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High early strength concrete studies.

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HIGH EARLY STRENGTH CONCRETE STUDIES

A THESIS

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by

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ABSTRACT

Revibration and two admixtures were employed in a research programme , designed to produce high early compressive strength concretes , employing moderate steam (1/0°F) and moist (initial mixing temperature of 80 to 85°F) curing . The two admixtures were a lignonsulphonic type water-reducing agent and fly ash . Revibration , water reducing agents , and fly ash (10% replacement of cement) combined with revibration were found effective in increasing the strength development of high strength concrete at all ages tested . Moist curing was found more effective in increasing the strength of concrete than the moderate steam curing , at all ages .

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Chapter I

INTRODUCTION

There are many situations in which high early strength concrete produced with or without steam curing can be effectively used . For example , in the precast concrete industry , early high-strength is desirable in the production of many structural members , concrete pipes and masonry units . Low pressure steam curing is commonly used in this industry to accellerate the early strength development .

High early-strength is also highly desirable in prestressed-concrete applications . Continued growth in this industry is dependent to a large extent on its economy . Two important factors in the economy of prestressed concrete are the cost of producing early high-strength concrete and the cost savings which can be effected by the early application of the prestress which permits more efficient utilization of forms and stressing equipment . In the production of prestressed concrete it is generally required that a minimum strength of 4000 to 5000 psi be obtained before transfer of prestress is permitted . Steam curing is used less in prestressed concrete applications than in ordinary precast concrete , because of the loss of prestress due to temperature rise (one degree F temperature rise produces stress loss of about 160 psi) . On the other hand , the shrinkage and creep of steam-cured concrete is much less than for moist-cured concrete .

Much is already known about procedures to be followed to produce high early strength concrete . To begin with , it is desirable to use high early strength cement , good aggregates and a low water-cement ratio . Many[8] studies have also been carried out to study the effect of such factors as high speed slurry mixing , vibration , revibration and pressure moulding, different types of admixtures and many different curing procedures (low and high-pressure steam curing , curing with hot gases etc.) .

The purpose of the experimental programme reported in this thesis is to investigate the effect of revibration and two chemical admixtures (a water-reducing agent and fly ash) on the early strength development of concrete subjected to both moist curing and moderate steam curing (140 F) conditions .

Chapter II

FACTORS AFFECTING EARLY STRENGTH DEVELOPMENT OF CONCRETE

In this chapter, the most important factors which affect the early strength of concrete are considered.

A. The Water-Cement Ratio

The cementing medium in concrete is produced by the chemical reaction between cement and water. The inherent strength of this medium is primarily a function of the ratio of the amount of these two components, that is the water-cement ratio. It has been found by many researchers that the optimum high strength of concrete can be obtained at that water-cement ratio which is as low as possible and still permits full compaction. Abrams [6] obtained strengths of the order of 40,000 psi using mixes with a water-cement ratio of 0.08 by weight, but clearly considerable pressure was necessary to obtain a properly consolidated mix of such proportions.

When cement and water react, an internal deficiency of water in the system may occur unless additional curing water is supplied. If this deficiency occurs, the rate and degree of ultimate hydration may be reduced. Such deficiencies are more likely to occur in low water-cement ratio mixes of concrete. It has been found [6] that the minimum practical water-cement ratio for complete hydration varies between 0.36 and 0.38.

For steam-cured concrete Merritt et al [17] showed that lower water-cement ratios produce higher strengths within the range of properly consolidated mixtures. Butt et al [26] showed that the components of steam-cured concrete, solid (cement and aggregate), liquid (mixing water), and gaseous (entrained and entrapped air) , tend to expand in various degrees under the influence of heat , and the distortion of the primary structure of a freshly-laid concrete is due first of all to a volume expansion both of free water and air ; this expansion is hundreds of times higher than that of the solid components of the concrete . A lower water-cement ratio ; therefore , allows a shortening of the pre-steaming period and an increase in the rate of temperature rise during steaming . It also provides for the shortening of the steaming period at a constant temperature and allows the use of a higher temperature . Thus , lower water-cement ratios can allow a shorter steam curing cycle.

B. Types and Characteristics of Cement

The individual minerals present in cement have different rates of hydration , strength development , heat evolution , etc . The amount of heat evolved when cement hydrates can be calculated from the following equation (27) :

Heat of hydration of 1 gram of material (in cal/gm.) =

$$136 (C_3S) + 62 (C_2S) + 200 (C_3A) + 30 (C_4AF)$$

where C_3S and C_3A hydrate fairly rapidly and consequently develop heat at a fast rate , C_2S and C_4AF hydrate more slowly and develop heat at a slower rate.

There are several types of cement available commercially to meet the various needs in the building industry . The five standard types of Portland cement (Normal (I), Modrate Heat (II), High Early Strength (III), Low Heat (IV), and Sulphate Resistant (V)) differ mainly in their rates of strength development and heat evolution . Type III cement develops strength more rapidly than the other types of cement ; however , there is little difference in the ultimate strength of cements of all types [6]. The different strength performances of the different types of cement is achieved by imposing certain limits on the chemical composition and fineness of grinding of the cement.

Among the four main compounds of Portland cement (C_3S , C_2S , C_3A , and C_4AF) , the silicates C_3S and C_2S are primarily responsible for the strength development . C_3S contributes most to the strength development during the first four weeks and C_2S influences the gain in strength from four weeks onwards . For example , Neville [6] reported test results for neat C_2S and C_3S pastes . At the age of 7 days the C_2S paste had no strength while the strength of the C_3S paste was about 6000 psi ; however , at the age of 18 months the strength of the C_2S and C_3S pastes were about 10,000 psi . C_3A contributes to the strength at one to 3 days and possibly longer , but causes retrogression at an advanced age particularly in cements with a high C_3A or $C_3A + C_4AF$ content . The effect of C_4AF on the development of strength is debatable but it certainly makes no appreciable positive contribution . [6] .

Hanson [18] reported that the behavior of concretes containing types I and III cements appear to be quite similar when subjected to steam curing . Type III cement concrete will attain slightly greater acceleration of early strength .

Klieger [21] reported that types I , II , and III are influenced in a like manner by temperature . Verbeck [29] showed also that the characteristics of the hydration products of types I and III cements were similar when hydration occured at temperatures between 40 and 230°F .

Budnikov [28] studied eight cements of various mineralogical compositions and having specific surfaces of approximately 3000 cm^2/gm and reported that

Portland cements containing approximately 45% C_3S and approximately 10% C_3A were the most suitable for low pressure steam curing . Nurse [35] reported that for cement paste the optimum C_3A content is 8 to 12% at room temperature and 9 to 10% for steaming at temperatures between 80 and 90°C , although higher contents are found satisfactory in mortars (1:3) . With C_4AF the best strength is found at 12 to 14% at room temperature and 12 to 15% (or higher in mortars) on steaming . At both temperatures the best strength is obtained at about 55% of C_3S (alite) . Butt et al [26] reported that as far as steam curing is concerned , cements of a high C_3S content are considered desirable. Higher C_3A contents sharply lower the strength of steamed alite cements and belite cements . Higher C_2S contents in cements destined for steam-curing , is undesirable since these cements produce low strength values especially at shortened periods of steam curing .

Mironov [25] suggested that pre-casting plants should be supplied with high early strength cements of several grades to meet the demands of various techniques . He recommended the use of high early strength cement with 50-60% C_3S and 6-9% C_3A for plant fabrication of concrete products with moderate steam-curing (130-160°F) . He reported that blast-furnace slag cements are most efficient for steam-curing at temperatures up to 212°F.

C. Properties of Aggregate

Aggregate composes about 75% of the material in concrete . Both the fine and coarse aggregates can have a bearing on the potential compressive strength of concrete . For example , the gradation , surface texture and shape of both the fine and coarse aggregates and the proportions in which they are combined can affect the water requirement for a given workability and cement content and thereby , indirectly , affect the resultant compressive strength . The amount of a given aggregate that can be accommodated in a cement paste of a particular water-cement ratio depends upon its influence on the workability of the resulting mixture . The limiting amount is that maximum amount which can be used and still attain full compaction of the concrete . Increasing the aggregate content in a mix with a fixed water-cement ratio progressively decreases the consistency and workability of the concrete [5] . Although the aggregate-cement ratio has been proven to be a secondary factor in the compressive strength of concrete , it has been found that for a constant water-cement ratio , a leaner mix leads to higher strengths .

The type of aggregate used in a concrete mix can also exert a direct influence on the compressive strength . Kalpan [10] reported that the use of different types of coarse aggregate in a given concrete mixture (constant water-cement ratio) results in a 29% variation in compressive strength . It has also been reported that for water-cement ratios below 0.40 (at constant water-cement ratio) , the use of crushed aggregate has given strengths up to 38% higher than when gravel is used [30]. Collins [2] stated that for concretes having strengths of 7000 psi or more , the aggregate sets a limit on the strength attainable , this limit generally lying in the range from 12,000 to 15,000 psi . The maximum size of coarse aggregate is claimed by many authorities to affect the compressive strength of concrete [6] . However , Kleiger [5] claimed that the maximum size of any given aggregate affects strength only indirectly as it influences the water requirement for a given consistancy .

The fine aggregate plays an important role in the concrete as it combines with the cement paste to form a mortar and fill the voids between the particles of coarse aggregate . Smith et al [8] reported that the use of coarse sand (fineness modulus of approximately 3.0) in high compressive strength concrete was desirable . Kennedy (32) stated that there is a tendency for strength to decrease with decreasing fineness modulus .

Variations in aggregate would be expected to exert some influence on the affect of steam curing treatments ; however , in structural concrete the affect appears to be minor . The aggregate does not enter into the chemical reactions , so its affect is primarily due to its thermal properties. The limited data available indicates that the differences that exist between the various aggregates do not significantly alter the affect of steam curing . Light-weight aggregates , in general , have lower thermal coefficients of expansion than dense aggregates , so produce less volume change during steaming ; therefore , it appears to be necessary to to provide a longer pre-steaming period for dense , than for light-weight concretes (34) .

D. Admixtures

There are many admixtures which affect the early strength of concrete . However , only those types of admixtures used in this research programme will be discussed here .

1. Water-Reducing Agents

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

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

The principal component of the water-reducing admixtures considered in the classifications above are surface active agents, i.e., substances which because of their chemical configuration are concentrated at the interface between two immiscible phases and alter the physiochemical force acting at this interface. Interfacial tension is always present at the interface between any two completely immiscible phases. Dispersion may be facilitated by a reduction in the interfacial tension of the system. As the term water-reducing implies, the primary function of this type of admixture is to reduce the water requirment of a concrete mix while maintaining the desired plasticity and workability (31).

The Concrete Division of the U.S. army Engineer Waterways Experiment Station (4) carried out an intensive investigation to develop information on the performance in pastes, mortars and concrete of several proprietary water-reducing admixtures. Water was added to the pastes and mortars as required to produce a normal consistency. The water-cement ratios for concrete mixes ranged from 0.39. Thirteen chemical admixtures were tested and two Portland cements were used (Type I manufactured in Mississippi and a Type II manufactured in Alabama). The fine aggregate was a natural siliceous sand from Mississippi and a crushed limestone from Tennessee; the coarse aggregates were a crushed traprock from Connecticut and a crushed limestone from Tennessee.

The test results indicated the following: for the pastes, seven of the admixtures permitted a 10% or greater reduction in the amount of mixing water required to produce a paste of normal consistency as compared with the amount required when no admixture was used . For the mortars , eight of the admixtures permitted a 5% or greater reduction in the amount of mixing water required to produce a mortar having a flow in the specified range (100 to 115%) . Of the fifteen mortar mixtures prepared , five exceeded the strength of the control mixture by less than 20% . All seven mixtures and water-reducers permitted a 5% or greater reduction in the mixing water . In the concrete tests only five water-reducing admixtures were tested in fifteen mixtures . It was found that all but three of the mixtures produced a reduction in the water-cement ratio , the reduction varying from 0.05 to 0.40 gal. of water per bag of cement . Six of the fifteen mixtures had lower compressive strengths at two days than the control mixture ; however , two of the six were within 8% of the control . Three of the mixtures had lower compressive strengths than the control at 28 days but the difference in strength was not over 9% in any case, . All other mixes averaged an increase in compressive strength of 11% over the control mix .

Smith et al (8) working with water-cement ratios from 0.29 to 0.40 in the production of high-compressive strength concrete concluded that water-reducing admixtures are definitely beneficial . Their results showed that the 7 , 28 and 90 days compressive strengths were 11 , 21 and 19% respectively greater than the control mixes .

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

Thomson (31) showed that water-reducing agents can effectively lower the water requirement of low water-cement ratio mixes . Their greatest benefical effect on strength appears to be in the early ages and at the higher water-cement ratios .

Mielenz (23) reported that properly used water-reducing and set-retarding admixtures increase the strength of steam-cured concrete (135 F) over that of concrete without such admixtures , and that the strengths improved with increasing length of pre-steaming period up to 5 or 6 hours .

2. Pozzolanic Materials (Fly Ash)

Pozzolan is defined in ASTM C219 as "a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties". Examples of such materials which can be used in amounts ranging from 10 to 50 percent of the weight of the cement are: fly ash, volcanic ash, heat-treated diatomaceous earths, and either heat-treated or raw shales or clays. The effect of pozzolans upon the strength of Portland-pozzolan concrete varies markedly with the particular pozzolan used. Depending on the pozzolan used, Portland cement replacements of as high as 30% can sometimes be made and still achieve equivalent ultimate strengths to plain mixes. It is claimed that the use of small percentage replacements (say 10%) can result in higher strengths of mortar and concrete than those for plain mixes.

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

Smith et al [8] using water-cement ratios of 0.29 to 0.37 showed that at least 10% by weight, of the Portland cement used in high-compressive-strength concrete, can be replaced by pozzolans such as fly ash or calcined shale. The strength increase was 16% over the non-pozzolanic mixes at 90 days.

Two Portland cement clinkers (1 low, 1 high in free CaO, $3 CaO \cdot Al_2O_3$, and K_2O) were blended with three fly ashes (2 containing spherical viterous particles, 1 containing fine irregular crystals of high porosity) in various proportions. Compressive strength tests were among several made on the mixes at equal consistencies and at equal water-cement ratios . Strengths changed little for equal water-cement ratio mixes up to 20% of the two viterous ashes , with 300 day strengths slightly greater than that of the original cement ; with up to 40% ash , the strength after a few years should be greater than for the cement . At equal consistencies , the 20 and 30% ash blends were often stronger than the cement alone., because the water requirement could be reduced . No strength differences were observed between mixes blended by grinding the mixture and those ground separate before blending (41) .

Chamberlin (37) reported that the use of 30% of fly ash in moist-cured concrete reduced the compressive strength at age 1-day about 15% .

There are limited data on the effect of fly ash as a replacement of part of the Portland cement on the early strength of steam-cured concrete. Whathey (24) showed that fly ash replacements in the amount of 25% of Portland cement may be used satisfactorily with a curing temperatures above 160 F . Chmmberlin et al (22) reported reduced strength at all ages when using a calciried shale as a 20% replacement , steam-cured at 160 F . Olson (33) indicated the advantage of fly ash and natural cement in amounts up to 20% of the Portland cement .

Stolnikov (36) reported that steam-curing of concrete with a cement ash binder (35% of Portland cement-25% of ash - 40% of slag) greatly increases its strength , particularly tensile strength . At 28- day age concrete with 30% and 40% admixtures of fly ash had lower strength than concrete without the admixture . The specimens were steam-cured at the 2-day age according to the following schedule : heating for 2 hours ., curing for 5 hours at 175 to 195 F , then cooling slowly for 17 hours .

E. Mixing

The object of mixing is to coat the surface of all aggregate particles with cement paste , and to blend all the ingredients of concrete into a uniform mass . There may be occasions when concrete has to be mixed by hand and , because in this case uniformity is more difficult to achieve , particular care and effort are necessary . Mixing concrete by hand is expensive in labour and it is , therefore , not surprising that mechanical mixers have been in general use for a great many years .

There is often a tendency to mix concrete as rapidly as possible ,and it is , therefore , important to know what is the minimum mixing time necessary to produce a concrete uniform in composition and , as a result , of satisfactory strength . It has been found that the average strength of concrete increases with an increase in mixing time . Abrams [6] showed that the rate of increase falls rapidly beyond about one minute and is not significant beyond two minutes . Within the first minute , however , the influence of mixing time on strength is of considerable importance . For instance , Shalon [6] calculated that , for a given required strength , increasing the mixing time from 30 sec. to 1 min. permits a saving in the cement content of as much as half a bag per cubic yard .

Slurry mixing had aroused some interest in its effect on strength. The process involves the advance preparation of a cement-water mixture which is then blended with aggregate to produce concrete . Higher compressive strengths thus obtained are presumably attributable to more efficient hydration of the cement resulting from the more intimate contact between cement particles and water achieved in the vigorous blending of cement paste .

Bloem [38] conducted tests on mortars using a water-cement ratio of 0.6 and on concretes using an average water-cement ratio of 0.76 . In the mortar tests , mixtures of a constant water-cement ratio were made by

(1) hand mixing of the water and cement prior to adding the sand , (2) slow -speed mechanical mixing of the cement paste , and (3) high-speed mixing of the cement-water paste . For all three methods , elapsed times for the various stages of mixing were the same , as was the procedure for blending the sand with the cement paste. Mechanical mixing of the cement-water slurry at slow speed produced no change in the properties of the mortars from those obtained by hand-mixing . Mixing of the cement-water slurry at a very high speed using a blender similar to milk shake mixer (10,000 rpm) produced an average increase of 13% in compressive strength for the three test ages of 3 , 7 and 28 days . In the concrete tests there was a significant increase in compressive strength for the high-speed mixing , averaging 10% greater than that obtained by hand mixing . The strength advantages was essentially constant in terms of pounds per square inch at the three test ages of 3 , 7 , and 28 days , with the result that the percentage difference decreased from 13 to 6% as the strength level increased .

Thomson [31] found that high-speed slurry mixing produced strength increases of 20% to 30% at the 7-day age and somewhat higher strengths at 28 days but at 3 months the affect appeared negligible .

Ray et al [39] reported that when 2 to 3 hours were allowed to elapse between mixing the concrete and preparing the test cylinders , the strength was higher than if the specimens were made either earlier or later . The increase over those made soonest was approximately 20% . The authers. attributed this to decrease in water-cement ratio due to evaporation losses and absorption of water by the aggregates .

F. Compaction

The strength of the concrete is controlled primarily by the water-cement ratio , provided the concrete is fully compacted . Actually , strength is related to the voids-cement ratio , the voids being the sum of the volumes of water and air in the concrete , the volume of air being an index of the efficiency of compaction . The air in this case is not the air which we intentionally entrain in the paste by means of air-entraining cements or air-entraining admixtures , but is entrapped air resulting from the use of dry , harsh mixes . Any technique of compaction is suitable, provided full compaction can be attained . If full compaction is attained , the water-cement ratio will then be as good a criterion of strength as voids-cement ratio , since the amount of entrapped air voids would be small and exert little influence on the magnitude of the voids-cement ratio .

Klieger (5) pointed out that the restriction limiting use of the water-cement ratio law to "plastic" , "workable" mixtures properly should be interpreted to mean to "fully compacted mixtures with a minimum of entrapped air voids " . Thus , as the water-cement ratio is progressively reduced for a mixture by decreasing the amount of water used , the concrete will become progressively less workable and progressively greater effort will be required to achieve full compaction . He showed that for concrete of zero slump placed by both hand-placing and vibration , the strength ratios of vibrated to hand placed concrete ranged from 1.00 to 1.09 for about a 5% average increase in strength of the vibrated concretes .

This indicates that in stiff , low water-cement ratio mixes , mechanical compaction must be resorted in order to compact these mixes efficiently .

Davies (40) studied the effects of compaction of concrete by vibration and concluded that : "The effectiveness of vibration depends mainly on its acceleration , and not on the individual values of its frequency and amplitude ; but , very small amplitudes of the order of 0.002 inches , are comparatively ineffective . There is little to choose between vertical linear and horizontal circular vibration ; vertical circular vibration is definitely better than either . The effectiveness of vibration increases with its acceleration , probably up to at least 20 g ; but above 12 g the increase is slow ".

The Joint Committee of the Institutions of Structural and Civil Engineers [(41)] emphasized the importance of compaction in the attainment of the compressive strength for which the constituents and proportions of a mix were selected . The report points out that with a properly proportioned concrete mixture " extended vibration will be wasteful of effort but not harmful to the concrete " . If , on extended vibration , segregation of the concrete mixture occurs , this indicates that the mixture is not properly proportioned .

According to Sawyer and Lee [(42)] the possibility of over-vibrating is not critical insofar as the compressive strength of concrete is concerned ; thus , an extension of the vibration time beyond that necessary to obtain satisfactory compaction or over-vibration is not harmful with dry mixes or with those in which the mortar content was low .

Similar results were confirmed by the work of the Research Committee of the Institutions of Civil and Structural Engineers [(43)] . At a water-cement ratio of 0.4 and frequencies of 1500 vibrations per minute , the strength increases appreciably with the time of vibration up to about 3 minutes and thereafter the increase is only small . For a frequency of 8,000 vibrations per minute ; however , the strength still increases appreciably with time of vibration even after 12 minutes . At a water-cement ratio of 0.50 the rate of increase of strength with time of vibration is small after 15 seconds with frequencies of 1,500 to 5,000 vibrations per minute and after 30 seconds with frequencies of 8,000 vibrations per minute. The Research Committee showed that for short periods of vibration the greater strengths are obtained with small frequencies especially at the lower water-cement ratios but that the higher frequency of 8,000 vibrations per minute gave greater strengths at the lower water-cement ratios when vibration was prolonged to twelve minutes.

G. Revibration

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

Both the test age at which revibrated specimens give the greatest strength increase and the optimum time for revibration after the initial casting are topics of much controversy. Butt et al [26] reported that according to some authors the breaking down of a cement paste structure during its formation does not influence the hardened cement paste strength. However, the break down of the structure after setting lowers the strength sharply. This shows that the time of revibration should be before the final setting of the cement paste.

Vollick [9] reported the effect on 28-day strength of revibration at intervals of 1 to 4 hours after placing. Maximum strength increase resulting from revibration varied from 8.5 percent to 17.1 percent and averaged 14 percent for the mixes with water-cement ratios ranging from 0.61 to 0.75. Maximum strength increase of the mixes with water-cement ratios ranging from 0.5 to 0.63 varied from 6.9 percent to 18.7 percent and averaged 13.7 percent. All maximum strength gains were obtained when revibration was carried out 2 hours after placing .

Sawyer and Lee (42) also studied the effects of delayed revibration on concrete , with and without air entrainment . The concrete was revibrated after delays ranging from 45 minutes to 6 hours . The greatest increase in compressive strength of revibrated concrete was at 7 days for the specimens without air entrainment . This increase was approximately 36 percent and occurred when revibration was carried out after a 4 hours delay. The corresponding increases for the 28 and 90 days specimens were 24 percent and 15 percent , respectfully . The increase in strength of the air-entrained specimens was approximately half of the non-air-entrained at each test age with the maximum increase in strength occurring when revibration was carried out about 3 hours after casting . The water-cement ratios used in the non-air-entrained mixes varied from 0.70 to 0.77 and in the air-entrained mixes varied from 0.59 to 0.68 . Bastian (44) reported increases in compressive strength for cube specimens of 38% at 2 days , 27% at 3 days , 12% at 5 days and 10% at 28 days . The time of revibration was 4 hours after casting in all instances.

Mirenov (25) reported that prolonged and repeated vibration results in the destruction of initially loose strutures and in the appearance of new , more compact ones and can accelerate the hardening and raise the 24-hour strength of concrete by 100% .

Thomson (31) found that revibration appears to be most effective in the low water-cement ratio mixes and at the 28-day test age , but his results for this technique were rather inconclusive .

To date , two theories have been advanced by Sawyer and Lee (42) to account for the increased compressive strengths produced by revibration . In the first theory , it is believed that the mortar and concrete would be more densely consolidated, thereby permitting more advantageous use of the hydration products. The second theory contends that the vibratory disturbances in some way accelerate and extend the production and consequently increase the amount of the strengthening hydrates at ages up to 90 days.

H. Curing

Curing is one of the most important factors affecting the performance of concrete. Curing (6) is the name given to procedures used for promoting the hydration of cement, and consists of the control of temperature and of moisture movement from and into the concrete. More specifically, the object of curing is to keep concrete saturated, or as nearly saturated as possible, until the originally water-filled space in the fresh cement paste has been filled to the desired extent by the products of hydration of cement. The necessity for curing arises from the fact that hydration of cement can take place only in the presence of water. For this reason, a loss of water by evaporation from the capillaries must be prevented. Furthermore, water lost internally by self-desiccation has to be replaced by water from outside. Both the availability of water and the temperature are extremely important aspects of curing, particularly with regard to early high-strength development. Therefore, adequate curing of concrete is essential in order to develop to a high degree the desirable properties of concrete.

1. Mixing and Curing Temperature

Temperature seems to affect the hydration and hence development of strength in two ways. First there is the known effect of temperature on any chemical reaction, the rate of reaction increasing as the temperature increases. However, a second factor may be that the type of hydration product obtained or the physical make up of the product is influenced by the temperature during this hydration . Lower temperatres may be conducive to a better hydration product or better physical structure of the product .

Klieger (21) reported that concrete made with type III cement at an initial mixing temperature of 120 F had a 1-day compressive strength 148% of that at 73 F ; however , at 1 year the strength of the same concrete was 84% of the 73 F strength . He also showed that there is a casting and curing temperature , which may be considered optimum with regard to the ultimate strength developed . For type I and II cements this optimum is 55 F . For type III cement the optimum is 40 F . At 1 , 3 , and 7 days , concrete strengths increased with an increase in the initial and early curing temperature of the concrete ; however , this increase in initial and curing temperatures considerably lowers strengths at later ages . The increase in the curing temperature from 70 to 115 F speeds up the chemical reactions of hydration and consequently increase the early strength of concrete without any ill-effects on the later strength ; however , a higher temperature during placing and setting , although it increases the very early strength , may adversely affect the strength from about 7 days onwards .

Price (7) showed that increasing the temperature during first two hours after mixing affects the development of strength of concrete . A higher temperature was found to result in a higher strength during the first few days , but beyond the age of 1 to 4 weeks the situation changed radically .

2. The Temperature-Time Relation

The separate influences of temperature and time on strength development of Portland cement products have been extensively studied and reported since the earliest use of cement. Attempts to express the combined effects of temperature and time as a single function were made by Nurse,(14) Saul(15) and Rastrup(55). These relations are based on the product of temperature and time, the product corresponding to a degree of maturity of the cement paste or concrete.

The so-called Nurse-Saul relation is the most generally accepted it takes the form

$$M = \sum (C + 10)\Delta t$$

where M = maturity factor

C = degree centigrade

t = time

Nykanen(45) has suggested a modification of the Nurse-Saul function for temperatures below 0°C, namely,

$$M = K(C + 15)\Delta t$$

where the coefficient K varies from 0.2 to 0.4 depending on the cement. Bernhardt(54) developed a similar modification.

Bergstrom(46) used extensive American and European strength data to support the general validity of the Nurse-Saul function, and found very slight dispersion within the results, which indicates the good quantitative character of this maturity relation. Lyse(47) reported similar good correlation.

The various forms of the maturity function have been discussed extensively in the literature.

There is general agreement that the temperature-time formulae are of value provided they are used with care. It is generally conceded; however, that it fails in accuracy at very high or very low —

temperatures . Some fear is expressed in its use at varying temperatures . It is regarded as applicable only to Portland cements .

McIntosh (48) considers that the Nurse-Saul function lends to overestimate strengths at low maturities and underestimate them at high maturities . He suggests that the time during which the concrete is in the plastic state should not be included in the calculations .

Klieger (21) reported poor correlation between strength and "degree-days ". Alexander and Taplin (49) found "important systematic deviations" from the maturity rule .

3. Standard Moist Curing

The importance of keeping concrete saturated in order to attain greatest strength development has already been emphasized . The recognition of this has led to the development of so-called standard moist curing procedures . These require that the test specimens should be removed from the molds not less than 20 hours nor more than 48 hours after molding and stored in a moist condition with free water maintained on all surfaces of the specimens at all time at a temperature within the range of 73.4 ± 3 °F until the time of testing . The concrete specimens usually are stored in either moist air , or lime-water . Curing with water has been long recognized as the most satisfactory method .

According to Smith et al (8) continious moist-curing of the concrete for at least 28 days is necessary to develop compressive strength in excess of 10,000 psi at 90 days . Klieger (5) reported that for low water-cement ratio concretes , it is more necessary to supply additional water during curing than in the case with higher water-cement ratio concretes . Price (7) showed that at the 80 days age concrete specimens that had been continuously moist-cured showed higher compressive strength than any whose curing had been interrupted . However , in tests of specimens at the 90 days age , he found higher strengths for specimens moist-cured to 28days and thereafter stored in laboratory air .

Kleiger (5) reported that the availability of curing water during the first 24 hours period in which the test cylinders were in molds increased the strength of concrete . By using saturated aggregate prior to use , and ponding the top of the cylinder immidiately after casting , he found that the strength of specimens was 850 psi to 1000 psi greater at 28 days than that of comparable specimens made with dry aggregates and cured under damp burlap .

4. Low-Pressure Steam Curing

Low pressure steam curing means curing with saturated steam atmospheric pressure, necessarily at temperatures below 212 F . The primary benefit of low pressure steam curing is the rapid strength gain which it imparts to concrete products . However , certain limitations must be observed or the concrete can be damaged rather than benefited by steaming .

It has been reported by many investigators that more than 60% of the moist cured 28-day strength may be obtained in 24 hours (34) . Henson (18) reported compressive strength of concrete in excess of 4000 psi 18 hours after casting . This was about 65% of the 28-day strength of standard moist-cured specimens . Higginson (50) indicated that about 50% of the 4000 psi 28-day strength was obtained under 24 hours of steam curing and a slightly higher percentage for higher strength concrete .

The earliest strength data reported by Running and Carlson (19) for concrete block was at 3 days . At this age many of the blocks given 15 hours of steam curing had compressive strengths of 50 to 85 percent of the 28 day moist-cured strength ; however , the steam-cured block had been dried to 40 percent of total absorption prior to test. Shideler [12] reported almost identical results on another study conducted at the Portland Cement Association laboratories. National Concrete Masonry Association [51] reported results of cured block, at temperatures between 130° and 200°F for various periods between 4 and 13 hours in plants of member companies. The 3-day strength of steam-cured block ranged from 54 to 79 percent of the 28-day strength of block moist-cured 14 days and then air dried 14 days. At present, there is not yet a generally accepted opinion concerning the optimum steam-curing cycle. The effect of variations in the steam curing periods on the optimum strength development will be discussed in the following sections.

a. Pre-steaming Period

The so-called pre-steaming period is the period of delay from the time of mixing of the concrete components with water until the application of steam. During this period some hydration of cement occurs which provides some stability to the product prior to exposure to steam.

Saul [15] reported that the srength of concrete raised to 212°F in 2 hours was about one-half that of concrete given a slow initial temperature rise. He suggested that the concrete should not reach a temperature of 120°F for at least 2 hours after casting and 212°F for at least 6 hours after casting.

Shideler [12] observed swelling and circumferential cracking in cylinders raised quickly to 185°F and showed the advantage of a delay period prior to steaming. Further tests [13] indicated that a 3 hour pre-steaming period was desirable.

Hanson [18] concluded that a pre-steaming period of about

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5 hours produced maximum strength at all ages. The 28-day steam cured strengths was about 80 to 95% of the 28-day moist cured strength.

Merritt and Johnson (17) reported that the higher steam curing temperatures require longer delay periods to produce the maximum strength. At 1 day the greatest strength was obtained by steaming at 175°F after a 3 hour delay. At 28 days the highest strengths were produced with temperatures of 125 and 150 F after 6 hours delay prior to steaming; they indicated also that at all temperatures, the specimens given a 6-hour delay prior to steaming had the best gain in strength between the 1 day test and the 28 day test.

Chamberlin et al (13) found that a delay of 2 to 6 hours prior to steaming, produced strength 15 to 40% higher at age 24 hours than when steaming was started immidiately after the concrete was placed.

Butt et al (26) reported that the strength of a concrete of 2 hours pre-steaming was higher than the same concrete of 4 hours pre-steaming. The optimum time of a pre-steaming of concretes made from Portland cement varied in the range of 2 to 10 hours. They suggested that the beginning of setting can be considered as the optimum time of pre-steaming. Alite cements (high early strength cements) allowed a shorter pre-steaming period.

b. Rate of Temperature Rise

Saul (15) found that the best strength results were obtained at a rate of temperature rise of about 27°F along with a pre-steaming period of 3 to 4 hours.

Hanson (16) indicated that a rate of temperature rise of 40°F per hour produced optimum strength results. Higher rates produced a slight reduction in strengths with pre-steaming periods of 3 hours or more.

Mangotich[20] found that variations in the rate of temperature rise within the range of 12 to 48 F per hour had little effect on the compressive strength.

But et al[26] found that a slow temperature rise prior to steaming compensated for the absence of presteaming. They found that a quick temperature rise (up to 175 F) led to a considerable loss of strength. They indicated that "step-by-step temperature rise" produced no serious adverse effect on the strength.

c. Maximum Temperature

Several investigators[34] have found that the most effective results are obtained when the concrete is cured at a temperture between 150 F and 180 F.

Chamberlin et al[14] found that the 165 F produced optimum strength results with strengths slightly higher than those obtained with 130 F at early ages and equal strength at later ages. Hanson[18] indicated that a temperature of 175 F gave highest strengths although this provided only a slight adventage over those obtained at 150 F.

Saul[15] obtained good results with concrete temperatures of 212 F when this was reached only after 6 hours of steaming.

Mironov et al[26] reported that 70% of the standard moist cured concrete strength (of a concrete having a water-cement ratio of 0.40) was obtained when the duration of isothermal steaming amounted to: at 140 F - 9 hours, at 176 F - 5 hours, and at 212 F - 4 hours, respectively. The absolute value of maximum strength at elevated temperatures, was less than that at lower temperatures of steam curing for the same concrete.

Butt et al[26] found that an increased isothermal steaming period lowered sharply the strength gain of a concrete . The higher the isothermal temperature , the more sharp was the drop in the strength gain .

d. Period of Temperatures Drop

By period of temperature drop is meant the period during which the maximum temperature of the concrete is lowered at a controlled rate to room temperature .

Budnikov et al[28] found that the rate of temperature drop did not influence the strength of concrete . However , Reinsdorf[52] indicated that a sharp temperature drop influenced the strength of concrete units at early ages .

Kuenning and Carlson[19] reported that the strength of units allowed to soak was less than those cured at constant maximum temperature . Reductions due to soaking generally were less than 15% . On the contrary , Mansfield[53] reported soaking gave higher strength than constant maximum temperature at ages exceeding 28 hours . soaking did not cause a significant reduction in strength when temperature was not permitted to drop faster than 5°F per hour .

Summary of Pertinent Findings

The production of high strength concrete (both at early and later ages) requires the use of lower water-cement ratios than those generally used . Concrete proportioned using such low water-cement ratios will be "drier" ,"harsher", and less "workable" than usual , Consequently , the mixing,placing , and compaction procedures employed will need to be modified in order to achieve fully compacted homogeneous concrete . It is important that vibration be prolonged enough to produce better compaction. Compaction of the coarse particles can not be greatly improved, it seems that there is considerable scope for compaction of the cement particles, even of the crystalline structure. Such compaction would increase the density of tensile bond and thus increase cohesion; by analogy with soil mechanics, increased compaction would also increase internal friction.

It is obvious that aggregates of high-crushing strength and of good quality must be used. The use of crushed aggregates of low maximum size seems to produce higher strength concrete than gravel aggregates.

For high strength at early ages it appears that high-early strength cement should be used whether curing is by steam or standard moist curing. High-early-strength cement with a high C_3S content (50-60%) and a low C_3A content (6-9%) appears to be suitable for optimum strength development.

Fly ash and other pozzolanic materials have often been used to replace 10 to 30% of the Portland cement in concrete mixes. It has been indicated that by replacing a small percentage (10 to 20%) of Portland cement with fly ash, a significant increase in compressive strength at later ages can be obtained. However, it appears that the effect of fly ash as a partial replacement of cement on the early-strength development of steam cured specimens has not been investigated.

Water-reducing agents, by lowering the water requirement for a given consistency, are known to produce increased compressive strengths. Some authorities claim that the increased compressive strength afforded by the water-reducing agents is greater than would be expected from the amount of water-reduction produced. The effect of water-reducing agents on early and later age strength development has not been investigated for steam cured specimens. Also there is not unanimity on their effectiveness or on the percentage strength increases to be expected in moist cured specimens .

Revibration has been investigated as a means of increasing the compressive strength of concrete of various classes . However , information on the effectiveness of revibration on strength at early ages and with steam cured specimens is very limited .

Curing procedures have variable effects on the early and later age strength development of concretes . Both the availability of water and the temperature are extremely important aspects of curing , particularly with regard to early high-strength development . Continuous or subsequent (in the coarse of steam-curing) moist-curing within specified temperature limits seems to produce increased strength concrete . However , there is not yet a generally accepted opinion concerning the optimum steam-curing cycle .

ACI Committee 513 (34) recomended a steam curing cycle for structural elements which includes a pre-steaming period in excess of three hours , a temperature rise rate of approximately 40°F per hour and a maximum temperature of 150° to 175°F for a period of 12 to 18 hours .

For the production of precast pre-steamed concrete structures a maximum temperature of 140°F or less should be used to minimize pre-stress losses due to temperature drop .

The use of high early strength cements in the low water-cement ratios range requires a shorter steam curing cycle .

Higher maximum temperature of steam curing led to a greater reduction in strength at later ages as compared with standard moist curing .

Chapter III

EXPERIMENTAL PROGRAMME AND PROCEDURES

The main purpose of this programme was to establish the effects of (a) revibration, (b) a water-reducing agent and (c) fly ash (10 and 20% as replacement of cement), on the strength development of concrete in conjunction with low pressure steam and moist curing. This was done using the following methods :

(1) Moderate low pressure steam curing with a maximum temperature of 140°F , followed (24 hours after mixing) by subsequent moist curing at a temperature of 73 ± 3°F . The mixes treated in this manner will subsequently be called "steam cured mixes" .

(2) Moist curing with initial mixing temperature of 80°F to 85°F , followed (24 hours after mixing) by subsequent moist curing at temperature of 73 ± 3°F . The mixes treated in this manner will subsequently be called "moist cured mixes" .

A. Mix Proportions

1. Water-Cement Ratio

Three water-cement ratios (0.35 , 0.40 , and 0.45 "net") were used with the moderate steam curing method . One water-cement ratio of 0.40 "net" was used with the moist curing method .

In the mixes where the water reducing agent was used , the water content was reduced by 6% (by weight) to give the same consistency as the standard mixes .

2. Percentage of Sand to Total Aggregate

In all mixes the percentage of sand to total aggregate was 50%. In the preliminary experimental work , three concrete mixes containing 30% , 40% , and 50% sand were used . It was found that the mixes with 50% sand produced more workable mixes with higher compressive strengths .

3. Aggregate-Cement Ratio

In all mixes the aggregate to cement ratio was 3.5 : 1 , (by weight) . This ratio produced more workable mixes with higher compressive strengths than did the concrete produced with aggregate-cement ratios of 3.0 : 1 and 4.0 : 1 which were also used in the preliminary mixes .

B. Materials

1. Cement

Preliminary tests using Lake Ontario Type III cement , Lake Ontario Type I and St.Mary's Type I cement showed the best results could be obtained using the Lake Ontario Type III cement . This was therefore the only cement used in the main body of the research work .

2. Coarse Aggregate

The coarse aggregate used in this programme was Dundas Dolomite (maximum size 3/8) , conforming to ASTM specifications for concrete aggregates . C 33 . . The Dundas aggregate was dried in the oven for 24 hours at a temperature of 212 °F , and then left in metal drums to cool to room temperature before being used . The physical properties of the Dundas crushed aggregate used in this programme may be found in Appendix A.

3. Sand

The sand used was a well-graded natural sand from the west pit at Paris , Ontario , which meets ASTM specification . C 33 . . It was dried in the oven for 24 hours at a temperature of 212 °F , and then left in metal drums to cool to room temperature before being used . The properties of the sand used in this programme may be found in Appendix A.

4. Fly ash

The fly ash used in this programme was obtained through the courtesy of the Detroit Edison Company , from the Trenton Channel Power Plant . The physical and chemical properties of the fly ash may be found in Appendix A.

5. Water-Reducer

The water reducing agent used in this programme was a lignosulphonic acid type admixture ("WRDA") obtained from W.R. Grace and Company of Canada Limited . The recommended dosage of 6.5 ounces per 87.5 lbs of cement was used in all water reducing mixes .

C. Mixing Procedure

All mixes were prepared using a drum mixer (figure 1) manufactured by Soiltest Incorporated of 1½ cubic foot capacity and powerd by a 1/3 H.P. electric motor suitable for 220 volts , 60 cycle , and 3 phase AC operation . The concrete was mixed according to ASTM specification C 192.

D. Moulding and Compaction

Nine 3 x 6 cylinders were moulded from each batch . The moulds were placed on the VIBCO Table Vibrator shown in figure 2 (model U.S. 450 , 115 volts , 2.8 amp. 10,000 V.P.M.) and were not removed at any time during the filling and tamping operations . The concrete was placed in four layers in the cylinders . Anti-clockwise rotation of the moulds was followed during the moulding . After each layer was placed the concrete was tamped with a wooden mallet (figure 3) 10 times . The filling opperation took approximately 10 minutes with occasional anti-clockwise rotation of the moulds . The time and tamping proccedure used in the experiment were found by Thomson (31) to give the best results when working with such stiff mixes . The filled moulds were covered with wet burlap for 24 hours for moist cured specimens and 4 or 6 hours (presteaming periods) for steam cured specimens .

E. Workability

The workability of the batches was established using the flow table test (figure 2) . The test was concucted accordeing to ASTM specification C 124 .

F. Unit Weight and Air Content of Fresh Concrete

These were measured using a 4 x 6 metal mould (figure 2) . The calibration of the container was done with water at laboratory temperature of 70 ± 2 °F . The mould was filled at the same time as the other nine moulds using the same opperation of filling and tamping . After filling , the weight of fresh concrete in the mould was determined and the unit weight and air content were established according to ASTM specification C 138 . Any batches containing more than 2% air were discarded .

G. Revibration

The specimens which were revibrated were placed on the VIBCO table vibrator three hours after mixing . The revibration was done with occasional anti-clockwise rotation of the moulds for ten minutes .

H. Curing

1. Moist curing

The mixing temperature was held at 80° to 85° F . The room temperature during mixing was recorded for each batch . After moulding , the specimens were covered with wet burlap for 24 ± 1 hours then the specimens were removed from the steel moulds , labeled , and then placed in the water tank until they were tested. The temperature of the water in the tank was held at $73 \pm 3^{\circ}F$.

2. Steam curing

After moulding, the specimens were covered with wet burlap for 4 or 6 hours (pre-steaming periods), and then the wet burlap was removed before steaming. The metal based were removed from the moulds 30 minutes before steaming, and were placed in the steam chamber on a grating shelf covered with wet burlap as shown in figure (4). The specimens which were steam cured with the bases of the moulds removed showed higher strengths in the preliminary mixes than the specimens without removing the bases. The following steam curing cycle was used in this programme.

a. Pre-steaming Period

Four and six hour pre-steaming periods were used. These pre-steaming periods were carefully choosen to match with the recommendations of the ACI Committee 517 [34].

b. Period of Temperature Rise

It was difficult to keep the rate of temperature rise constant; however, the rate of temperature rise was controlled so as not to exceed $40^{\circ}F$ / Hour. The temperature rise from ($76 \pm 2^{\circ}F$) to ($140 \pm 2^{\circ}F$) was in approximately 4 hours.

The steam was controlled by changing the steam pressure entering the chamber. In the first step the steam pressure was controlled at 1 psig for 1½ hours, then the pressure was changed to 2 psig for 2½ hours. Table (A) shows the chamber temperature from the time of steaming up to the required temperature of $140^{\circ}F$. Several different rates of temperature rise (between 10 and $20^{\circ}F$/hour) were used in the preliminary investigation. An example is shown in table (B). The preliminary results

Table A

Steaming Time (hr.:min.)	Steam Chamber Temperature (°F)	Steam Pressure (psig)
0:00	76 ± 2	
0:30	96 ± 2	
1:00	108 ± 2	1.00
1:30	116 ± 2	
2:00	125 ± 2	
2:30	130 ± 2	
3:00	134 ± 2	2.00
3:30	137 ± 2	
4:00	140 ± 2	

Table B

Steaming Time (hr.:min.)	Steam Chamber Temperature (°F)	Steam Pressure (psig)
0:00	76 ± 2	0.50
0:30	86 ± 2	0.50
1:00	94 ± 2	0.70
1:30	104 ± 2	1.00
2:00	114 ± 2	1.50
2:30	123 ± 2	2.00
3:00	129 ± 2	2.50
3:30	135 ± 2	2.50
4:00	140 ± 2	

showed that these slight changes in the rates of temperature rise were found to have little effect on the early compressive strength of the concrete used.

c. Period at Maximum Temperature

The chamber temperature was controlled at 140°F for a period of 4 hours. In preliminary studies, concrete specimens were cured using steam durations of 4, 8 and 12 hours at 140°F. These studies showed no significant differences in early age strengths; hence it was decided to use the four hour steaming period for the main programme of studies.

d. Period of Temperature Drop

At the end of the eight hour steaming the specimens were left in the closed chamber to cool. The rate of temperature drop was controlled to give a drop in the temperature from 140°F to 90°F in about 8 hour during the night. The humidity after 8 hours was found to be 95 %. After 8 hours the specimens were covered with wet burlap and left to cool to 76°F in about one hour by spraying cold water on the walls and ceiling of the curing chamber.

e. Subsequent Moist Curing

After cooling to 76°F, the specimens were removed from the moulds, labeled, and then placed in the water tank for subsequent moist curing until they were tested. Preliminary tests showed that the subsequent moist curing increased the strength development of the steamed concrete.

I. Steam Curing Chamber

Steam curing was accomplished in a concrete block room lined with bituminous material. The room has one steam-tight door. The interior is approximately 6 by 7 ft. in area and 8ft. high. A steel grating shelf 2.5 by 6 ft. in area covered with wet burlap was placed inside the room at a hight of .50ft. above the floor..

The steam was supplied through a brass perforated pipe of one inch diameter and 6 ft. long located 2 3/4 ft. above the shelf . A fan fixed to the wall at the same level as the pipe forced circulation of the saturated air around the specimens . A thermometer was placed three inches above the center of the shelf . The temperature around the specimens was continuously recorded from outside. The humidity was approximately 100% inside the room during steaming . The steam pressure entering the chamber was controlled through a regulating valve shown in figure (5) .

J. Compressive Strength Tests

Upon removal of the test specimens from the water tank , they were covered with wet burlap . Unit weight determinations (saturated surface-dry) were made on each specimens in order to keep a close check on the uniformity of the test specimens . The specimens were capped with high-compressive strength (10,000 psi) sulphur compound . Three specimens of each type were tested at each test age (3,7 and 28 days) . The specimens were tested in the saturated surface-dry condition by using a 300,000 lbs. capacity hydraulic testing machine . Testing procedure were in accordance with ASTM specification C 39 .

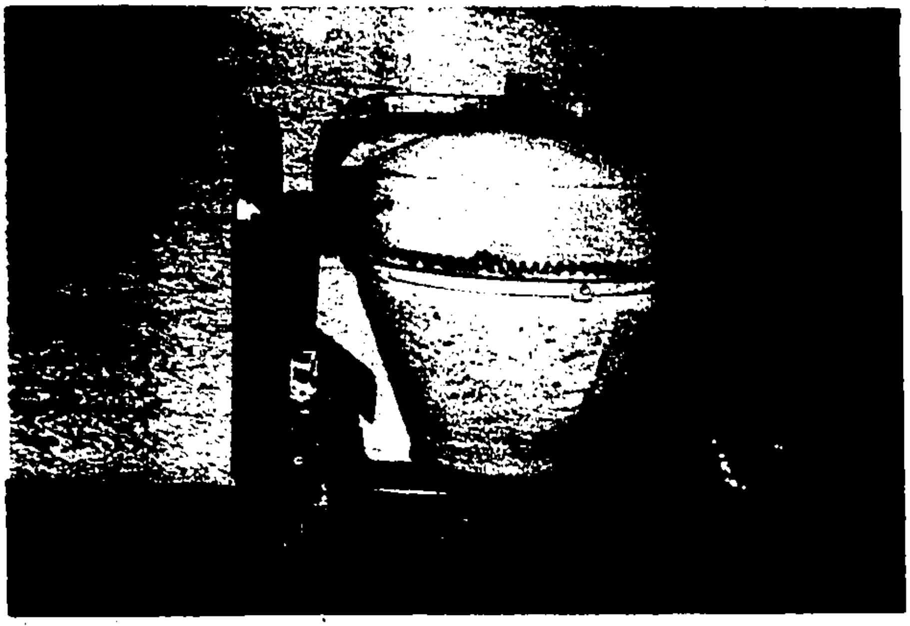


Figure 1 , Drum Mixer

Figure 2 , A – Flow Table
B – Steel Air Meter , C – Vibrating Table

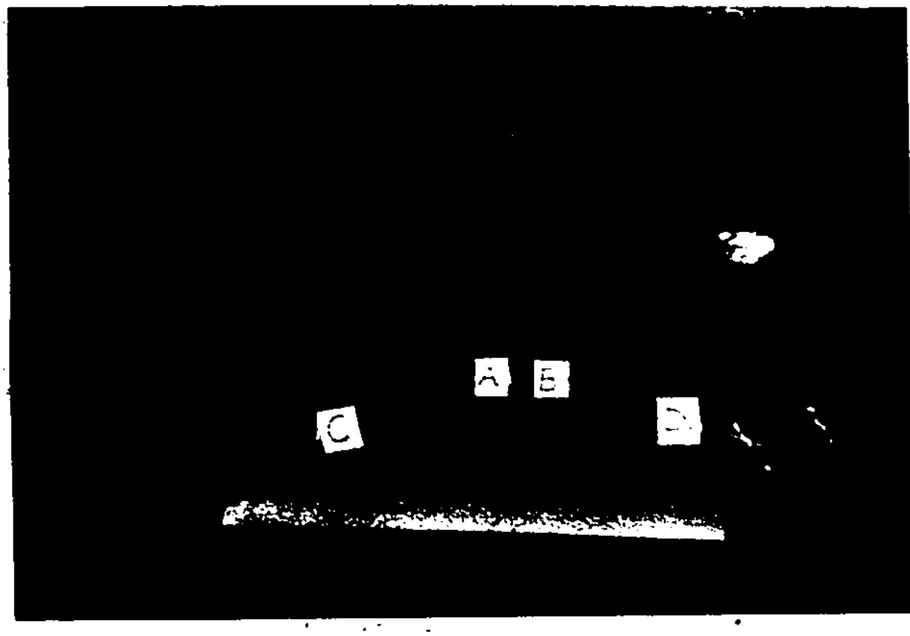


Figure 3 , A - Assembled Mould
B - Mould Base , C - Rubber Hammer , D - Wooden Tamping Mallet

Figure 4 , Steel Grating Shelf

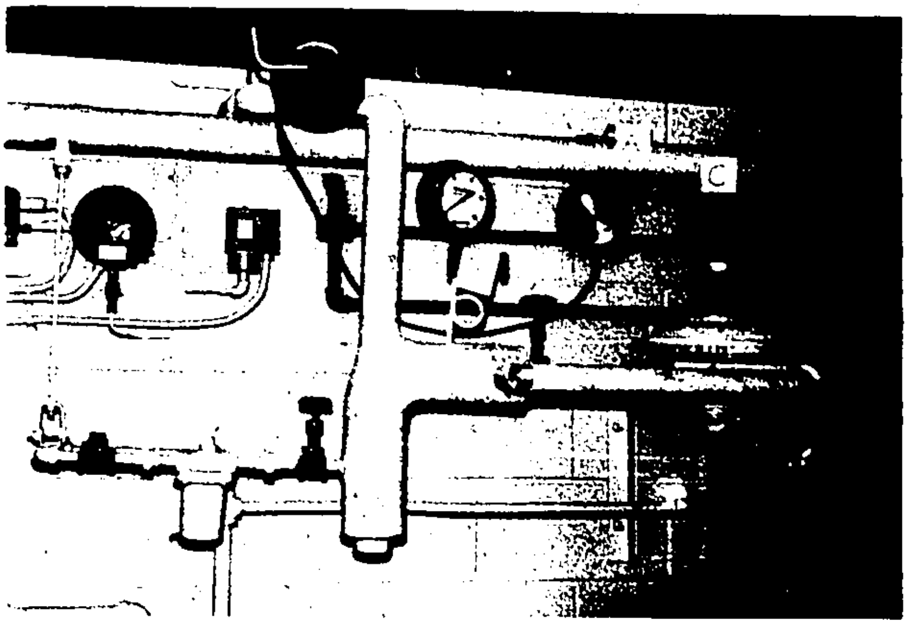


Figure 5 , A – Thermometer
B – Steam Pressure Gage , C – Regulating Valve

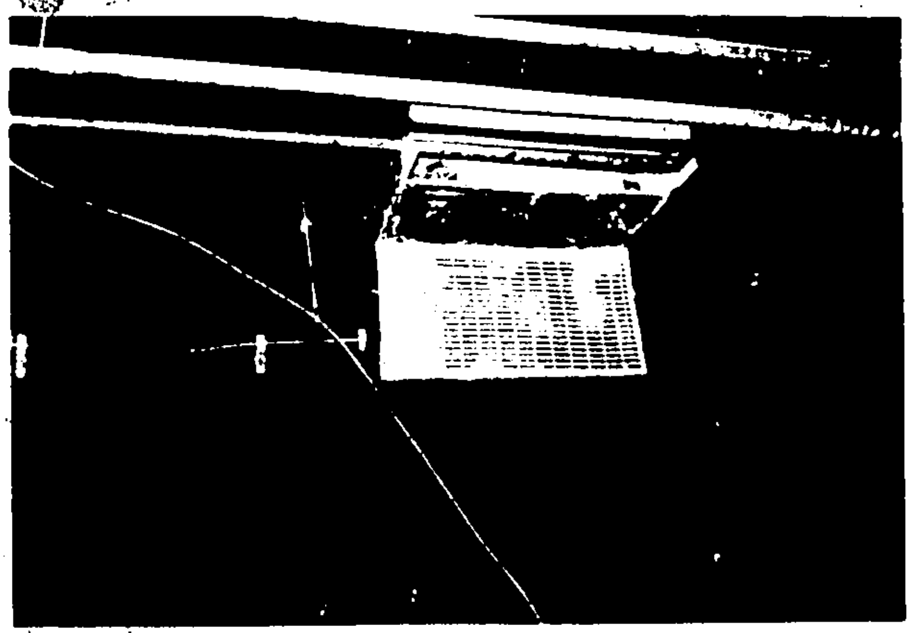


Figure 6 , Steam Curing Chamber

Chapter IV

DISCUSSION OF RESULTS

The results of the experimental programme are presented in tables 1 through 13 , and are plotted in graphs 1 through 29 . The tables of results include ; mean strength values , standard deviations , coefficients of variation , percent higher or lower than standard , and indicate whether or not the differences are statistically significant at the 0.1% , 1% , 5% , and 10% levels (e.g., yes 0.1 means that the difference is statistically significant at the 0.1 % level) .

The (water-cement ratio) - (strength) relationships for all mixes are presented in graphs 1 through 13 . Graphs 1 through 4 present standard moist-cured mixes versus steam-cured mixes with a pre-steaming period of 6 hours . Graphs 5 through 8 present standard moist-cured mixes versus steam-cured mixes with a presteaming period of 4 hours . Graphs 9 through 13 present steam-cured mixes with a presteaming period of 6 hours versus steam-cured mixes with a presteaming period of 4 hours .

The (age) - (strength) relationships are presented in graphs 14 through 29 . Graphs 14 through 17 present standard steam-cured mixes with a presteaming period of 6 hours versus moist-cured mixes . Graphs 18 through 22 present moist-cured mixes versus steam-cured mixes with presteaming periods of 4 and 6 hours . Graphs 23 through 29 present a comparison of the strength development of concretes subjected to revibration and concretes containing admixtures (water reducer and fly ash) .

A. The effect of Water-Cement Ratio.

As would be expected the normal water-cement ratio strength relationships held for all mixes at all ages investigated , i.e, for any given mix the lower the water-cement ratio the higher the strength , graphs 1 through 13 .

B. Comparison of Moist Curing and Steam Curing

The experimental results for moist-cured mixes showed consistently higher compressive strengths than steam-cured mixes at all ages (2 , 7 , and 28 days) , graphs 1 through 8 . At the age of 2 days the moist cured specimens gave strengths 8 to 20% higher than steam cured mixes , while at the ages of 7 and 28 days the moist cured specimens ranged from 9 to 20 percent higher , graph 18 .

While one would expect the moist cured specimens to produce higher strength at later ages the results for the 2-day tests are rather surprising , However , a number of factors may have contributed to these results , firstly , the laboratory in which the mixes were prepared was not temperature controlled and during the time when these mixes were made up the lab temperature was 80 to 90 F . It is possible that the heat of hydration during the first 24 hours could have resulted in even higher concrete temperatures during that period also it must be remembered that Type III (High Early Strength) cement was used .

C. The Effect of The Presteaming Period

From tables 8 through 10 and graphs 9 through 13 , it is seen that the 6-hour presteaming period produced higher concrete strengths than the 4-hour presteaming . Specimens subjected to the 6-hour presteaming ranged from 0.5 to 9.0% higher than for the shorter presteaming period . The best relative performance for the 4-hour presteaming was indicated for the 10%

fly ash mix (revibrated) at a water-cement ratio of 0.40 . However , in all cases the 6-hour presteaming seemed to be more effective .

D. Effect of Revibration

The revibrated mixes proved more effective in increasing the compressive strength of the higher water-cement ratios mixes (0.40 and 0.45) than for the low water-cement ratio of 0.35 at all ages , graphs , 1 , 5 , and 14 .

The revibrated steam-cured mixes produced strength values ranging from 1% to 15% higher than for standard steam-cured mixes , graphs 1 and 5. Similiarly , the revibrated moist cured mixes (at a water-cement ratio of 0.40) produced strengths between 5% and 18% higher than the standard moist-cured mixes at all ages , graph 14 .

E. Effect of Water-Reducing Agent

At early ages (2 and 7 days) , the mixes containing the water-reducing admixture proved more effective in increasing the compressive strength at the higher water-cement ratios of 0.40 and 0.45 , than for the lower water-cement ratio of 0.35 , graphs 2 , 6 , and 15 . The steam cured mixes containing the water reducing agent showed strength levels ranging from 5% to 19% , higher than the standard steam-cured mixes , at the higher water-cement ratios of 0.40 and 0.45 and at the early ages (2 , and 7 days) . At the age of 28 days , the increase in strengths ranged between 3% and 9%, graphs 2 , and 6 .

At a water-cement ratio of 0.45 , the steam-cured mixes with 6 hours presteaming gave higher strengths (between 3% and 9%) , than the standard moist-cured mixes at the age of 2 days , graph 2 .

The steam-cured mixes showed lower strengths (between 3% and 14%) , than the standard moist-cured mixes at the age of 28 days , graph 2 .

At a water-cement ratio of 0.40 , the moist-cured mixes containing the water reducer produced a higher strength (of 8%) at the 7-day age only . At the 2 and 28-day ages the strength differences were insignificant , graph 15 .

F. The Effect of Fly Ash

The experimental results for the fly ash mixes showed consistently lower compressive strengths than the standard mixes at early ages , the lowest strengths being produced by the mixes containing 20% fly ash as a partial replacement of cement., graphs 4 , 8 , and 17 .

When steam-cured mixes containing 10% fly ash were subjected to revibration , these mixes showed higher compressive strengths , than the standard steam-cured mixes at higher water-cement ratios of 0.40 and 0.45 , and at the ages of 7 and 28 days , graphs 3 , and 7 .

At the age of 28 days , the mixes containing 10% fly ash showed a slight increase in strength or equal strength to the standard mixes for a water-cement ratio of 0.35 , graphs 3 , 7 , and 16 .

G. Comparison of Effect of Revibration and Admixtures

From graphs 23 through 29 , both the mixes containing water reducing agent and the mixes subjected to revibration produced higher strengths at all ages than the mixes containing 10% fly ash .

At early ages (2 and 7 days) the revibrated mixes appear to procuce slightly higher strengths than the mixes containing the water-reducing agent at the low water-cement ratio of 0.35 for steam cured specimens . On the contrary , the situation was reversed at a high water-cement ratio of 0.45 . In this case at the age of 28 days , both mixes showed no significant difference in strength , graphs 23 through 28 .

At a water-cement ratio of 0.40 , the revibrated mixes produced higher strength than the mixes containing the water reducing agents at all ages (2 , 7 , and 28 days) for moist cured specimens , graph 29 .

TABLE NO. 1
SUMMARY OF 2 DAY EXPERIMENTAL RESULTS, PRESTEAMING PERIOD: 6 HOURS

W/C	Analysis	Ref. No. 1 Standard Moist-cured	Ref. no. 2 Standard Steam-cured	Revibration Steam-cured	Water Reducer Steam-cured	Fly Ash 10% Steam-cured	Fly Ash 20% Steam-cured	Fly Ash 10% Revibration Steam-cured
0.35	Mean-PSI	8040	7330	7900	7450	6810	6320	----
	Standard Dev.-PSI	123.5	347	286	139	84.5	128.5	----
	Coeff. of Var. (%)	1.54	4.75	3.62	1.87	1.24	2.03	----
	% higher or lower than Reference 1	----	-8.83	-1.74	-7.34	-15.3	-21.39	----
	Significance - %	----	yes o.1	no	yes o.1	yes o.1	yes o.1	----
	% higher or lower than Reference 2	+9.69	----	+7.78	+1.64	-7.09	-13.78	----
	Significance - %	yes 0.1	----	yes 1.0	no	yes 1.0	yes 0.1	----
0.40	Mean-PSI	6830	6180	6460	6650	5600	4960	5550
	Standard Dev.-PSI	325	258	118	146.2	116.5	103	94.5
	Coeff. of Var. (%)	4.75	4.19	1.82	2.20	2.08	2.06	1.71
	% higher or lower than Reference 1	----	-9.52	-5.42	-2.64	-18.01	-27.38	-18.74
	Significance - %	----	yes 1.0	yes 5.0	no	yes o.1	yes 0.1	yes 0.1
	% higher or lower than Reference 2	+10.52	----	+4.53	+7.61	-9.39	-19.74	-10.19
	Significance - %	yes 1.0	----	yes 5.0	yes 1.0	yes 0.1	yes 0.1	yes 0.1
0.45	Mean-PSI	5130	4740	5155	5640	4210	3660	4680
	Standard Dev.-PSI	283	88.5	140	181	92.1	112	191
	Coeff. of Var. (%)	5.50	1.81	2.70	3.22	2.18	3.06	4.09
	% higher or lower than Reference 1	----	-7.60	+.49	+9.94	-17.93	-28.65	-8.77
	Significance - %	----	yes 1.0	no	yes 1.0	yes 0.1	yes 0.1	yes 1.0
	% higher or lower than Reference 2	+8.23	----	+8.76	+18.99	-11.18	-22.78	-1.27
	Significance - %	yes 1.0	----	yes 0.1	yes 0.1	yes 0.1	yes 0.1	no

TABLE NO. 2

SUMMARY OF 7 DAY EXPERIMENTAL RESULTS, PRESTEAMING PERIOD: 6 HOURS

W/C	Analysis	Ref. No. 1 Standard Moist-cured	Ref. no. 2 Standard Steam-cured	Revibration Steam-cured	Water Reducer Steam-cured	Fly Ash 10% Steam-cured	Fly Ash 20% Steam-cured	Fly Ash 10% Revibration Steam-cured
0.35	Mean-PSI	9900	8650	8940	8890	8090	7050	----
	Standard Dev.-PSI	157	207	152.5	266.5	190	433	----
	Coeff. of Var. (%)	1.59	2.40	1.71	3.03	2.35	6.15	----
	% higher or lower than Reference 1	----	-12.63	-9.70	-10.20	-18.28	-28.79	----
	Significance - %	----	yes 0.1	yes 0.1	yes 0.1	yes 0.1	yes 0.1	----
	% higher or lower than Reference 2	+14.45	----	+3.35	+2.77	-6.47	-18.50	----
	Significance - %	yes 0.1	----	yes 5.0	no	yes 0.1	yes 0.1	----
0.40	Mean-PSI	7640	6850	7355	7650	6550	5640	6710
	Standard Dev.-PSI	255	202	239	158	258.5	165.5	152.5
	Coeff. of Var. (%)	3.37	2.92	3.24	2.07	3.97	2.94	2.27
	% higher or lower than Reference 1	----	-10.34	-3.73	+0.13	-14.27	-26.18	-12.17
	Significance - %	----	yes 0.1	yes 10.0	no	yes 0.1	yes 0.1	yes 0.1
	% higher or lower than Reference 2	+11.53	----	+7.37	+11.68	-4.38	-17.66	-2.04
	Significance - %	yes 0.1	----	yes 1.0	yes 0.1	yes 5.0	yes 0.1	no
0.45	Mean-PSI	6155	5645	6100	6350	5300	4700	5830
	Standard Dev.-PSI	165.5	161.5	132.5	66.2	104.5	90.5	147
	Coeff. of Var. (%)	2.69	2.87	2.17	1.05	1.97	1.93	2.52
	% higher or lower than Reference 1	----	-8.29	-0.89	+3.17	-13.89	-23.64	-5.28
	Significance - %	----	yes 0.1	no	yes 5.0	yes 0.1	yes 0.1	yes 1.0
	% higher or lower than Reference 2	+9.03	----	+8.06	+12.49	-6.11	-16.74	+3.28
	Significance - %	yes 0.1	----	yes 0.1	yes 0.1	yes 1.0	yes 0.1	yes 10.

TABLE NO. 3

SUMMARY OF 28 DAY EXPERIMENTAL RESULTS, PRESTEAMING PERIOD: 6 HOURS

W/C	Analysis	Ref. No. 1 Standard Moist-cured	Ref. no. 2 Standard Steam-cured	Revibration Steam-cured	Water Reducer Steam-cured	Fly Ash 10% Steam-cured	Fly Ash 20% Steam-cured	Fly Ash 10% Revibration Steam-cured
0.35	Mean-PSI	11350	9510	10010	10290	9710	9500	----
	Standard Dev.-PSI	304	85.3	384	104.2	165	79.7	
	Coeff. of Var. (%)	2.68	0.90	3.83	1.02	1.70	.84	
	% higher or lower than Reference 1		-16.21	-11.81	-9.34	-.14.45	- 16.30	
	Significance - %		yes 0.1	yes 0.1	yes 0.1	yes 0.1	yes 0.1	
	% higher or lower than Reference 2	+19.35		+5.26	+8.20	+2.10	-0.11	
	Significance - %	yes 0.1		yes 1.0	yes 0.1	yes 5.0	No	
0.40	Mean-PSI	9720	8530	9040	9050	8250	7960	8350
	Standard Dev.-PSI	377	197	174	548	149.5	137	260
	Coeff. of Var. (%)	3.88	2.32	1.93	6.04	1.82	1.72	3.11
	% higher or lower than Reference 1		-12.24	-7.00	-6.89	-15.12	-18.11	-14.09
	Significance - %		yes 0.1	yes 1.0	yes 5.0	yes 0.1	yes 0.1	yes 0.1
	% higher or lower than Reference 2	+13.95		+5.98	+6.10	-3.28	-6.68	-2.11
	Significance - %	yes 0.1		yes 0.1	yes 10	yes 5.0	yes 0.1	no
0.45	Mean-PSI	8050	7320	7850	7800	6830	6300	7600
	Standard Dev.-PSI	185.5	147	82.6	126	119.5	141	168
	Coeff. of Var. (%)	2.30	2.00	1.05	1.61	1.75	2.24	2.21
	% higher or lower than Reference 1		-9.07	-2.48	-3.11	-15.16	-21.74	-5.59
	Significance - %		yes 0.1	yes 5.0	yes 10	yes 0.1	yes 0.1	yes 1.0
	% higher or lower than Reference 2	+9.97		+7.24	+6.56	-6.69	-13.93	+3.83
	Significance - %	yes 0.1		yes 0.1	yes 0.1	yes 0.1	yes 0.1	yes 5.0

TABLE NO. 4

SUMMARY OF 2 DAY EXPERIMENTAL RESULTS, PRESTEAMING PERIOD: 4 HOURS

W/C	Analysis	Ref. No. 1 Standard Moist-cured	Ref. no. 2 Standard Steam-cured	Revibration Steam-cured	Water Reducer Steam-cured	Fly Ash 10% Steam-cured	Fly Ash 20% Steam-cured	Fly Ash 10% Revibration Steam-cured
0.35	Mean-PSI	8040	7400	7730	7340	6770	5850	----
	Standard Dev.-PSI	123.5	181.5	111.5	122	145.5	133.5	----
	Coeff. of Var. (%)	1.54	2.45	1.45	1.67	2.15	2.29	----
	% higher or lower than Reference 1	----	-7.96	-3.86	-8.71	-15.80	-27.24	----
	Significance - %	----	yes 0.1	yes 1.0	yes 0.1	yes o.1	yes 0.1	----
	% higher or lower than Reference 2	+8.65	----	+4.46	-0.81	-8.51	-20.95	----
	Significance - %	yes 0.1	----	yes 1.0	no	yes 1.0	yes 0.1	
0.40	Mean-PSI	6830	5690	6160	6390	5230	4550	5850
	Standard Dev.-PSI	325	212	186	330	85	201	366
	Coeff. of Var. (%)	4.75	3.47	3.02	5.16	1.62	4.41	6.25
	% higher or lower than Reference 1	----	-16.69	-9.81	-6.44	-23.43	-33.38	-14.35
	Significance - %	----	yes 0.1	yes 1.0	yes 5.0	yes 0.1	yes0.1	yes 0.1
	% higher or lower than Reference 2	+20.04	----	+8.26	+12.30	-8.08	-20.04	+2.81
	Significance - %	yes 0.1	----	yes 1.0	yes 1.0	yes 0.1	yes 0.1	no
0.45	Mean-PSI	5130	4640	5300	5250	3935	3540	4550
	Standard Dev.-PSI	283	96.5	147	230	88.5	92	133.7
	Coeff. of Var. (%)	5.50	2.08	2.77	4.39	2.25	2.62	2.96
	% higher or lower than Reference 1	----	-9.55	+3.31	+2.34	-23.29	-30.99	-11.31
	Significance - %	----	yes 1.0	no	no	yes 0.1	yes 0.1	yes 0.1
	% higher or lower than Reference 2	+10.56	----	+14.22	+13.15	-15.19	-23.71	-1.94
	Significance - %	yes 1.0	----	yes 0.1	yes 0.1	yes 0.1	yes 10	no

TABLE NO. 5

SUMMARY OF 7 DAY EXPERIMENTAL RESULTS, PRESTEAMING PERIOD: 4 HOURS

W/C	Analysis	Ref. No. 1 Standard Moist-cured	Ref. no. 2 Standard Steam-cured	Revibration Steam-cured	Water Reducer Steam-cured	Fly Ash 10% Steam-cured	Fly Ash 20% Steam-cured	Fly Ash 10% Revibration Steam-cured
0.35	Mean-PSI	9900	8450	8560	8240	7665	6650	
	Standard Dev.-PSI	157	191	53.3	372	217	236.5	
	Coeff. of Var. (%)	1.59	2.25	0.62	4.52	2.83	3.55	
	% higher or lower than Reference 1		-14.65	-13.54	-16.77	-22.58	-32.83	
	Significance - %		yes 0.1	yes 0.1	yes 0.1	yes 0.1	yes 0.1	
	% higher or lower than Reference 2	+17.16		+1.30	-2.49	-9.29	-21.30	
	Significance - %	yes 0.1		no	no	yes 0.1	yes 0.1	
0.40	Mean-PSI	7640	6750	7255	7310	6400	5440	6700
	Standard Dev.-PSI	255	234	97	307	232	60.9	315
	Coeff. of Var. (%)	3.37	3.48	1.34	4.20	3.14	1.11	4.70
	% higher or lower than Reference 1		-11.65	-5.04	-4.32	-16.23	-28.80	-12.30
	Significance - %		yes 0.1	yes 1.0	yes 10	yes 0.1	yes 0.1	yes 0.1
	% higher or lower than Reference 2	+13.19		+7.48	+8.30	-5.19	-19.41	-0.74
	Significance - %	yes 0.1		yes 0.1	yes 1.0	yes 5.0	yes 0.1	no
0.45	Mean-PSI	6155	5750	6000	6090	4950	4425	5600
	Standard Dev.-PSI	165.5	139	96	112	119.5	99.5	74.5
	Coeff. of Var. (%)	2.69	2.42	1.60	1.84	2.41	2.25	1.33
	% higher or lower than Reference 1		-6.58	-2.52	-1.06	-19.58	-28.11	-9.02
	Significance - %		yes 1.0	yes 10	no	yes 0.1	yes 0.1	yes 0.1
	% higher or lower than Reference 2	+7.04		+4.35	+5.91	-13.91	-23.04	-2.61
	Significance - %	yes 1.0		yes 1.0	yes 0.1	yes 0.1	yes 0.1	yes 5.0

TABLE NO. 7

SUMMARY OF EXPERIMENTAL RESULTS OF MOIST-CURED MIXES, W/C= 0.40

Age in day	Analysis	Ref. No. 1 Standard Moist-cured	Ref. no. 2* Standard Steam-cured	Revibration Moist-cured	Water Reducer Moist-cured	Fly Ash 10% Moist-cured	Fly Ash 20% Moist-cured	Fly Ash 10% Revibration Moist-cured
2	Mean-PSI	6830	6100	7250	6810	5810	4850	
	Standard Dev.-PSI	325	258	129	347	320	276	
	Coeff. of Var. (%)	4.75	4.19	1.79	5.10	5.50	5.70	
	% higher or lower than Reference 1		-9.52	+6.15	-0.29	-14.93	-28.99	
	Significance - %		yes 1.0	yes 5.0	no	yes 0.1	yes 0.1	
	% higher or lower than Reference 2	+10.52		+17.31	+10.19	-5.99	-21.52	
	Significance - %	yes 1.0		yes 0.1	yes 1.0	yes 5.0	yes 0.1	
7	Mean-PSI	7640	6850	8950	8250	7510	6610	
	Standard Dev.-PSI	255	202	171.5	238.5	398	222	
	Coeff. of Var. (%)	3.37	2.92	1.92	2.90	5.30	3.35	
	% higher or lower than Reference 1		-10.34	+17.15	+7.98	-1.70	-13.48	
	Significance - %		yes 0.1	yes 0.1	yes 1.0	no	yes 0.1	
	% higher or lower than Reference 2	+11.53		+30.66	+20.44	+9.64	-3.50	
	Significance - %	yes 0.1		yes 0.1	yes 0.1	yes 1.0	yes 10	
28	Mean-PSI	9720	8530	10280	9500	9690	8650	
	Standard Dev.-PSI	377	197	159	159	111.5	3.07	
	Coeff. of Var. (%)	3.88	2.32	1.55	1.68	1.15	3.55	
	% higher or lower than Reference 1		-9.07	+5.76	-2.26	-0.31	-11.01	
	Significance - %		yes 0.1	yes 1.0	no	no	yes 0.1	
	% higher or lower than Reference 2	+9.97		+20.52	+11.37	+13.60	+1.41	
	Significance - %	yes 0.1		yes 0.1	yes 0.1	yes 0.1	no	

* Presteaming= 6 hours

TABLE No. 8

SUMMARY OF 2 DAY EXPERIMENTAL RESULTS

W/C	Presteaming or Moist P.S.-hour	Analysis	Standard	Revibration	Water Reducer	Fly Ash 10%	Fly Ash 20%	Fly Ash 10% Revibration
0.35	6 Group I	Mean- PSI	7330	7900	7450	6810	6320	
		Stand. Dev.- PSI	347	286	139	84.5	128.5	
		Coeff. of Var.-%	4.75	3.62	1.87	1.24	2.03	
	4 Group II	Mean- PSI	7400	7730	7340	6770	5850	
		Stand. Dev.- PSI	181.5	111.5	122	145.5	133.5	
		Coeff. of Var.-%	2.45	1.45	1.67	2.15	2.29	
		I higher or lower than II -%	-0.95	+2.20	+1.50	+.59	+8.03	
		Significance %	no	no	no	no	yes 0.1	
0.40	6 Group III	Mean- PSI	6180	6460	6650	5600	4960	5550
		Stand. Dev.- PSI	258	118	146.2	116.5	103	94.5
		Coeff. of Var.-%	4.19	1.82	2.20	2.08	2.06	1.71
	4 Group IV	Mean- PSI	5690	6160	6390	5230	4550	5850
		Stand. Dev.- PSI	212	186	330	85	201	366
		Coeff. of Var.-%	3.47	3.02	5.16	1.62	4.41	6.25
		III higher or lower thanIV -%	+8.61	+4.87	+4.07	+7.07	+9.01	-5.13
		Significance %	yes 1.0	yes 1.0	no	yes 0.1	yes 0.1	yes 10
0.45	6 Group V	Mean- PSI	4740	5155	5640	4210	3660	4680
		Stand. Dev.- PSI	88.5	140	181	92.1	112	191
		Coeff. of Var.-%	1.81	2.70	3.22	2.18	3.06	4.09
	4 Group VI	Mean- PSI	4640	5300	5250	3935	3540	4550
		Stand. Dev.- PSI	96.5	147	230	88.5	92	133.7
		Coeff. of Var.-%	2.08	2.77	4.39	2.25	2.62	2.96
		V higher or lower Than VI -%	+2.16	-2.74	+7.43	+6.99	+3.39	+2.86
		Significance %	yes 10	no	yes 1.0	yes 0.1	yes 10	no

TABLE No. 9

SUMMARY OF 7 DAY EXPERIMENTAL RESULTS

W/C	Presteaming or Moist P.S.-hour	Analysis	Standard	Revibration	Water Reducer	Fly Ash 10%	Fly Ash 20%	Fly Ash 10% Revibration
0.35	6 Group I	Mean- PSI	8650	8940	8890	8090	7050	
		Stand. Dev.- PSI	207	152.5	266.5	190	433	
		Coeff. of Var.-%	2.40	1.71	3.03	2.35	6.15	
	4 Group II	Mean- PSI	8450	8560	8240	7665	6650	
		Stand. Dev.- PSI	191	53.3	372	217	236.5	
		Coeff. of Var.-%	2.25	0.62	4.52	2.83	3.55	
		I higher or lower than II -%	+2.37	+4.44	+7.89	+5.54	+6.02	
		Significance %	no	yes 0.1	yes 1.0	yes 1.0	yes 10	
0.40	6 Group III	Mean- PSI	6850	7355	7650	6550	5640	6710
		Stand. Dev.- PSI	202	239	158	258.5	165.5	152.5
		Coeff. of Var.-%	2.92	3.24	2.07	3.97	2.94	2.27
	4 Group IV	Mean- PSI	6750	7255	7310	6400	5440	6700
		Stand. Dev.- PSI	234	97	307	232	60.9	315
		Coeff. of Var.-%	3.48	1.34	4.20	3.14	1.11	4.70
		III higher or lower thanIV -%	+1.48	+1.38	+4.65	+2.34	+3.68	+0.15
		Significance %	no	no	no	no	yes 5.0	no
0.45	6 Group V	Mean- PSI	5645	6100	6350	5300	4700	5830
		Stand. Dev.- PSI	161.5	132.5	66.5	104.5	90.5	147
		Coeff. of Var.-%	2.87	2.17	1.05	1.97	1.93	2.52
	4 Group VI	Mean- PSI	5750	6000	6090	4950	4425	5600
		Stand. Dev.- PSI	139	96	112	119.5	99.5	74.5
		Coeff. of Var.-%	2.42	1.60	1.84	2.41	2.25	1.33
		V higher or lower Than VI -%	-1.83	+1.67	+4.27	+7.07	+6.21	+4.11
		Significance %	no	no	yes 0.1	yes 0.1	yes 0.1	yes 1.0

TABLE No. 10

SUMMARY OF 28 DAY EXPERIMENTAL RESULTS

W/C	Presteaming or Moist P.S.-hour	Analysis	Standard	Revibration	Water Reducer	Fly Ash 10%	Fly Ash 20%	Fly Ash 10% Revibration
0.35	6 Group I	Mean- PSI	9510	10010	10290	9710	9500	
		Stand. Dev.- PSI	85.3	384	104.2	165	79.7	
		Coeff. of Var.-%	0.90	3.83	1.02	1.70	0.84	
	4 Group II	Mean- PSI	9610	9845	10000	9690	8900	
		Stand. Dev.- PSI	295	353	154	240	108	
		Coeff. of Var.-%	3.07	3.60	1.54	2.48	1.22	
		I higher or lower than II -%	-1.04	+1.68	+2.90	+0.21	+6.74	
		Significance %	no	no	yes 1.0	no	yes 0.1	
0.40	6 Group III	Mean- PSI	8530	9040	9050	8250	7960	8350
		Stand. Dev.- PSI	197	174	548	149.5	137	260
		Coeff. of Var.-%	2.32	1.93	6.04	1.82	1.72	3.11
	4 Group IV	Mean- PSI	8100	8655	8370	7850	7640	8650
		Stand. Dev.- PSI	103	111	357	150	292	430
		Coeff. of Var.-%	1.27	1.28	4.26	1.92	3.82	4.98
		III higher or lower thanIV -%	+5.31	+4.45	+8.12	+5.10	+4.91	-3.47
		Significance %	yes0.1	yes 1.0	yes 5.0	yes 0.1	yes 5.0	no
0.45	6 Group V	Mean- PSI	7320	7850	7800	6830	6300	7600
		Stand. Dev.- PSI	147	82.6	126	119.5	141	168
		Coeff. of Var.-%	2.0	1.05	1.61	1.75	2.24	2.21
	4 Group VI	Mean- PSI	7030	7690	7450	6350	6020	7245
		Stand. Dev.- PSI	183	85	248	162.5	141	181
		Coeff. of Var.-%	2.61	1.11	3.33	2.56	2.34	2.50
		V higher or lower Than VI -%	+4.13	+2.08	+4.70	+7.56	+4.65	+4.90
		Significance %	yes 1.0	yes 1.0	yes 5.0	yes 0.1	yes 1.0	yes 1.0

TABLE No. II

SUMMARY OF 2 DAY EXPERIMENTAL RESULTS

W/C	Presteam-ing or Moist P.S.-hour	Analysis	Standard	Revibrat-ion	Water Reducer	Fly Ash 10%	Fly Ash 20%	Fly Ash 10% Revibration
0.4	Moist-cured Group I	Mean-	6830	7250	6810	5810	4850	
		Stand. Dev.- PSI	325	129	347	320	276	
		Coeff. of Var.-%	4.75	1.79	5.10	5.50	5.70	
	6 Group II	Mean- PSI	6180	6460	6650	5600	4960	
		Stand. Dev.- PSI	258	118	146.2	116.5	103	
		Coeff. of Var.-%	4.19	1.82	2.20	2.08	2.06	
		I higher or lower than II -%	+10.52	+12.23	+2.41	+3.75	-2.22	
		Significance %	yes 1.0	yes 0.1	no	no	no	
0.40	Moist-cured Group III	Mean- PSI	6830	7250	6810	5810	4850	
		Stand. Dev.- PSI	325	129	347	320	276	
		Coeff. of Var.-%	4.75	1.79	5.10	5.50	5.70	
	4 Group IV	Mean- PSI	5690	6160	6390	5230	4550	
		Stand. Dev.- PSI	212	186	330	85	201	
		Coeff. of Var.-%	3.47	3.02	5.16	1.62	4.41	
		III higher or lower thanIV -%	+20.04	+17.69	+6.57	+11.09	+6.59	
		Significance %	yes 0.1	yes 0.1	yes 10	yes 1.0	yes 10	
	Group V	Mean- PSI						
		Stand. Dev.- PSI						
		Coeff. of Var.-%						
	Group VI	Mean- PSI						
		Stand. Dev.- PSI						
		Coeff. of Var.-%						
		V higher or lower Than VI -%						
		Significance %						

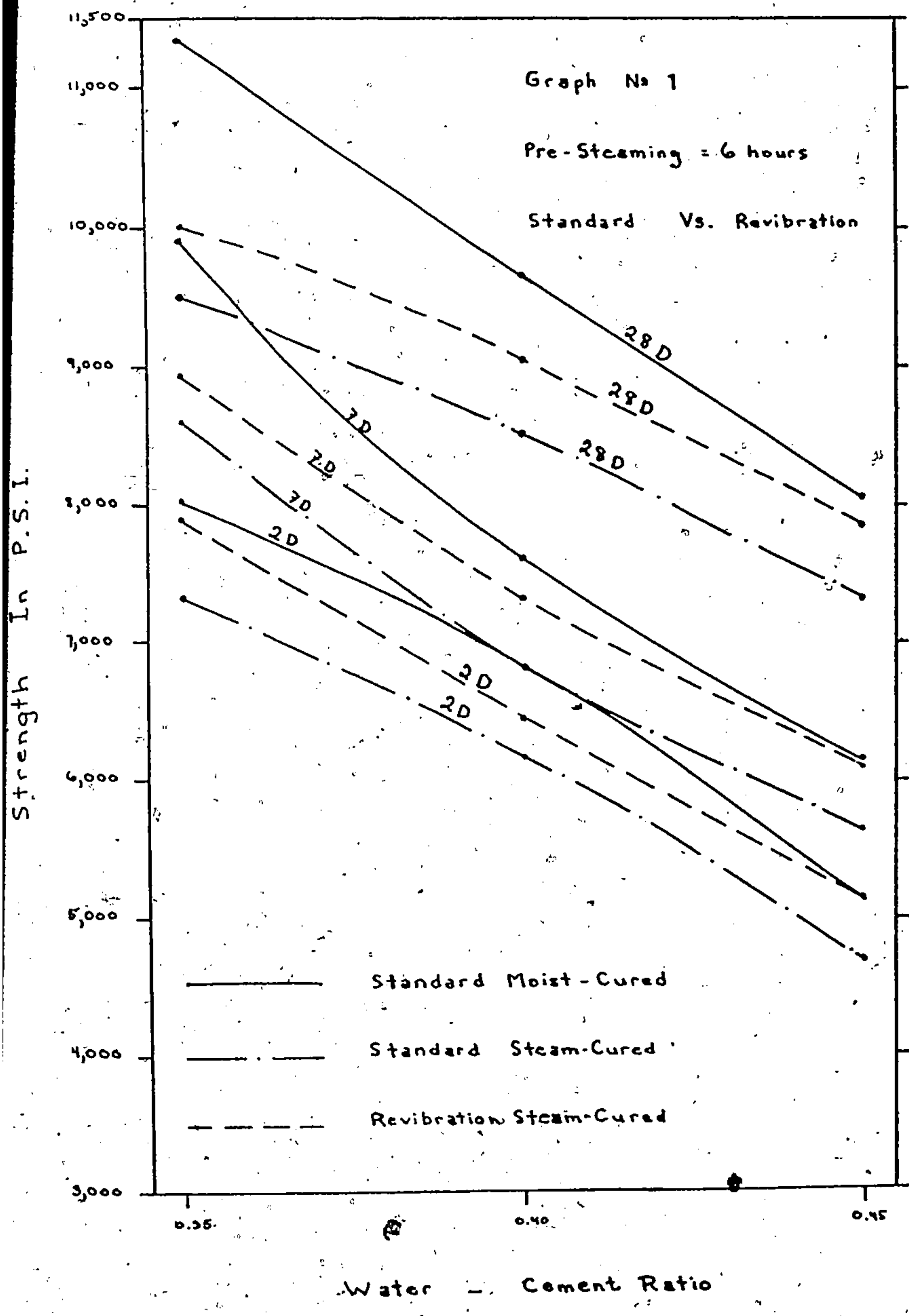
TABLE No. 12
SUMMARY OF 7 DAY EXPERIMENTAL RESULTS

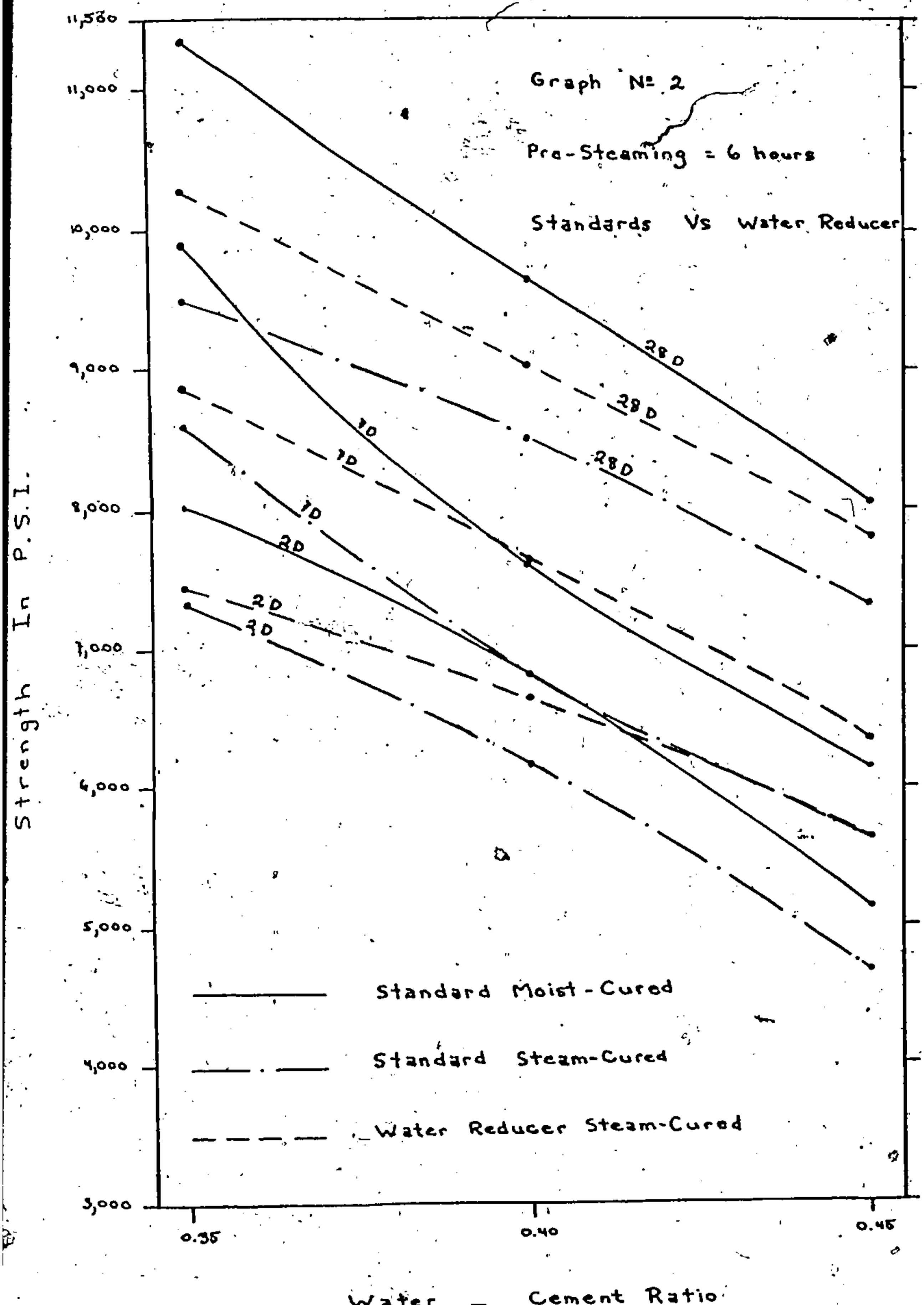
W/C	Presteaming or Moist P.S.-hour	Analysis	Standard	Revibration	Water Reducer	Fly Ash 10%	Fly Ash 20%	Fly Ash 10% Revibration
0.40	Moist-cured Group I	Mean- PSI	7640	8950	8250	7510	6610	
		Stand. Dev.- PSI	255	171.5	238.5	398	222	
		Coeff. of Var.-%	3.37	1.92	2.90	5.30	3.35	
	6 Group II	Mean- PSI	6850	7355	7650	6550	5640	
		Stand. Dev.- PSI	202	239	158	258.5	165.5	
		Coeff. of Var.-%	2.92	3.24	2.07	3.97	2.94	
		I higher or lower than II -%	+11.52	+21.69	+7.84	+14.66	+17.20	
		Significance %	yes 0.1	yes 0.1	yes 1.0	yes 0.1	yes 0.1	
0.40	Moist-cured Group III	Mean- PSI	7640	8950	8250	7510	6610	
		Stand. Dev.- PSI	255	171.5	238.5	398	222	
		Coeff. of Var.-%	3.37	1.92	2.90	5.30	3.35	
	4 Group IV	Mean- PSI	6750	7255	7310	6400	5440	
		Stand. Dev.- PSI	234	97	307	232	60.9	
		Coeff. of Var.-%	3.48	1.34	4.20	3.14	1.11	
		III higher or lower thanIV -%	+13.19	+23.36	+12.86	+17.34	+21.51	
		Significance %	yes 0.1	yes 0.1	yes 0.1	yes 0.1	yes 0.1	
	Group V	Mean- PSI						
		Stand. Dev.- PSI						
		Coeff. of Var.-%						
	Group VI	Mean- PSI						
		Stand. Dev.- PSI						
		Coeff. of Var.-%						
		V higher or lower Than VI -%						
		Significance %						

TABLE No. 13

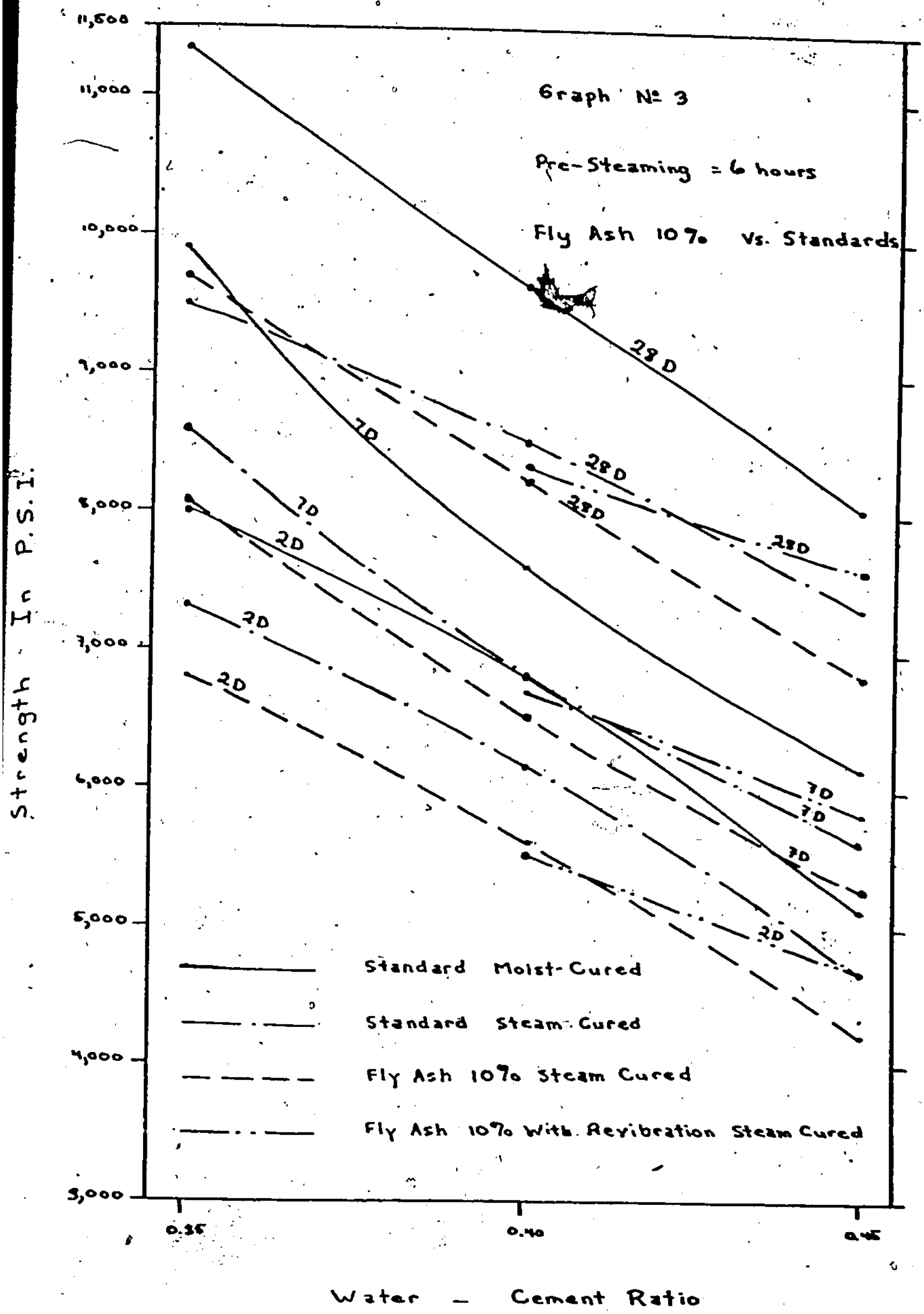
SUMMARY OF 28 DAY EXPERIMENTAL RESULTS

W/C	Presteam-ing or Moist P.S.-hour	Analysis	Standard	Revibrat-ion	Water Reducer	Fly Ash 10%	Fly Ash 20%	Fly Ash 10% Revibration
0.40	Moist-cured Group I	Mean- PSI	9720	10280	9500	9690	8650	
		Stand. Dev.- PSI	377	159	159	111.5	307	
		Coeff. of Var.-%	3.88	1.55	1.68	1.15	3.55	
	6 Group II	Mean- PSI	8530	9040	9050	8250	7960	
		Stand. Dev.- PSI	197	174	548	149.5	136	
		Coeff. of Var.-%	2.32	1.93	6.04	1.82	1.72	
		I higher or lower than II -%	+9.97	+13.72	+4.97	+17.45	+8.67	
		Significance %	yes 0.1	yes 0.1	yes 10	yes 0.1	yes 0.1	
0.40	Moist-cured Group III	Mean- PSI	9720	10280	9500	9690	8650	
		Stand. Dev.- PSI	377	159	159	111.5	307	
		Coeff. of Var.-%	3.88	1.55	1.68	1.15	3.55	
	4 Group IV	Mean- PSI	8100	8655	8370	7850	7640	
		Stand. Dev.- PSI	103	111	357	150	292	
		Coeff. of Var.-%	1.27	1.28	4.26	1.92	3.82	
		III higher or lower thanIV -%	+20.00	+18.78	+13.50	+20.34	+13.22	
		Significance %	yes 0.1	yes 0.1	yes 0.1	yes 0.1	yes 0.1	
	Group V	Mean- PSI						
		Stand. Dev.- PSI						
		Coeff. of Var.-%						
	Group VI	Mean- PSI						
		Stand. Dev.- PSI						
		Coeff. of Var.-%						
		V higher or lower Than VI -%						
		Significance %						

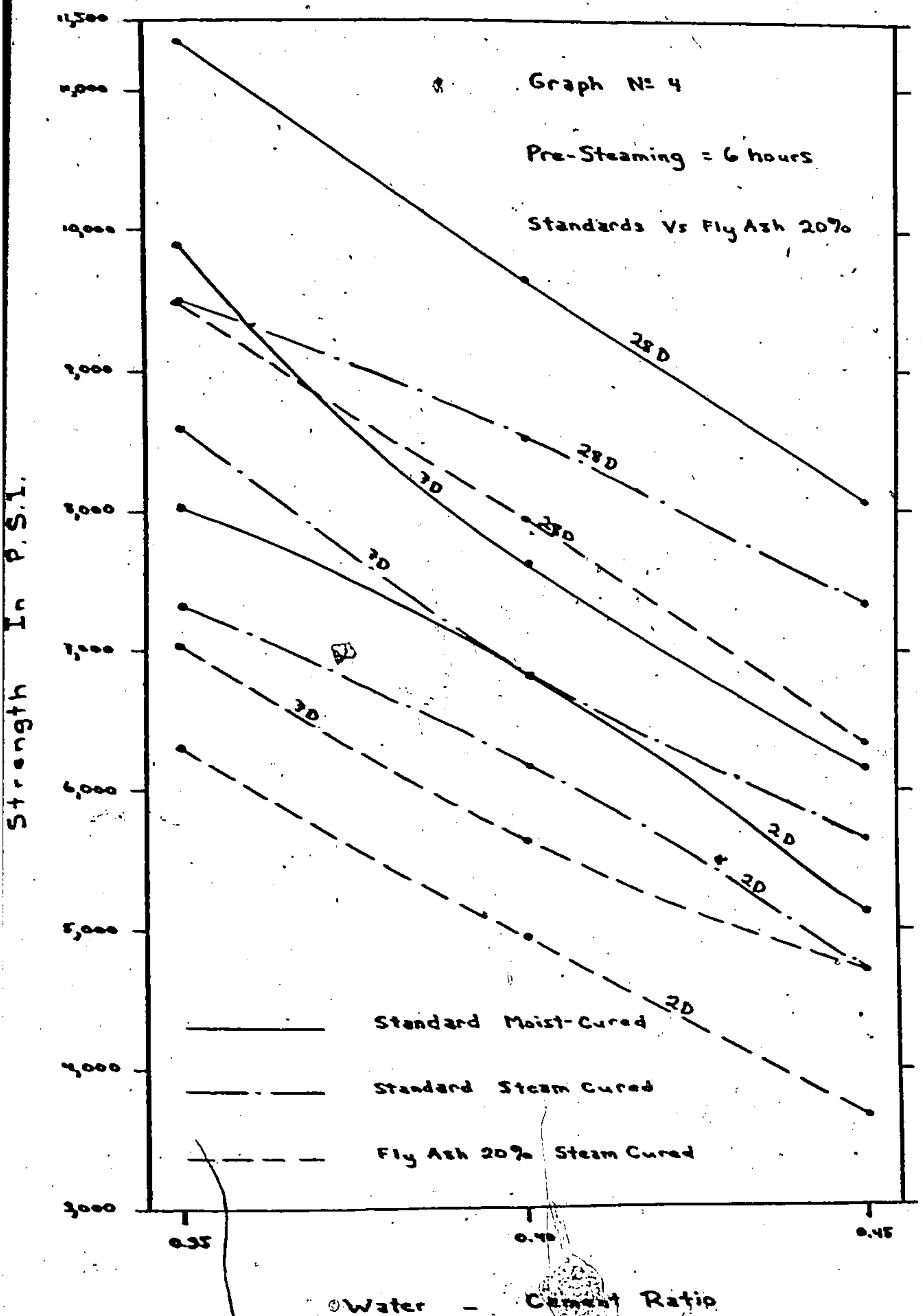

Graph No 1
Pre-Steaming = 6 hours
Standard Vs. Revibration
28 D
28 D
28 D
7 D
7 D
7 D
2 D
2 D
2 D
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
0.35
0.40
0.45
Water - Cement Ratio
Standard Moist-Cured
Standard Steam-Cured
Revibration Steam-Cured



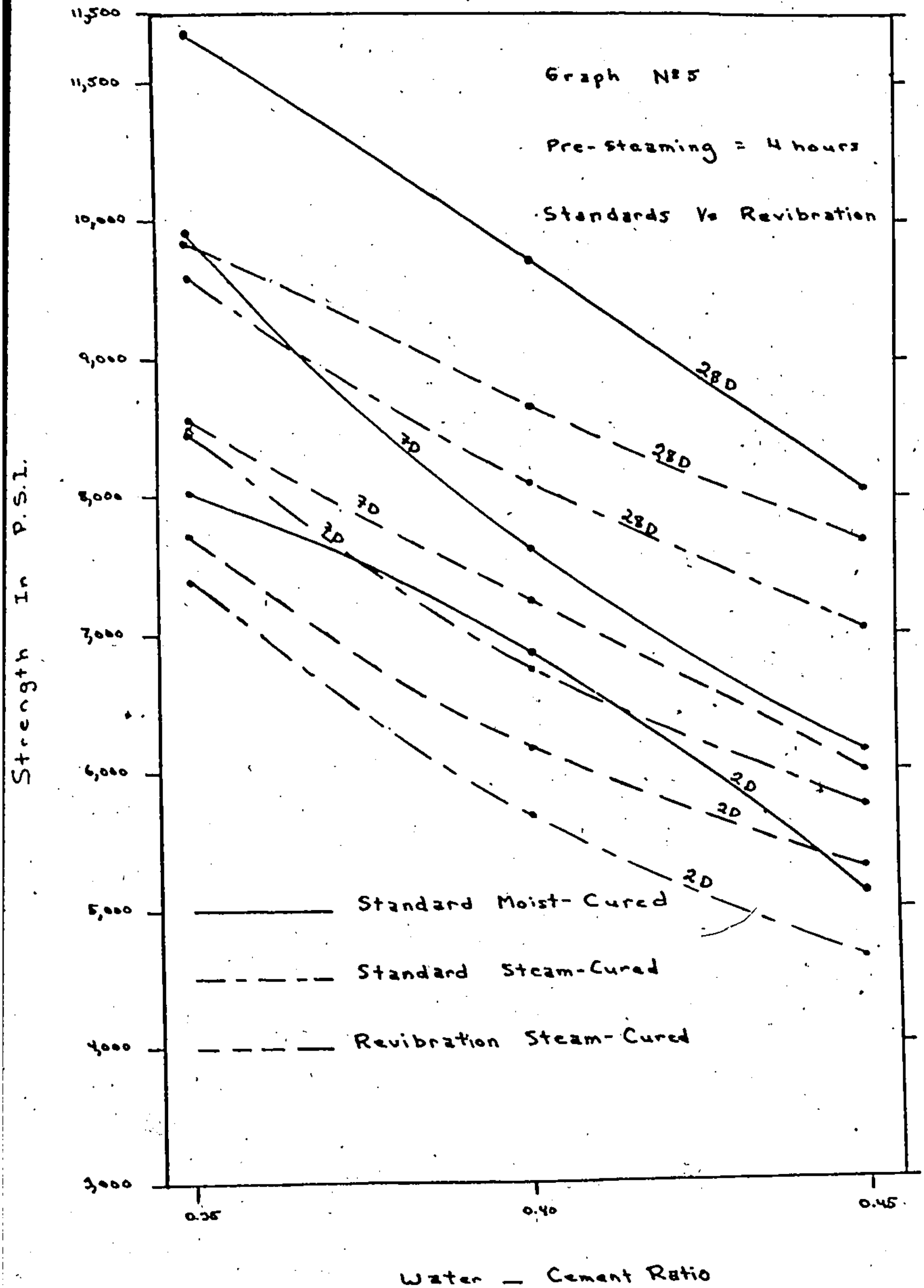
Graph № 2
Pre-Steaming = 6 hours
Standards Vs Water Reducer
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
28 D
28 D
28 D
7 D
7 D
7 D
2 D
2 D
2 D
0.35
0.40
0.45
Water — Cement Ratio
Standard Moist-Cured
Standard Steam-Cured
Water Reducer Steam-Cured

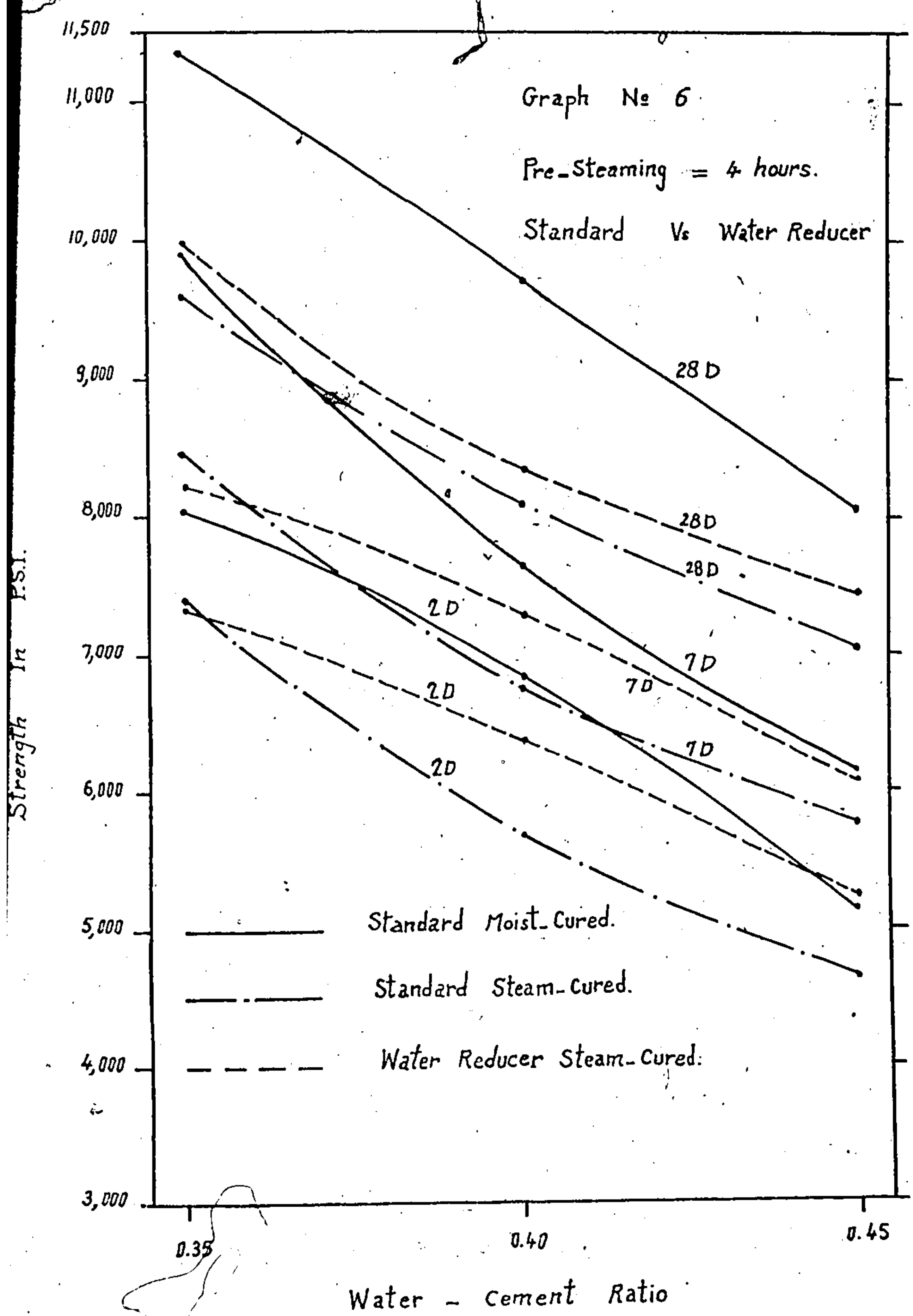


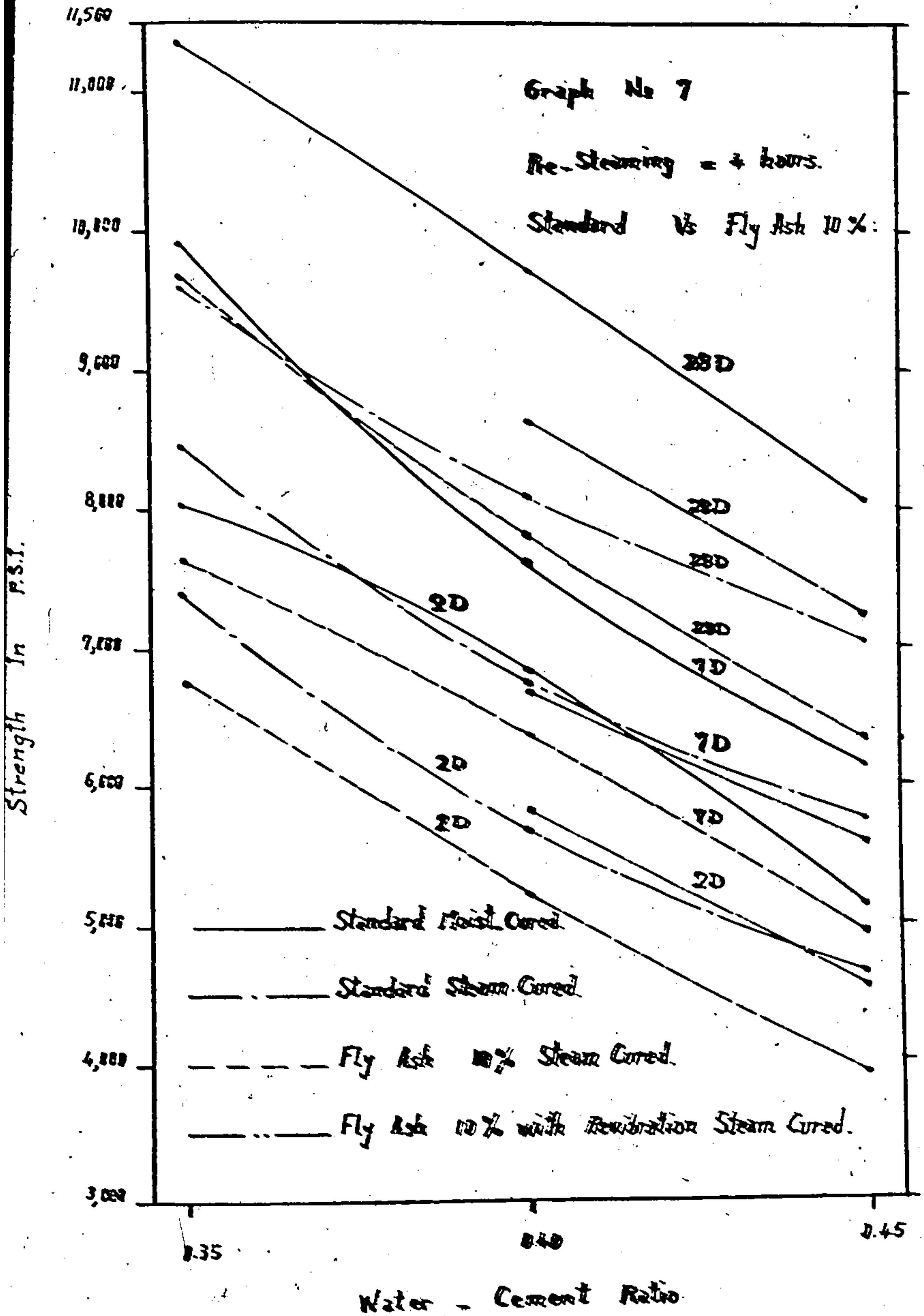
Graph № 3
Pre-Steaming = 6 hours
Fly Ash 10% Vs. Standards
Strength In P.S.I.
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
28 D
7D
2D
0.35
0.40
0.45
Standard Moist-Cured
Standard Steam Cured
Fly Ash 10% Steam Cured
Fly Ash 10% With Revibration Steam Cured
Water — Cement Ratio



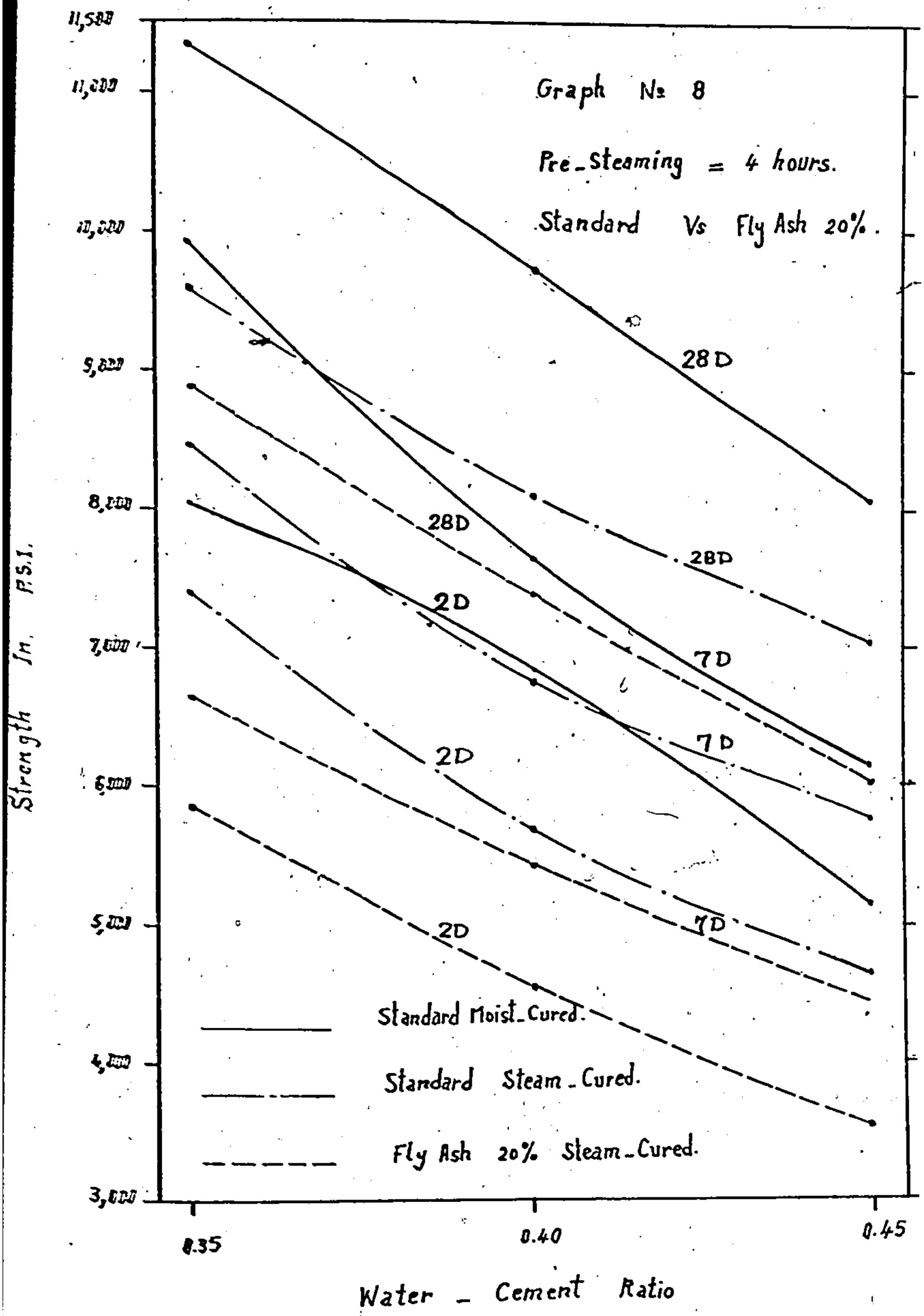
Graph No 4
Pre-Steaming = 6 hours
Standards Vs Fly Ash 20%
28D
28D
7D
28D
7D
7D
2D
2D
2D
Standard Moist-Cured
Standard Steam Cured
Fly Ash 20% Steam Cured
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
0.35
0.40
0.45
Strength In P.S.I.
Water - Cement Ratio

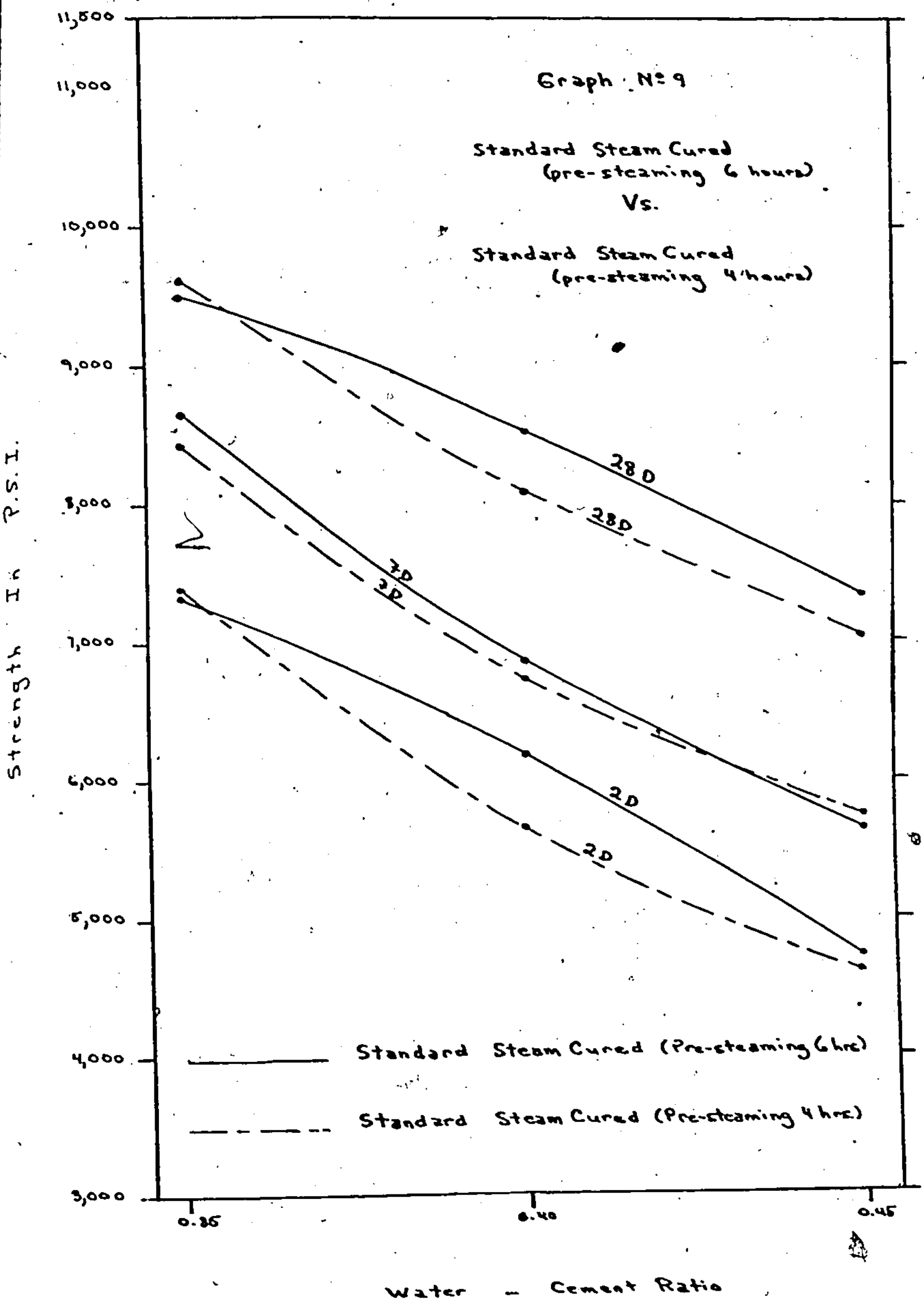

Graph Nº 5
Pre-Steaming = 4 hours
Standards Vs Revibration
28D
28D
28D
7D
7D
2D
2D
2D
2D
Standard Moist-Cured
Standard Steam-Cured
Revibration Steam-Cured
Strength In P.S.I.
Water — Cement Ratio
0.35
0.40
0.45
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,500
11,500


Graph № 6
Pre-Steaming = 4 hours.
Standard Vs Water Reducer
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
28 D
28 D
28 D
7 D
7 D
7 D
2 D
2 D
2 D
Standard Moist-Cured.
Standard Steam-Cured.
Water Reducer Steam-Cured.
0.35
0.40
0.45
Water - Cement Ratio

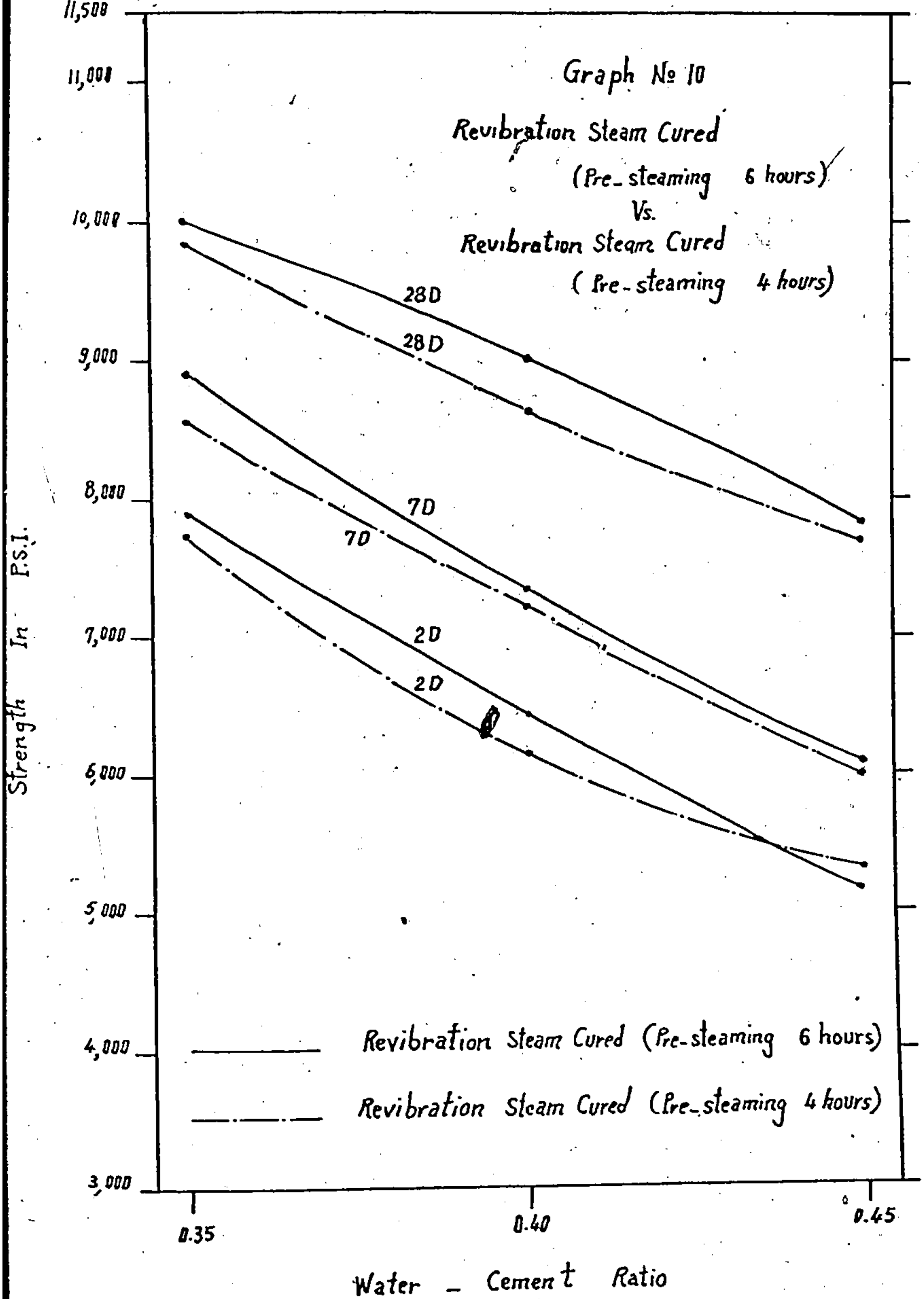


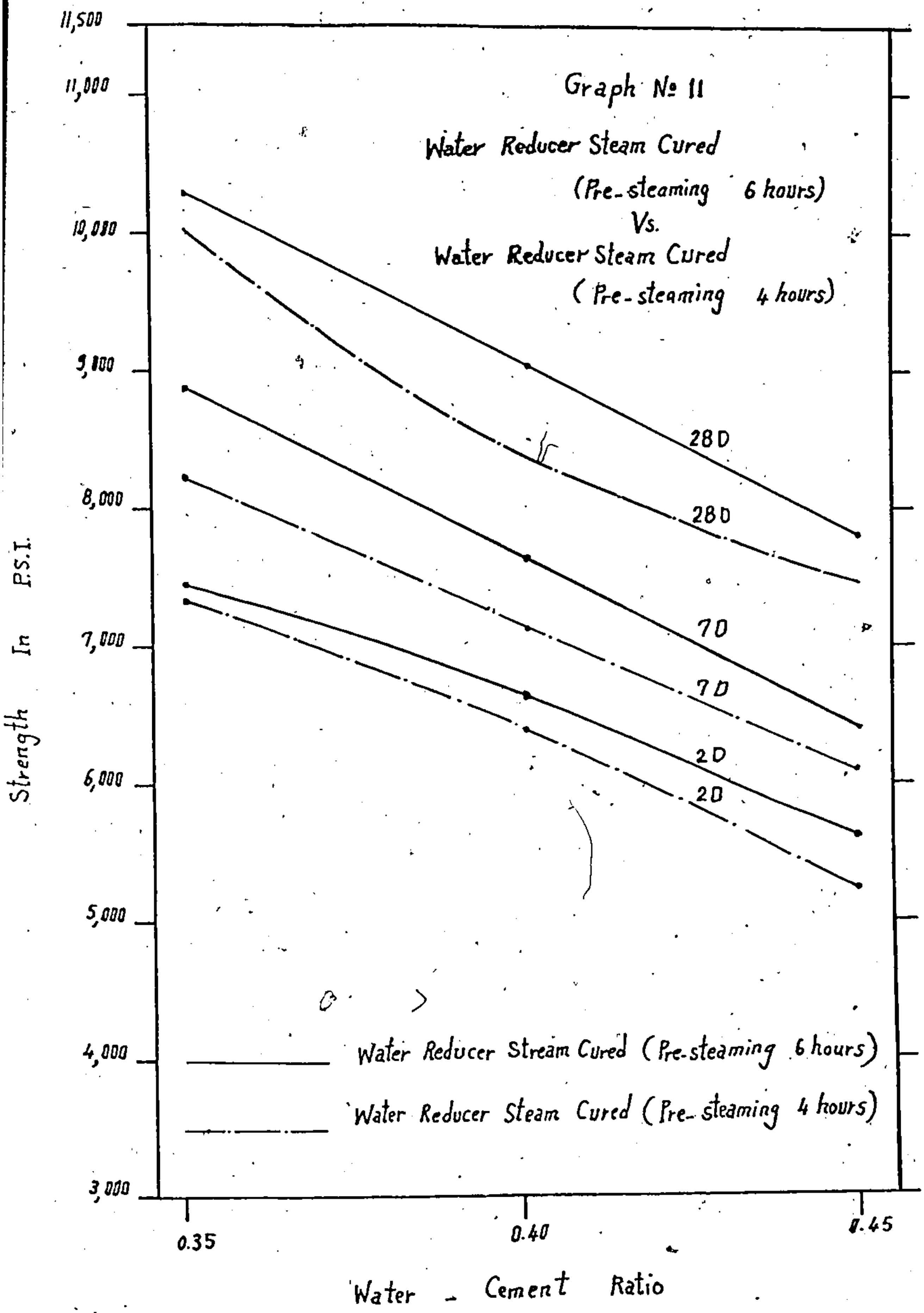
Graph No 7
Re-Steaming = 4 hours.
Standard Vs Fly Ash 10%:
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
28D
28D
28D
28D
7D
7D
7D
7D
2D
2D
2D
Standard Moist Cured.
Standard Steam Cured.
Fly Ash 10% Steam Cured.
Fly Ash 10% with Revibration Steam Cured.
0.35
0.40
0.45
Water - Cement Ratio

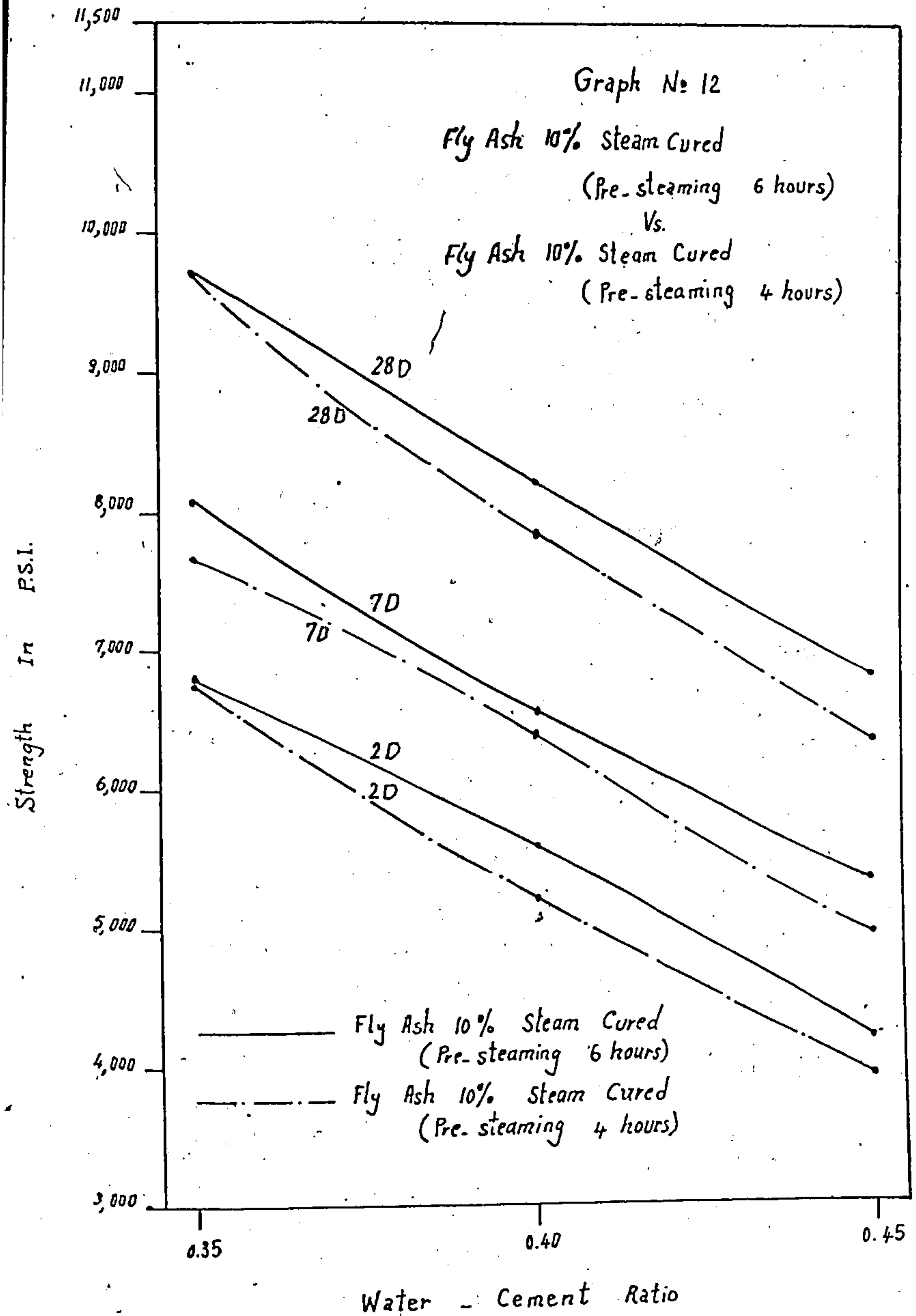

Graph № 8
Pre_Steaming = 4 hours.
Standard Vs Fly Ash 20%.
Strength In P.S.I.
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
28D
28D
28D
7D
7D
7D
2D
2D
2D
Standard Moist_Cured.
Standard Steam_Cured.
Fly Ash 20% Steam_Cured.
0.35
0.40
0.45
Water _ Cement Ratio

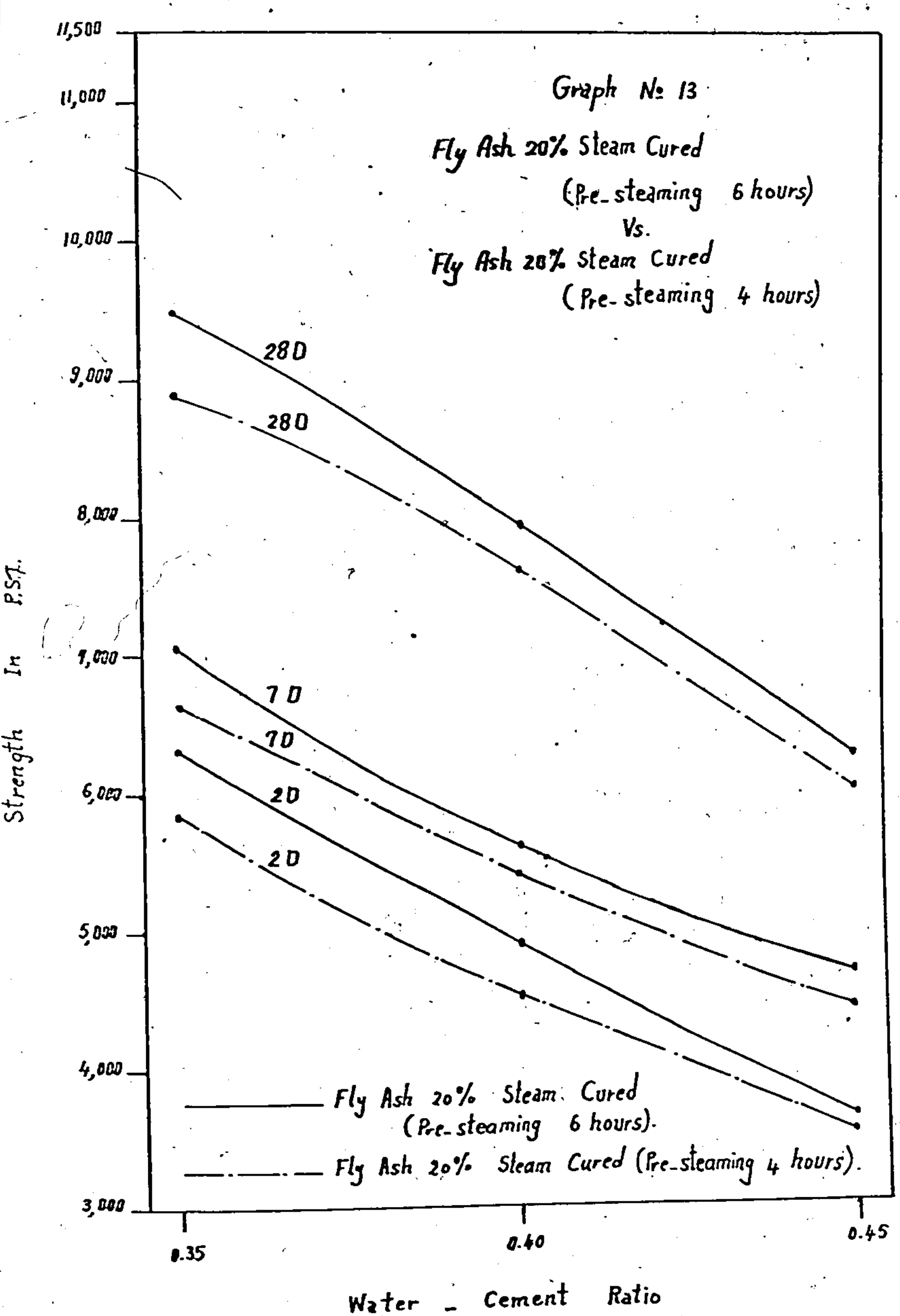


Graph No 9
Standard Steam Cured (pre-steaming 6 hours)
Vs.
Standard Steam Cured (pre-steaming 4 hours)
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength in P.S.I.
28 D
28 D
7 D
7 D
2 D
2 D
Standard Steam Cured (Pre-steaming 6 hrs)
Standard Steam Cured (Pre-steaming 4 hrs)
0.35
0.40
0.45
Water - Cement Ratio

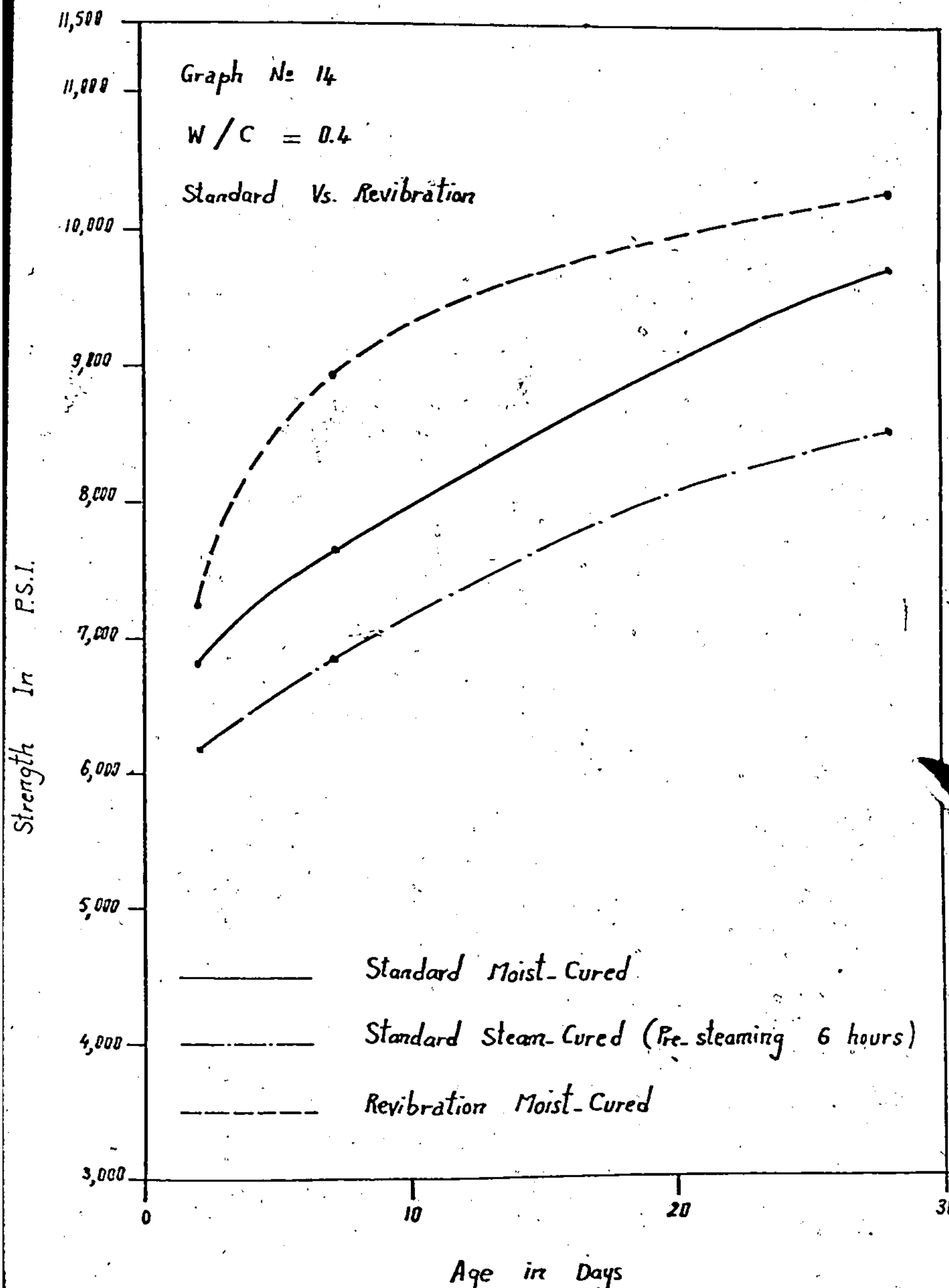

Graph № 10
Revibration Steam Cured
(Pre-steaming 6 hours)
Vs.
Revibration Steam Cured
(Pre-steaming 4 hours)
28D
28D
7D
7D
2D
2D
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
0.35
0.40
0.45
Water - Cement Ratio
Revibration Steam Cured (Pre-steaming 6 hours)
Revibration Steam Cured (Pre-steaming 4 hours)

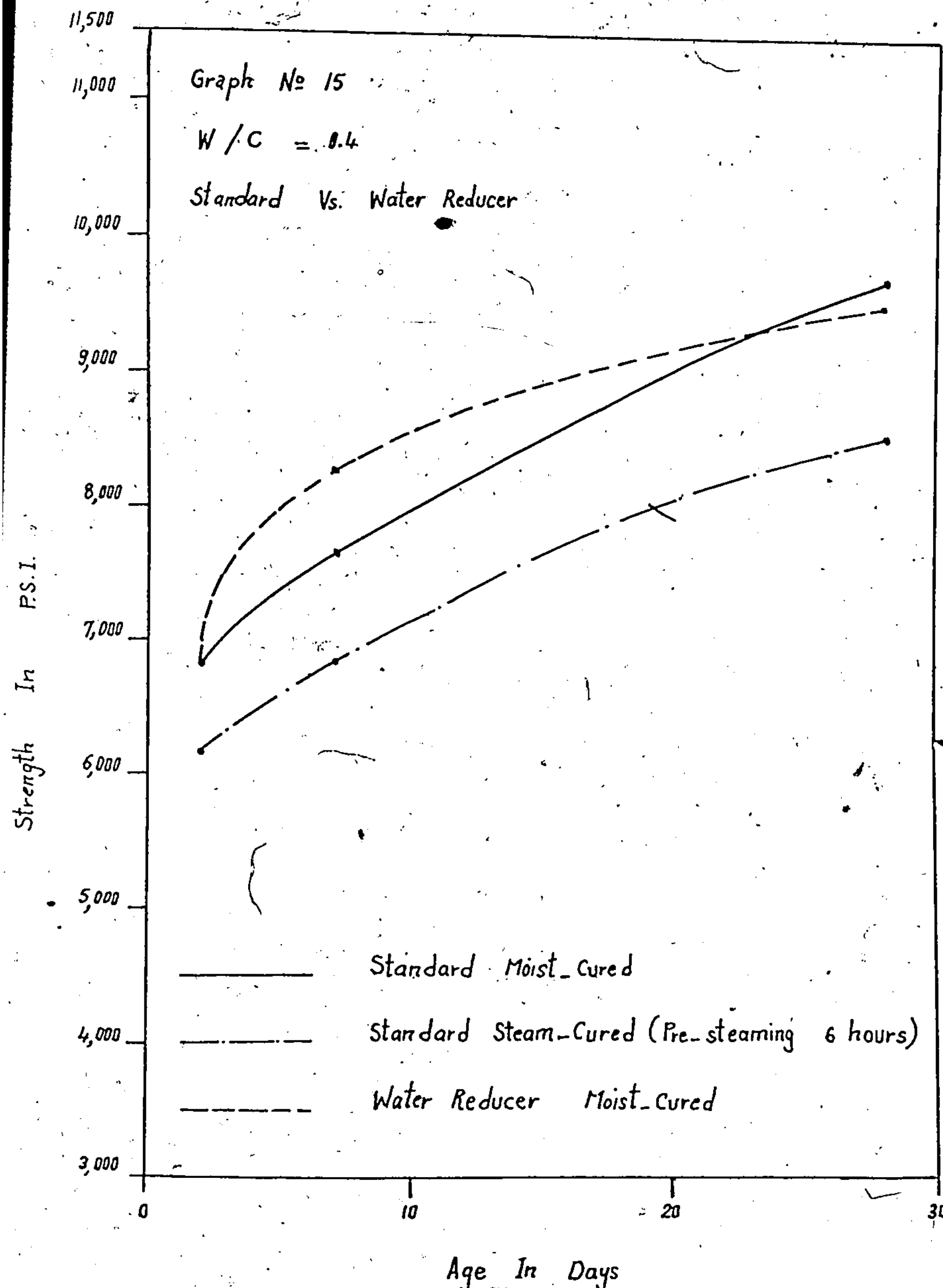

Graph № 11
Water Reducer Steam Cured
(Pre-steaming 6 hours)
Vs.
Water Reducer Steam Cured
(Pre-steaming 4 hours)
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
28D
28D
7D
7D
2D
2D
Water Reducer Stream Cured (Pre-steaming 6 hours)
Water Reducer Steam Cured (Pre-steaming 4 hours)
0.35
0.40
0.45
Water - Cement Ratio


Graph No 12
Fly Ash 10% Steam Cured
(Pre-steaming 6 hours)
Vs.
Fly Ash 10% Steam Cured
(Pre-steaming 4 hours)
28D
28D
7D
7D
2D
2D
Fly Ash 10% Steam Cured
(Pre-steaming 6 hours)
Fly Ash 10% Steam Cured
(Pre-steaming 4 hours)
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
0.35
0.40
0.45
Water - Cement Ratio

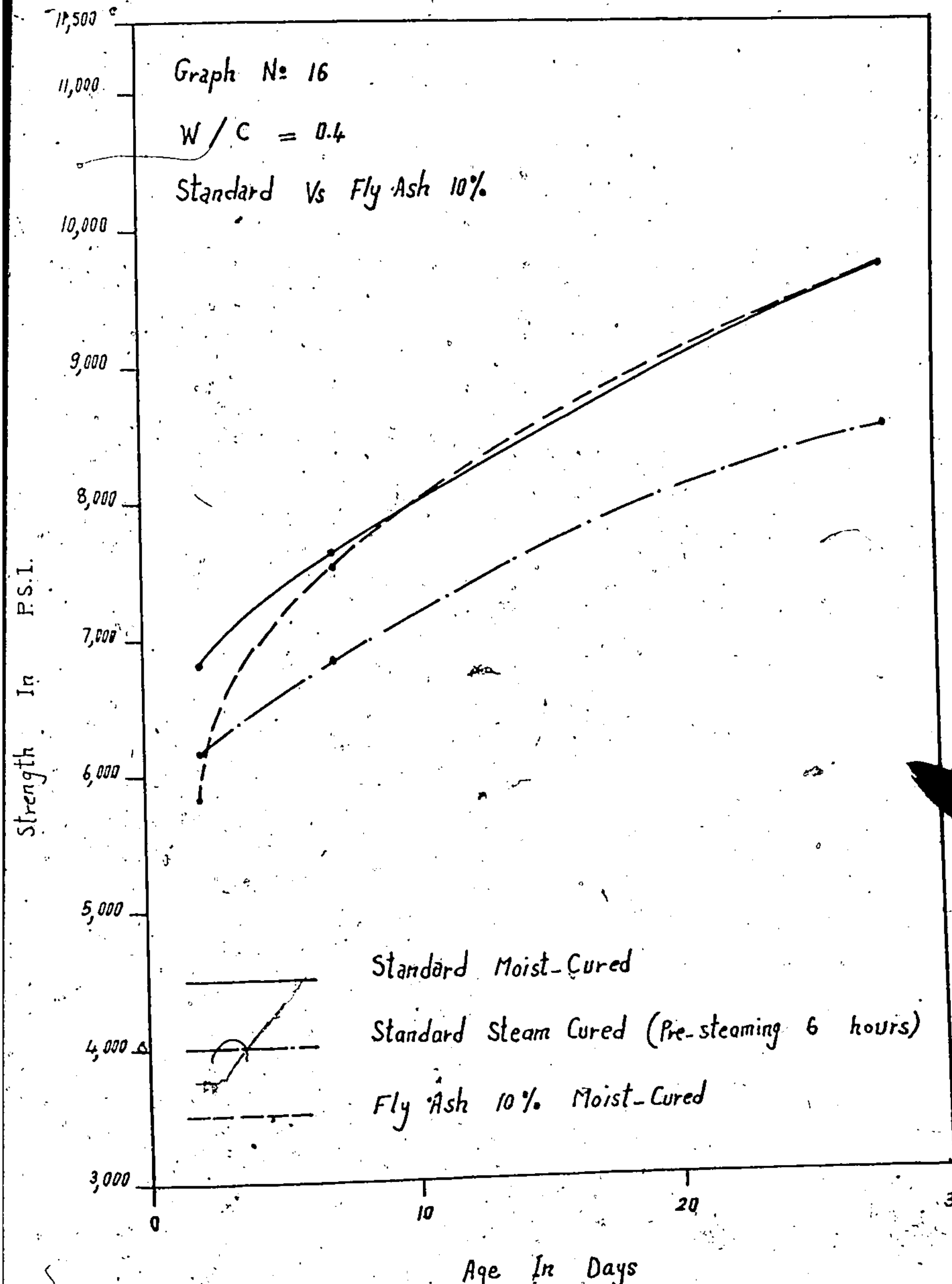


Graph No 13
Fly Ash 20% Steam Cured
(Pre-steaming 6 hours)
Vs.
Fly Ash 20% Steam Cured
(Pre-steaming 4 hours)
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
28 D
28 D
7 D
7 D
2 D
2 D
Fly Ash 20% Steam Cured
(Pre-steaming 6 hours).
Fly Ash 20% Steam Cured (Pre-steaming 4 hours).
0.35
0.40
0.45
Water - Cement Ratio

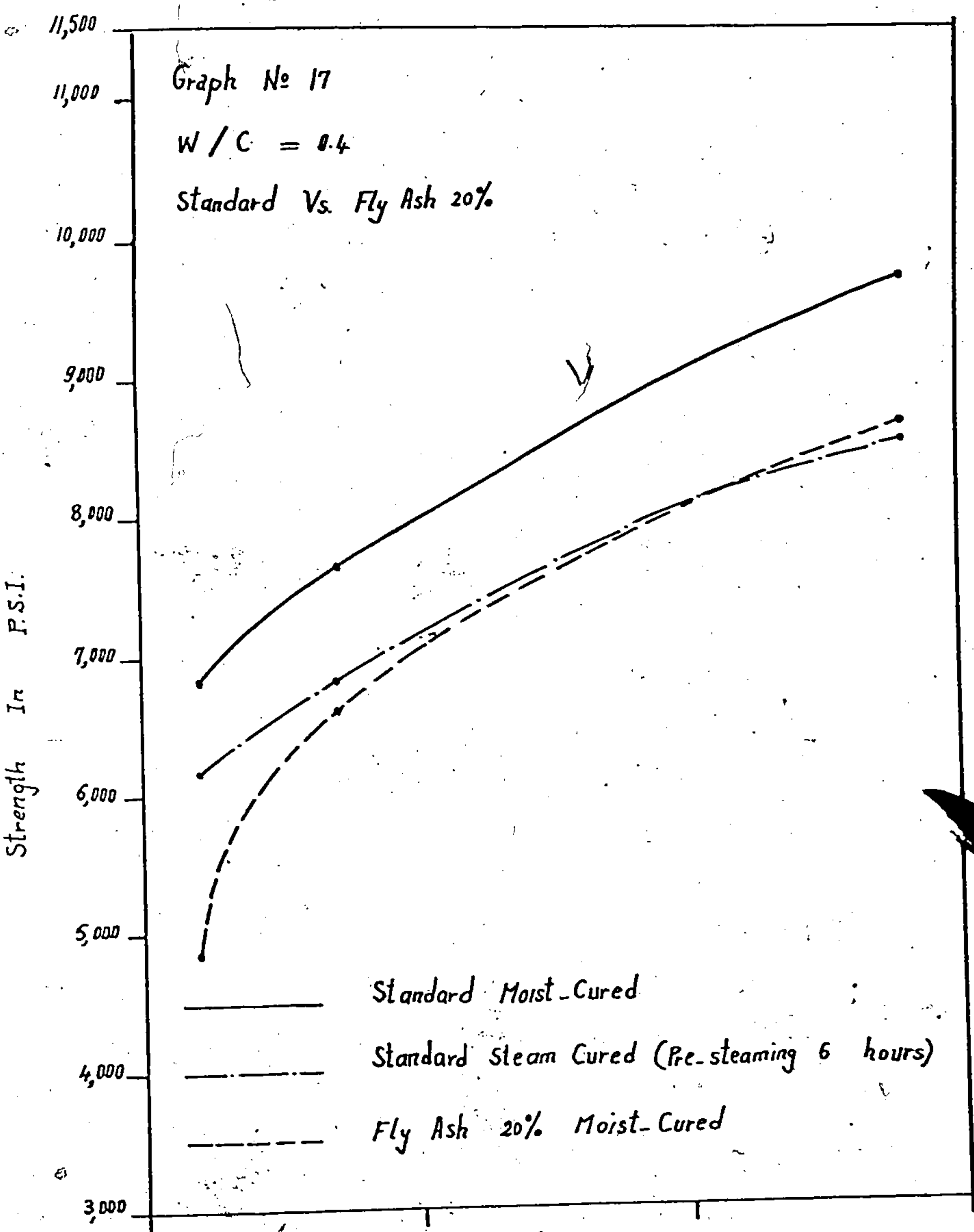

Graph № 14
W / C = 0.4
Standard Vs. Revibration
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
0
10
20
30
Age in Days
Standard Moist-Cured
Standard Steam-Cured (Pre-steaming 6 hours)
Revibration Moist-Cured



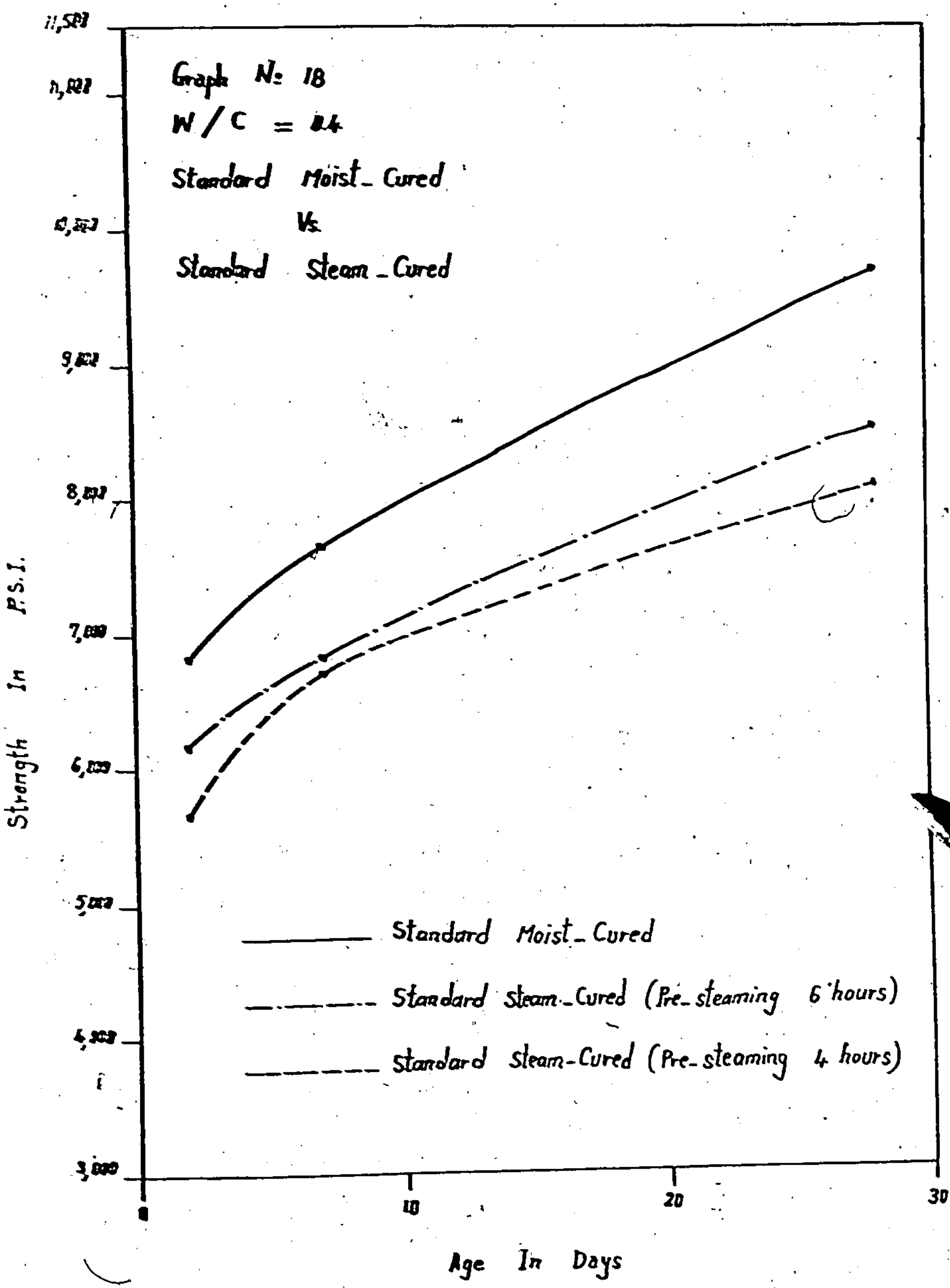
Graph № 15
W / C = 0.4
Standard Vs. Water Reducer
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
Standard Moist_Cured
Standard Steam_Cured (Pre_steaming 6 hours)
Water Reducer Moist_Cured
0
10
20
30
Age In Days



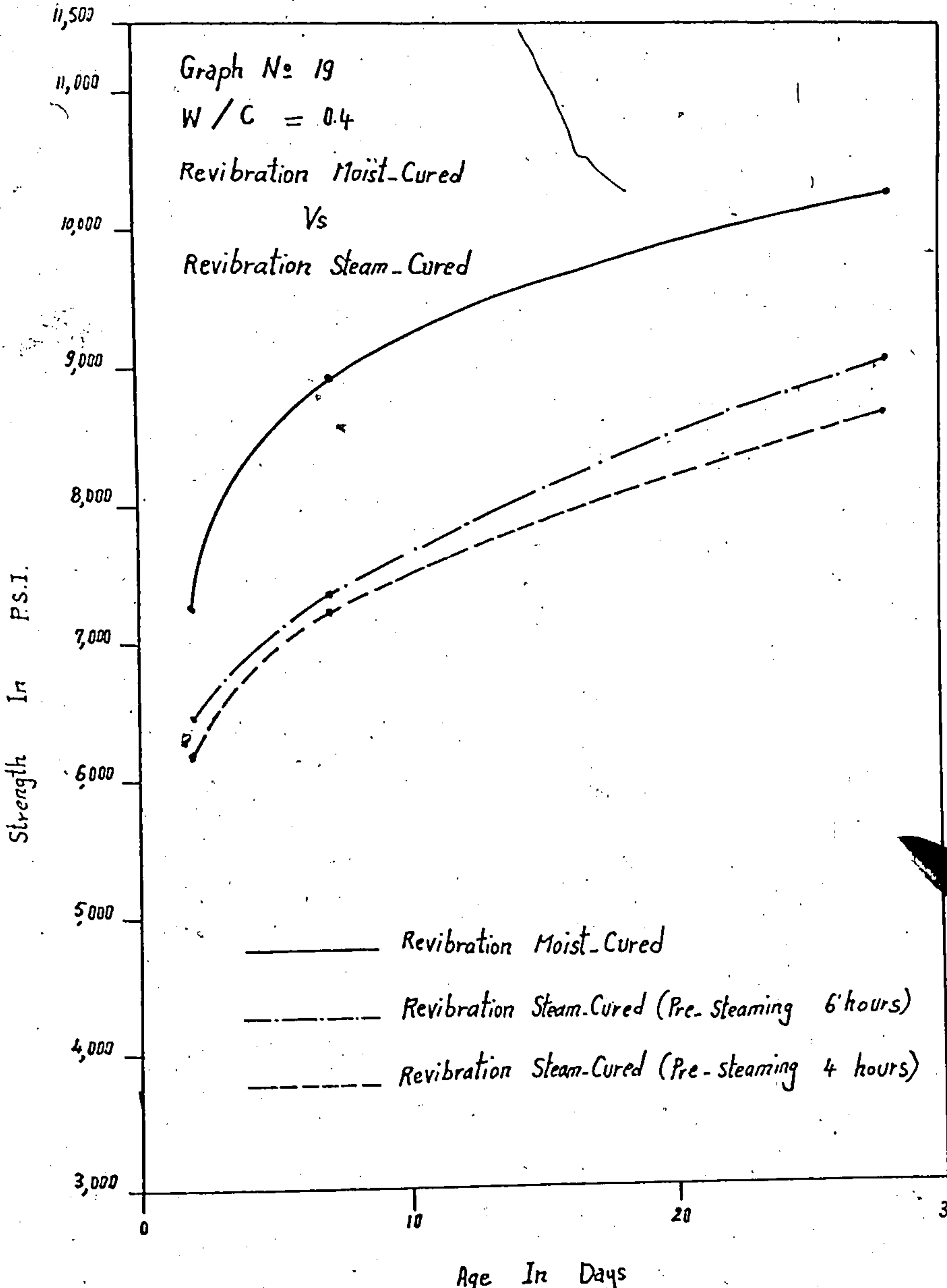
Graph No 16
W/C = 0.4
Standard Vs Fly Ash 10%
Strength In P.S.I.
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
0
10
20
30
Standard Moist-Cured
Standard Steam Cured (Pre-steaming 6 hours)
Fly Ash 10% Moist-Cured
Age In Days

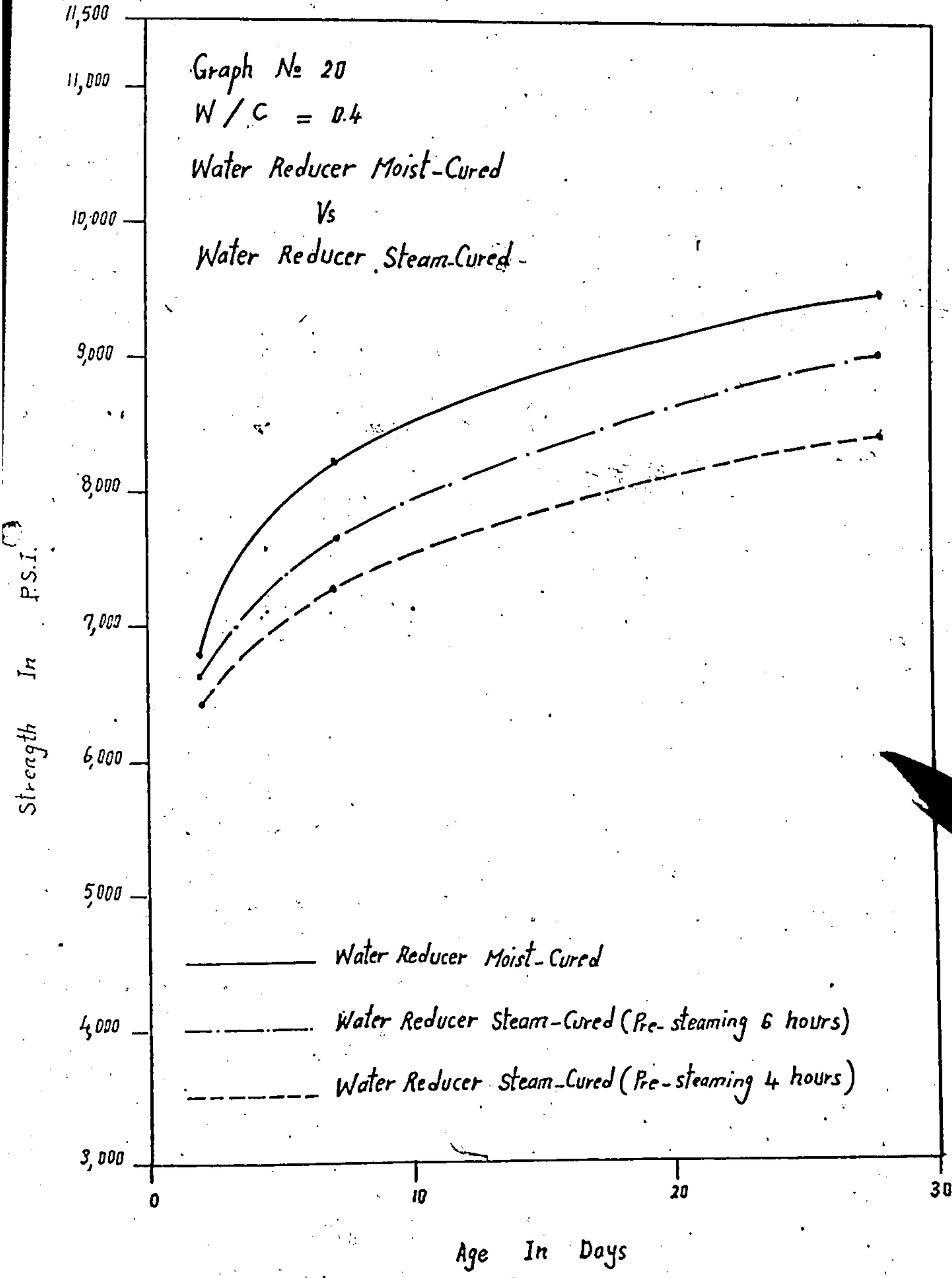


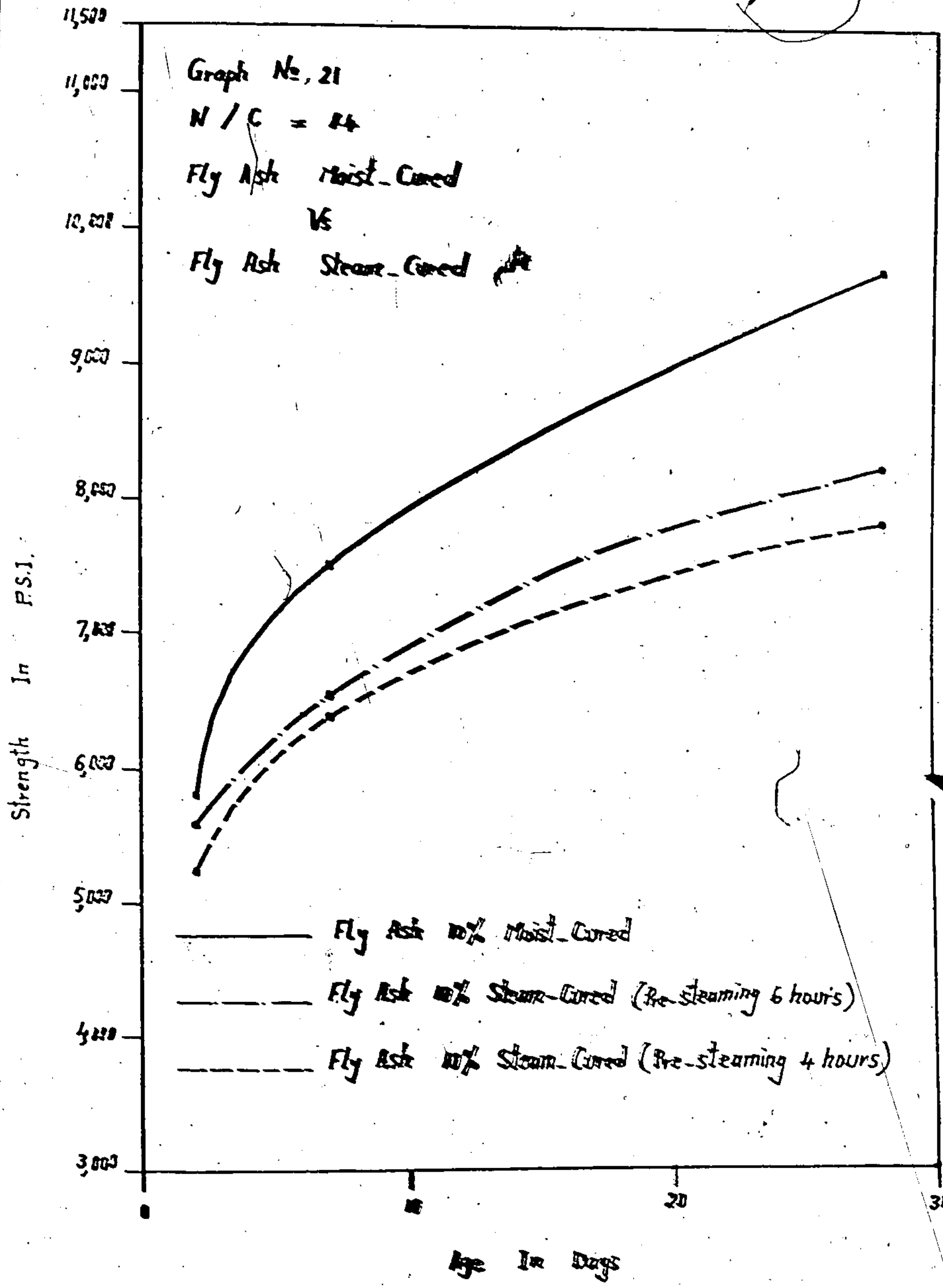
Graph № 17
W / C = 0.4
Standard Vs. Fly Ash 20%
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
Standard Moist_Cured
Standard Steam Cured (Pre_steaming 6 hours)
Fly Ash 20% Moist_Cured



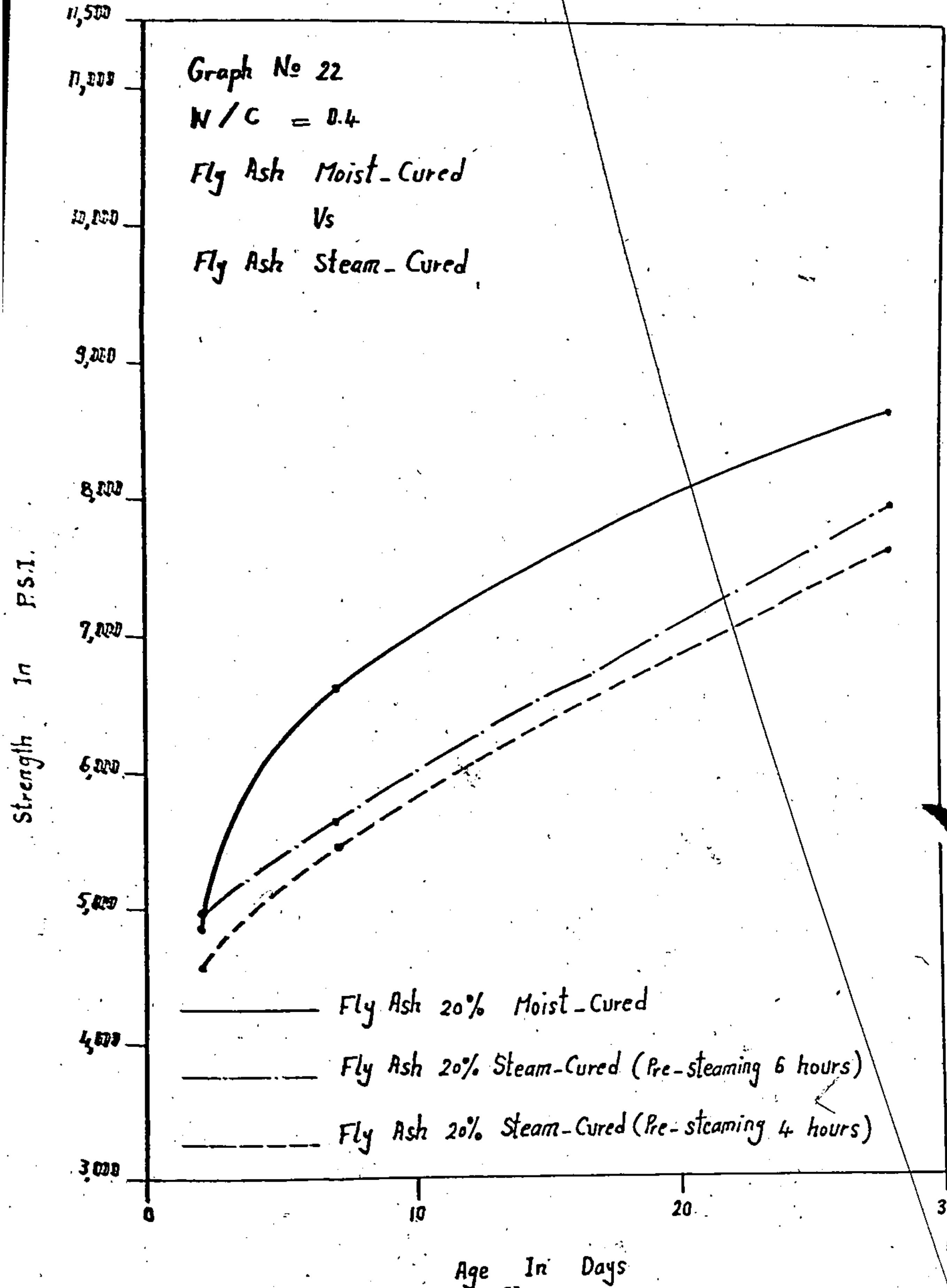
Graph No 18
Standard Moist_Cured
Vs
Standard Steam_Cured
Standard Moist_Cured
Standard Steam_Cured (Pre_steaming 6 hours)
Standard Steam-Cured (Pre-steaming 4 hours)
Strength In P.S.I.
Age In Days
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
0
10
20
30

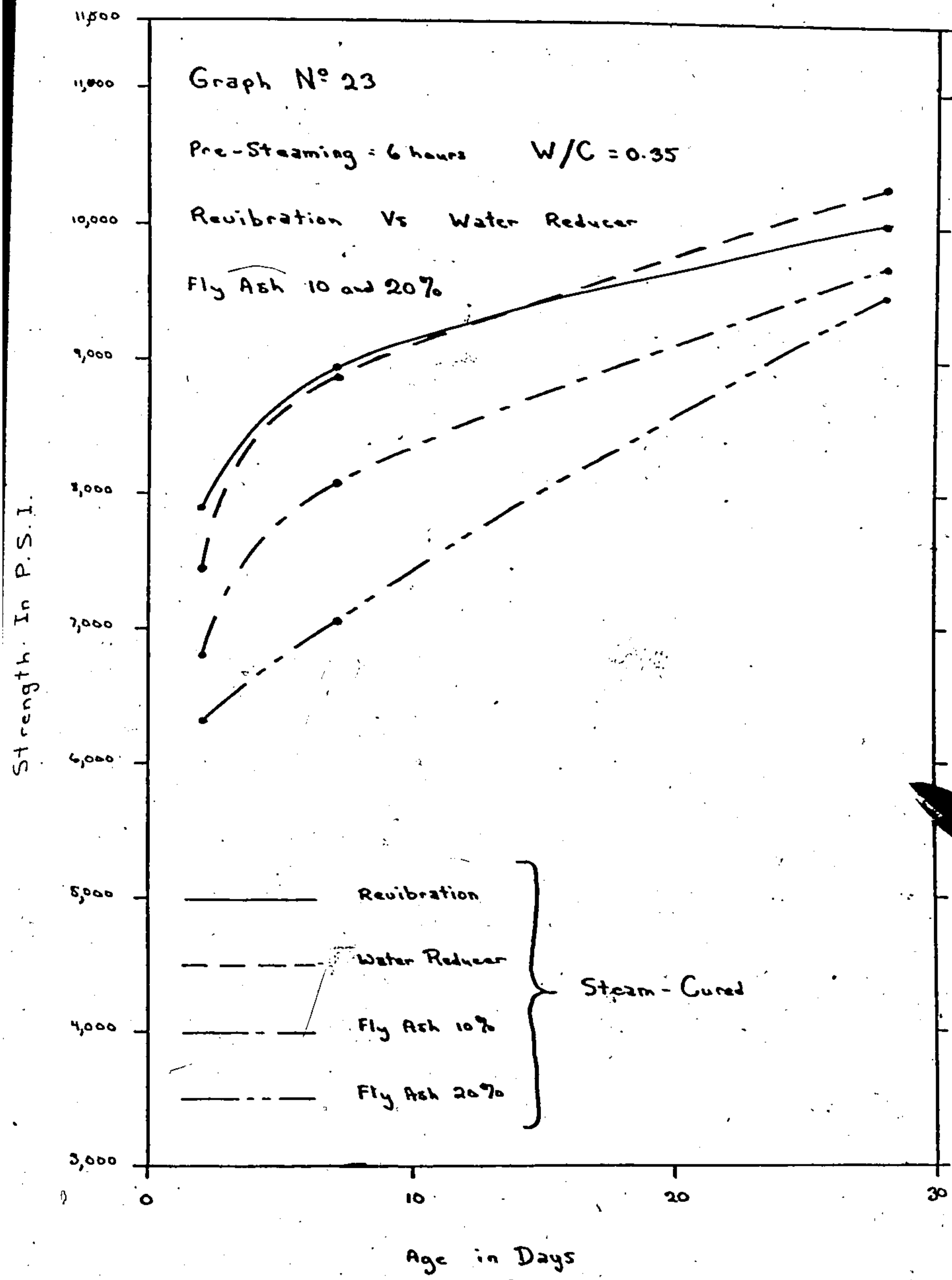

Graph No 19
W / C = 0.4
Revibration Moist_Cured
Vs
Revibration Steam_Cured
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
Revibration Moist_Cured
Revibration Steam-Cured (Pre-Steaming 6 hours)
Revibration Steam-Cured (Pre-steaming 4 hours)
0
10
20
30
Age In Days


Graph № 20
W / C = 0.4
Water Reducer Moist-Cured
Vs
Water Reducer Steam-Cured
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
0
10
20
30
Age In Days
Water Reducer Moist-Cured
Water Reducer Steam-Cured (Pre-steaming 6 hours)
Water Reducer Steam-Cured (Pre-steaming 4 hours)

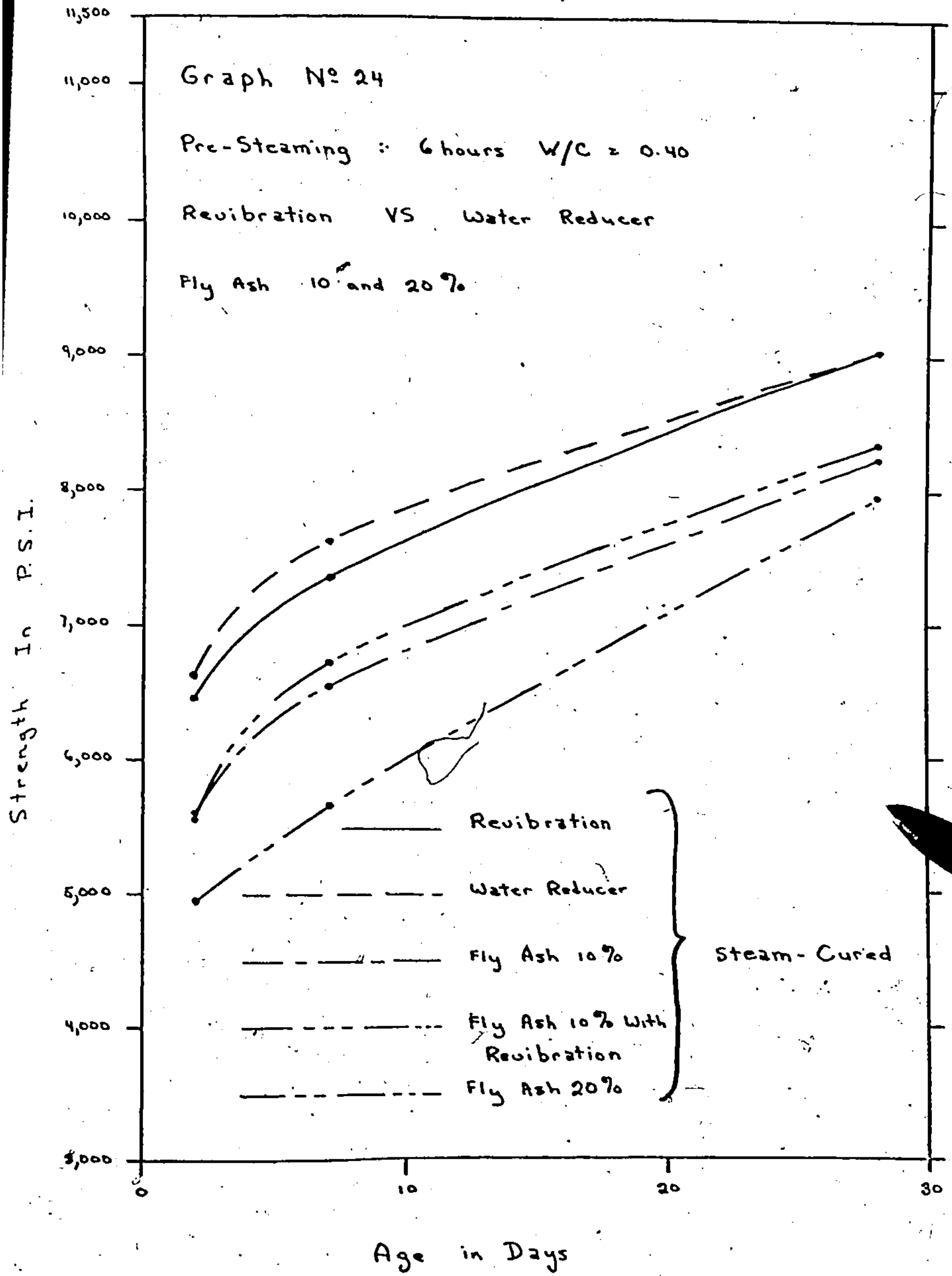


Graph No. 21
W / C = .44
Fly Ash Moist_Cured
Vs
Fly Ash Steam_Cured
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
Fly Ash 10% Moist_Cured
Fly Ash 10% Steam_Cured (Pre-steaming 6 hours)
Fly Ash 10% Steam_Cured (Pre-steaming 4 hours)
0
10
20
30
Age In Days

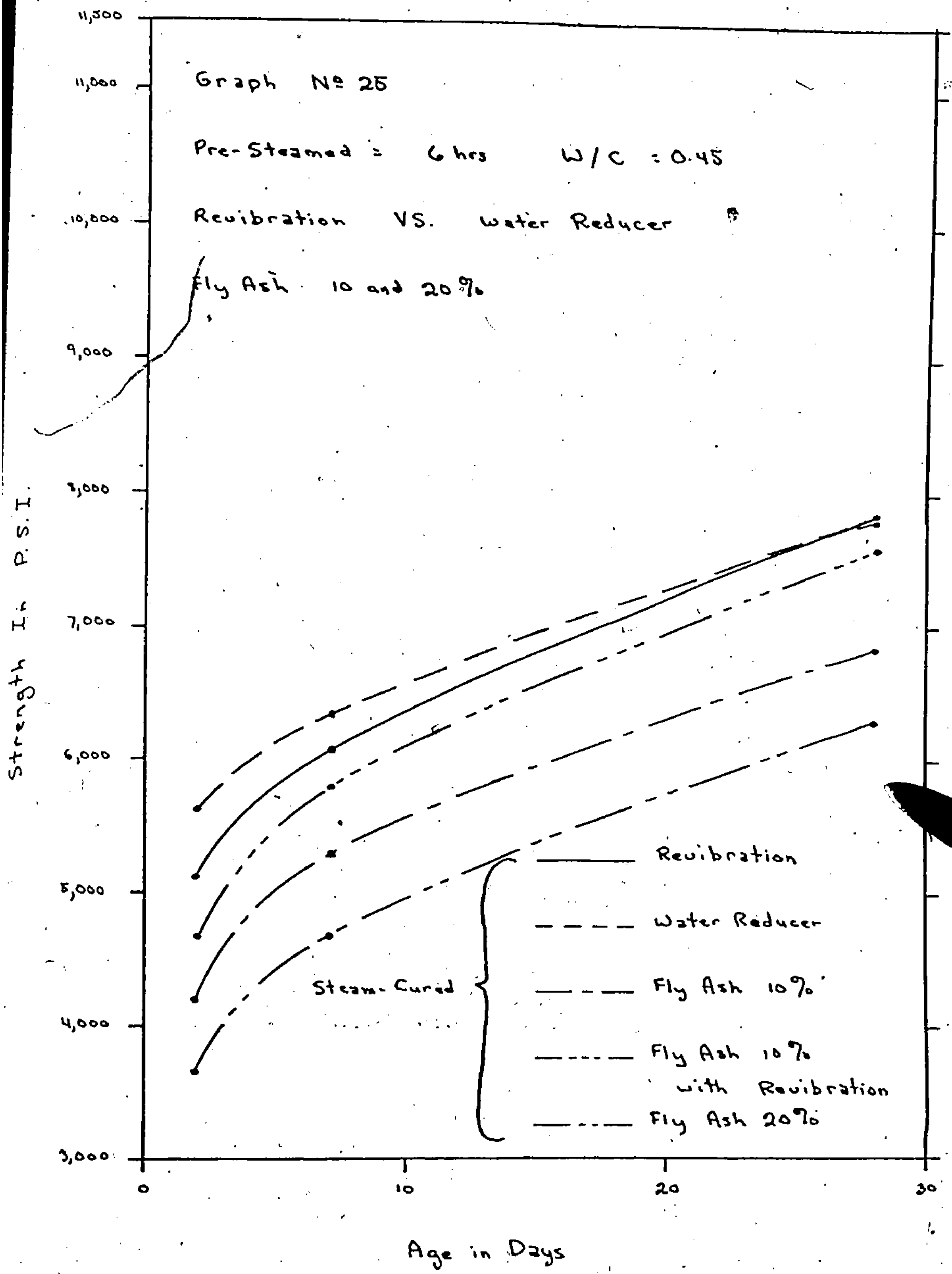

Graph No 22
W / C = 0.4
Fly Ash Moist_Cured
Vs
Fly Ash Steam_Cured
Strength In P.S.I.
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
0
10
20
30
Age In Days
Fly Ash 20% Moist_Cured
Fly Ash 20% Steam-Cured (Pre-steaming 6 hours)
Fly Ash 20% Steam-Cured (Pre-steaming 4 hours)

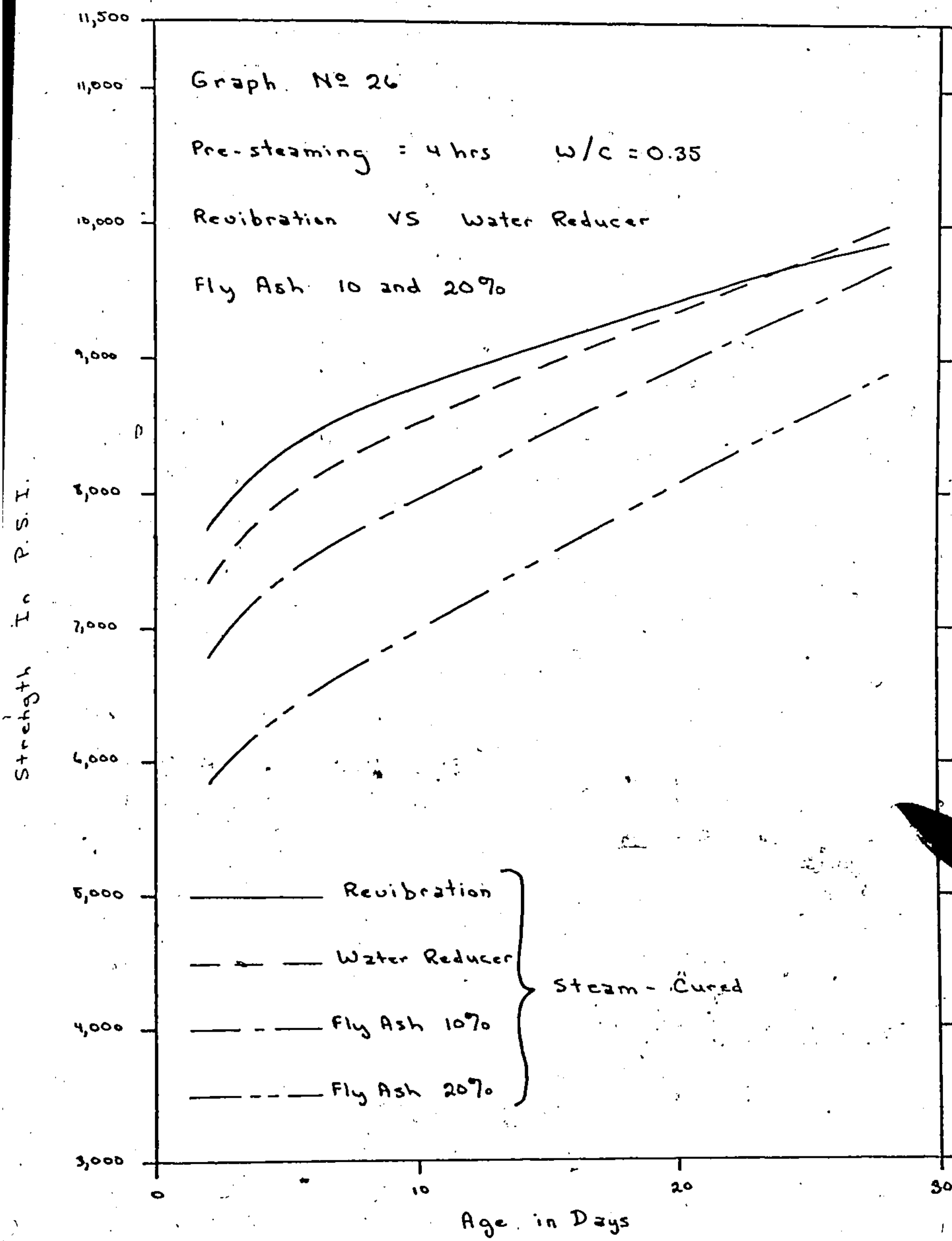


Graph N° 23
Pre-Steaming = 6 hours W/C = 0.35
Revibration Vs Water Reducer
Fly Ash 10 and 20%
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
0
10
20
30
Age in Days
Revibration
Water Reducer
Fly Ash 10%
Fly Ash 20%
Steam-Cured

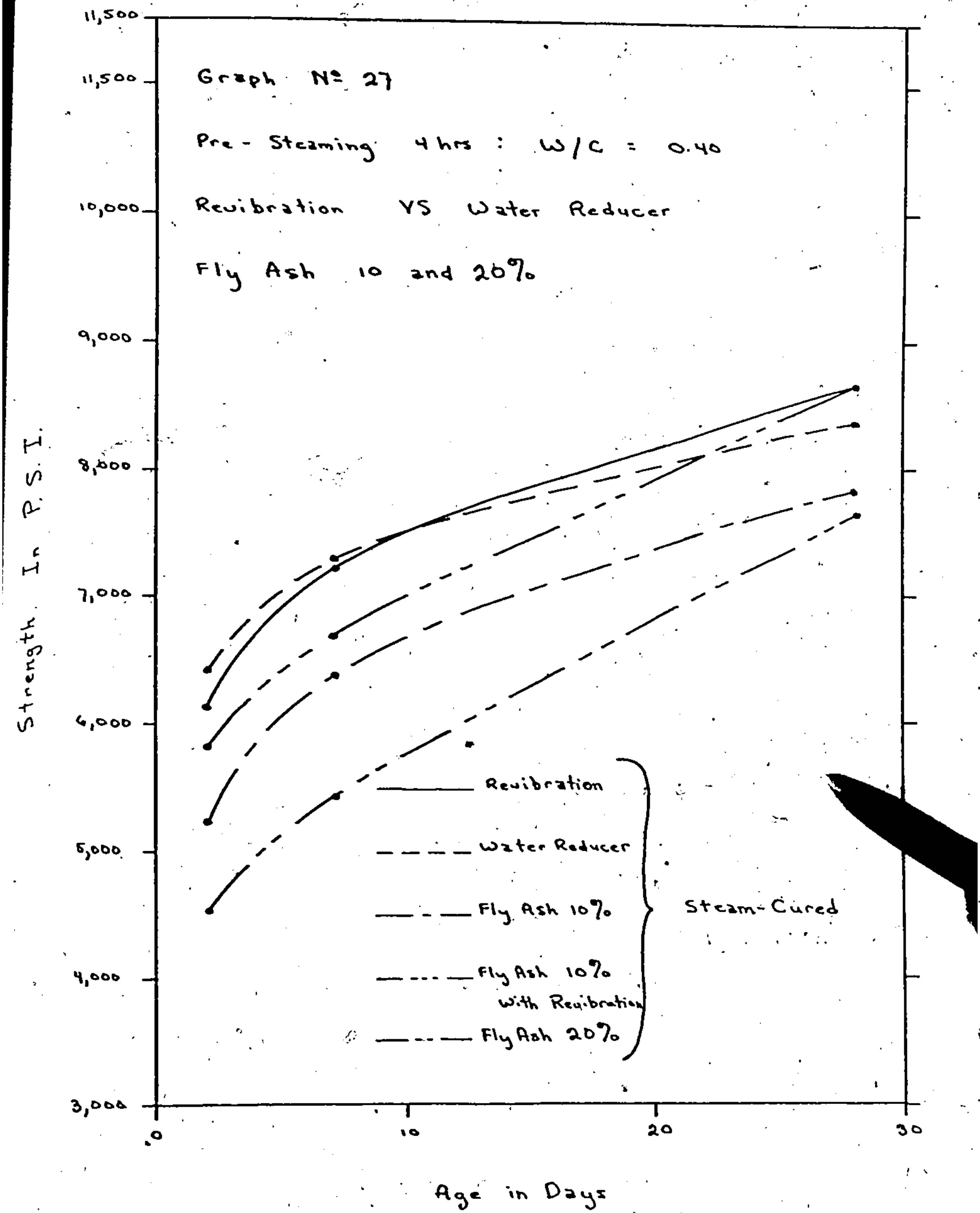


Graph № 24
Pre-Steaming : 6 hours W/C = 0.40
Revibration VS Water Reducer
Fly Ash 10 and 20 %
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
0
10
20
30
Age in Days
Revibration
Water Reducer
Fly Ash 10 %
Fly Ash 10 % with Revibration
Fly Ash 20 %
Steam-Cured

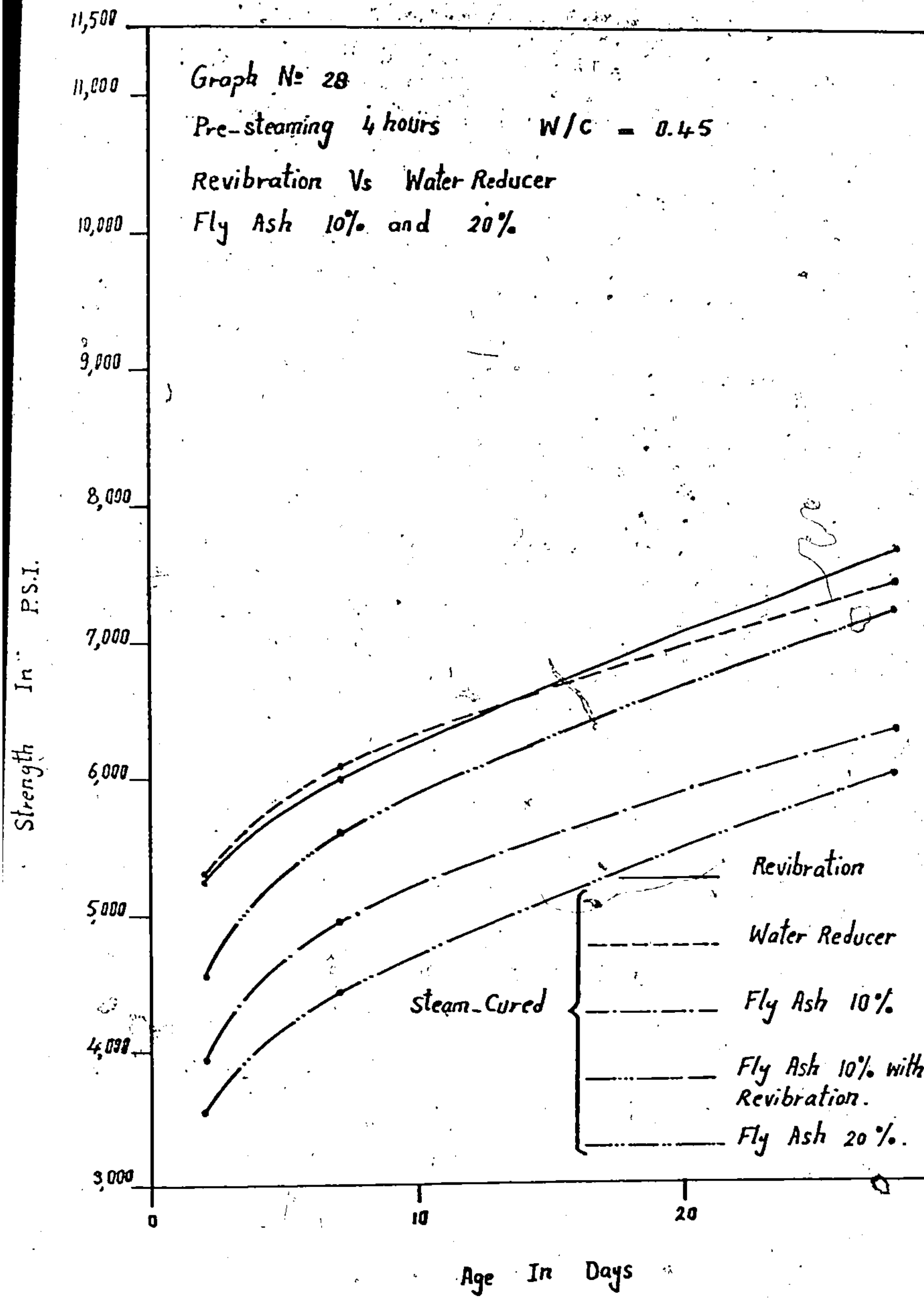

Graph № 25
Pre-Steamed = 6 hrs W/C = 0.45
Reuibration VS. Water Reducer
Fly Ash 10 and 20%
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
0
10
20
30
Age in Days
Reuibration
Water Reducer
Fly Ash 10%
Fly Ash 10% with Reuibration
Fly Ash 20%
Steam-Cured

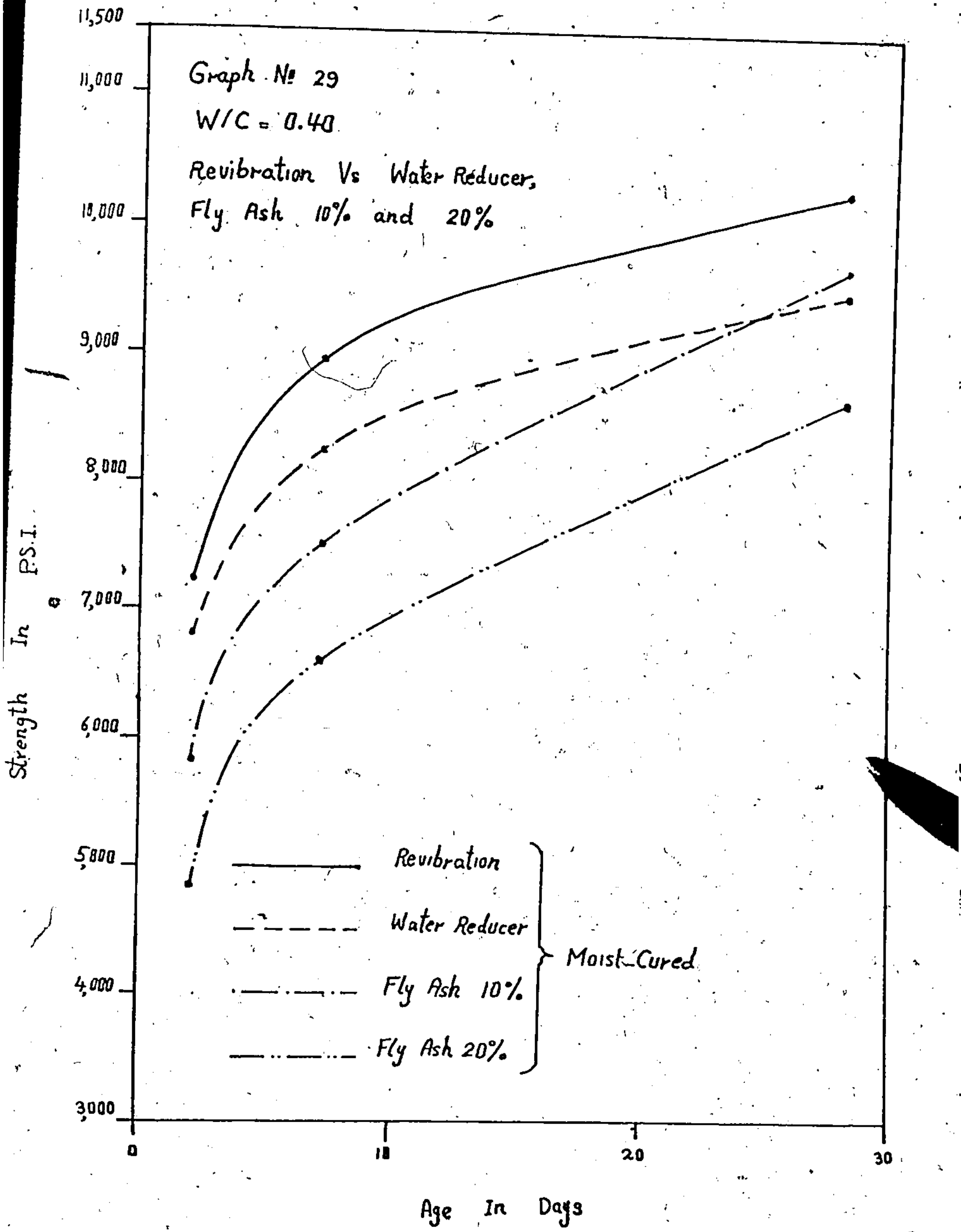


Graph № 26
Pre-steaming = 4 hrs w/c = 0.35
Reuibration VS Water Reducer
Fly Ash 10 and 20%
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
0
10
20
30
Age in Days
Reuibration
Water Reducer
Fly Ash 10%
Fly Ash 20%
Steam - Cured



Graph Nº 27
Pre - Steaming 4 hrs : W/C = 0.40
Revibration VS Water Reducer
Fly Ash 10 and 20%
11,500
11,500
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
0
10
20
30
Age in Days
Revibration
Water Reducer
Fly Ash 10%
Fly Ash 10% with Revibration
Fly Ash 20%
Steam-Cured


Graph № 28
Pre-steaming 4 hours W/C = 0.45
Revibration Vs Water Reducer
Fly Ash 10% and 20%
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
Strength In P.S.I.
0
10
20
30
Age In Days
Revibration
Water Reducer
Fly Ash 10%
Fly Ash 10% with Revibration.
Fly Ash 20%.
steam_Cured


Graph No 29
W/C = 0.40
Revibration Vs Water Reducer, Fly Ash 10% and 20%
11,500
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3000
Strength In P.S.I.
0
10
20
30
Age In Days
Revibration
Water Reducer
Fly Ash 10%
Fly Ash 20%
Moist Cured

Chapter V

CONCLUSIONS

Based on the results of these experiments, the following conclusions would appear to be warranted :

1. Moist curing with initial mixing temperature of 80 to 85 F appears more effective in increasing the compressive strength than moderate steam curing, at all ages (2, 7, and 28 days).

2. The 6 hour presteaming period seems to produce higher compressive strengths than the 4 hour presteaming period.

3. Revibration appears promising to increase the compressive strength of high water-cement ratio (0.40 to 0.45) concretes both for moist-cured and steam-cured concretes at all ages.

4. Water-reducing agents can effectively lower the water requirement of concrete mixes by 6%. Their greatest benifical effect in increasing the compressive strength appears to be at early ages (2, 7 days) and at the higher water-cement ratios (0.40 and 0.45), for both moist and steam curing.

5. A 10% replacement of cement with fly ash appears to produce slightly higher 28 day strengths at the low water cement ratio of 0.35 but lower strengths at early ages (2, and 7 days); for both moist and steam curing.

6. A 10% replacement of cement with fly ash, combined with revibration appears promising as a means of increasing the compressive strength of steam-cured concretes at later ages (7 and 28 days) and in the higher

water-cement ratio mixes (0.40 and 0.45).

7. The mixes containing 20% fly ash as a partial replacement of cement appear to reduce the compressive strength at all ages for both moist and steam curing. The greatest reductions were observed at the higher water-cement ratios.

8. Water-reducing agents appear more effective in increasing the early strength (at the ages 2, and 7 days) of steam-cured concretes than of moist-cured concretes at a high water-cement ratio of 0.45.

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APPENDIX A

APPENDIX A

TABLE I

CHEMICAL AND PHYSICAL TEST RESULTS OF LAKE ONTARIO HIGH EARLY PORTLAND CEMENT

Chemical Analysis	
C_3S	45.6 %
C_2S	27.0 %
C_3A	9.9 %
C_4AF	7.2 %
Physical Tests	
Fineness,	
Wagner sq. cm/gm	4980
Blaine sq. cm/gm	
Soundness.	
Autoclave Expansion, percent	0.04
Setting Time	
Gillmore	
Initial, hr.,: min.	2:50
Final, hr.,: min.	5:40
Compressive Strength, psi	
1 day	2950
3 days	4100
7 days	5162
28 days	6187

APPENDIX A

TABLE II

COMPOSITION OF PARIS SAND

Sieve Sizes Percent Retained	No. 4	No. 8 12.5	No. 14 15.4	No. 28 26.1	No. 48 30.6	No. 100 10.5	Pass No. 100 4.9	Total No. 8 to - No. 100	Quality Phys.	 Chem
		Amount of Particles in Percent by Count in Various Sieve Sizes								
Dolomite	36.5	54.7	55.0	28.0	18.3	16.3	25.4	31.1		
Dolomite , pitted	3.6	3.7						.5		
Dolomite , calcitic	25.0	7.1	5.7	10.0	4.9			5.8		
Limestone	3.6	.3	1.7	2.7	2.7	12.7		3.2		
Limestone , dolomitic	3.6	2.0	7.0	12.7	6.7			6.7		
Marl , aphanitic	12.4	5.4	4.3	5.7	6.3	.3		4.8		
" , brittle		.7	1.0	.3	1.0			.7	Fair	Delet.
" , friable	.9	.3	.7	1.0				.6	Poor	Delet.
Shaly, calcareous Sandstone, brownish		13.0	6.7	5.0	5.7	1.5		5.9		
Shaly sandstone distinctly limonitic	2.7	1.7	2.3	1.0	1.0	1.2		1.3		Delet.
Ironstone	2.7	1.0	1.0	2.3	1.0	.3		1.3		Delet.
Sandstone		1.3	1.7	.3	.7	.3		.7		
, brittle		.3						X	Fair	
Recent Sandstone		.7	1.0	.7	.7			.6		
Chert T. S. 1247	.9	1.0	.3	1.0	.3	.3		.5		
Aplite T. S. 1247		2.0	2.7	5.0	6.0	4.1		4.2		
Granite	4.5	2.0	2.3	4.0	2.0	3.3		2.6		
, brittle		.3	.3					.1	Fair	
Gneiss		.7	1.3	.3				.4		
Diabase	.9	.7		.3	.3			.3		
Hornfels T. S. 1247		.3	1.3	1.3				.6		

APPENDIX A

TABLE II

QUALITY OF PARTS SAND.

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

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

Deleterious particles: Soft marl and ironstones

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

APPENDIX A

TABLE II

PARTICLE SHAPE AND SURFACE OF PARIS SAND (in Percent)

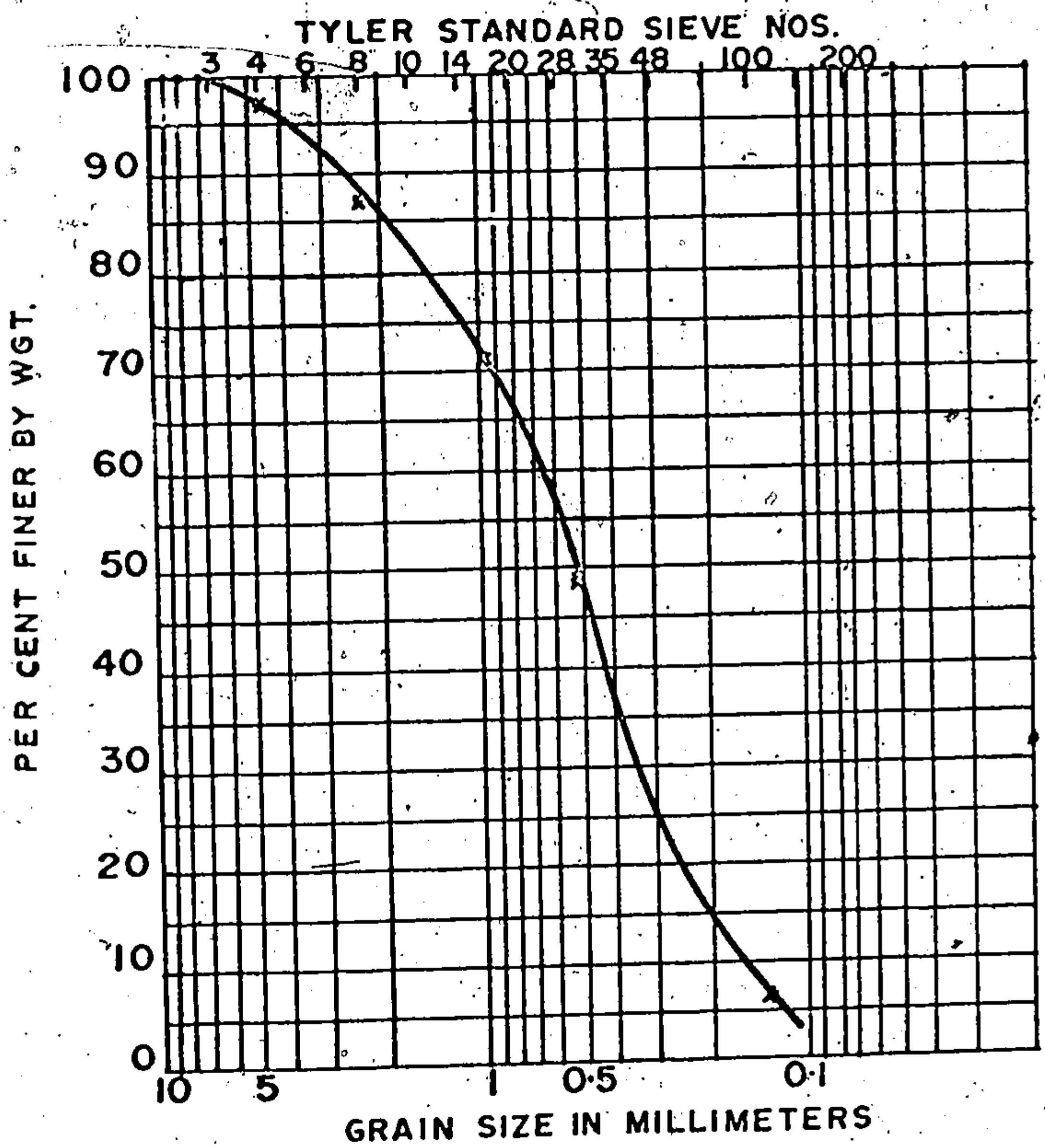
	Retained on Sieve Sizes						Pass	TOTAL
	No. 4	No. 8	No. 14	No. 28	No. 48	No. 100	No. 100	No. 8 to No. 100
Shape of Particles								
Angular , subangular								
Cubic particles	67	83	89	89	88	78	90	87
Flat particles	8	8	2	1	2	6	5	3
Oblong particles		x	x	x		1	x	x
Rounded , subrounded								
Cubic particles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

x = Amounts less than one percent

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

APPENDIX A

Figure I



GRAIN SIZE DISTRIBUTION
FOR
PARIS SAND

APPENDIX A

TABLE III

PROPERTIES OF DUNDAS DOLOMITE COARSE AGGREGATE

TYPICAL PETROGRAPHIC CHARACTERISTICS

Structure : Random, relatively frequently stylolitic; vuggy .

Texture : Uniformly fine grained (microcrystalline), single grains (in various numbers) mesocrystalline, rarely kryptocrystalline. Euhedral to subhedral .

Composition : (in percent)	Particles	Dusty Coating
Dolomite	99.1	95.9
Quartz (authigenic)	.3	1.5
Feldspar	x	.3
Clayey material and organic matter	.4	.7
Pyrite	x	x
Limonite	x	.3
Sulphate	.1	.9
Accessory Minerals	x	.4

Accessory minerals : Chert , amphibole , pyroxene , garnet , zircon .

x - amounts less than 0.1 percent .

Classification : Dolomite

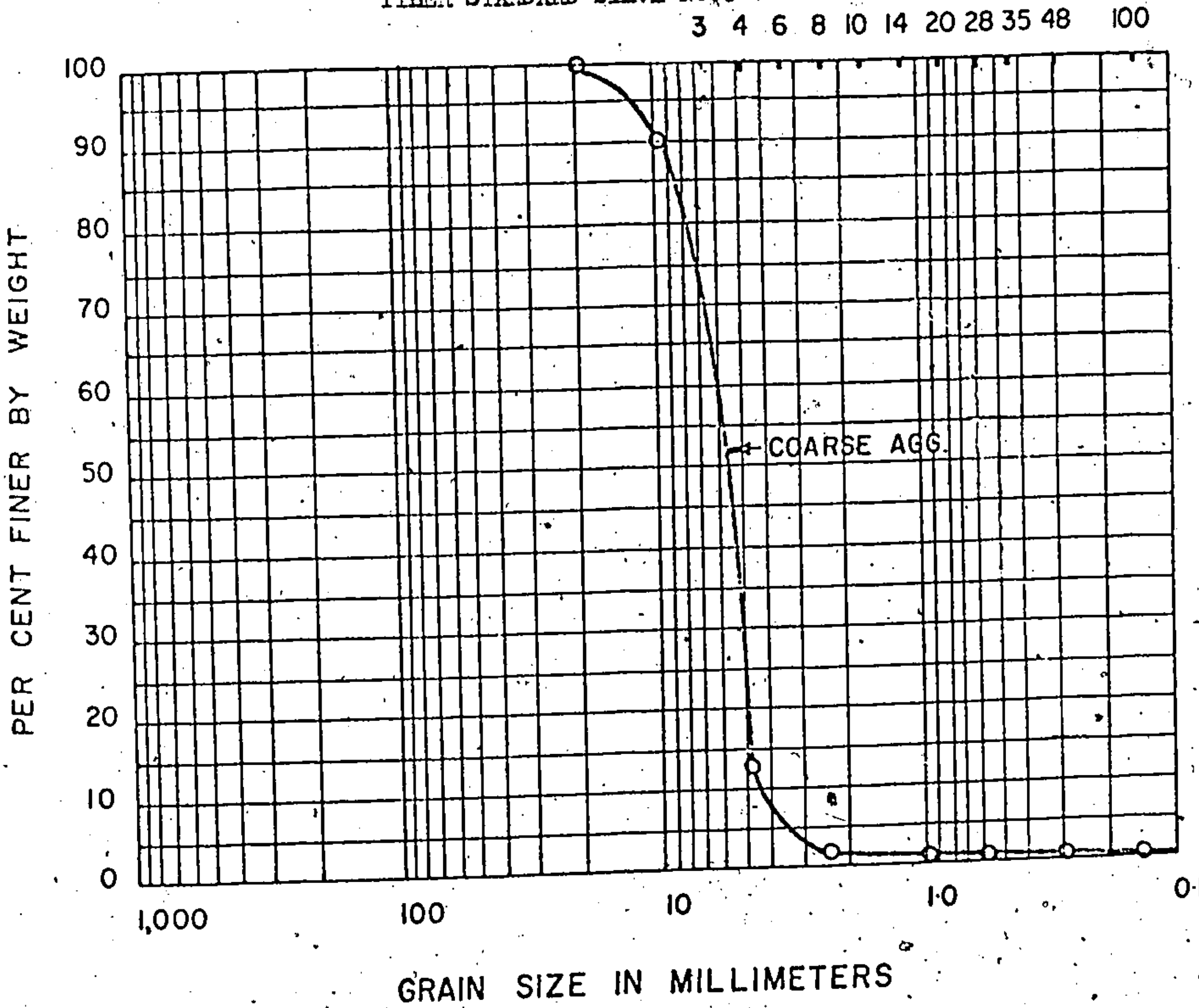
*Provided by Dr. L. Dolar-Mantuani .

APPENDIX A

Figure II

SIEVE ANALYSIS OF AGGREGATE

TYLER STANDARD SIEVE NOS.



Appendix A

TABLE IV

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

Physical Properties

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

Chemical Components, percent of dry weight

A. Spectrographic analysis

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

B. Chemical analysis

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

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

APPENDIX B

Test Data of Steam-Cured Mixes
(Water-Cement Ratio: 0.35)

Type of Mix	Presteaming Period (Hour)	Room Temp. at Mixing F	Compressive Load (lbs)		
			2 days	7 days	28 days
Standard	6	73	50900	61750	66750
			50000	59000	67750
			50500	60000	66750
		85	52250	62000	67000
			53750	61750	67500
			53750	63000	68250
Standard	4	74	50200	60000	68250
			52500	59500	66500
			53950	58300	65750
		86	53250	60000	71750
			52750	62250	68250
			52000	59000	67500
Revibration	6	75	53500	62250	70600
			54000	62750	68000
			51800	61750	75600
		76	57900	64500	71250
			57500	64000	71500
			57700	63750	68500
Revibration	4	76	53500	60700	70500
			54700	61300	73750
			55000	61800	70250
		77	54800	60300	67000
			53900	59000	67750
			55700	61000	68000
Water Reducer	6	80	52600	62750	73000
			52800	61500	67000*
			51500	60000	73250
		76	53400	63800	72400
			51900	64200	71600
			54200	60300	73400
Water Reducer	4	81	50800	56500	71000
			51600	55500	70500
			51800	56000	71500
		77	52200	59300	72400
			51600	61700	69300
			53400	60900	70100

* Rejected

APPENDIX B

Test Data of Steam-Cured Mixes (Water-Cement Ratio: 0.35)					
Type of Mix	Presteaming Period (Hour)	Room Temp. at Mixing F	Compressive Load (lbs)		
			2 days	7 days	23 days
Fly Ash 10%	6	79	48100	55000	68750
			47700	56500	55500
			48400	58500	69000
		80	49200	57200	67100
			47500	57400	70300
			48200	58600	68200
Fly Ash 10%	4	81	48000	53500	70500
			48300	54000	96250
			47800	55500	66000
		79	46400	53800	68200
			49600	56700	67300
			47750	52400	69800
Fly Ash 20%	6	82	44800	47800	67000
			44600	48500	66500
			43200	51300	67000
		85	45900	51750	66750
			45300	49100	68100
			44500	50800	67400
Fly Ash 20%	4	83	40000	40900*	62250
			42500	46900	63000
			40750	44600	62250
		86	41500	46600	63750
			42300	48700	62500
			41700	48550	64000
Fly Ash 10% Revibration					
Fly Ash 10% Revibration					

* Rejected

APPENDIX B

Test Data of Steam-Cured Mixes
(Water-Cement Ratio 0.40)

Type of Mix	Presteaming Period (Hour)	Room Temp. at Mixing F.	Compressive Load (lbs)		
			2 days	7 days	28 days
Standard	6	78	40000	43100	60000
			44400	42800	55400
			43600	42500	60250
		84	45000	46350	62750
			44400	50800	60250
			44300	45500	60800
Standard	4	78	38100	46500	57000
			39500	42700	57500
			39900	45550	58750
		83	41700	45000	57250
			41800	42500	57000
			40100	42100	58675
Revibration	6	77	44500	49100	66000
			45000	52200	63755
			45600	51600	64000
		80	46750	53900	63000
			46100	53100	62500
			46200	51900	64500
Revibration	4	77	42900	51750	62500
			44400	51350	61500
			41500	50100	61750
		80	44700	51600	60250
			43200	51500	61250
			44900	52100	60750
Water Reducer	6	75	45900	54750	61000
			46300	54300	62000
			48100	53950	59250
		77	47500	52000	67250
			48300	54500	69000
			47600	55200	66000
Water Reducer	4	76	42300	52400	57250
			44500	52300	57000
			43000	51700	59750
		78	45700	51250	62000
			48000	50500	62500
			47500	52750	61250

[illegible]

[illegible]	[illegible]	[illegible]	Compressive Load (lbs)		
			[illegible]	7 days	28 days
[illegible]	[illegible]	[illegible]	[illegible]	17200	50000
			[illegible]	15700	57750
			[illegible]	17500	56750
			[illegible]	17400	59250
			[illegible]	18100	59500
			[illegible]	17950	59000
[illegible]	[illegible]	[illegible]	[illegible]	12550	55000
			[illegible]	13600	56250
			[illegible]	15520	55750
			[illegible]	15300	55000
			[illegible]	14000	54000
			[illegible]	15400	57000
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	55500
			[illegible]	39700	55000
			[illegible]	37400	55250
			[illegible]	35500	57750
			[illegible]	23600	57250
			[illegible]	20900	56650
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	54000
			[illegible]	36100	53300
			[illegible]	[illegible]	53500
			[illegible]	32250	53250
			[illegible]	35000	52000
			[illegible]	35400	50000
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	57900
			[illegible]	18400	62000
			[illegible]	16200	57000
			[illegible]	15700	60500
			[illegible]	[illegible]	58500
			[illegible]	17600	55500
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	57100
			[illegible]	15000	58000
			[illegible]	15000	60000
			[illegible]	19200	[illegible]
			[illegible]	14800	63000
			[illegible]	30900	63500

Test Data of Steam-Cured Mixes
(Water-Cement Ratio: 0.45)

Type of Mix	Presteaming Period (Hour)	Room Temp. at Mixing F	Compressive Load (lbs) 2 days	7 days	28 days
Standard	6	76	33550	40200	51800
			33750	41700	52000
			33150	38600	52400
		78	34200	39600	53250
			34100	38900	50100
			32600	40550	51800
Standard	4	78	33300	41300	51700
			32750	39300	48400
			33500	41700	49700
		79	31800	40200	50950
			32650	39900	49200
			32900	41500	48750
Revibration	6	76	36300	43500	55750
			35700	42200	55100
			35200	42600	55700
		82	37900	43700	54600
			37200	44200	55900
			36800	42900	56200
Revibration	4	76	36700	43000	55000
			38200	41600	53700
			37700	42200	54900
		84	36200	41900	54300
			37400	43400	53900
			39100	42300	55100
Water Reducer	6	78	38800	44500	56300
			38900	44950	55200
			38500	44550	54000
		78	41100	44500	55500
			41300	45200	55750
			40700	45700	54250
Water Reducer	4	80	35100	43200	41000*
			35800	42600	53750
			36200	42400	51800
		79	39100	43700	50250
			38600	42200	52750
			37800	44200	54800

* Rejected

APPENDIX B

Test Data of Steam-Cured Mixes (Water-Cement Ratio:0.45)					
Type of Mix	Presteaming Period(Hour)	Room Temp. at Mixing F	Compressive Load (lbs)		
			2 days	7 days	28 days
Fly Ash 10%	6	79	29200	36600	48800
			29500	37000	47500
			30500	37500	48400
		79	30800	38400	49900
			30600	36300	47800
			29100	37100	48300
Fly Ash 10%	4	80	27200	35000	45200
			27800	34200	43500
			27600	34000	44000
		80	28100	35100	46400
			27300	36200	45900
			28900	35700	44200
Fly Ash 20%	6	79	25000	32800	44000
			25200	33200	46150
			25700	32200	43250
		75	26000	33600	45200
			26200	33900	44400
			27300	33700	44700
Fly Ash 20%	4	81	24000	30400	41750
			24600	30850	41600
			25200	30800	43050
		76	25600	31800	42200
			25700	32200	42600
			25300	31500	44300
Fly Ash 10% Revibration	6	86	33500	39900	54300
			34600	41600	53750
			31200	42800	53250
		83	32300	40500	52000
			32600	42000	53600
			34600	41400	55600
Fly Ash 10% Revibration	4	87	30600	38800	49300
			31700	40300	52400
			33200	39400	52300
		84	31100	39400	50000
			32300	40000	51900
			32400	39750	51300

APPENDIX B

Test Data of Moist-Cured Mixes (Water-Cement Ratio: 0.35)

Type of Mix	Room Temp. at Mixing	Compressive Load (lbs)		
		2 days	7 days	28 days
Standard	82	55750	70000	82700
		56250	71750	70000*
		56500	70750	80400
	83	57000	69000	77200
		57250	70000	79700
		58750	68750	81200

Test Data of Moist-Cured Mixes (Water-Cement Ratio: 0.45)

Type of Mix	Room Temp. at Mixing	Compressive Load (lbs)		
		2 days	7 days	28 days
Standard	80	37600	41200	58600
		38900	43100	57000
		37600	42700	58250
	81	34900	45620	55500
		34500	42500	56750
		34300	43200	56250

* Rejected

Test Data of Moist-cured Mixes
(Water-Cement Ratio: 0.40)

Type of Mix	Room Temp. at Mixing	Compressive Load (lbs) 2 days	7 days	28 days
Standard	79	46600	55000	67750
		45900	53800	65500
		47800	50700	66250
	80	36900*	54750	71750
		50800	56000	70750
		50750	53750	71000
Revibration	72	50900	64300	71600
		52200	63250	72750
		52700	64800	72000
	73	50300	63800	72500
		51000	61500	71250
		50900	62500	73000
Water Reducer	80	49400	58600	67750
		51800	61500	66000
		49900	58000	68000
	81	45600	57750	67250
		46600	57750	65500
		46300	56500	68250
Fly Ash 10%	77	44300	55750	69000
		41800	56000	69600
		42700	55250	68400
	78	40600	50250	67750
		38500	50000	67500
		38800	51750	68200
Fly Ash 20%	72	35200	47250	63250
		35600	48250	63500
		37000	48250	60750
	74	31700	44000	62000
		33400	46500	58500
		33000	46750	58750

* Rejected

VITA AUCTORIS

1943 Omar Ahmed El-Zein was born in Gaza Palestine, on May 4, 1943.

1949 In September, 1949, he entered Gaza College, where he obtained his elementary education.

1953 In September, 1953, he enrolled at Yarmook Preparatory School, where he obtained his preparatory education.

1957 In September, 1957, he enrolled at Palestine Secondary School where he obtained his secondary education.

1960 In September, 1960, he enrolled at the University of Cairo, Facult of Engineering; in June, 1965, he was graduated from the University of Cairo with a Bachelor of Civil Engineering Degree.

1965 In November, 1965, he worked at the Ministry of Public Works, Kuwait, as Structural Engineer.

1967 In September, 1967, he enrolled at the University of Windsor in order to obtain the degree of Master of Aplied Science in Civil Engineering.