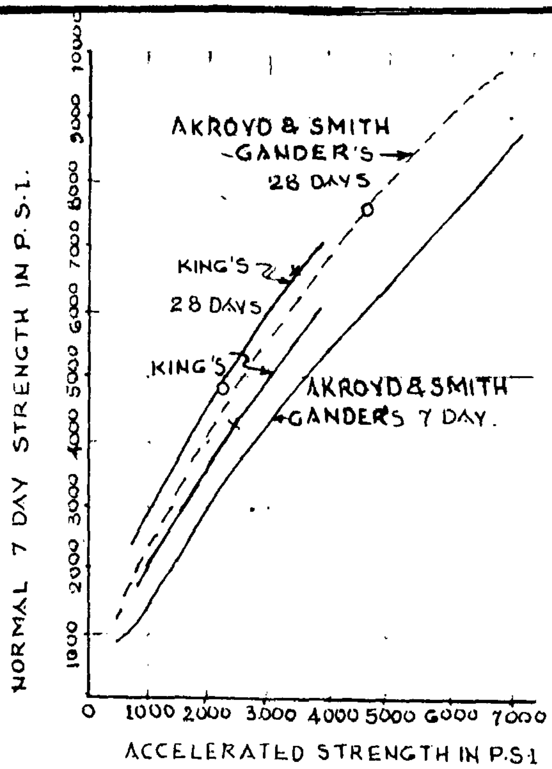

AKROYD & SMITH
GANDER'S
28 DAYS
KING'S
28 DAYS
KING'S
AKROYD & SMITH
GANDER'S 7 DAY.
NORMAL 7 DAY STRENGTH IN P.S.I.
1000
2000
3000
4000
5000
6000
7000
8000
9000
0
1000 2000 3000 4000 5000 6000 7000
ACCELERATED STRENGTH IN P.S.I

FIG. 73

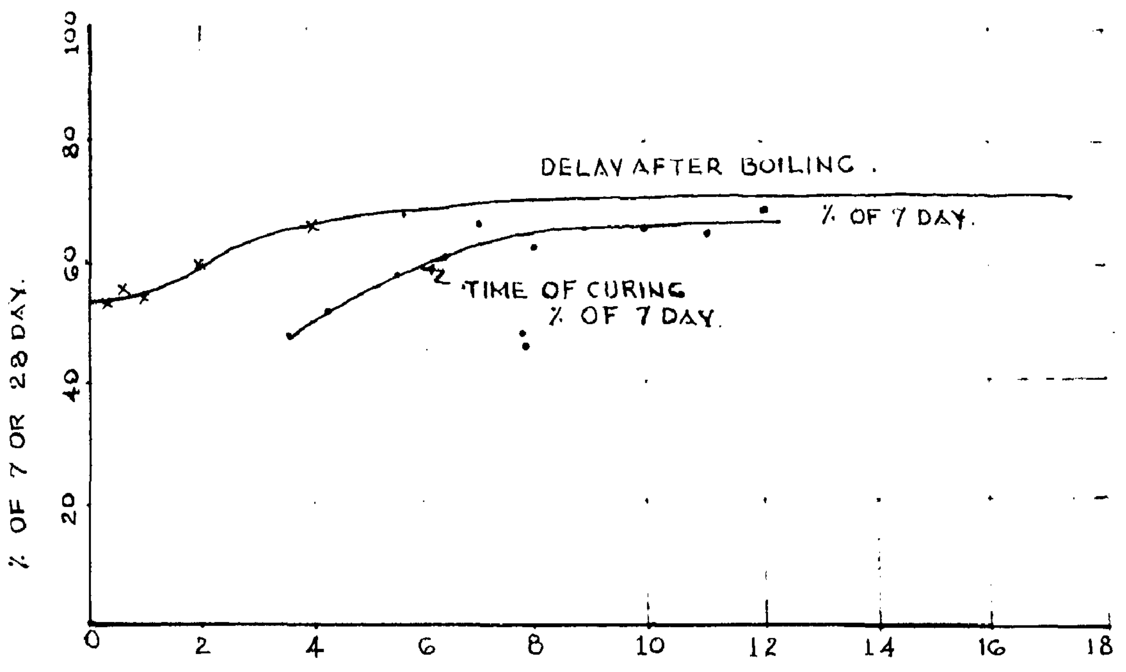


FIG. 74

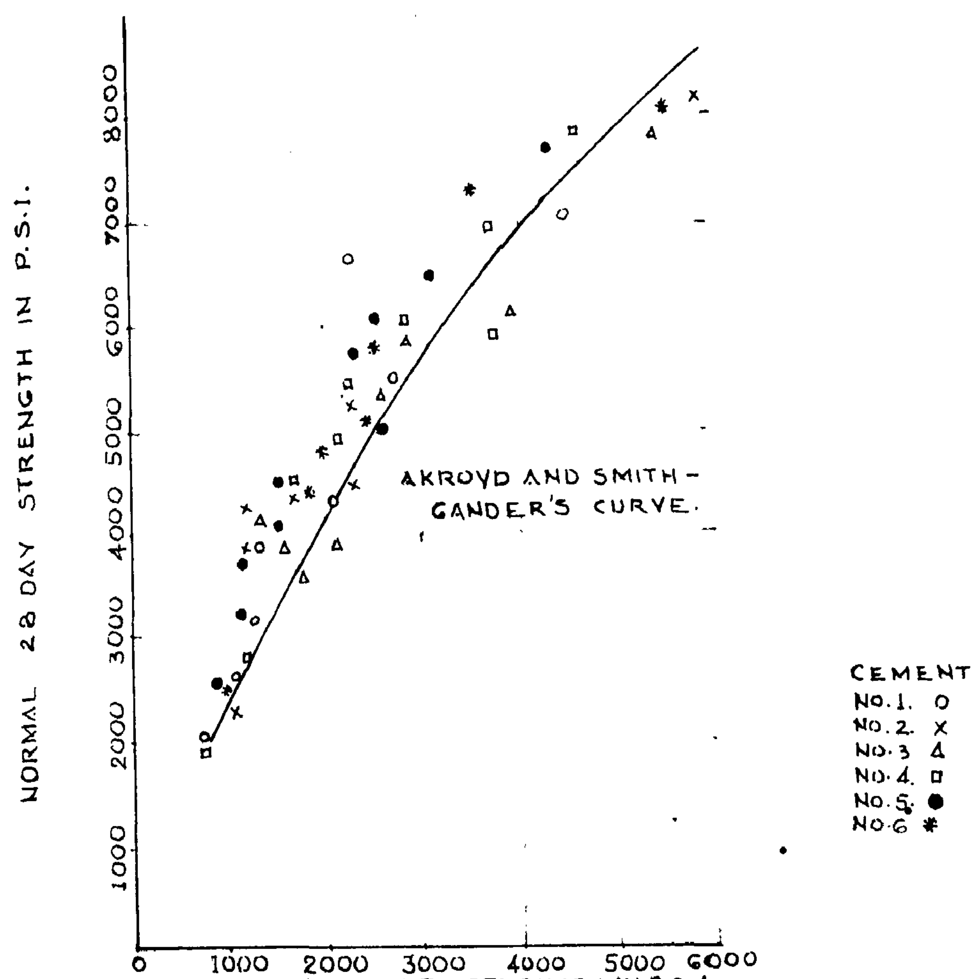


FIG 75

TESTS ON CEMENT BOILING METHOD.

of this study are shown in Fig. No.74. From this it can be observed that the rate of increase of strength after a period of 9 hours is insignificant.

7.1.3. Effect of Delay after Boiling.

Tests carried out[3] for a period upto $10^1/_2$ hours showed that the increase in strength for one hour delay was 8% more than the 7-day strength. After 6 hrs. there seem to be no appreciable increase in strength. If the tests were not done within an hour the correction to the final results are necessary as shown in Fig. No.74.

7.1.4. Effect of Water Temperature.

There will be a gradual increase in strength as the temperature of the water rises from 50°C to 100°C, but the difference in strength between 80°C and 100°C was negligible.

7.1.5. Effect of Cement.

The separate curves are necessary for each brand of cement if accuracy is required within ± 5%[3]. Fig. 75 shows the results of Akroyd[2] who used six different types of cement.

7.1.6. Variation Due to Aggregate.

The original curve by Akroyd and Smith-Gander were superimposed by the results obtained for different aggregates by Akroyd which showed that it predicts the strength lower by about 800 lbs/sq.in. For accuracy separate curves should be drawn for each aggregate. The results obtained by Akroyd are shown in Fig. No.70.

7.1.7. Variation Due to Size of Cubes.

It has been observed that the size of cube has no marked effect on strength(1).

7.2. MODIFIED BOILING WATER CURING.

The cubes half an hour after casting was placed in a thermostatically controlled tank for 24 hours. At the end of this time they were removed from the tank and with their moulds cubes were plunged into boiling water for 3½ hours.

When the concrete is 24 hours old, the curing temperature can be increased rapidly without harming the concrete. When these results are plotted the relation is same as that of 7-day and 28-day normal curing as given by the Cement and Concrete Association, England.

The results published by Akroyd(1) on modified boiling methods are shown in Fig. Nos. 78 to 80. Fig. No.78 shows the effect of various types of cement on the strength. The effect of cement was less at 28-days. Fig. No.80 shows the effect of various types of aggregates on compressive strength of concrete. For accuracy the separate curves for each aggregate should be drawn(1). The effect on cube size on compressive strength is shown in Fig. No.77. The cube has no effect on the strength prediction if same size of cube is used in both the results. The smaller size are

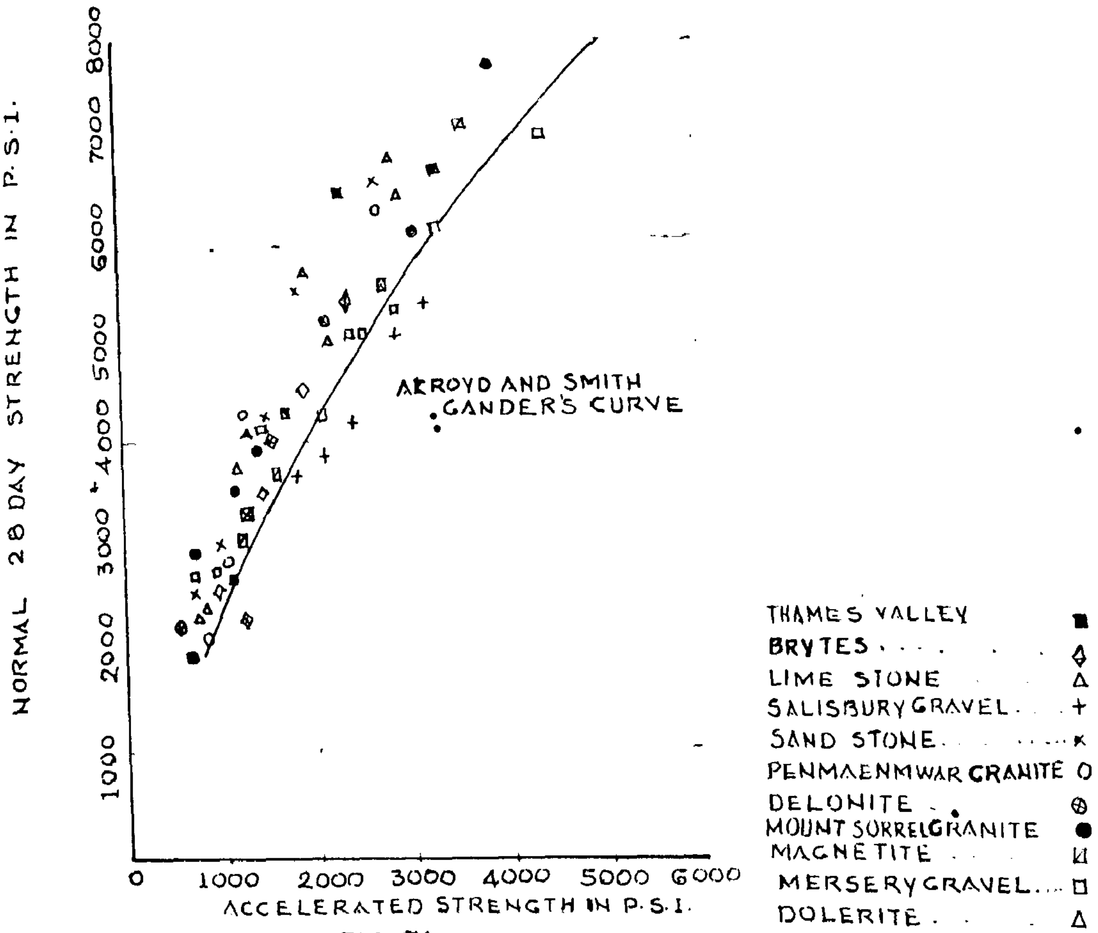


FIG. 76
TESTS ON AGGREGATES BOILING METHOD.

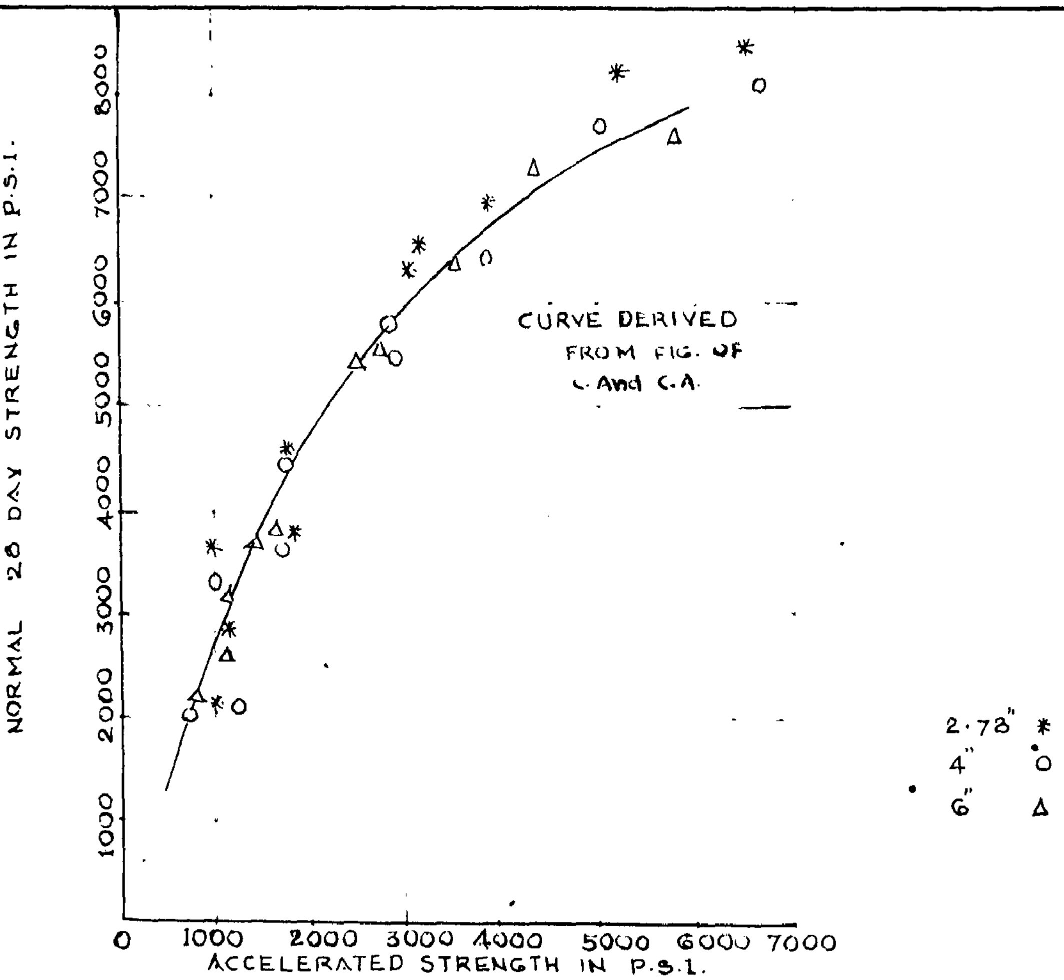


FIG. 77
TEST ON CUBE SIZES MODIFIED BOILING METHOD.

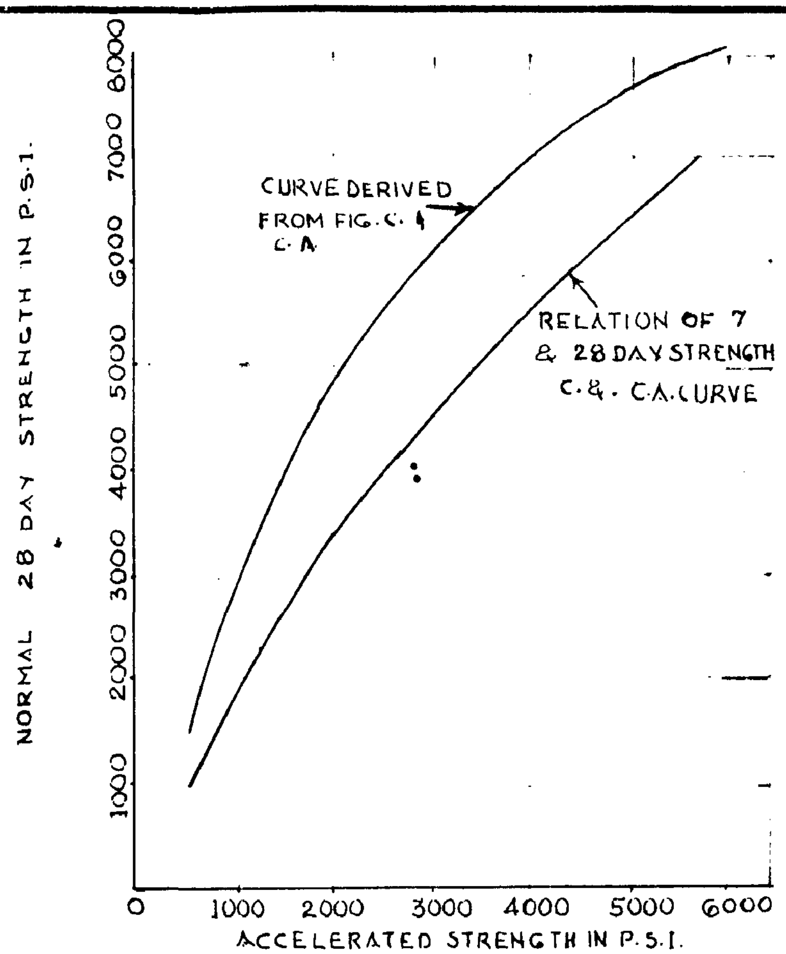


FIG. 78

TESTS ON CEMENT MODIFIED BOILING METHOD.

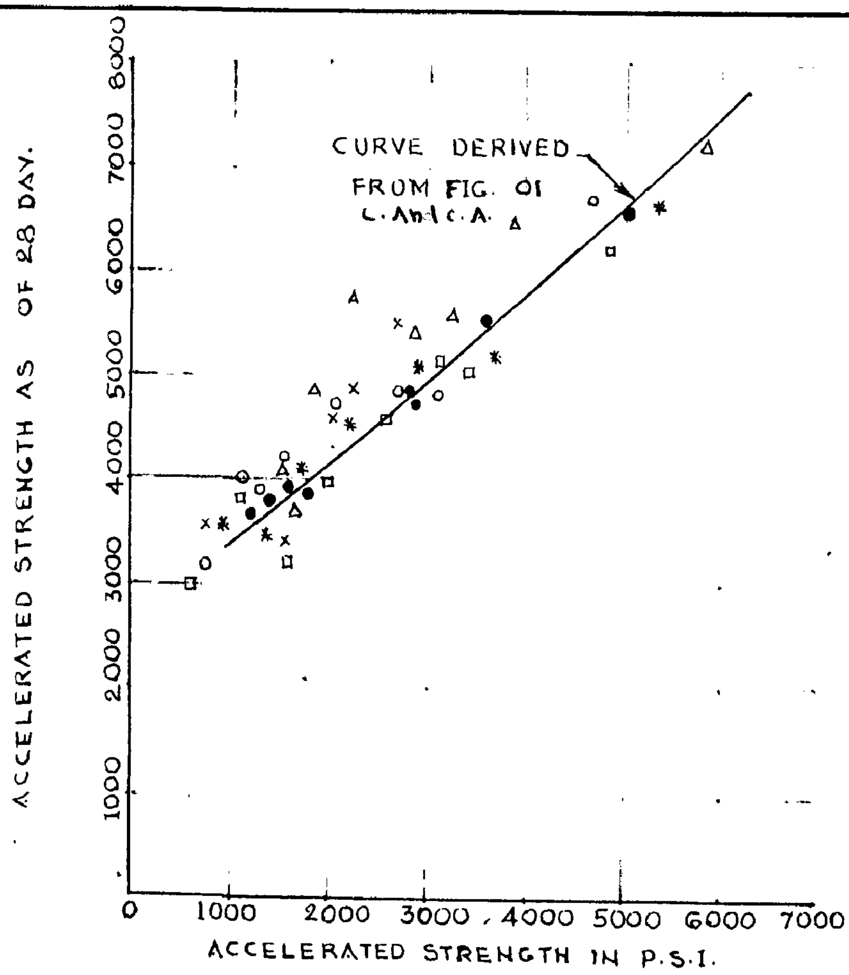


FIG. 79

MODIFIED BOILING RESULTS.

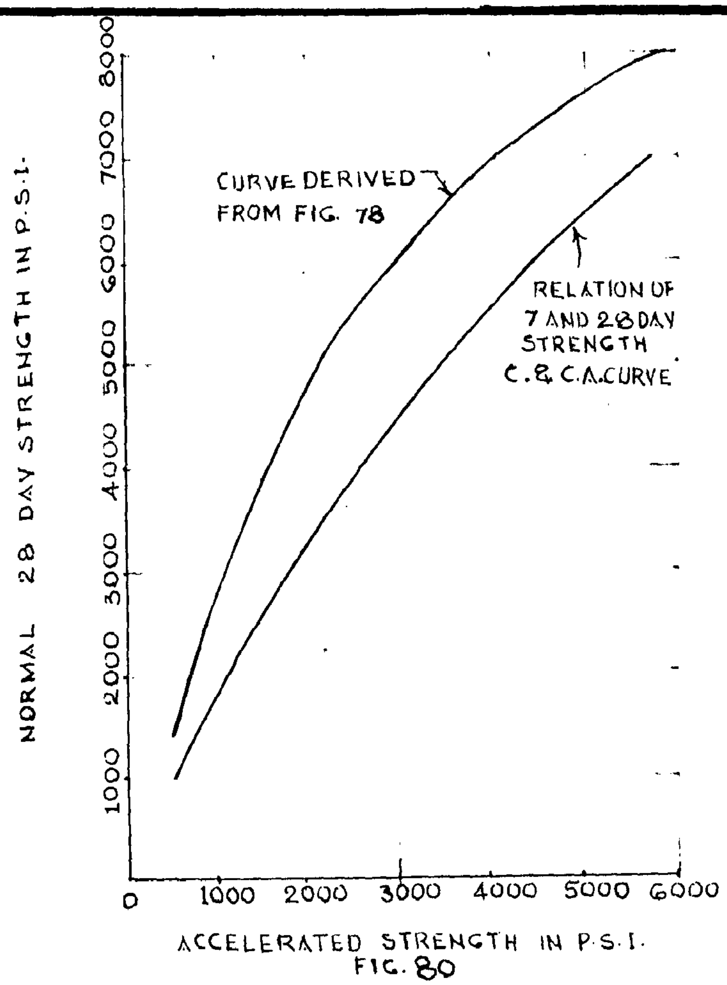


FIG. 80

TESTS ON AGGREGATES MODIFIED BOILING METHOD.

found to have tendency to give higher prediction.

7.3. CURING AT 25°C.

1962 H.S.Thompson(2) had developed a method which sought to combine simplicity of operation with reasonable accuracy of prediction. He found the temperature which will give about the same strength in 24 hours curing in water as Prof. King's oven curing method would give in 7 hours. He cured at 25°C, the results of accelerated strength when plotted against normal strength, gave approximately same curve as that of Prof. King.

The advantages of using this technique are:-

(1) Any danger of burns or scalds when handling cubes at higher temperature was avoided.

(2) No complications arose through the need for modified curing cycles to enable tests to be completed during normal working hours.

(3) When a correctly positioned immersion heater a larger tank of water can easily be kept at a steady temperature using a cheap industrial thermostat.

(4) Within the limits of the size of the tank, fresh batches of cubes can be immersed at any time while other cubes are still being cured.

(5) The risk of thermal shock to the concrete is avoided.

CHAPTER VIII

DISCUSSIONS

3.1. To explain the reactions involved during the process of hardening and setting many theories have been put forward. They can be divided into two major parts.

1. Crystallisation Theory and
2. Colloidal Theory.

3.1.1. Crystallisation Theory.

This theory can be divided into three phases (1) Chemical phenomenon of hydration, (2) The physical phenomenon of crystallisation and, (3) The mechanical phenomenon of hardening.

Gypsum on moderate heat decomposes as follows:-

$$CaSO_4 \cdot 2H_2O \longrightarrow CaSO_4 \cdot 1/2\ H_2O + 1\tfrac{1}{2}\ H_2O$$

on treating the product with water gypsum is again formed.

$$CaSO_4 \cdot 1/2\ H_2O + 1\ \tfrac{1}{2}\ H_2O \longrightarrow CaSO_4 \cdot 2H_2O + 3900\ \text{Cals.}$$

In a solution which is just saturated crystallisation cannot take place. If the supersaturation is maintained temporarily, the equilibrium will be established by crystallisation. The slow evaporation of the solvent, a change in temperature (in the direction of decreasing solubility) will produce a condition of supersaturation. The solubility ratio of $CaSO_4 \cdot 1/2\ H_2O$ to $CaSO_4 \cdot 2H_2O$ was seven as found by Le Chatelier.(83). As a result of marked differences between the solubility of the anhydrous (or only partially hydrated) salt and the hydrated salt crystallisation of cements take place. And this reaction will approach completion as the hydrate separates out, the solution is left unsaturated with respect to the anhydrous material.

The final hardness or strength of mass, according to Le Chatelier, will depend upon the cohesion of the crystals and upon their mutual adhesion. The reaction which brings about the hardening in the cement is a splitting of $3CaO.SiO_2$ giving $CaO.SiO_2$ hydrated.

$$3CaO.SiO_2 + aq = CaO.SiO_2.\ 2\tfrac{1}{2}\ H_2O + 2Ca(OH)_2$$

The tricalcium aluminate ($3CaO.Al_2O_3$) is believed to form tetracalcium aluminate ($4CaO.\ Al_2O_3$) hydrate.

$$3CaO.\ Al_2O_3 + Ca(OH)_2 + aq(water) = 4CaO.\ Al_2O_3.\ 12H_2O$$

The initial set is caused by the hydration and crystallization of the calcium aluminate.

The final set is caused by the beginning of the decomposition of tricalcium silicate, for complete hydrolysis.

$$3CaO.\ Al_2O_3 + 6H_2O \rightarrow 3Ca(OH)_2 + Al_2O_3.\ 3H_2O$$

$$3CaO.\ SiO_2 + nH_2O \rightarrow 3Ca(OH)_2 + SiO_2.\ aq$$

If one mole of CaO was removed then

$$3CaO.\ SiO_2 + nH_2O \rightarrow Ca(OH)_2 + 2CaO.\ SiO_2.\ aq$$

If two moles of CaO were removed, then

$$3\ CaO.\ SiO_2 + n\ H_2O \rightarrow 2Ca(OH)_2 + CaO.SiO_2.\ aq.$$

8.1.2. Colloid Hypothesis.

Michaëlis(40) believed that monocalcium compounds remain after hydrolysis and thereby the residue is enriched with anions and charged electronegatively, while the cations Ca^{++}, Na^{+} and K^{+} are partly or entirely removed. As soon as the concentrations of the lime water is sufficient, the cations wander to the anions and form the hydrated calcium silicate.

Rohland(41) believe that setting consists chiefly in the hydration of $2CaO.\ SiO_2$ with the formation of the hydrate $2(2CaO.\ SiO_2)\ H_2O$. Any additional CaO which might come from a composition of $3CaO.\ SiO_2$ was converted into $Ca(OH)_2$. The Al_2O_3 will be converted into $3CaO.\ Al_2O_3$ in presence of $Ca(OH)_2$.

$$Al_2O_3 + Ca(OH)_2 = 3CaO.\ Al_2O_3.\ H_2O$$

In concrete rich in silica, some $CaO.\ SiO_2$ was believed to react with aluminates to form a double silicate of lime and alumina.

A comprehensive study was made by Gonnerman(42) on the effect of the various compounds present in the cement. $3CaO.SiO_2$ was found to be chiefly responsible for strength at early ages and continued to be effective in increasing strength at later ages also. $2CaO.\ SiO_2$ contributed little to strength upto 28 days but was largely responsible for the increase in strength beyond that period.(42) Tricalcium aluminate contributed to strength to an important degree upto 28 days but thereafter its effect diminished and became negligible after a year. The role of $4\ CaO.\ Al_2O_3.\ Fe_2O_3$ was not clearly indicated but probably has little effect at any age. The relationship between the strength developed by a cement and the extent of hydration was studied by number of investigators(12). The exact relation has not been established.

8.2. CHEMICAL ACCELERATORS.

8.21. Calcium Chloride.

The addition of calcium chloride was found to increase the heat contributed at the end of 24 hours by $3CaO.SiO_2$ and $4CaO.Al_2O_3.Fe_2O_3$, but decreased the heat contributed by $3CaO.Al_2O_3$. When added to cement paste the strengths contributed by $3CaO.SiO_2$ and $2CaO.SiO_2$ were increased and that contributed by $3CaO.Al_2O_3$ was decreased.(20) No consistent effect was observed on the heat contributed by $2CaO.SiO_2$. The addition of calcium chloride increases the heat liberated during first few hours and also shifts the peak of maximum heat liberated to an early age. Such an effect gives an earlier set and hence an increase in strength at early ages.

The addition of gypsum to normal cement retards the setting time of cement by removing the excess of alkali. $CaCl_2$ is found to accelerate the precipitation of calcium sulfoaluminate, probably accompanied by precipitation of the chloroaluminate.

8.2.2. Sodium Hydroxide.

The action of alkali hydroxides would be to interact with gypsum to produce alkali sulphates and thus accelerate the early hydration and set of cement.

$$CaSO_4 + 2NaOH = Ca(OH)_2 + Na_2SO_4$$

The calcium silicates (3CaO. Si O_2 and 2CaO. SiO_2) were found to react with NaOH. In low concentrations of NaOH hydrolysis took place, producing and increase in pH and the formation of $Ca(OH)_2$ crystals. But as the concentrations of NaOH is increased above its optimum limit, the pH is decreased and there will be no hydrolysis and hence no crystals of $Ca(OH)_2$ will be produced.

8.2.3. Chemical Accelerators.

$CaCl_2$ and Na_2 SiO_3 are well known as chemical accelerators. Caustic soda is generally used to impart surface hardness. $CaCl_2$ was found to be more effective than any other accelerator used. The addition of 2% $CaCl_2$ gives the 28-day strength in 7 days, while the same percentage of sodium silicate requires 11.5 to 18.0 days, which is almost twice the time required by $CaCl_2$. As far as cost is concerned both cost same and hence $CaCl_2$ should be used. Caustic soda was tried as a chemical accelerator, at the optimum percentage of 3/4 the strength gained over normal curing varies from 10 to 12% at 28-day. Instead of adding 2% $CaCl_2$ to achieve more strength, it will be more economical to add more cement i.e. to reduce the w/c ratio.

8.3. OVEN CURING.

The comparison of results of 6 hrs, 12 hrs. and 24 hrs oven curing show that the rate of increase in strength of the cube decreases as the hours of curing increases. The probable reason for this may be, that the concrete is wet in the beginning and the water contained in it may be sufficient for curing in early hours. When the number of hours increases the cube loses its water even though all precautions are taken, and cube will not longer contain self water sufficient enough to cure itself. Hence we find that in first 6 hours the strength gained is 53% to 58% of 28-day strength, in next 6 hours 61.1% to 70.7% and 69.7% to 80.0% in next 12 hours. The upper limit has only increased from 58% to 80% in next 18 hours of curing. The results of 6 hours can be taken as the optimum for predicting 28-day strength. The results of low ages may not have attained a strength to give reliable results. The final products are unknown but it is definite that the chemical reaction between normal curing and oven curing is different. The high gain in strength in case of oven curing is due to extra heat supplied over normal curing.

The 6-hr. curing was adopted by Prof. King, Ordman and Bondre, and T.N.W Akroyd. The graph of accelerated strength against normal strength of 28-day are reproduced in Fig. No.34. The variations in the results predicted by Prof. King's graph will be always more above normal strength of 4000 lbs./sq.in. The error goes on increasing as the normal strength increases. The King's curve gives lower strength than other's curve for lower normal strengths. The error in predicting is not more upto 6000 lbs/ sq.in. The results when compared with those of Ordman and Bondre's shows that it will predict higher strengths for a mix having a strength more than 4000 lbs./sq.in. while for lower strength mixes it predicts comparatively lower strengths. The error in any mix is not more than ± 200 lbs./sq.in. for mixes upto 6000 lbs./sq.in. normal strength. The results when compared with those of T.N.W. Akroyd show that they always predict higher strength and curve is nearly parallel to the curve obtained from the present investigation in the range of 3000 lbs./sq.in. to 6000 lbs./sq.in. The error in prediction will be 200 to 300 lbs./sq.in. The results of the oven curing shows that the experimental curve obtained predicts strengths lower than those predicted from the results of any other authority. The difference varies from mix to mix. The probable reason may be difference in the rate of temperature rise of oven, the initial temperature of oven, and the final temperatures at which the cubes are cured.

In the present investigation the initial oven temperature was kept at 60°C. In most of the investigations which have been carried out by other workers the initial oven temperature was fixed at room temperature. An initial temperature of 60°C was kept because of the fact that the oven used to take more than the 6 hours (curing period) for reaching the temperature of 60°C. Another reason for keeping an initial temperature of 60°C was to facilitate in the comparison of oven curing with steam curing.

There was also a difference between the rate of temperature rise as obtained in the present investigation and in other investigations. The rate of increase in temperature obtained by author was one degree centigrade in every three minutes while that obtained by other investigators was one degree centigrade in every two minutes.

The final temperature of curing was chosen as 185°F (85°C) by T.N.W. Akroyd and Ordman and Bondre because they used blue cement which has got optimum temperature of 185°F. The temperature selected by Prof. King was 200°F (93.3°C), and by Dewan and author as 212°F (100°C). The temperature should not be more than the boiling point of water. The oven condition i.e. its make, type, capacity and how the temperature is measured also affects the results. T.N.W. Akroyd had shown in his results that the different ovens will give different results. The capacity of oven and number of cubes cured at a time in the oven also affects the results. Six cubes were cured at a time in the oven to avoid this effect. The method of prevention of the escape of moisture from the cubes also affects the results.

The probable error in Ordman, Bondre and King's results is less than that in author's curve. Akroyd assumed that if the relation between the accelerated strength expressed as % of normal strength versus normal strength is a straight line, then the relation between the accelerated and normal strength is a parabola. This assumption of the relation to be a parabola gave a deviation in the results.

The results of 24-hrs. oven curing gives the 7-day normal cured strength which agrees with the results obtained by R.L.Dewan[2]

6.3.1. The equation was obtained to find out the maximum error (standard error).

For 6 hours oven curing the results when plotted on logarithm base gave a straight line. So the relation is

$\log y = m \log x + \log c$ was assumed

where y = 28-day normal strength

x = 6-hr accelerated strength.

changing the co-ordinates $Y = \log y$ $X = \log x$

$C = \log c$

and applying the method of least square

$$Y = mX + C$$

S = error $= \Sigma (Y - mX - C)$

$\therefore \frac{\partial S}{\partial m} = 0, \quad \frac{\partial S}{\partial C} = 0$ gives

$$\Sigma Y = m \Sigma X + C.n$$

$$\Sigma XY = m \Sigma X^2 + C \Sigma X$$

From our results we obtain

$\Sigma X = 71.37096$

$\Sigma Y = 82.88057$

$\Sigma XY = 250.0938$

$\Sigma X^2 = 221.1694$

$\Sigma Y^2 = 294.5049$

which gives $m = 0.495922$ and $C = 2.10504220$

$\therefore$ the equation is

$$Y = 0.456822\, X + 2.16304236$$

or

$$Y = 145.56\, x^{0.456822}$$

$$\text{mean } \bar{X} = \frac{\Sigma X}{n} = \frac{71.37895}{23} = 3.10343261$$

$$\bar{Y} = \frac{\Sigma Y}{n} = \frac{82.29057}{23} = 3.57785522$$

Standard Deviation

$$\sigma_x = \sqrt{\frac{\Sigma x^2}{n} - \bar{x}^2}$$

$$= 0.1659955$$

$$\sigma_y = \sqrt{\frac{\Sigma y^2}{n} - \bar{y}^2}$$

$$= 0.0789645$$

Coefficient of Correlation

$$\gamma = \frac{\frac{1}{n}\Sigma XY - \bar{X}\bar{Y}}{\sigma_x \sigma_y}$$

$$= 0.911712418$$

For value of $\gamma = 1$ it gives perfect correlation

$$\text{Standard error} = \sigma_y \sqrt{1 - \gamma^2}$$

$$= 0.0789645 \sqrt{1 - (0.911712418)^2}$$

$$= 0.032441617$$

$$= \frac{0.03241017 \times 100}{3.5778307}$$

$$= 0.907\%$$

The error is with respect to log. scale for normal scale.

$$\bar{Y} = 3.57783$$

$$\therefore \quad \bar{y} = 3783.0 \text{ lbs./sq.in.}$$

The range of Y in predicting will be

$$Y = 3.57783 \pm 0.03241$$

$$= 3.61024 \text{ or } 3.54542$$

$$\therefore \quad y = 4070.8 \text{ or } 3510.0 \text{ lbs./sq.in.}$$

The error in value of y (upper limit)

$$= \frac{4070.8 - 3783}{3783} \times 100$$

$$= 7.76\%$$

The error in lower limit of y

$$= \frac{3783 - 3510.0}{3783} \times 100$$

$$= 7.2\%$$

The error can be reduced by taking more number of specimens as it is fact that the error goes on decreasing as the number of samples goes on increasing.

8.4 STEAM CURING.

For the steam curing at atmospheric pressure, the graph of accelerated strength versus normal strength when plotted on log. scale, gave a straight line relationship similar to that obtained for oven curing.

Let the equation of straight line be

$$\log y = m \log x + \log C$$

where,

y = 28-day normal strength

x = 6-hr steam cured strength.

changing to new coordinates

$$Y = m X + c$$

where,

$Y = \log y$

$X = \log x$

$c = \log C$

and applying the method of least square from our results we obtain,

$\Sigma X = 62.00326$

$\Sigma Y = 63.37219$

$\Sigma XY = 231.73100$

$\Sigma X^2 = 200.37963$

$\Sigma Y^2 = 210.1253$

$n = 10$

Using these parameter in equations and solving for value of m and C

$$\Sigma Y = m\,\Sigma X + Cn$$

$$\Sigma XY = m\,\Sigma X^2 + C\,\Sigma X$$

We get

$$m = 0.25224006 \text{ and}$$

$$C = 2.7012047$$

$$\therefore\ Y = 0.25226\,X + 2.7012247$$

The equation in original coordinates

$$y = 504.85\,x^{0.25226}$$

mean value of

$$\bar{X} = \frac{\Sigma X}{n} = \frac{32.33018}{10} = 3.2[illegible]302301$$

$$\bar{Y} = \frac{\Sigma Y}{n} = \frac{33.37230}{10} = 3.[illegible]47230$$

Standard deviation

$$\sigma_x = \sqrt{\frac{\Sigma X^2}{n} - \bar{X}^2}$$

$$= 0.20[illegible]77$$

$$\sigma_y = \sqrt{\frac{\Sigma Y^2}{n} - \bar{Y}^2}$$

$$= 0.07061044$$

Coefficient of Correlation

$$r = \frac{\frac{1}{N}\Sigma XY - \bar{X}\bar{Y}}{\sigma_x \sigma_y}$$

$= 0.7$[illegible]

Standard Error $= \sigma_y \sqrt{1 - r^2}$

$= 0.0708$[illegible] $\sqrt{1 - (0.7\text{[illegible]})^2}$

$= 0.04$[illegible]

$= \frac{0.04\text{[illegible]}}{0.\text{[illegible]}} \times 100$

$= 1.$[illegible] %

The error is with respect to log. scale for normal scale.

$\bar{Y} = 3.$[illegible]

$\bar{y} =$ [illegible]7.73 lbs./sq.in.

The range of Y in predicting will be

$Y = 3.$[illegible] $\pm$ 0.04[illegible]

$= 3.$[illegible] and $3.$[illegible]

$\therefore y =$ [illegible].7 to [illegible].0

The error in value of y (upper limit)

$= \frac{\text{[illegible]}.7 - \text{[illegible]}.7}{\text{[illegible]}7.7} \times 100$

$=$ [illegible]

The error in lower limit

$$= \frac{3067.7 - 3302.0}{3302.0} \times 100$$

$$= 19.8\ \%$$

The error in predicting strength by steam curing is more and hence the results of oven curing are expected to give better results. The standard error for oven curing method is 7% which gives results within ± 300 lbs./sq.in. The strength obtained by steam curing is less as compared to that of oven curing for the same period. The probable reason being the difference in type of curing. In oven curing the water which is present in concrete is available for the curing while in steam curing it is supplied by the steam. The final products due to chemical changes are unknown. The results cannot be compared with other authorities as no reference in this type of work is available. The work done by R.L.Bowen for 6 hours shows the relationship as

$$y = 1.830\ x + 1237 \text{ for 1:2:4 and 1:3:6 cement concrete}$$

$$y = 2.011\ x + 370 \text{ for 1:4:8 cement concrete}$$

In the above equations it was found that there were arithmatical mistakes in their derivation. Author has tried to correct these mistakes. A relation $y = 0.967x + 2350$ is obtained after applying corrections. If a straight line of best fit is fitted to the results obtained in the present investigation, we obtain the relation,

$$y = 1.02\,x + 2200$$

Where x and y are the accelerated strength and 28-day normal strength respectively which closely agrees with the relation $y = 0.907\,x + 2250$ obtained by Owen.

8.6 MATURITY RELATIONS.

The maturity relations for both type of curing have been found. The one was found in °F.hr to compare it with the results obtained by Sandre and Graham for the oven curing at 180°F (82°C). The relations obtained by both are linear. The relation being

$$\%\ 28\text{-day Strength} = A + B \log_{10} \frac{\text{Maturity}}{2000}$$

where A and B are constants and it will be different for different types of curing and normal strength. The value of constants varies with the curing temperatures. The value of B remains constant in author's results, while the value of A varies with the strength. The value of A in both the results are nearly same, hardly there is a variation of 2%. The value of A and B in Sandre and Graham are same. The value of B is more in author's results as it will give more strength for the same period, which is quite natural as the curing temperature is more which gives more maturity for the same period. The results were compared for the same period of maturity and for same normal strength.

To compare the results of Bendre and Ordman with that of author's for oven curing, maturity of 3000°F-hr was selected and taking the mix having 28-day normal strength of 6000 lbs./sq.in.

The value of constants A and B are 20.8 and 38.8 respectively.

β of 28-day strength $= 20.8 + 38.8 \log_{10} 3$

$= 60.3\ \beta$

Accelerated strength $= 6000 \times 0.603$

$= 3618$ lbs./sq.in.

By author's results the value of A = 39.0 and B = 80.0

β of 28-day strength $= 39.0 + 80.0 \log_{10} 3$

$= 77.3\ \beta$

Accelerated strength $= 6000 \times 0.773$

$= 4638$ lbs./sq.in.

or to obtain the accelerated strength of 3618 lbs./sq.in. maturity required is 1083°F-hr or the time required is 20% less. This shows that the curve plotted for a particular temperature is valid only if the cubes are cured in the same manner and at the same temperature. It can be applied to any age of curing.

A similar law for steam curing was established and it is also represented by a straight line. The value of constants will be different from those obtained for oven curing. Comparing the the results of the two, it is found that in this method the value of A remains constant while B varies with the strength in the same order as the strength. The variations of both the constants are linear. The temperature range within which this law is applicable has not been established. If we assume, as in case of oven curing, that there are as many relationships as there are temperatures of curing, then the above law would be applicable only for curing temperature of 100°C.

The statement made by Saul that the same law can be applied whatever may be the combination of the time and temperature provided the cubes have not been attained 50°C until 1 1/2 to 2 hours nor 100°C until 5 or 6 hours after mixing was verified for the cubes cured at 60 p.s.i., 80 p.s.i and 120 p.s.i.

For normal strength of 4000 lbs./sq.in. the 6 hours steam curing at 60 p.s.i. gave maturity of 3440°F-hr (1720, 1560 and 160°F-hr for waiting period, heating period and cooling time respectively). The strength attained was 2250 lbs/sq.in. For atmospheric steam curing the accelerated strength corresponding to maturity of 3440°F hr. was found to be 1800 lbs/sq.in. For 80 p.s.i. and 120 p.s.i. curing the maturities obtained for 6 hours curing were 3072°F-hr and 3310°F-hr respectively. The accelerated strength obtained from graph Nos. 61 and 63 were 3000 and 3300 lbs/sq.in. respectively. For atmospheric curing corresponding to maturities of 3072°F-hr and 3310°F-hr, the strength obtained from atmospheric curing were 1950 and 1950 lbs/sq.in. So it can be concluded that just like oven curing there will be different laws for the concrete cured at different temperatures. Same maturity gave the results varying by 100%.

Some of the cubes were left in water, after it has attained the room temperature to find the gain in strength after accelerated curing. It was found that for both oven curing and steam curing (6 hr. curing), the cubes could not reach 7 days normal strength even after 7 days of normal curing following the accelerated curing. The reason may be that after it has been accelerated cured the strength gain may be at the retarding rate.

The high pressure curing for the same maturity gave higher strength due to the extra latent heat supplied by steam. The strength increases with the pressure, as the temperature and so the heat gained by the steam increases.

8.6. ELECTRIC CURING.

As far as electric curing is concerned, the results when plotted on the logarithmic scale shows the sharp bend at accelerated strength of 2000 lbs/sq.in. The correlation for the strength below the accelerated strength of 2000 lbs./sq.in. or normal strength of 6000 lbs/sq.in. was found by the method of least squares.

Assuming the best fit to be a straight line of the form

$$\log y = n \log x + \log C$$

where

y = 28-day normal strength

x = 24-hr electric cured strength.

and changing into new co-ordinates

$$Y = mX + C \quad \text{where} \quad Y = \log y$$
$$X = \log x$$
$$C = \log c$$

From our results we obtain,

$$\Sigma X = 67.07629$$
$$\Sigma Y = 61.86807$$
$$\Sigma XY = 290.0888$$
$$\Sigma X^2 = 186.6810$$
$$\Sigma Y^2 = 320.4884$$
$$n = 10$$

by the method of least square we get

$$\Sigma Y = m\,\Sigma X + Cn$$
$$\Sigma XY = m\,\Sigma X^2 + C\,\Sigma X$$

Substituting the values and solving for m and c we get

$$m = 0.1060153834 \text{ and}$$
$$c = 2.077$$

$\therefore$ the equation of a line

$$\log y = 0.106 \log x + 2.077$$

$$\therefore \quad y = 243.42\, x^{0.106}$$

mean value of X, $\bar{X} = \frac{\Sigma X}{n}$

$$= \frac{67.07629}{10}$$

$$= 2.534291000$$

$$\bar{Y} = \frac{\Sigma Y}{n} = \frac{64.25967}{18}$$

$$= 3.569981666$$

Standard Deviation

$$\sigma_x = \sqrt{\frac{\Sigma X^2}{n} - \bar{X}^2}$$

$$= 0.2130921$$

$$\sigma_y = \sqrt{\frac{\Sigma Y^2}{n} - \bar{Y}^2}$$

$$= 0.068133$$

Coefficient of correlation

$$r = \frac{\frac{1}{n}\Sigma XY - \bar{X}\bar{Y}}{\sigma_x \sigma_y}$$

$$= 0.57879$$

Standard Error $= \sigma_y \sqrt{1 - r^2}$

$$= 0.068133 \sqrt{1 - (0.57879)^2}$$

$$= 0.0556$$

$$= \frac{0.0556}{3.56998} \times 100 = 1.56\%$$

For the average value of Y,

$$\bar{Y} = 3.01693$$

$$y = 3760 \text{ lbs./sq.in.}$$

The limits in value of Y will be

$$= 3.01693 \pm 0.0063$$

$$= 3.02253 \text{ or } 3.01123$$

$$\therefore y = 4203.7 \text{ or } 3236.4 \text{ lbs./sq.in.}$$

The error in value of y (lower limit)

$$= \frac{3760 - 3240.4}{3240.4} \times 100$$

$$= 16.03$$

The error in value of y (upper limit)

$$= \frac{4203.7 - 3760.0}{3760.0} \times 100$$

$$= 11.70 \%$$

The error is greater than those of the two methods. The results do not agree with those of Prof. Govind Rao, except for the richer mixes.

CONCLUSIONS.

Following conclusions can be derived from the present study.

1. 28-day strength of concrete mix can be predicted within an standard error of 7% from the 6-hour strength of an oven cured cube from the relation.

$$y = 215.80\ x^{0.4603}$$

where, y = 28-day strength of concrete

x = 6 hours oven cured strength of concrete.

2. The oven curing at 100°C for 24 hours approximately gives the 7-day normal cured strength.

3. The 28-day strength of a concrete mix can be predicted from the 6-hour steam cured strength of a concrete by the relation

$$y = 604.3\ x^{0.25226}$$

where y = 28-day strength of concrete

x = 6-hour steam cured strength of concrete.

4. Standard error in predicting normal strength by steam curing at atmospheric pressure would be ± 20% with 90% certainty.

5. 24 hours steam curing gives the 7-day normal strength

for richer mixes, i.e. strength above 4000 lbs./sq.in. while in leaner mixes atleast 80% of 7-day strength will be obtained.

6. The maturity of a concrete and the normal strength can be related in a linear form of

$$\% \text{ of 28-day strength} = A + B \log_{10} \frac{\text{maturity}}{1000}$$

for calculating the maturity the datum has been selected as -8.35°C (11°F)

7. The maturity relationship is different for both types of curing.

8. The maturity relationship is different for different curing temperatures.

9. The law is independent of the quality of cement, w/c ratio, A/C ratio, the shape of the specimens.

10. The A and B are constants and for each case a separate constant is designated.

11. The variations of A and B are linear and increase with strength increase.

12. The value of A remains approximately constant in the oven curing and B remains approximately constant in the steam curing.

13. Oven curing gives least standard error in predicting 28-day strength.

14. The strength gained by cubes after accelerated curing increases at a retarding rate and for all mixes it was less than the normal cured strength.

15. The high pressure curing gives more accelerated strength.

16. In 6 hours curing at 120 lbs/sq.in. above atmosphere it gives approximately the 28-day strength.

17. In case of electric curing the rate of temperature rise and its maximum values are functions of A/C ratio for a fixed W/C ratio.

18. The leaner the mix and smaller the proportion of sand to aggregate, the higher is the electrical resistivity of concrete.

19. The energy consumed depends upon the W/C ratio, the consumption increases with a decrease in W/C ratio.

20. The energy consumed is least in steam curing for the same percentage of normal strength (See appendix 1).

21. The strength obtained in 24-hrs curing is much less than the 7-day normal strength.

22. The calcium chloride is effective as accelerator as sodium silicate and sodium hydroxide.

23. The optimum percentage of sodium hydroxide by weight of cement is found to be 3/4%.

24. The addition of more sodium hydroxide above optimum limit gives lesser strength.

25. The setting time of concrete can be reduced to 5 minutes by adding $1\frac{1}{2}$ % to 2% of sodium hydroxide.

26. The addition of accelerators are uneconomical as more strength can be obtained by choosing the richer mix in half the cost.

27. Though the prediction of 28-day strength is most accurate by oven curing method, the steam curing is recommended for prediction as it can be applied to structures.

SCOPE FOR FURTHER STUDY.

Further research on this subject should be carried out to establish an optimum temperature for oven curing and an optimum pressure for high pressure steam curing. For this the work may be carried out in the following manner.

Different types of cement with different water cement with different water cement ratios and proportion of aggregates should be used. After casting the cubes, they should be oven cured at different temperatures ranging from 55°C to 120°C. The curing time may be kept constant at 6 hours. From the relation between the 6-hr accelerated cure strength with temperature of curing, an optimum temperature can be found out.

To determine the optimum pressure for high pressure steam curing, similar experiments should be carried out by using different pressures of curing. From the results obtained, the optimum pressure can be found out.

APPENDIX

- APPENDIX -

Relative Cost.

(1) Oven Curing.

Six cubes were cured at a time. From average time-temperature relationship (Fig. 27) time required to attain 100°C. is equal to 2 hrs. and 20 mts. Power consumed for this period will be 2.33 x 3000 is equal to 7000 watts. For 6 hrs. total curing, for remaining period the number of time circuit make and break was observed and found nearly 1/4 time the circuit was on. So, power consumed for remaining period of 3 hrs. and 40 mts. is equal to 3.67 x 3000 x 1/4 = 2750 watts.

Time required to attain 60°C was about 3 hours. So, power consumed is equal to 3 x 1500 = 4500.

So, total power consumed is equal to 7000 + 2750 + 4500 = 14250 watts = 14.25 K.wh.

Therefore, power consumed per cube is equal to $\frac{14.25}{6}$ = 2.37 K.WH.

(2) Steam Curing.

Six cubes were cured at a time. Time required to attain 100°C. from 60°C is equal to 3 hrs. Power consumed at the rate of 2000 watts/hr = 7000 watts. Power consumed for remaining period of 3 hrs. is equal to 3 x 1000 = 3000 watts.

Time required to attend 60°C. was 2 hrs. and 15 mts. Power consumed for this period is equal to 2.25 x 2500= 5625 Watts. So, total power consumed is equal to 7500 + 3000 +5625 is equal to 16125 watts = 16.125 K.W.H.

Therefore, power consumed per cube is equal to $\frac{16.125}{6}$

= 2.954 K.W.H.

(3) Electric Curing.

The energy consumed by this method was plotted as shown in Fig. No.70, for different water-cement ratios. The power required to cure one cube for 24 hrs. at 60 volts for water-cement ratios of 0.4 and 0.35 were 1412 and 772 watts respectively. Taking average of both, power consumed per cube is equal to 1.092 Units.

From the above, it is clear that electric curing works out to be the cheapest method of curing, while oven curing and steam curing are approximately equally costly. Cost of steam curing is slightly more than oven curing (6%), but the ease with which steam curing can be done and the higher strength obtained offset the above said disadvantage in cost.

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