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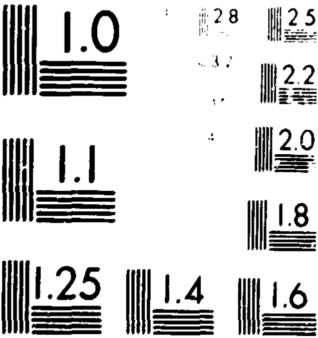

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HIGH-ALUMINA CEMENT AS BUILDING MATERIAL*

by

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003559

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ABSTRACT

High Alumina Cement (also known as Alumineus Cement) is produced by heating a mixture of limestone and bauxite to fasing, quickly attains a very high strength and is, in its original form salphate resistance. At hydration metastable aluminates are found, crysta ising in hexagonal system, which transform into a stable cubic compound. This results in a reduction in volume of gel and increased porosity called "Conversion" with a reduction in strength. This effect can be minimized if the water/cement ratio is low.

In 1974 two beams of a roof collapsed in England, although this design was in accordance with the code. Apparently either the manufacture of the beams was unsatisfactory or the cement was at fault. Prior to this Prof. A. M. Neville listed several failures in building containing HAC. Consequently the safety of many structures need to be investigated. This led to the issue of a joint Department of Environment / Department of Education and Science Circular: terminating the use of HAC in building until further notice; calling on existing buildings incorporating HAC concrete to be regarded as suspect, that a further programme of action be effected starting with those buildings with the greatest risk.

As purported in the DOE/DES Circular the factors which are believed to have contributed to the loss of strength; are complex because the extent of research that went into this area was not impressive. The problem was further complicated by the various manufacturing processes which implied varied composition thus obscuring research data obtained in the past to the effect that solid aggreement was not attainable. With this realization, the author conducted intensive investigation of the British brand Commercial HAC. The research study covered more or less the overall behaviour of the cement concrete, giving more attention to prestressed concrete units, under various curing conditions. The investigations geared to long term and short term storages were directed to standard tests of HAC concrete samples, chemical tests, creep, shrinkage, pretensioning bond transfer, flexure and shear strengths of pretensioned beams and test development and instrumentations for the topics under study. The presentation of this paper discusses the First-Phase Study conducted at the University of Bradford, Yorkshire, England.

A short and long term studies of standard tests comprising of cylinders, cubes and flexural prisimatic beams, were made. Unlike Prof. A. M. Neville, based on his own research data on neat cement and that of Talaber's long term study, advocating the dangers pertinent to the use of HAC in structural buildings, we are of the opinion that provided proper safeguards are strictly

observed initially there will be no cause for alarm. The research was based on 1 : 1.6 : 3 concrete mix with free-water/cement ratio of 0.35. Twenty four hours after placement of fresh concrete, specimens were stored either in dry room (16°C and 45% R.H.), normal curing (21.5°C) and 95 - 100% R.H.) or hot-water tank (45°C and 100% R.H.). According to Talaber (using Hungarian cement (quoted by Neville) about 50% of the maximum ultimate strength will be lost for those specimens stored in open air in Budapest. Neville, from the study made on neat cement, concluded that it was insufficient for the use in prestressed concrete. In our case the losses based on 24 hr. strength (680 kg/cm^2) for normal and dry storages were zero and 50 per cent respectively after two-year storages. For the dry condition there appeared to have no sign of strength recovery and the loss could be higher than anticipated. For hot-water storage the maximum loss in strength was 25 per cent after seven day storage due to full conversion. It appears that specimens stored in dry room suffered most, evidently not due to conversion as verified by d.t.a. tests but due to deployment of harsh mix followed by subsequent storage in dry room. This could possibly affect the water of crystallization which is vital to the strength development of the concrete.

It must be noted here that unlike previous code practice a minimum cement content of 400 kg/m^3 of concrete was employed. It has also been found that the rate of flexural strength development will be higher if the temperature in wet room is kept about 22°C instead of the standard of 18°C. For tropical countries it would be appropriate if steam curing is applied to achieve full conversion.

Keywords:

Acidity, Alkalinity, Aluminous cement, Alkaline hydraulysis, Conversion, Cubic crystallization, D.T.A. Free Water/Cement Tatio, Full conversion, Hexagonal Crystallization, Refraotory Concrete, Total Water/Cement Ratio, Ultrasonic Test.

INTRODUCTION

HAC is produced from bauxite and limestone and has quite different properties from Portland Cement, made from calcareous and argillaceous materials. It hardens rapidly and quickly; and obtains a very high strength (e.g. a cube strength of 68 N/mm^2, or 680 kg/cm^2 in 24 hours). In its original composition, it resists chemical attacks of sulphides and dilute acids. It is unique as compared with Portland cement inasmuch as in connection with refractory aggregates it resists temperatures upto 1500°C. It is, however, subject to chemical influence due to alkalis, resulting in alkaline hydrolysis. Consequently, it is essential to avoid the use of aggregates, particularly flint sand containing alkalis.

On hydration of HAC aluminates are formed which crystallise in the hexagonal system and are metastable. In contact with water and at temperature above 25°C, they fairly rapidly transform into a stable cubic crystallized compound.[1] This results in a reduction in volume and hence in increased porosity of the concrete with the consequence that also the strength may be considerably reduced. This process, which is known under the term "conversion"[2], was originally not fully recognised and failure of HAC concrete occured mainly due to the fact that the water/cement ratio was too high and/or the compaction was inadequate. The railway tunnel in Iraq[3] is a living example where water/cement ratio of 0.75 - 0.9 was employed as recommended by the manufacturers. Good compaction is essential to obtain a dense material.

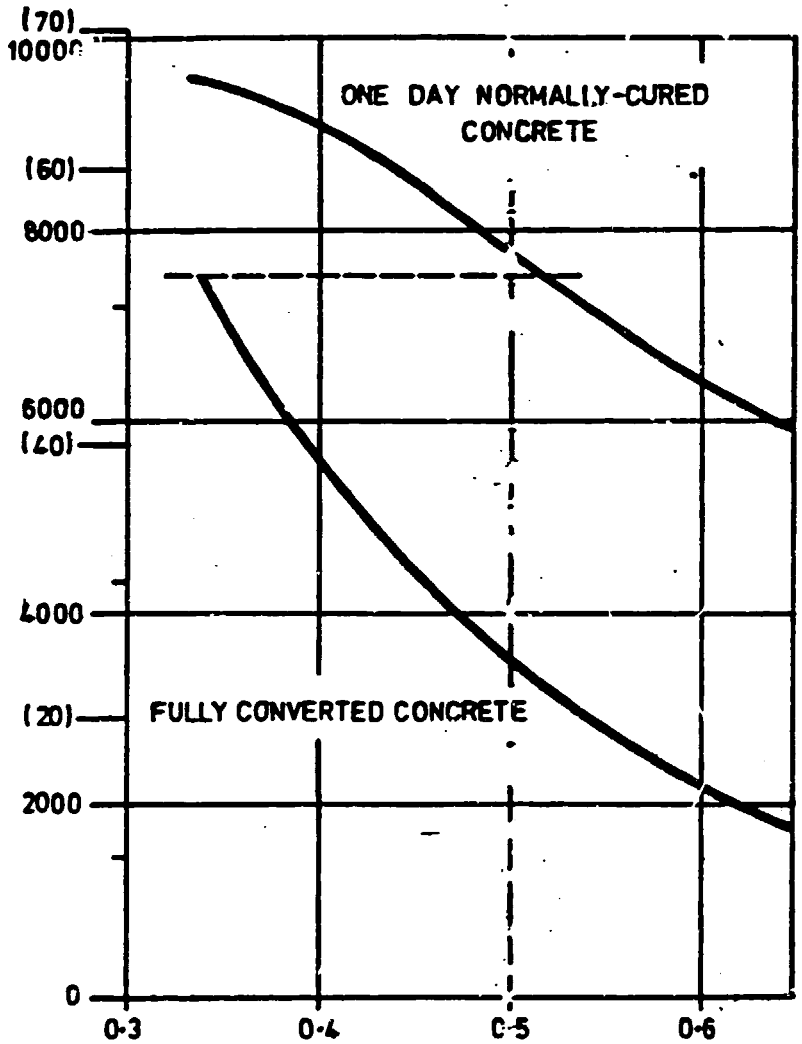
The idea of HAC was introduced in the year 1908 in France[4] where a patent was proposed for the manufacture of an aluminous cement by fusing a mixture of limestone and bauxite. The manufacture was commenced with by the Lafarge factory in France in 1916. Between the commencement of manufacture and the second world war it was employed in France apparently without specific care regarding quantity and quality of water. Thus, sea water was used and the water/cement ratio was not limited, with the consequence that a great number of cases of failure occured and replacement by Portland cement had to be made.

In 1943[4] the use of HAC was forbidden for permanent use in state buildings in France. After the Second World War failures occured also in Hungary and Germany, whereupon the use of HAC was banned in 1963. In Great Britain it was originally left to the manufacturers of HAC to give advice for its use. Neverthless some unsatisfactory results were obtained, but the use of HAC was not forbidden. By the introduction of prestressing in the long line process[5] soon after the second World War, some British prestressed concrete manufacturers considered HAC as more suitable because it allowed an early transfer to prestress, unmoulding and reuse of the moulds. Early research by the Building Research Station[2] showed that a low water/cement ratio was essential to avoid great reduction in strength due to conversion. However this was not low enough. CP114 published in 1948, permitted its use for reinforced concrete and recommended a 1:2:4 mix with total W/C ratio of 0.58. Until fairly recently (1973 at the height of the Camden School collapse in England) most of the researchers focussed their attention to standard mix, namely 1:2:4 and W/C ratio of 0.6. No research had been advanced to see the strength development on lower than 0.5 water/cement ratios so as to strike on the most suitable mix which would minimize the adverse effection strength. If there were, they were either scattered ones based on neat cement or HAC concrete with varied aggregate textures or varied curing temperature and compaction time. There is an evidence to show that even the water/cement ratios cited above appear to have been based on free water/cement ratios rather than on the total as claimed. Masterman referred to research by the Building Research Station included in the book by F.Lea and N.Davey who, as early as 1933, recognized the importance of low water/cement ratio, and also the influence of heat and humidity on conversion. However Kidan & Wilby[6] think it was not low enough considering the overall situation.

In 1960 a drafting committee for a Code of Practice on precast concrete was set up. This resulted in the Code of Practice, CP116,[7] published in 1965 and in metric version in 1969. It was considered advisable to include a specification for HAC to avoid failures particularly since the advice by the HAC manufacturers which was requested in previous codes was often based on statements by non-technical salesmen. An extensive survey on HAC appeared in 1963 by Neville[3] which dealt with many test results and showed many failures where HAC had been used. To clarify the matter an adhoc committee of the Institution of Structural Engineers[8] was set up which prepared a report in 1964 upon which the specifications of the Drafting Committee CP116 were based. This adhoc committee consisted of ten members, one of whom was Professor Neville who was at that time the

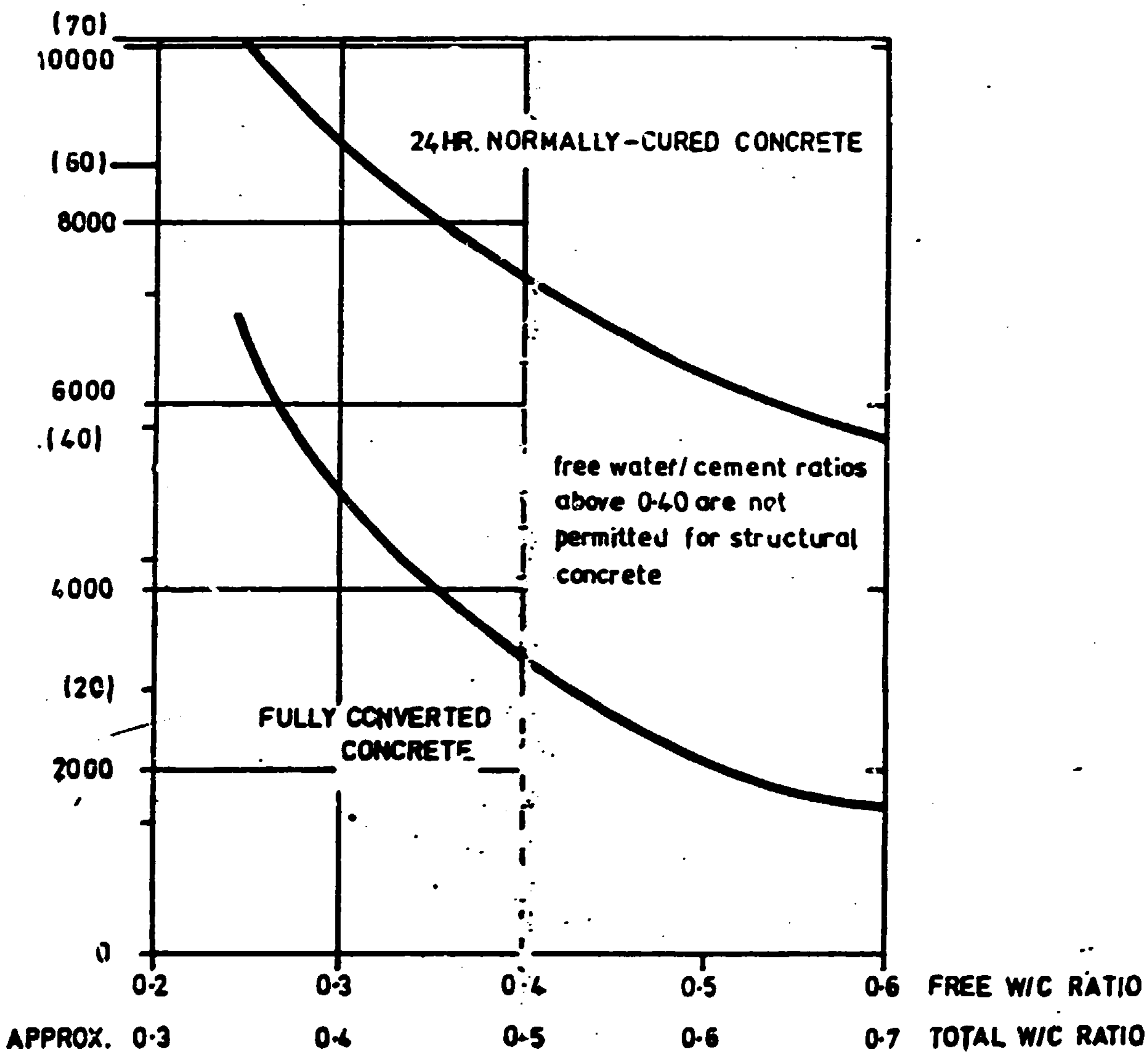
Dean of Engineering at the Unive sity of Calgary, Alberta, Canada. In the summary of the report it was stated a low water/cement ratio not exceeding 0.5 for R/C and 0... for prestressed. It stated further where adequate precautions are not met to minimize rapid conversion, strength should be based on full conversion. The shortcoming of this code was that the one-day strength was specified as $67N/mm^2$ instead of $83N/mm^2$.(Fig.) apparently in order to make easier for the concrete producers. This lower strength correspond to a water/cement ratio of 0.53 higher than that specified. On the question of shrinkage and creep the code failed to give proper guidance; instead it refers to Manufacturer's advice. As regards to cement content the code specified the maximum amount of HAC to be 265 to 400 kg/m^3 of concrete. How such low cement content with total water/cement of 0.4 is compatable as regards to workability, even if vibrator is employed, is beyond our understanding.

In 1972 the British Code CP 10[9] appeared in which the curves Fig.1 were modified to those shown in Fig.2. This code covers both precast and in-place concrete. The use of the last part is contrary to that specified in CP 16. It casts more doubt whether it would be possible to consolidate fully cast in place concrete of such low water/cement ratio with limited cement amount. CP110 does not contain any reference to the Report, which refers to the dangers of using aggregates containing alkalis. After the collapse of the two beams of the roof over the swimming pool, the part of CP110 relating to HAC was deleted in 1974 and this was approved by parliament in January 1975.



CP. 116 : 1965
CODE OF PRACTICE - PRECAST CONCRETE

FIG. 1



CP.110 : 1972
UNIFIED CODE OF PRACTICE

FIG. 2

WHAT WENT WRONG WITH HAC?

As stated in the introduction, HAC has been widely used as a substitute for portland cement in the manufacture of precast concrete products, due to its rapid gain in strength following the initial hardening of the concrete. This is particularly advantageous in the manufacture of prestressed concrete since it allows the prestressing force to be transferred to the concrete at an earlier date and thus permits a higher output of units.

The conversion of HAC was first recognized by Lea & Davey over 30 years ago. It occurs because some of the initial products of the hydration of this cement, at normal, are chemically metastable at ordinary temperatures, that is, they undergo a spontaneous change with time. This chemical change is accompanied by a change in the physical structure of the cement paste and an increase in the porosity of the concrete. The effect of these changes is to reduce the strength of the concrete but the magnitude of this reduction may vary widely. High water/cement ratios accelerate the rate of conversion of the concrete (see Fig. 3)[10], as may exposure to high temperature and humidity. It is also thought that rapid conversion of the concrete results in a fully converted concrete having much lower strength than would gradual conversion. Inspite of its great resistance to sulphates, it is possible, therefore, that with extended porosity due to conversion this resistance is completely annulled.[10] However the loss of strength of HAC concretes due to conversion is a complex phenomena which is not fully understood. The problem is still compounded by the different manufacturing process in different countries which implies different composition of the constituents and generalization of test results, as already sighted, could be misleading.[6]

WHAT IS CONVERSION?

The manufacturing process of HAC is not standarized as that of Portland cement and hence contradicting views are liable to emerge in view of composition variations in cements.

Lea[1] stated that the main hydrate phase in set HAC was CAH10. This has also been confirmed by Wells and Carlson and Schneider.[11] The hydration, without temperature rise, of the monocalcium aluminate can be written as.

$$CaO.\ Al_2O_3 + 10H_2O \longrightarrow CaO.\ Al_2O_3 \ .\ 10H_2O \ . \qquad (1)$$

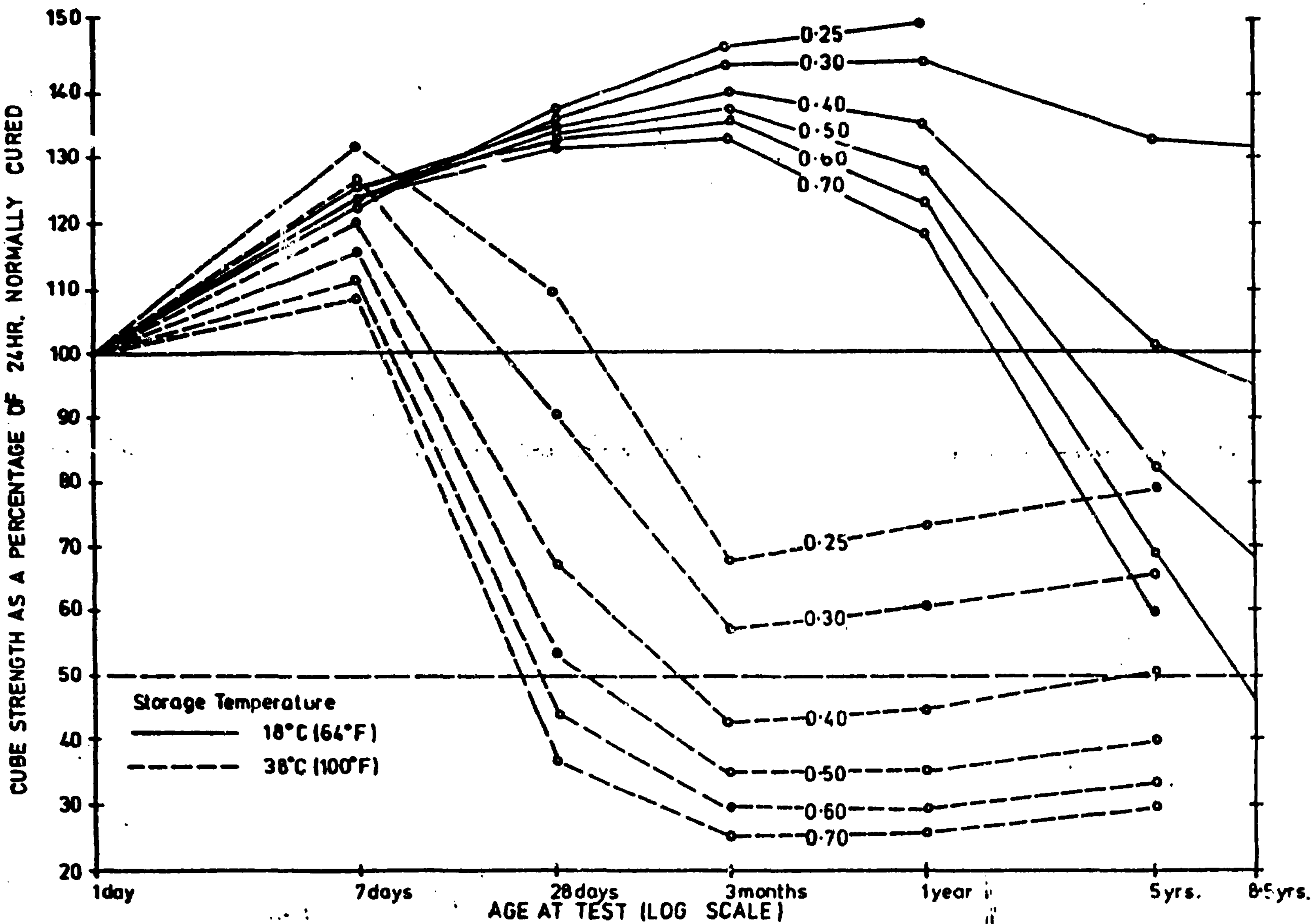


Fig. 3 EFFECT OF STORAGE TEMPERATURE ON CUBE STRENGTH DEVELOPMENT OF HAC CONCRETE AT VARYING FREE WATER-CEMENT RATIOS

The resulting compound is calle the moncalciumaluminate decalydrate (CAH_{10}) which has hexagonal crystals. If the increase in temperature of the surroundings is allowed to rise and this effect is transmitted to the concrete by either of the two processes, according to Midgely[11],

(1) If the increase in temperature in humid conditions is either substantial or occurs frequently, the conversion occurs directly

$$3(C_a . Al_2O_3 . 10H_2O \longrightarrow 3C_aO . Al_2O_3 . 6H_2O + 2(Al_2)_3 . 3H_2O) + 18, H_2O \quad ..... \quad (2)$$

(2) If the temperature rise is small, conversion occurs in two steps :

$$2(C_aO . Al_2O_3 . 10H_2O_3 \longrightarrow 2C_aO , Al_2O_3\ 3H_2O + AL_2O_3 . 3H_2O + 9H_2O \quad .....(3a)$$

$$3(2C_aO . Al_2O_3\ 8H_2O) \longrightarrow (3C_aO . Al_2O_3 . 6H_2O) + Al_2O_3 . 3H_2O + 9H_2O \quad .....(3b)$$

For large casts, the hydration of CA can provoke a block of HAC concrete (see Fig. 17 as obtained by Davey) several cubic meters in volume. Under these conditions hydration follows the reaction; that is;

$$3(C_aO . Al_2O_3) + 12H_2O \longrightarrow 3C_aO . Al_2O_3 . 6H_2O + 2(Al_2O_3 . 3H_2O) \quad ...... \quad (4)$$

THEORIES ACCOUNTING LOSS OF STRENGTH

The adverse effects of conditions uch as high W/C ratio Fig. 3 which was not realised earlier, high curing or service temperature, the presence of friable alkalis and the possibility of chemical attack are the interacting phenomena with which HAC suffers[11]. There are at least five rival theories to account for this loss of strength :

(a) Mechanical breaking of the cement bond by chemical reaction of CAH_{10} form C_3AH_6 and $- AH_3$,

(b) The formation of $C_3\ AH_6$, in the presence of free-iron compounds, weakons the bonding power of the paste,

(c) The bending strength of $C\ AH_6 + -AH_3$ is less thar CAH_{10} ,

(d) Dehydration and ageing of the alumina gel, or

(e) The increase in porosity due to change in density of the materials involved.

Ilchenko and Lafuma[12] suggested that the reduction is attributed to some changes in the hydration products of the calcium aluminates (as in 'a'). Davey,[2] from the characteristics chocolate-brown colour, suggested that the lowering of strength is associated with oxidations of ferrous iron compounds in HAC; Rengade,[13] however, indicated that the change in colour was just incidental and concluded that similar colour could be observed at normal temperatures. Referring to (d) Wells and Carlson inferred that the loss of strength was due to the ageing of alumina gel; that is the crystallization of AH_3 from alumina gel.

Despite the various theories that exist, (e) suggested by Midgely appears to attract more attention and has received wide acceptance. The hexagonal aluminates tend to transform gradually with water, at ordinary temperatures, into cubic crystallized compound which is accelerated with increased temperature. This conversion results in a reduction in volume of gel and hence in increased porosity admitting loss in strength. The higher the temperature the faster conversion takes place. This entails that the loss of strength is a function of the rate of conversion. The authors[6] found that a cement which is allowed to convert slowly at at ordinary temperature or lower will lose, if at all, at a very slow rate whereas a cement which converts rapidly will lose strength at higher rate. This will be demonstrated later.

As discussed previously, another factor affecting reduction in strength is the initial water/cement ratio (Fig. 3). Midgely[11] suggested that with low water/cement ratio no diminution of strength is expected at elevated temperature; this was confirmed by French et al. The authors[6]; however, think there still exists loss in strength; though the reduction is minimal depending on condition of exposure.

Another factor which is worth mention is the alkaline attack, resulting in alkaline hydraulysis. Although HAC concrete, in its original form, has the advantage to resist rulphate attack with conversion, particularly if the water content of the mix is high, the strength is greatly reduced. Moreover, HAC concrete is liable to alkaline attacks.

AUTHORS INVESTIGATION[6]

The Research investigations which started in 1975 were made at the height when the collapse of two beams at the roof of the swimming pool of a school in London occured. It was time when reasons failed to prevail and the authorities were obviously very much concerned [illegible] when journalists and half-experts introduced action committees and writing articles in which the authorities were accused, For instance one journalist compared converted concrete with rotten concrete and another called HAC "rogue" cement. This highlighted in the termination of HAC for use in structural members at least temporarily. The Book by Neville, describing various failures and condemning the use of HAC, appeared in 1975.[c]

In the interest of the public and the building material HAC, despite its sensitiveness, which was mostly misunderstood by its users as another cement, the authors thought that fresh research be taken covering the overall behaviour of the material under various curing conditions. Despite "Neville's study of deterioration of structural Concrete made with HAC" the manufacturers still pressed the sale of HAC without drawing paper attention to the risks attendant on its use. Subsequent British Code on HAC appeared rather loose and inconclusive signifying the extent of research work, that went into it.

To this end, to simulate actual exposure conditions, three storage regimes were prepared, namely, normal condition (21°0 and 95-100 of R.H. dry condition (18°C and 45 % R.H.), and hot exposure condition (45°C and 100 % R.H.). The temperatures and relative humidities were controlled to an acceptable descrepancies as shown in slides 1, 2 and 3 by means of controller. The mix design was made in accordance with the work carried out by Newman on the design of concrete mix. The sand contained natural sand from river bed mingled with crushed sand to produce what is known as lintax concrete sand.(Table 1). The 10 and 20mm size gravel taken from river bed, were mostly rounded and some crushed. The Linetax concrete sand conformed to zone 2 of BS 882 grading zone. Chemical analysis of Lintax sand and chemical analysis of the commercial HAC employed through the experimental period were also performed (Table 2) Since past structural failures were for the most part blamed on the use of high water/content, minimum free water-cement ratio which allowed proper compaction of the fresh concrete without affecting workability was established. Owing to inherent differences in the consistence of cement pastes, high-alumina cement for the same mix proportions, give more workable mix than portland cement. Thus allowing the use of high-frequency vibrators for proper compaction with specified concrete lift, a free water/cement ratio of 0.35 was required for aggregate cement ratio of 4.6:1 (1:1.6:3). Such mix entails that the amount of cement necessitated per cubic meter of concrete is a minimum of 400 kg. This is contrary to the British Code according to which the maximum

Table 1. Typical chemical analysis of Lintax sand

Chemical Name	Chemical Description	Percentage Composition
Silica	SiO_2	96.82
Aluminium Oxide	Al_2O_3	4.49
Ferric Oxide	Fe_2O_3	0.97
Calcium Oxide	CaO	0.008 ± 0.001
Magnesium Oxide	MgO	0.02
Titanium Oxide	TiO_2	0.01
Chloride	Cl	0.0002
Sulphate	SO_3	0.025
Loss on heating at 105°C		6.5
Loss on ignition at 100°C of above dried sand		1.13

Table 2. Analysis of sample of cement Fond

Chemical Name	Chemical Description	Percentage Composition
Aluminium oxide	Al_2O_3	40.20
Calcium oxide	CaO	37.00
Silica	SiO_2	3.80
Ferric oxide	Fe_2O_3	11.60
Ferrous oxide	FeO	4.70
Titanium oxide	TiO_2	2.19
Magnesium oxide	MgO	Trace
Sodium oxide	Na_2O	0.08
Potassium oxide	K_2O	0.32
Sulphuric oxide	SO_3	0.12

Loss of ignition: 0.16 %

Surface area: 305 m^2/kg

amount should be not more than 265–400 kg/m^3. It appears to us, from practical point of view, it would be impossible to obtain a well compacted dense concrete with low cement quantity advocated by the codes. For the type of cement used, initial setting time was 3 hours 25 minutes and final was 3 hours 50 minutes.

Concreting was done in heavy workshop where the temperature varied from 8^o to 27^{o}C. The standard moulds consisted of six 150 mm diameter by 300 mm long cylinders, six 100 mm cubes and 100X100X500 mm standard beams. All standard cubes and beams were vibrated on a table vibrator while cylinders were vibrated with 25 mm diameter pockers. In all cases proper placement of concrete was strictly observed and hence vibration was restricted once the paste started to appear. To ensure proper hydration of the cement and to prevent premature evaporation of the water from surface of concrete, specimens were covered with wet sacks and impervious polythene sheet 8 to 10 hours after casting. Twenty four hours after casting, demoulding operations were effected and specimens were stored either in dry, normal or hot-water tanks. These standard specimens cover both for short term and long term tests. Other specimens which were not included in the discussion for this seminar were also stored in the appropriate storage regimes. Distructive and non-distructive tests were performed periodically for different storage conditions. To determine the degree of conversion, d.t.a. tests were performed on most specimens. The research data pertaining compressive strength, modulus of rupture, indirect tensile strength, stress-strain relationship, Modulus of elasticity, compressive strength based on ultrasonic tests, poisson's ratio and degree of conversion were analysed and interprated.

TEST RESULTS AND CONCLUSIONS

The problem must be looked at generally in two dimensions: the environmental conditions to which structures are to be exposed in their life-time and the degree and period of serviceability. Hence the designer is confronted with whether to base his analysis on the minimum strength attained during full conversion or the unconverted 24 hour strength; if and when the necessary informations on behaviour studies are at his disposal. Anything from chemical attacks due to alkali hydrolysis or due to porous nature of the concrete vulnerable to acid attacks down to the degree of environmental aggressiveness during the reasonable life time of the structure must be accounted for in the design requirements which were partially covered, in a loose manner, in the previous codes. The best criteria, although we don't claim we have covered it all, is to base the design on the lowest strength that could be achieved in the lifetime of the structure. But according to Talaber[1c], using Hungarian cement, about 50 percent of the maximum ultimate strength will be lost for those specimens stored in open air in Budapest (Fig.4). Neville[3], from the study made on neat cement with lowest strength of 13.8 N/mm^2, concluded that it was insufficient for the use in prestressed concrete. In our case, with the water-cement ratio of 0.35 and mix proportion of 1:1.6:3, the losses based on 24 hour strength for normal and dry storages are respectively zero and 50 percent respectively after two-year storage. For the hot water storage the maximum loss was about 25 percent which occurred between 6 and 8 days after cast. Figure 5 is typical representation of 24 hour strength and the variation in strength had been reasonably small. It appears that specimens stored in dry storage receives the worst of it. From the knowledge of degree of conversion for up to 15 months, there is no reason to believe conversion has caused such a colossal reduction. Because of the harsh mix imposed on the concrete, it is most probable that most of the unhydrated cement was not properly hydrated before it was placed in dry condition. In storages such as normal and hot water conditions it need not cause undue alarm if HAC concrete is used in the production of prestressed concrete. Precautions must be observed, as regards to proper gauging, placing, curing and proper selection of aggregates and prior knowledge of the structure functional requirements and the degree of exposure before attempt is made on the design of structural units. The higher the rate of conversion the lower the strength, but for a long term test the loss is minimal as shown in Figure 6 for the cube compressive-strength curves; dry room is exceptional for reasons explained elsewhere. This does not mean more conversion does not take

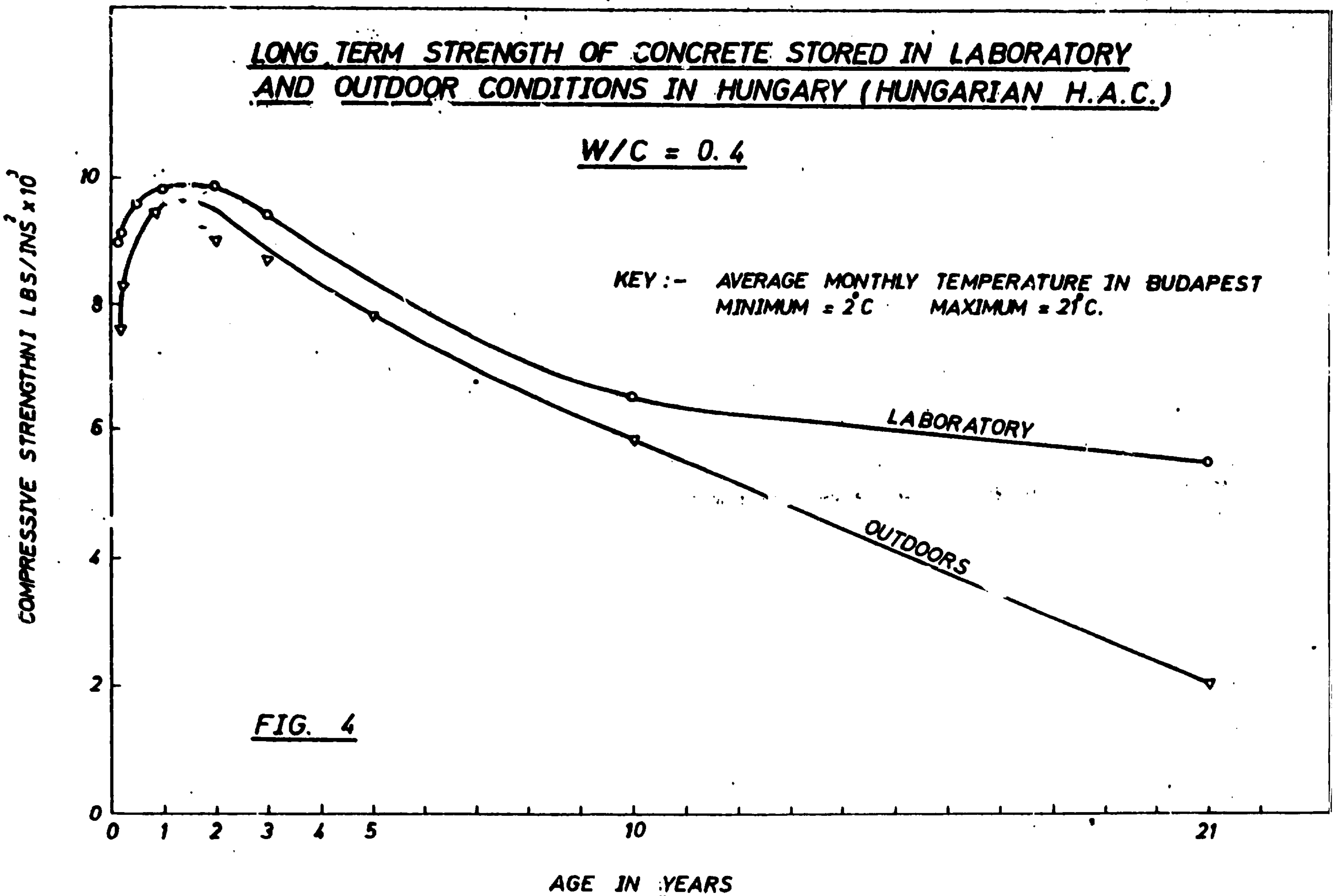


FIG. 4

Drawn by : Eng. Sayed Morsi

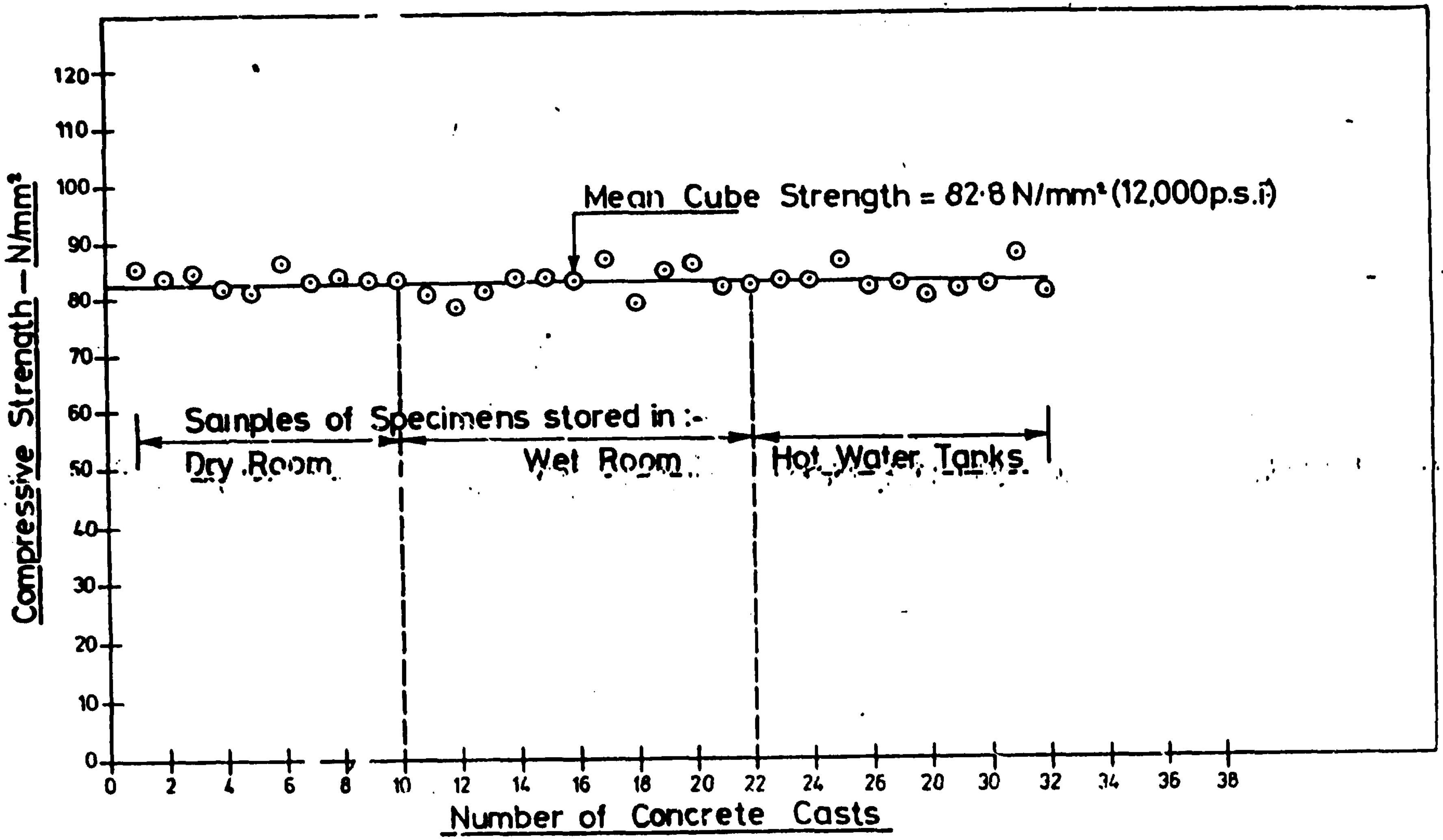


Fig. 5 Sample 24 Hr. Strengths Cast under Lab. Conditions 16 – 24°C. and S.D. = 2·8 N/mm²

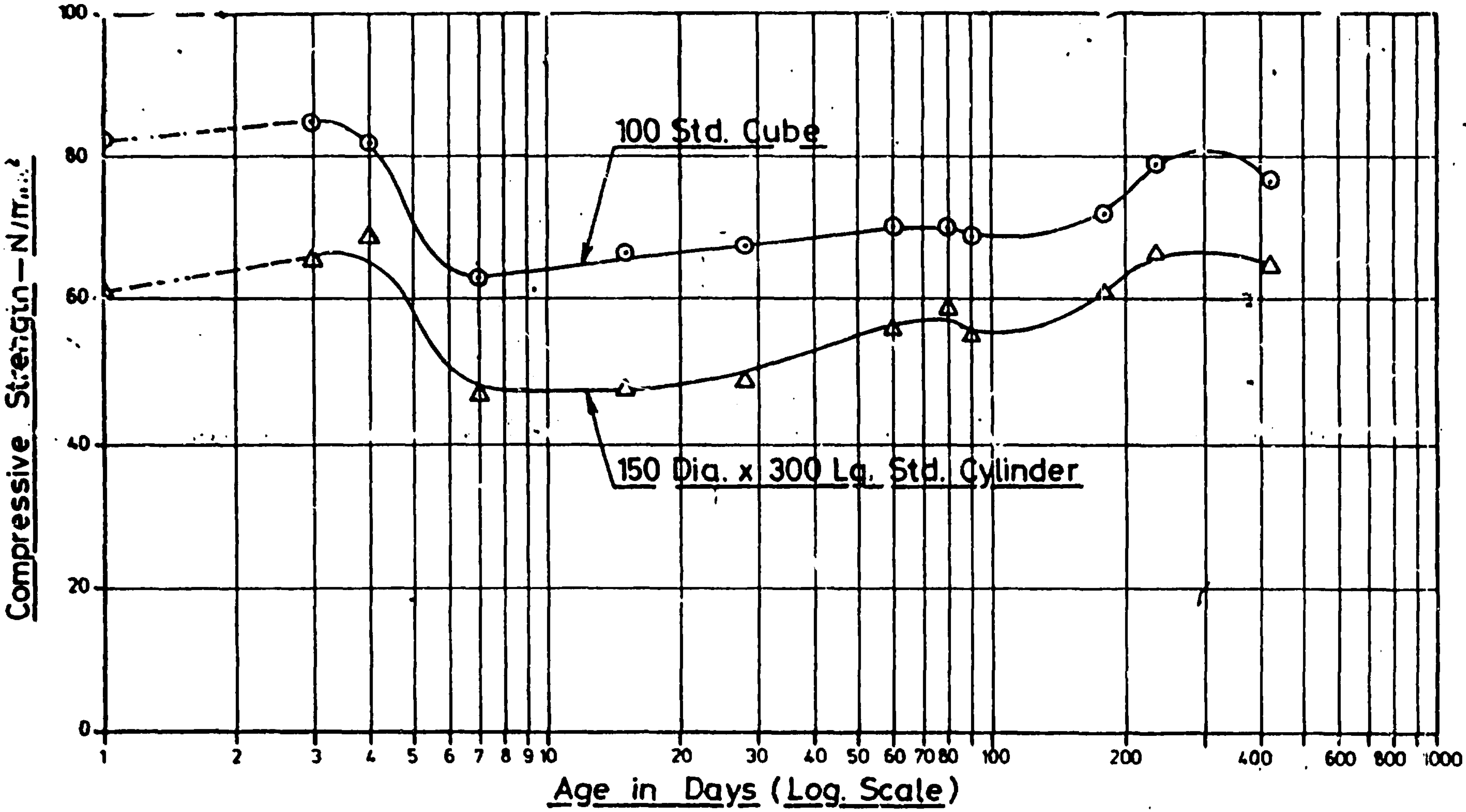


Fig. 6 Strength of H.A.C. Concrete stored in Hot Water Tank at 45°C

place at extended storage time but since gradual conversion reaction entails gradual opening and subsequent closing of pores due to further hydration as expected in curing-(wet) room storage the process is slow to cause abrupt reduction as expounded in hot water storage (Figure 6). So if we consider the minimum strength obtained from hot water storage ($45^{o}C \pm 1$) as the basis for our design, it is still more than adequate to use the material for prestressed structural members. At elevated temperature (other than that encountered in our project) further research is imperative; not only on compressive strengths but also on all other factors that affect the structural prestressing members built of HAC concrete.

As discussed previously the research thus far produced on HAC has been inconclusive . They are all scattered or quoted or the W/C ratio, the type of aggregate, the mix proportion and the type of cement are different, and in most cases conclusive results were only obtained from neat cement paste. Such being the case it is not surprising to leave us with conflicting results which highlighted in the roof collapses at Camden, Leicester, and Stepney, London, marking the end of its structural use. We trust that our intensive research on the subject in the treatize of each separate topic will help to inspire a fresh look on the subject and to recommend or suspend its uses based on clear knowledge of its behaviour and not otherwise. It would be impossible to produce 1:2:4 with free water/cement ratio of 0.35 without impairing the workability. It is, therefore, suggested a richer mix such as our own with cement content of 410 kg/m^3 of concrete be used. Neville also noted the loss of strength was less for richer mixes. This agrees with the recent introduction of cement content requirement of 400 kg/m^3 or more by Cement Fondue Lefarge. Alternatively, this may have adverse effect on the cost and puts the cement at a disadvantage to compete with Portland cements. This may be so at first glance but there are cases where the need dictates rather than price quotations. For instance the two significant advantages of HAC concrete, despite its anomaly, are its development of early strength amounting to almost 80 percent of its full strength within 24 hours and its superior resistance to acid attacks. In some cases, therefore, there seems to be a clear advantage to use the material in marine works, in underground works (such as piles) etc, provided strict supervision on indistrial level is taken. Under no circumstances should HAC be cast on site.

As shown in Figure 6 ,no mathematical relations between various regimes can be ascertained. The strength behaviour is dictated by the ambient conditions to which specimens are exposed.

As in Figure 5 , the 24 hour strength is nearly the same for all storage regimes. After three days storage in their respective storages, a significant change start to emerge while normal and dry storages show significant increase in strength and more or less of the same order up to 400 days. Specimens stored in hot water tanks shows slight increase up to 3 to 4 days and a rapid fall in strength after 6 to 7 days. On the overall, specimens stored in wet room shows higher values except in certain instances where conversion reaction seems to occur to a lesser degree. Such slow conversion and rehydration persist for a longer period until the concrete is fully converted (see Table 3). Thus we expect under such condition a cyclic behaviour where the strength time curve sags and hogs until the hexagonal aluminates transform into the more stable cubic aluminates. Such sluggish chemical activity does not induce appreciable lower strength, evidently not lower than 24 hour strength in the lifetime of the structure under wet condition.

As regards to dry air storage conversion has less to play as opposed to the two storage conditions (see Table 4). It has been over and over stated that conversion takes place in the presence of water. The free water, considering the conditions imposed on the specimen, could not have been responsible for conversion reaction to take place. Table 3 also demonstrates that the maximum degree of conversion obtained in DTA tests was 40 percent which could have been generated during sample taking or during DTA. Such explanation, however, does not clearly entail the cause for the colossal drop in strength at the age of 21 to 24 months. The causes, are due to deployment of harsh mix and provision of insufficient curing time followed by subsequent storage in dry room. That is since the free water-cement ratio used is 0.35, there will be a lot of unhydrated cement that need to be hydrated, complete hydration will only take place in the presence of water such as normal storage, and is also dependent on length of storage. Conversely, if specimens are placed in dry condition without sufficient curing period, the free water will partly evaporate and partly be used to take up further hydration. During the early stage, therefore, the strength increases with time (Figure 7) until no further free water remained. As time goes by there is some evidence to suggest that the water of crystallization could be affected as more evaporation takes place (see Figure 8). As more suction pressure continues the bond between the paste matrix and aggregate starts to break. From visual examination, the inner core of either cubes or cylinders was found to be extremely weak that disintegration of paste and aggregates was markedly vivid. This seems

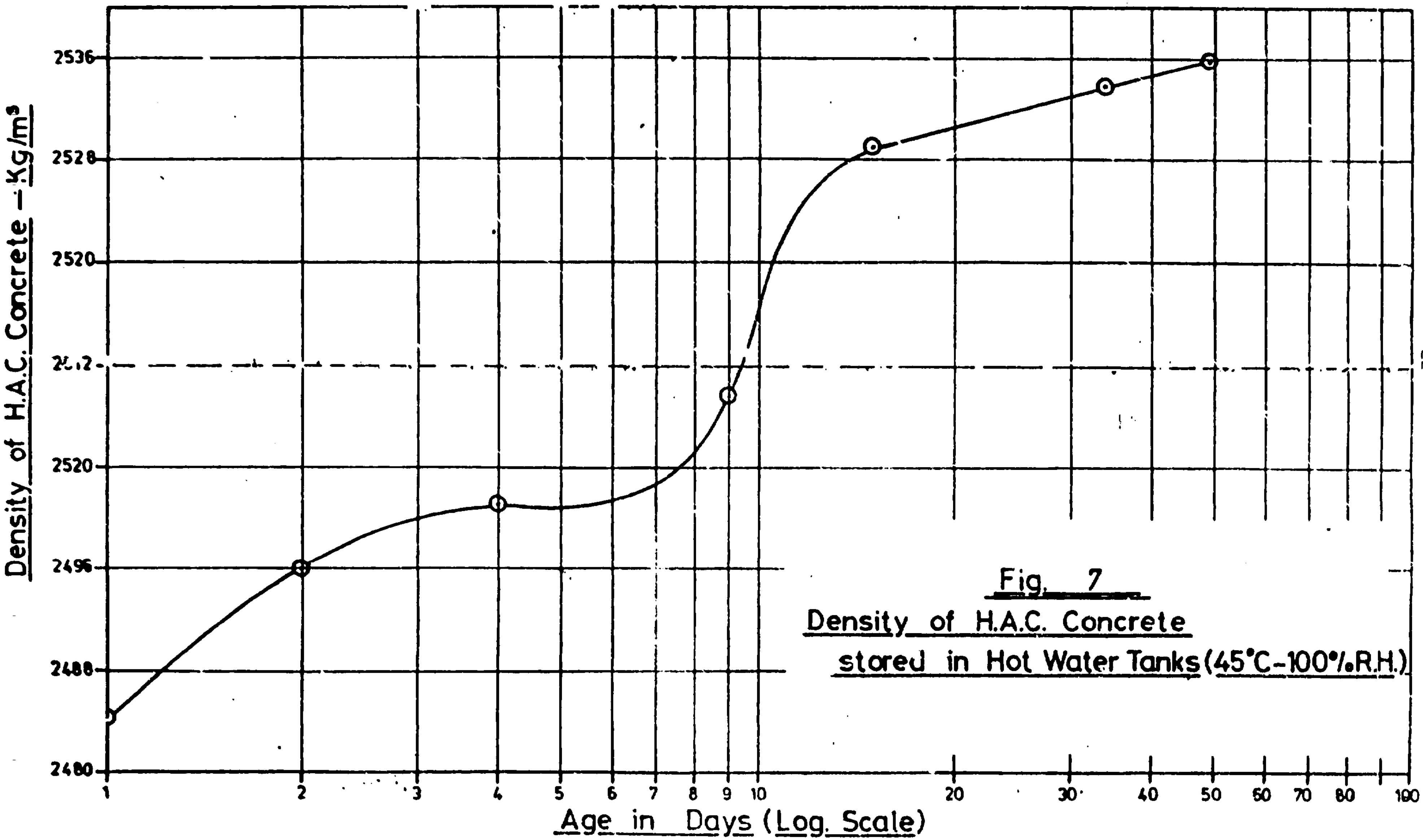


Fig. 7

Density of H.A.C. Concrete stored in Hot Water Tanks (45°C-100% R.H.)

Table 3 Degree of conversion of specimens stored in dry room

Serial No	Storage time in months	Compressive strength		Degree of conversion percent	Method of taking samples
		Cylinders N/mm^2	Cubes N/mm^2		
1	3	75	97	95	Hot drill
2	3	70	95	30	Hand crushed
3	6	60	93	30	"
4	9	59	90	90	Hot drill
5	9	63	93	44	Cool drill
6	10	60	94	31	Hand crushed
7	12	64	88	38	"
8	12	62	81	40	"
9	14	60	87	30	"
10	16	61	81	30	"

Table 4 Degree of conversion for specimens in normal curing

Serial No	Storage time in months	Strength in N/mm²		Degree of conversion	Method empl for taking sam
		Cylinders 150 x 300 mm	Cubes 100 x 100 x 100 mm		
1	3	73.1	94.5	83	Hot drill
2	3	72.6	95.0	40	Ground by h
3	9	58.6	94.6	55	Cold drill
4	9	65.6	95.4	65	Ground by h
5	12	62.3	85.3	65	"
6	12	68.5	94.9	91	Hot drill
7	12	79.2	94.3	50	Ground by h

Table 5 Degree of Conversion for Specimens in Hot-Water Tank

Concrete casting date	Test date	Storage period	Storage condition	24 hr strength cubes 4" x 4" x 4"	Periodical Strengths		Degree of conversion	Method for tracing samples	Cube strength N/mm^2
					6" x 12" cylinders	4" x 4" x 4" cubes			
9/9/77	13/9/77	4 days	HWT	11900 (82)	9956	11908	62 %	Cold Drill	82.1
11/8/77	18/877	7 days	HWT	12040 (83)	6599	9114	95+%	"	82.8
19/8/77	2/9/77	15 days	HWT	12469 (86)	7510	9738	90 %	"	67.14
26/8/77	23/9/77	28 days	HWT	12908 (89)	6908	9806	95 %	"	67.6
26/[illegible]/77	26/9/77	2 months	HWT	11970 (82.5)	8078	9880	92 %	Crushed	68.1
14/7/77	8/10/77	80 days	HWT	–	–	–	91 %	"	–
21/7/77	21/10/77	3 months	HWT	–	7431	9968	91 %	"	68.7
30/9/77	28/10/77	28 days	HWT	–	6714	8540	92 %	"	58.9
24/9/77	24/11/77	2 months	HWT	11774 (81.2)	8342	10144	95 %	"	69.7

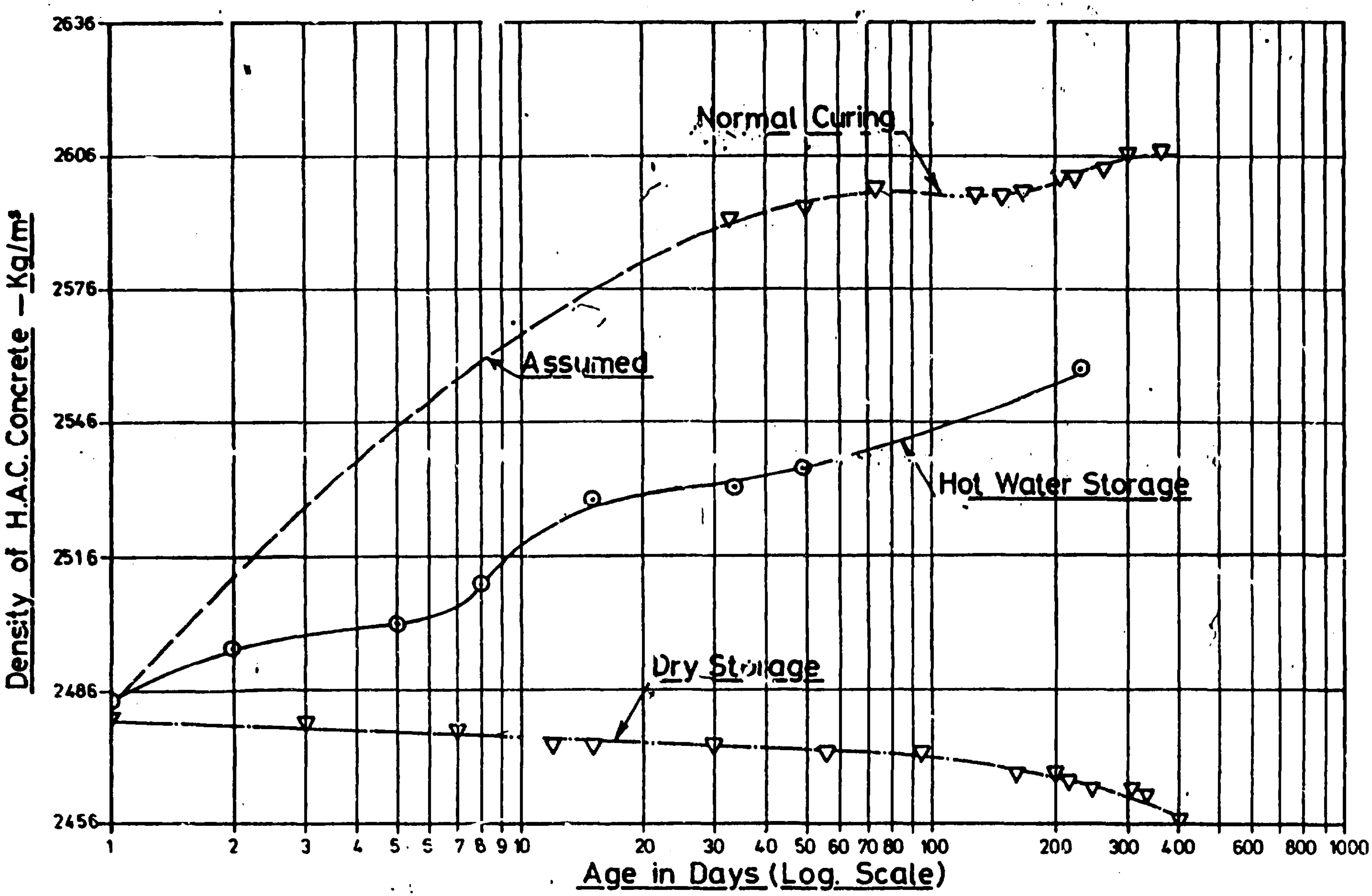


Fig. 8 Density of H.A.C. Concrete stored under Various Conditions

to afford an explanation that strength reduction is not always associated with conversion. It is true that rapid conversion encourages increase in porosity; but it must be realize that the cause of porosity are many and not necessarily conversion. For instance if we glance at Figure 2.3, we find very interesting characteristics which support suggestion put forward. It first loses density at a very slow rate up to 100 to 150 days then falls rapidly. Schnieder also stated that hydration at room temperature produced only one hydrate. CAH_{10}, and prolonged ageing for periods up to 1½ years, at 35 percent relative humidity and 25°C, did not convert this hydrate to the cubic form. It is, therefore, suggested very strongly that curing should prevail at all times so that maturity of crystals will not be hampered before structural units are permitted to serve their structural requirements in dry air condition.

The effect of prolonged storage in hot water (45°C) upon density is somewhere between the two discussed above. The very moment specimens are stored in hot water at elevated temperature, conversion commences immediately and density increases at slow rate up to 4 to 5 days (Figure 7). Since conversion and hydration, more or less, takes place simultaneously, the increase is interrupted for few hours until full conversion is completed (see Table 5). Here, it may be thought that conversion reaction is more persistent than the corresponding hydration. Then from 6 up to 15 days, probably due to increase of CAH_{10}, some increase in density is shown. A secondary conversion of some of the remaining CAH_{10} is expected between 15 to 40 days. From 40 up to 200 days the density increases with corresponding increase in strength. It appears here that hydration is a cyclic phenomenon and as there is less to convert during the subsequent hydration it can reasonably be assumed this phenomenon will cease after prolonged storage. The fact that the density increases and strength, therefore, rises after passing the minimum point suggest that the pore filling capacity of the conversion reaction products can be augumented by extra hydration products. Hence the minimum strength is attained and then gradually rises until eventually it approaches or exceeds the one day strength; but it will never be less than the minimum found earlier. As demonstrated in Figure 6 , the effect of storing specimens in hot water condition will produce rapid conversion. Comparing the densities (Figure 8) or strengths discussed previously, we see that the trends of the curves in normal curing and hot water storage are more or less the same except one goes at slow rate while the other goes at higher rate. It can be concluded, therefore, that the greater the rate of conversion the higher the matrix porosity and the lower the strength.

Figure 9 shows typical stress strain diagram for different storage regimes tested at 7 days. While the stress strain diagrams for normal curing and dry storage remain more or less the same and show more linearity, the hot water storage produces less linearity similar to normal Portland cement concrete behaviour having greater strain movement for equal load increment than the rest. This could be explained in terms of energy; that is the stronger concrete dissipates less energy than the weak one for the same incremental loads. The potential energy being the same for the three storage regimes, the specimens in hot water storage will fail first due to rapid dissipation of energy which comes under maximum strain energy theory credited to Betrami. Thus it can be concluded that the greater the energy of distoration the lesser the load capacity. However at certain stage where, perhaps, its physical make up ceases to be disrupted anymore, (That is where CAH_{10}/$C_3AH_6 + rAH_3$ progressively decreases.) and stability is reasonably maintained, the theory stated above loses its significance.

Referring to Figures 6 , 10, and 11 for clarity that once the lowest point is attained, there will be progressive strength development and lower energy of distortion for given load up to two months. After that the curvature falls under two months storage meaning that the strain energy for given load is the same for 3 months, 8 months, 13½ months etc but their potential strength is different. This is more pronounced on the 8 and 13½ month storage and there is strong point to suggest there is a gradual growth of C_2ASH_8 at prolonged storage[4]. As demonstrated in Figure 6 . the strength after recovery has exceeded that of 24 hour strength. We contoot, therefore, the notion that the fully converted strength will always be lower than that of unconverted one . The suggestion that the rate of reduction is higher than the rate of recovery is ambiguous in that while it is true that an abrupt reduction can take place at any time depending on the temperature and the rate of recovery is slow it would be wrong to assume that most of the strength lost will be recovered. As Midgley has suggested, it could well be that the diversity of thought existed because of the difference in the cementitous constituents from country to country. It must be realized that the silica content of cement Fondu Lafarge is on the higher side, between 2 and 4 percent. This is more of academic interest than the practical side; as engineers we are more interested in the minimum strength the structural unit liable to experience and strength recovery is of secondary matter which does

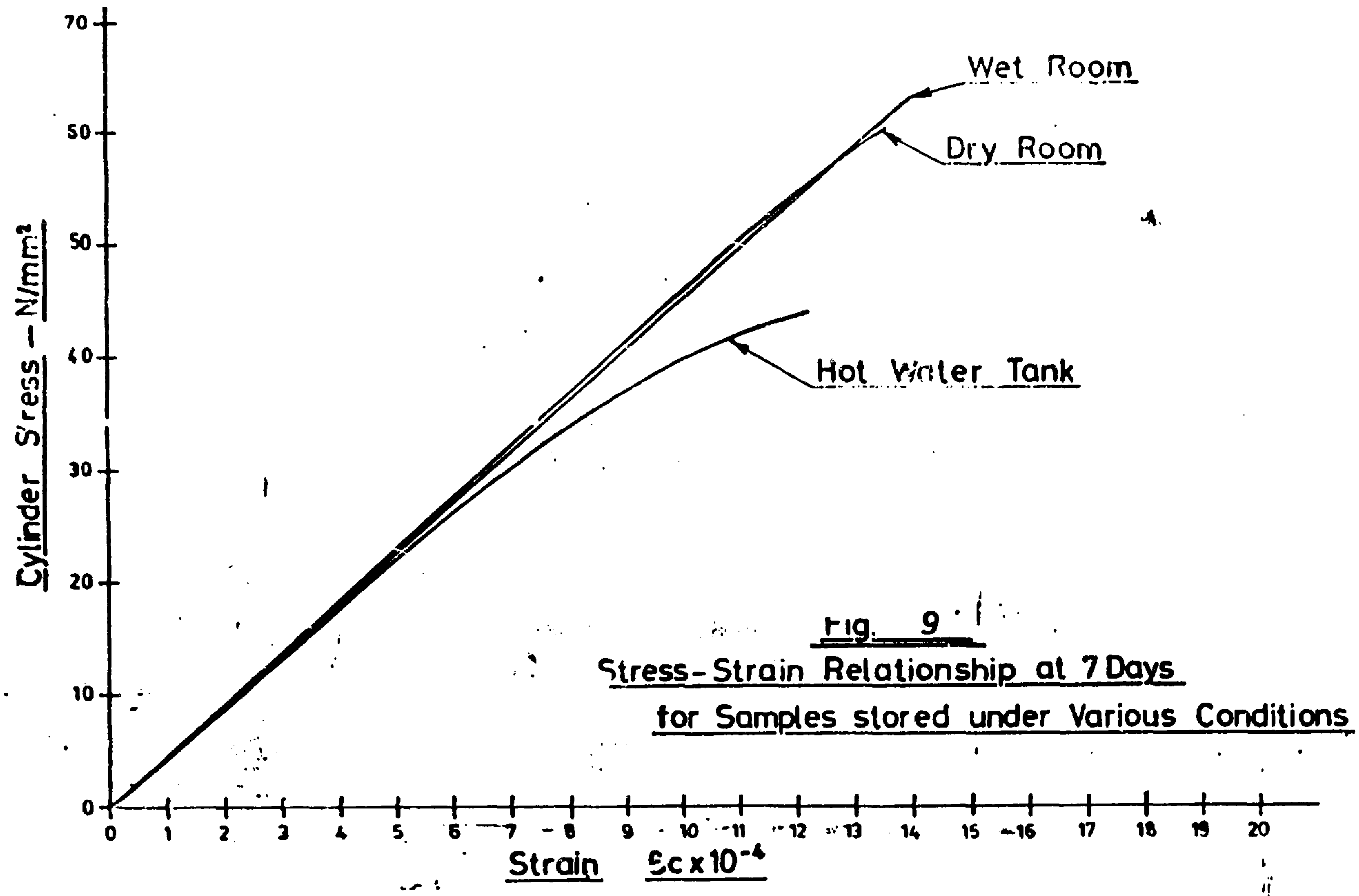


Fig. 9·1
Stress-Strain Relationship at 7 Days
for Samples stored under Various Conditions

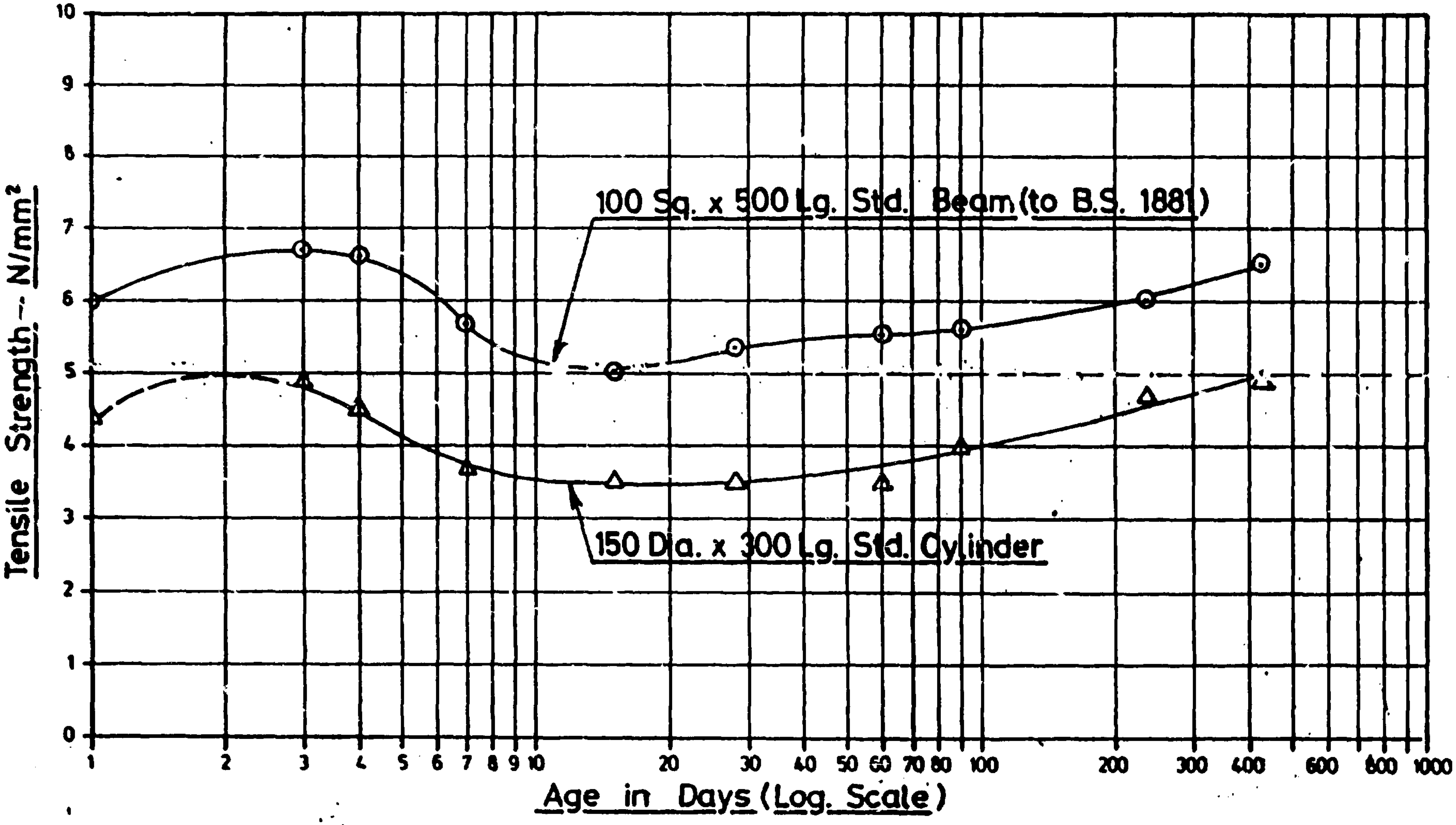


Fig. 10 Direct + Flexural Strength of H.A.C. Concrete stored in Hot Water Tank at 45°C

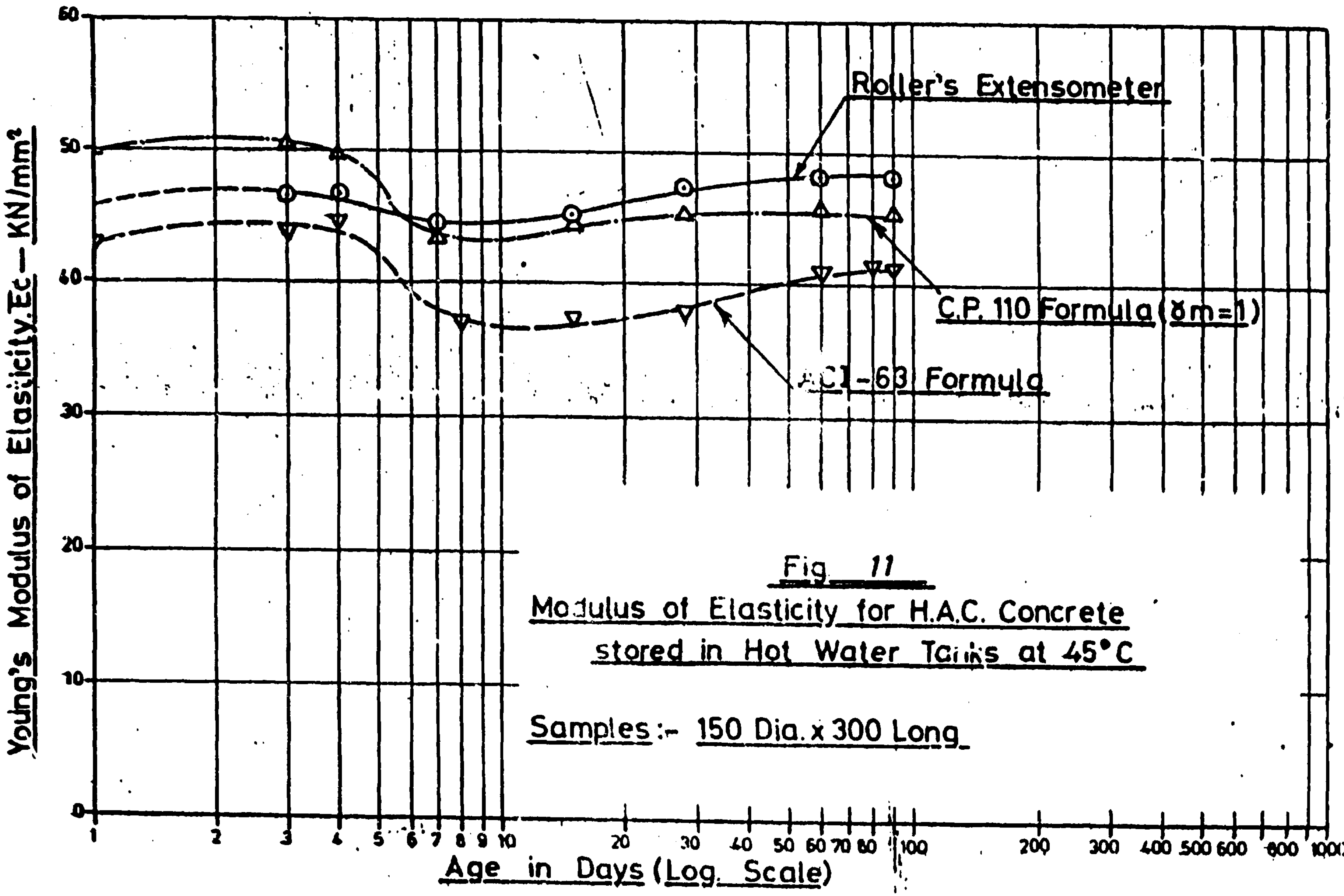


Fig. 11
Modulus of Elasticity for H.A.C. Concrete stored in Hot Water Tanks at 45°C

Samples :- 150 Dia. x 300 Long

not enter into the design calculation. Once the lowest strength is achieved, as in the case of hot water storage, however we have no reason to believe that on conversion of second cycle that the strength will be lowered. We cannot contest about the Hungarian cement, but we certainly do know that such thing will not occur in the British HAC.

Referring to Figure 12(b), the periodical modulus of rupture has similar trend as that in compression. The significant change (Fig.13) appears in normal storage where the rate of strength development is much higher than the rest. Such development was never reported by anyone in the past. It may well be that curing specimens at 18°C and below and 20 to 23°C produces different results. From results we obtained, it can safely be concluded that normal curing for HAC must be at 21 to 22°C.

It appears storage in dry condition proved to be the most critical (Figure 12(a). The flexural strength after 2 years was lower than the lowest strength obtained in hot water storage. The specimens stored in hot water tanks normally produces low strength at early age and on longer storage a slow but well defined recovery is observed (Figure 6).

Figure 14 also shows the indirect tensile strength under various storage regimes. The indirect tensile strength is generally insensitive to environmental conditions as compared to either compressive or flexural strength. Whether this is true or whether the Brazilian test does not offer the true nature of the behaviour is not clear, although storage in dry room proved superior up to 400 days with no change one way or another and then falls by comparatively bigger margin. As shown in Figure 14, specimens stored under normal curing prove weaker while on full conversion specimens in hot water became weaker by smaller order than the first and gradually takes over.

Comparing the modulus of rupture with the indirect tensile strength, it appears that there is direct comparison between the two. Especially for those specimens under normal storage there seems to be a contradiction between indirect and flexural strength; while the latter increases very rapidly the first reduces gradually and vice versa.

The modulus of elasticity, Figure 15, for the three storage regimes has very little variation and can be assumed constant for all practical purposes. The lowest should be taken for design to avoid risks. Normally the CP11 formula overestimates grossly the modulus capacity and care should be observed to avoid such misconception. Generally the ACI formula give a better result and this requires

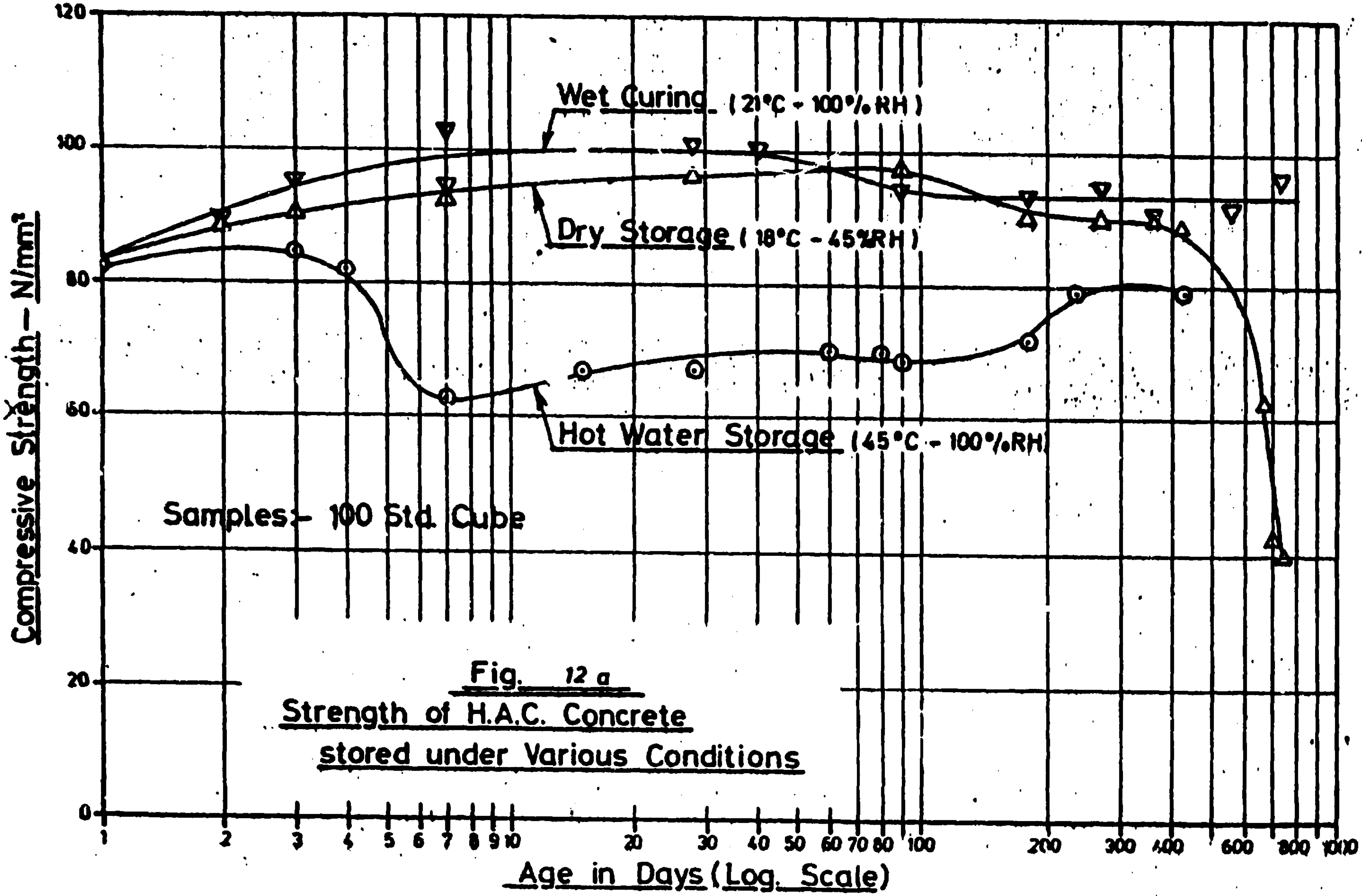


Fig. 12 a

Strength of H.A.C. Concrete stored under Various Conditions

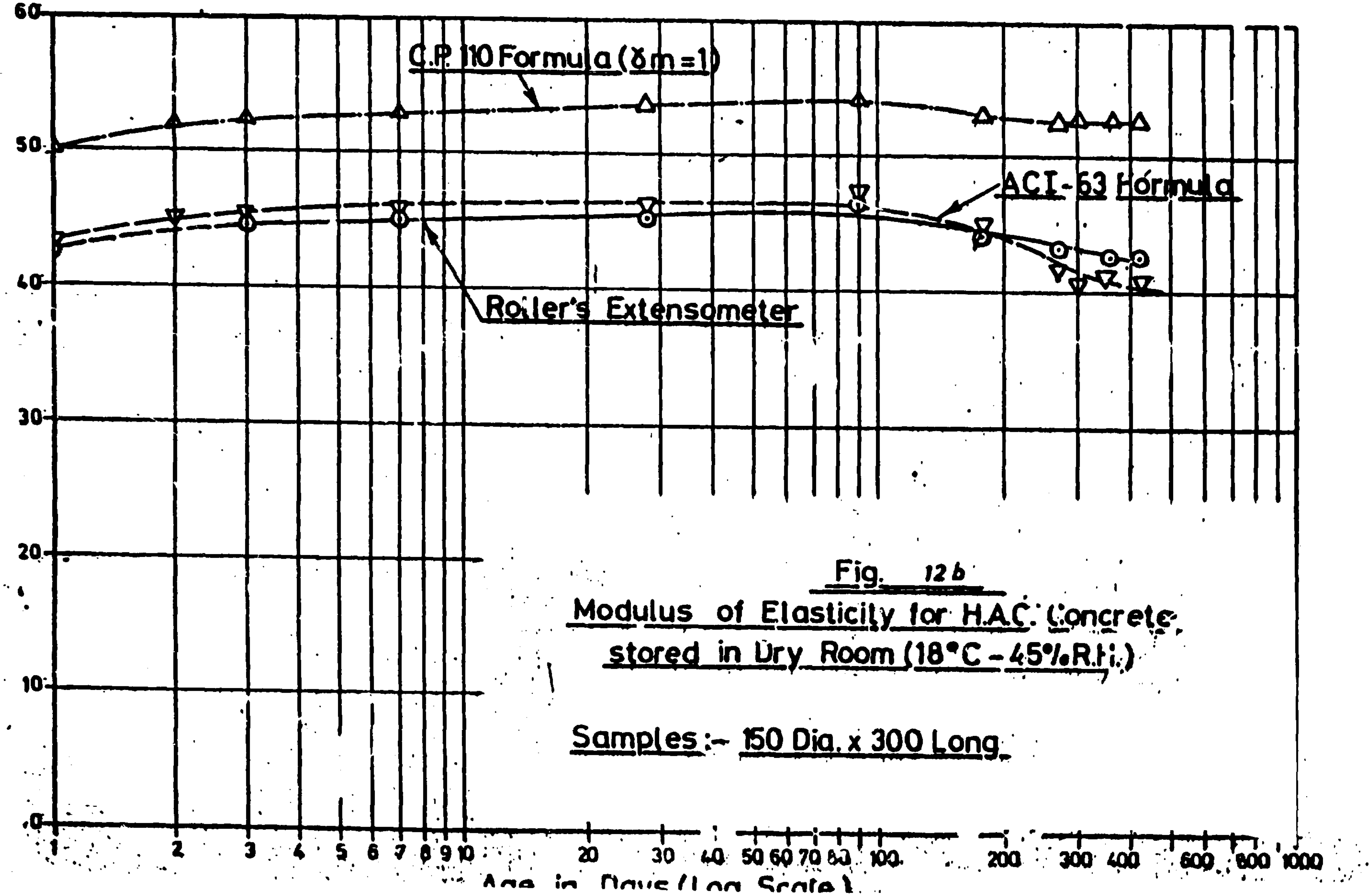


Fig. 12 b

Modulus of Elasticity for H.A.C. Concrete stored in Dry Room (18°C - 45% R.H.)

Samples :- 150 Dia. x 300 Long.

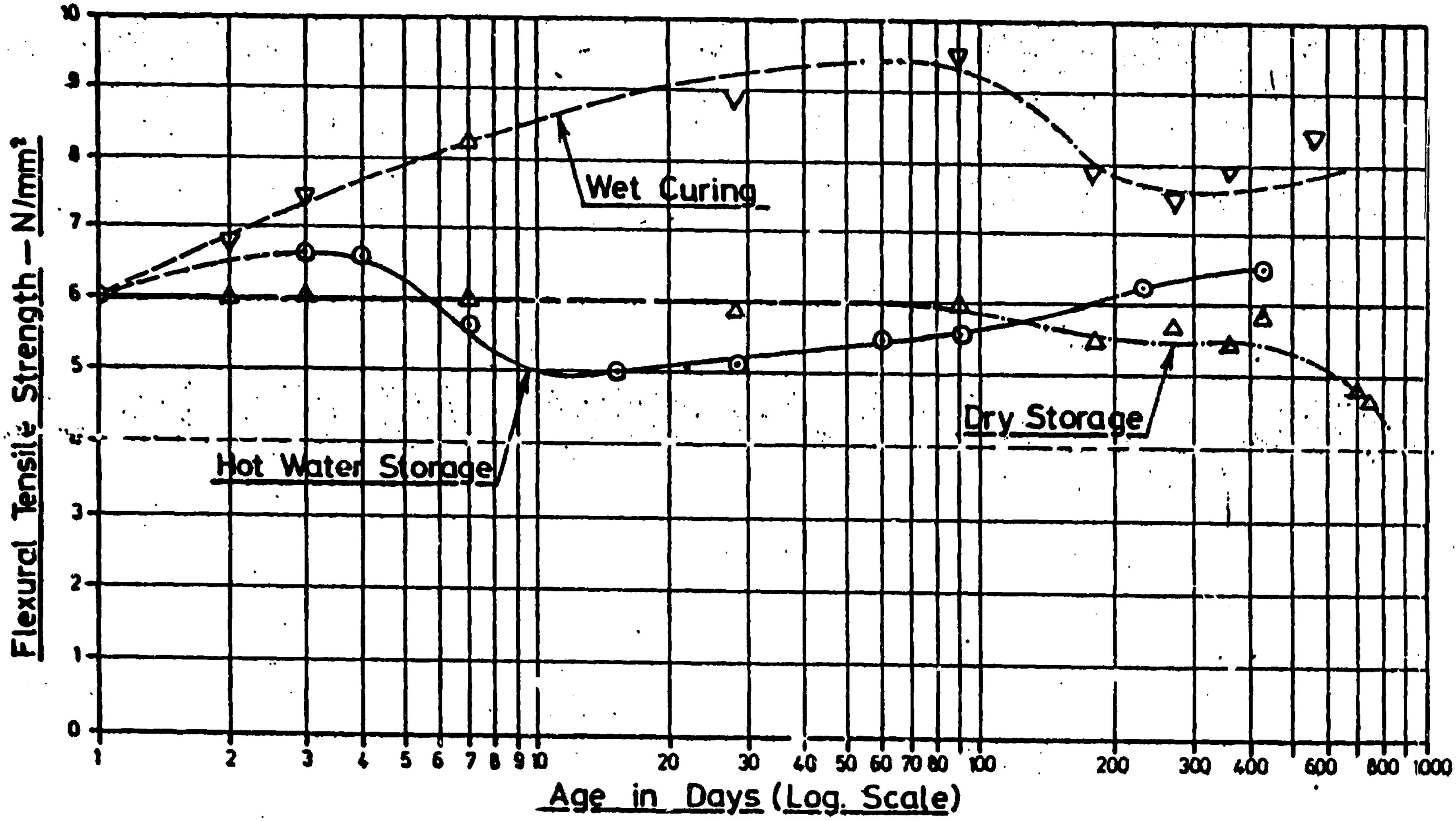


Fig. 13 · Flexural Strength of H.A.C. Concrete stored under Various Conditions

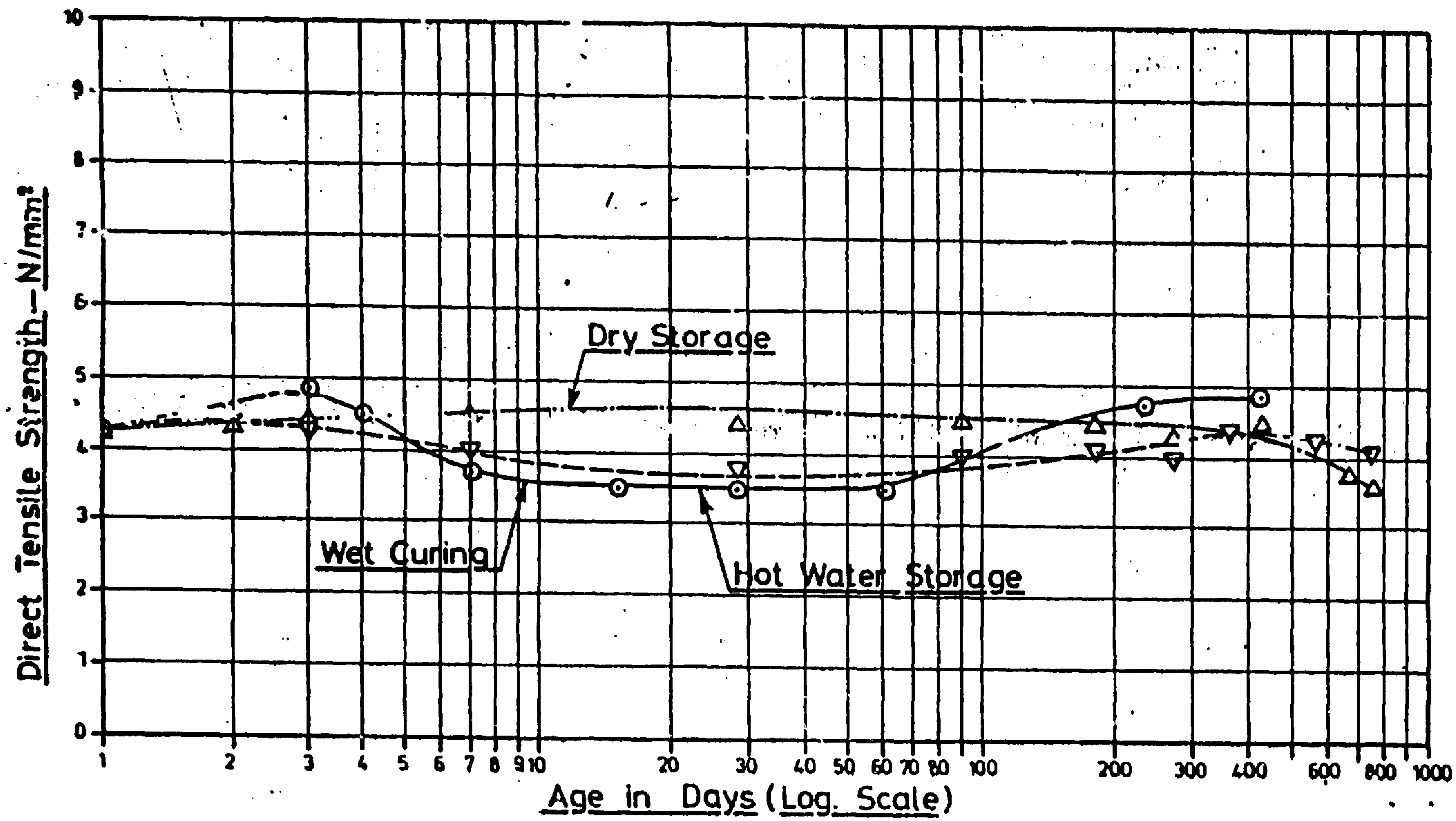


Fig. 14 Strength of H.A.C. Concrete stored under Various Conditions

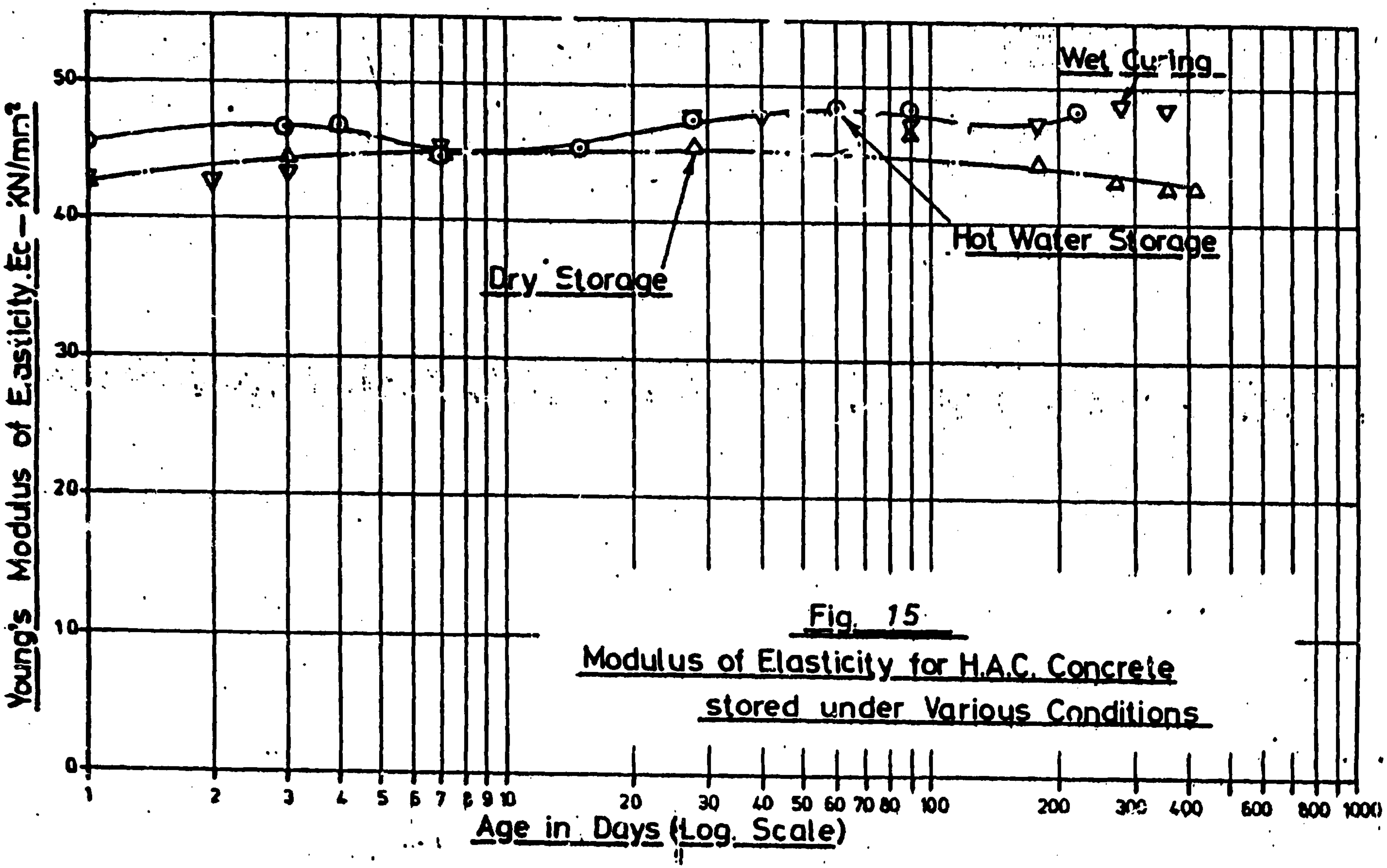


Fig. 15
Modulus of Elasticity for H.A.C. Concrete stored under Various Conditions

as a prerequisite the unit weight which helps to improve results. The inclusion of unit weight is more important in HAC concrete in view of its porosity due to conversion or to other factors. The unit weight as well as strength could also vary depending on mix proportions, water-cement ratio, type of aggregates and method of compaction.

The poissons ratio for different storage regimes do not appreciably. Thus for all practical purposes can be taken as 0.15.

ACKNOWLEDGEMENT

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Based on existing research discussed previously:

(a) Avoid mixing and placing operations when the atmospheric temperature is likely to remain above 29°C for any length of time. HAC is not supposed to be used unless proper precautions are taken.

(b) Restrict the maximum thickness of concrete to be placed in one operation to 400 mm. (Fig. 17 shows pronounced falling off if strength, due to adiabatic condition compared to normal curing.

(c) The concrete should be kept cool and moist during the first 24 hours to ensure curing and to assist the dissipation of heat due to hydration which is detrimental at early age.

(d) Use moulds, if possible, which will assist in dissipation of heat on placing and strip the formwork as soon as the concrete hardens.

(e) The mix design must be made according to Newman's treatize of HAC.

(f) The water/cement ratio must be kept as low as possible depending on the cement content, the free water cement ratio should not exceed 0.35 for prestressed concrete members and 0.4 for reinforced concrete.

(g) The cement content should not be less than 400 kg/m^3 of concrete to produce dense concrete free of porosity in order to resist chemical attacks of any kind.

(h) In climates where normal and/or lower temperature is ascertained at all times, the minimum characteristic strength can be taken as 24 hour strength.

(i) In the case of tropical climates and in places where the temperature is varied or the functional requirement of the HAC concrete members dictate that the structural units will experience high humidity and heat transfer then steam curing should be applied to achieve fully converted characteristic strength. The effect of curing temperature on conversion can be estimated from Fig. 16.

(j) Strict quality control must be observed at all times.

(k) The manufacture's agent must be competent enough to give the necessary advice on the use of HAC.

(l) The use of HAC with aggregates which might liberate soluable alkalis or lime must be avoided.

(m) HAC should not be used for cast-in-situ concrete, especially where the workmanship and some knowledge of the cement behaviour is not met.

(n) As verified in our experiment, the rate of flexural strength development will be higher if the temperature in normal curing is kept about 22°C instead of 18°C.

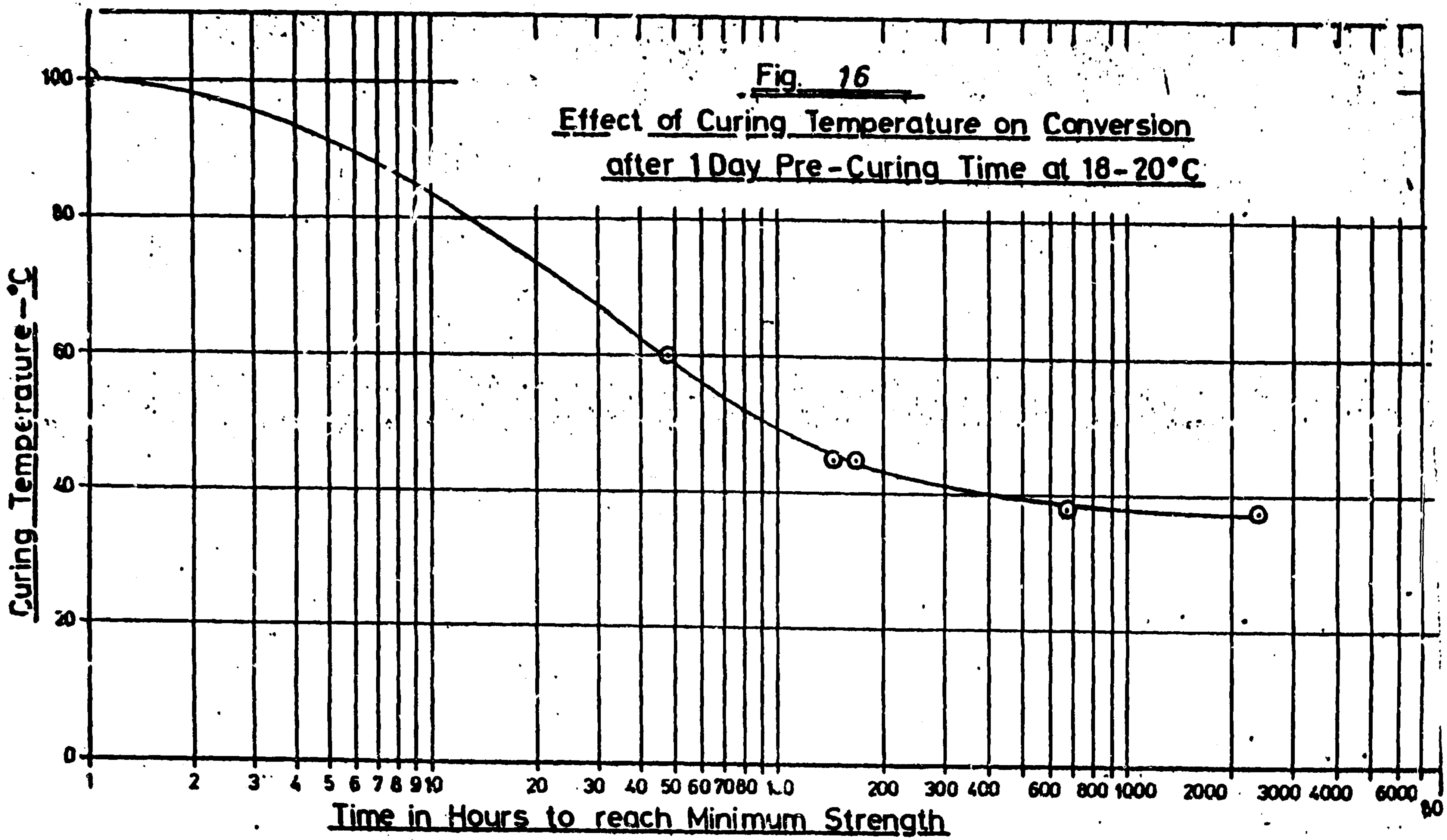

Fig. 16
Effect of Curing Temperature on Conversion
after 1 Day Pre-Curing Time at 18-20°C
Curing Temperature -°C
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
200
300
400
600
800
1000
2000
3000
4000
6000
Time in Hours to reach Minimum Strength

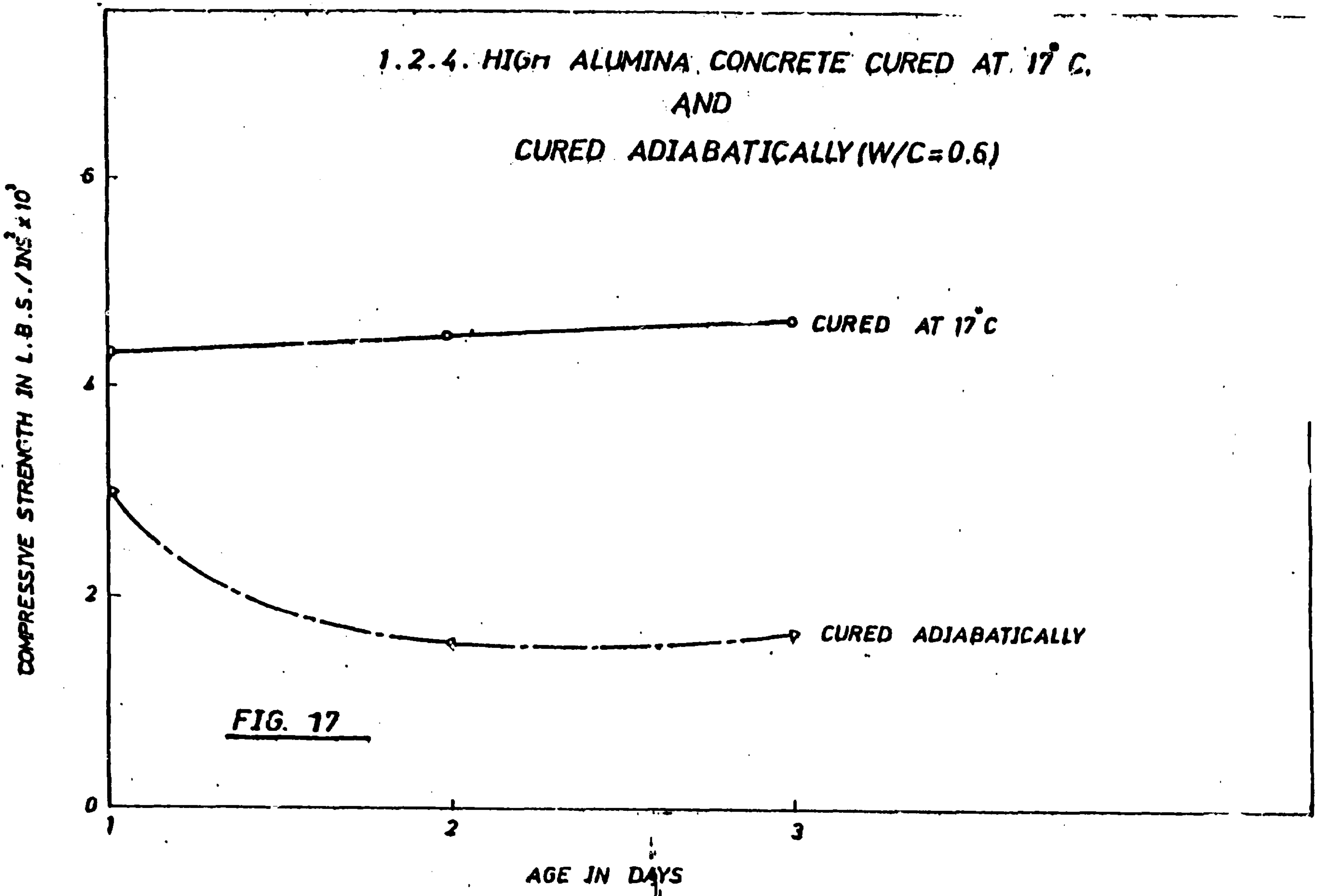

FIG. 17

Drawn by : Eng. Sayed Nord

REFERENCES:-

1. Lea, F.M., " The Chemistry of Cement and Concrete". Edward Arnold Ltd., London, 3rd Edition, 1970.

2. Davey, M., " Influence of Temperature upon the strength Development of Concrete", Build. Research Technical Paper, No.14. HMS, London,1933.

3. Neville, A.M., " A study of Deterioration of Structural Concrete Made of HAO " Proc.Inst.of Civil Engineers, Vol.25, July 1963, PP.287-324.

4. Robinson, T.D., " Aluminous Cement and Refractory Constables". edited by Taylor, The Chemistry of Cement, Academic Press, Vol.2, 1964.

5. Building Research Establishment, "High Alumina Cement Concrete in Buildings", CP 34/75, April 1975.

6. Kidan, K.G., " The overall Behaviour of HAO. Concrete Under Various Curing Conditions", Ph.D. Thesis, University of Bradford, W. Yorkshire, England, 1979.

7. British Standards Institution, " Structural Use of Precast Concrete in Buildings", CP 116, 1965.

8. Institution of Structural Engineers", Rreport on the use of High-Alumina Cement in Structural Engineering, August 1964, 17pp.

9. British Standards Institution, " The Structural Use of Concrete, CP110, No.1973, 154pp.

10. Adam Neville, P.J. Wainright, " High-Alumina Cement Concrete", The Construction Press Ltd., 1975, U.K.

11. Midgley, H.G., "Mineralogy of Set HAO", Transaction of British Ceramic Society, Vol.66, 3rd Edition, 197?.

12. Ikhenko and Lafuma, Chim. et Ind., 1937, 38, 438.

13. Rengade, E., L'Hopltallier, P. and Durand de Fontmagne, P., "Recherches sur les causes de certains phenomenes d'alterationde be tons de cement alumineux", Revue des Materibux de construction et des. Transports, Circulair series A., No.1, 5 January, 1943.

14. Newman, K. Design of Concrete.