THE EFFECT OF SHRINKABLE AGGREGATES ON THE STRUCTURAL PROPERTIES OF CONCRETE

By MOHAMED SALIH HASSAN
B.Sc., D.C.P.

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SUMMARY

The object of this study is to investigate the effect of shrinkable aggregates on the structural properties of concrete. Three types of Scottish aggregates, Blairgowrie and Eddleston gravels and Ratho-Whinstone aggregate, are investigated to determine their effect on concrete shrinkage. The latter two types of aggregate are known for their contribution to shrinkage of concrete and detrimental effect ~~to~~ on concrete structures.

In spite of the advices and recommendations offered by the Building Research Station to limit the use of shrinkable aggregate ~~for~~ to unreinforced structures, still the contractors are using them in buildings and structural concrete.

The investigations carried out within the scope of this thesis are a contribution towards the understanding of the adverse effects of shrinkable aggregate in concrete as well as an attempt to see the possibility of reducing their harmful~~l~~ effect.

The experimental work carried out covers a full investigation of the initial shrinkage strains for the above mentioned aggregates under variable water/cement ratios and variable cement and aggregate contents. Warping deflections for thin beams are investigated as well as the reduction of deflections by means of adding reinforcement in the compression zone.

Using the electrical resistance strain gauges, the internal strains due to shrinkage and applied load are determined and studied.

As a result of the investigations done, it is revealed that

shrinkable aggregate produce as much as three times shrinkage and warping deflections observed for normal types of aggregates. Moreover, shrinkage cracking is observed due to interaction between steel and concrete shrinkage. It is therefore advisable to avoid using shrinkable aggregate to ensure safety, efficiency and durability of concrete structures.

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CHAPTER I

INTRODUCTION

1. Concrete like many other materials undergoes a change in dimensions with gain or loss of moisture. With each change in water content the concrete tends to shrink or swell, and as a result of these changes in volume, stresses and strains are produced, that may affect the performance of the concrete structures.

It has been known for many years that certain types of shrinkable aggregates which exist in parts of Scotland and Northern England perform indifferently when used in cement products. These shrinkable aggregates lead to excessive deflections, shrinkage cracking and deterioration of concrete surfaces when subjected to weather conditions.

Normal types of aggregates might result in a shrinkage movement of about ~~0.2~~ 0.02 to ~~0.3%~~ 0.03%, but concrete~~s~~ made with shrinkable aggregate is drawing the attention of investigators to the importance of the control of shrinkage effects in concrete elements.

In the design of concrete structures, the role of shrinkage and creep is gaining increasing recognition, particularly for precast and prestressed concrete. It is necessary to understand the dimensional changes of prestressed structures due to creep and shrinkage so that reasonable estimates can be made of prestress losses, variation of camber, change of distance between bearings and stresses produced by restraint of deformation.

Many precast structures are made of members joined together in the field to form statically indeterminate structures in which creep and shrinkage can result in redistribution of moments and forces. (Pre-cast elements usually cured before building into the structures)

For thin concrete elements, mainly restrained floor slabs, shrinkage causes serious cracking and deflections which may endanger the utility of the structure when shrinkable aggregates are used without providing the necessary precautions against possible excessive deflections and cracking.

When shrinkage, creep and thermal effects combine together, serious and undesirable tensile stresses might develop and endanger the safety of the concrete element as a whole.

1.2 THEORETICAL REVIEW

1.2.1 Historical Review

It has long been realised that all materials made with Portland cement as a binding agent undergo a change in volume. Although this phenomenon is as old as the earliest form of concrete construction, it is only during the last thirty years that comprehensive research has been carried out on the shrinkage of concrete.

The research work done by Faber(23), Picket(3), Ross(9), Carlson(6), the Building Research Station(28) and so many other investigators and research associations produced a good deal of knowledge of the shrinkage of concrete elements.

In spite of these investigations the actual mechanism of shrinkage is not fully understood. The numerous factors affecting the shrinkage of concrete elements make it extremely difficult to apply any available data to conditions other than those under which the data was obtained.

1.2.2 Mechanism of shrinkage of cement paste

Many of the mechanical properties of hardened concrete depend mainly on the physical structure of the products of hydration(18). Fresh cement paste is a network of particles of cement in water. While cement is hydrating, cement grains in the paste become transformed into other physically and chemically different materials. The hardened paste consists of various compounds referred to as gel crystals. The gel formation contains capillary pores and interstitial gel pores(18),(20). The gel pores amount to about 30% of the gel volume.

Geras(20), referring to Powers and Brownyard, stated that the volume of the saturated cement gel is about 2.2 times that of the cement consumed in producing it. Consequently, the gel not only replaces cement, but also fills some of the originally water-filled space. The more the cement hydrates, the fewer and smaller are the capillary pores left within the paste. Generally, the hydration of cements results in a reduction of the volume of the system cement-plus-water. Plates 1.1, 1.2,

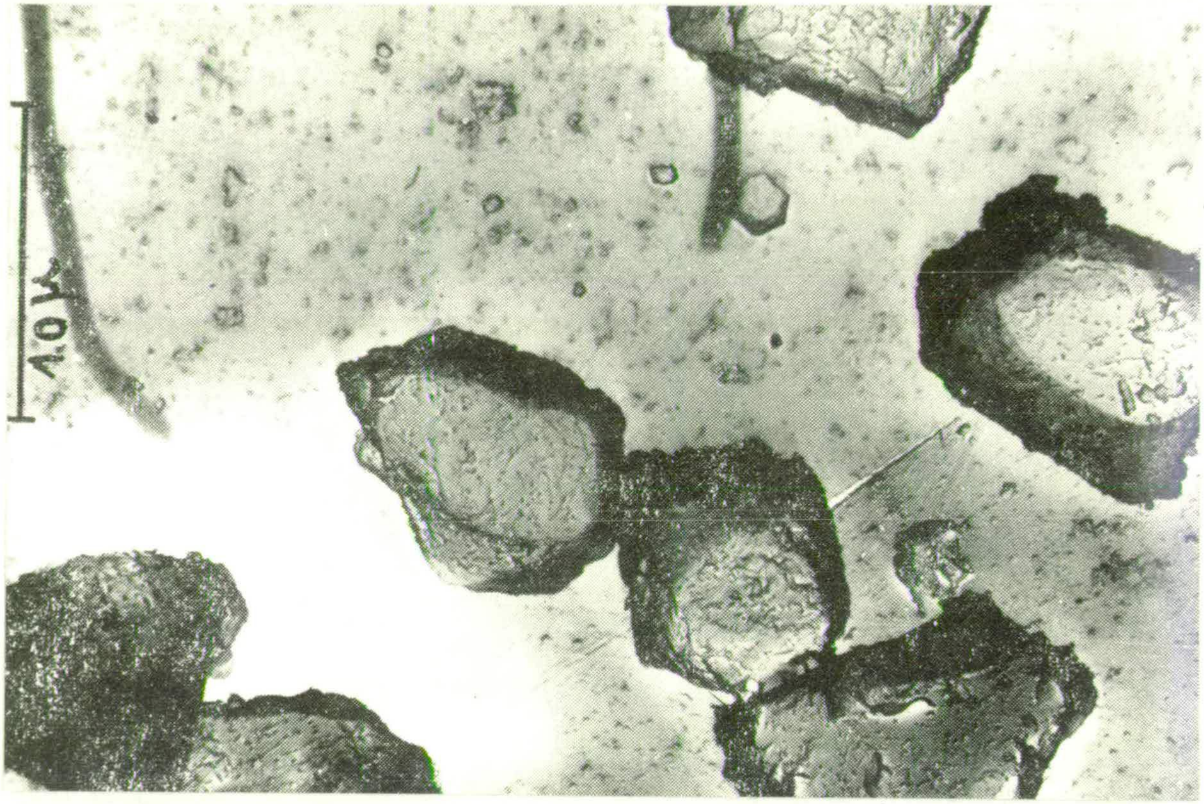


Plate.1.1 Cement grains shortly after mixing with water.

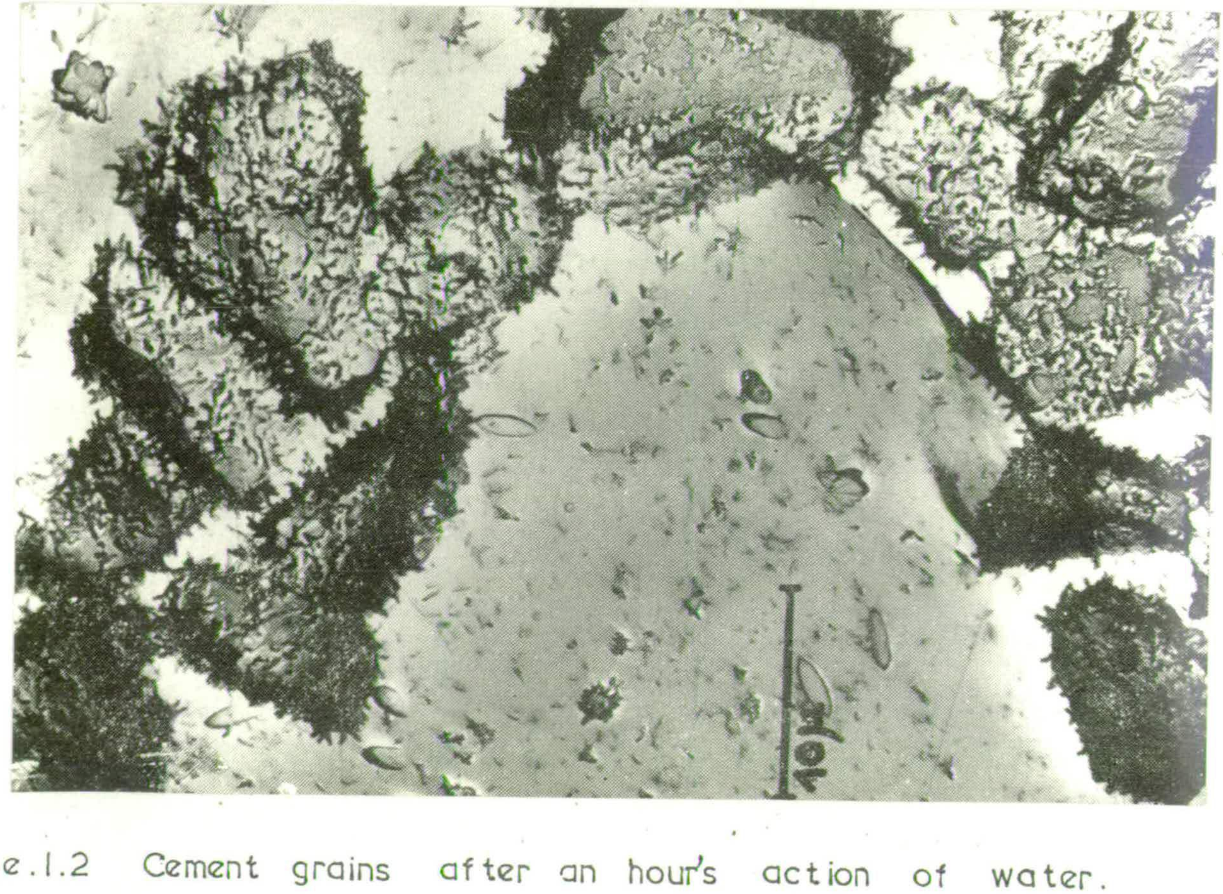


Plate.1.2 Cement grains after an hour's action of water.

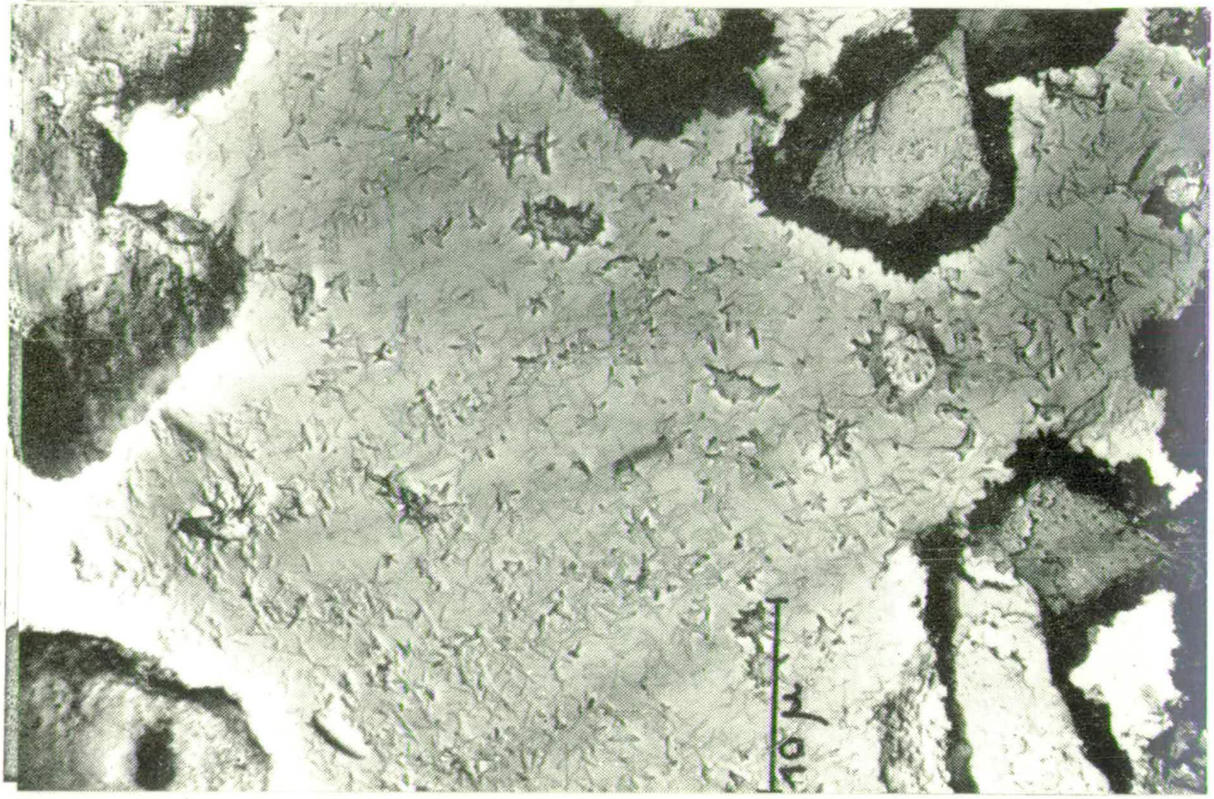


Plate. I.3. Cement grains after 24 hours action of water.

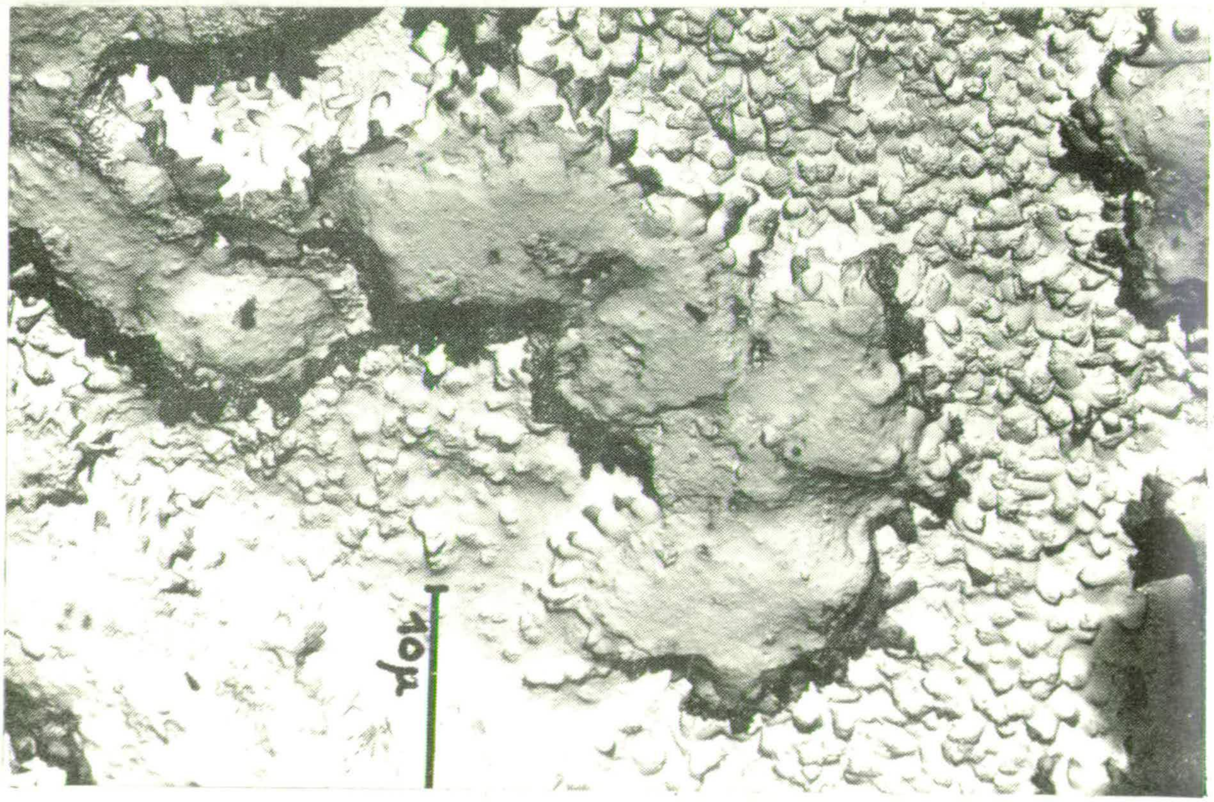


Plate. I.4. Cement grains after 28 days action of water.

1.3 and 1.4, referred to Czernin(38), show the process of hydration of cement under the action of water at different stages.

1.2.3 Mechanism of shrinkage of concrete

During the hydration process a large amount of free water becomes absorbed on the surfaces of the colloidal products of hydration(18). This water is held in varying degrees of firmness; at one extreme there is free water, at the other it is chemically combined. Between these two categories there is gel water held in a variety of other ways. The water held by the surface forces of the gel particles is called adsorbed water, and that part of it which is held between the surfaces of certain planes in a crystal is called zealitic water. Free water is held in capillaries and beyond the range of surface forces of the solid phase.

On drying, the capillary water and part of the water held in the gel pores evaporates, "Evaporable water". The non-evaporable water "chemically combined" or held in a chemical bond" has a vapour pressure lower than that of the ambient atmosphere. The quantity of such water is in fact a continuous function of the ambient vapour pressure. The amount of non-evaporable water increases as hydration proceeds, but even in a saturated paste, non-evaporable water can never become more than one half of the total water present.

The mechanism of shrinkage of concrete does not differ fundamentally from that of the cement paste. The shrinkage of concrete is in fact due to the shrinkage of the cement paste surrounding the aggregate. The only difference is that the aggregate will restrain the amount of shrinkage for ordinary concrete, to about 10% of that of the cement paste. The loss of free water in the capillary pores takes place first, and causes little or no shrinkage. As drying proceeds, the adsorbed water is removed, and the change in volume of the unrestrained cement paste at that stage is approximately equal to the loss of a water layer one molecule thick from the surface of all gel particles.

1.2.4 Classification of shrinkage

Garas(20) quotes Meyer and Nielsen's classification of shrinkage phenomenon with regard to their nature as follows:-

1. Intrinsic shrinkage; is defined as the change of volume which takes place without exchange of water with the medium surrounding the concrete. This is associated with hydration of the cement. It is irreversible as the water becomes a component of the solid products of cement hydration without any loss or gain of weight taking place.
2. Ecological shrinkage: is defined as the change in volume which takes place in conjunction with exchange of water with the surrounding medium. This is related

to the loss of water to the ambient atmosphere, and is essentially reversible.

The classification of shrinkage as intrinsic and ecological has not been widely accepted. The following classification was recommended:

(a) Pre-set shrinkage: or changes of volume that take place during setting. This is known as the plastic shrinkage. Lea(25), stated that, while in plastic condition the cement paste shrinks due to contraction of the system cement and water on hydration.

(b) Post-set shrinkage: or changes in volume which take place after setting. This includes drying shrinkage, differential shrinkage and carbonation shrinkage.

The pre-set and post-set classification is generally accepted in spite of the difficulty of drawing a demarcation line between them.

1.2.5 Factors influencing shrinkage

Factors influencing shrinkage are numerous, thus making any investigation of the order of magnitude of drying shrinkage rather a complex task. Since the experimental work dealt with in this thesis is not directed towards the investigation of the different factors that affect the concrete shrinkage, only some of the main factors will be discussed hereafter.

1.2.5.1 Effect of aggregate on shrinkage of concrete

Concrete is a neat cement paste that has been diluted with aggregate. Together they form a heterogeneous compound with its own mechanical and physical properties (3), (6), (7). If it is possible to remove the aggregate and leave the skeleton of neat cement, that skeleton should tend to shrink in all dimensions as much as a corresponding solid specimen of neat cement would do. Evidently, the presence of aggregate particles reinforces the skeleton against contraction. The ability of aggregate to restrain the cement paste depends on several important factors.

(a) The relative extensibility of paste and compressibility of aggregate.

(b) The bond of contact between paste and aggregate.

(c) Volume change of aggregate particles due to drying.

The aggregate generally reduces the shrinkage of the paste to about 10% of its value. In certain cases where the aggregate is compressible or susceptible to volume changes due to drying, it contributes to shrinkage. Generally, the grading of coarse aggregate has a minor effect on the magnitudes of shrinkage and mortars usually exhibit more shrinkage than concrete.

1.2.5.2 Effect of water/cement ratio

Water plays the most important part in determining the mechanical and physical properties of concrete. The strength, elasticity, creep and shrinkage of concrete are functions of the water content. A knowledge of the reason for water having such a large effect contributes to the understanding of the shrinkage of concrete. When cement hydrates, it fills the space originally occupied by the mixing water with hydration products, mainly gel (18),(26),(6). The volume of hydration products formed is therefore the volume of water plus the volume of cement consumed by hydration. Additional water tends to increase hydration to its optimum percentage; decreases the strength and elasticity of concrete and tends to increase the magnitude of shrinkage.

1.2.5.3 The relative effect of cement, aggregate and water contents

The three elements of concrete which in general control the magnitude of ultimate drying shrinkage for any mix are the cement content, the aggregate content and the water content.

The increase of water cement ratio promotes the hydration of cement and accordingly the magnitude of shrinkage, provided that the cement and aggregate contents are kept constant. More shrinkage is also expected if the cement content is increased while the two other factors are constant. In the meantime keeping the water cement ratio and the cement content constant, then the effect of aggregate in restraining the shrinkage of concrete becomes apparent.

The net effect of changing both the water-cement ratio and aggregate content is an approximate balance between two opposing tendencies(18,26), with the result that at any given water content, shrinkage is approximately the same regardless of how this water content is obtained.

1.2.5.4 Effect of size and shape of concrete element on shrinkage

The size and shape of a concrete member will influence the rate at which moisture moves to or from the concrete and therefore affect the rate of shrinkage. A great deal of literature is available concerning shrinkage and factors that affect its values, but information dealing with the effects of size and shape of the specimen is very scarce.

Ross(9) carried out a series of experiments using specimens of different shapes and sizes. He suggested that a suitable parameter to compare the shrinkage of members is the ratio of the exposed surface area S to the volume of the member V, "S/V".

Hansen and Mattock(2) have also shown that the volume/surface ratio "V/S" is a suitable parameter for the evaluation of the shrinkage data obtained from members of different sizes and shapes. It is suggested that specimens with the same "S/V" or V/S ratio tend to shrink approximately in the same manner and with the same magnitude.

1.3 REVIEW OF THEORETICAL ANALYSIS

The testing of concretes and mortars for shrinkage presents no difficulty, and the standard procedures were laid down in many specifications. "B.S.1881 - 1952(31), B.S. 1180, B.S.1217 and B.S. 2028."

The data provided from any test is only applicable to the specific conditions of the test, and even that might not have any resemblance to the shrinkage stresses and strains realised in practice, because of the effects of size and shape, variability of ambient conditions or the flexibility and degree of restraint of the structural element.

Many investigators have provided equations based on theoretical hypotheses or on experimental investigations. In the following paragraphs a brief review of the main theories will be given.

1.3.1 Gerald Picket's Analysis

1.3.1.1 Application of the equation of diffusion of heat

Picket(3) has derived theoretical expressions for the shrinkage of concrete, and the deformations and stresses due to shrinkage that occur during the course of drying. These expressions were derived on the assumption that the laws governing the development of shrinkage stresses in concrete were analogous to these governing the development of thermal stresses in an ideal body during cooling. Picket assumed that the diffusion equation applies to shrinkage even though the simple relations that were implied by that assumption were contrary to fact. He has applied the following differential equation:-

$$K \left[\frac{\partial^2 s}{\partial x^2} + \frac{\partial^2 s}{\partial y^2} + \frac{\partial^2 s}{\partial z^2} \right] = \frac{\partial s}{\partial t} \quad \ldots\ldots\ldots\ldots (1)$$

where K = the diffusivity of shrinkage.

Equation (1) becomes:-

$K \frac{\partial s}{\partial N} = f(S_x - \overset{s}{\beta})$ at exposed boundaries .... (2)

and

$K \frac{\partial s}{\partial N} = o$ at sealed boundaries ....(3)

where

N is the direction normal to the surface away from the body.

f = the surface factor, characteristic of the material and the boundary conditions.

S_x = the value that s will eventually reach under fixed ambient conditions.

s = the shrinkage value after any time t.

Equations (2) and (3) correspond to Newton's law of cooling at exposed boundaries and to no flow of heat past perfectly isolated boundaries in the analogous problem of flow of heat.

Picket had solved the equation for rectangular prisms drying from either one, two or four surfaces. This analysis of the shrinkage strains and stresses was not widely used because of the difficulty in evaluating the constants of the equation for each case and has also been criticised in assuming perfect analogy between the development of shrinkage stresses in concrete and thermal stresses in an ideal body during cooling.

1.3.1.2 Effect of aggregate on the shrinkage of concrete

In 1956 Picket(16) derived another theoretical formula for the effect of aggregate on the shrinkage of concrete. He considered a small spherical particle of aggregate in a sphere of concrete, assumed to be a homogeneous material. By equating the reduction in the volume of shrinkage of the total body due to the effect of the restraint of the inner sphere and the compressibility of the inner sphere caused by the outer sphere of concrete, he presented the following equations:-

$$S = S_o (1 - g)^{\alpha} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

and

$$\log \left(\frac{S_o}{S}\right) = \alpha \log\left(\frac{1}{1 - g}\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

The two equations are of the same significance; the second one was used for the graphical presentation of his data.

S = the unit linear shrinkage

S_o = the shrinkage that would occur if no aggregate were present.

g = the volume of the aggregate per unit volume of mix.

α = a factor considered as a function of g, since the elastic constants of the mixture, E and μ may depend on g.

1.3.2 Fulton's theoretical approach

Fulton(15) suggested a formula based mainly on Picket's equation discussed in the previous paragraph. Fulton's empirical formula was applied in calculating the shrinkage indices for different mixes, plotting the data in the form of curves relating the cement content, aggregate content, shrinkage indices and shrinkage strains. Figure 1 shows Fulton's curves and presentation of data. Fulton's empirical formula is:-

$$\frac{\delta L}{L} = K \frac{w}{c} (1 - A)^k \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where

δL = change in length of the specimen due to shrinkage under certain specified test conditions.

L = over-all length of specimen

K = constant whose value depends on the physical and chemical properties of cement and on the test conditions, taken as 0.52%.

w/c = water/cement ratio

A = the absolute volume of aggregate per unit volume of mortar.

k = shrinkage index, depends on the elastic modulus of the paste and of the aggregate and Poisson's ratio of these materials.

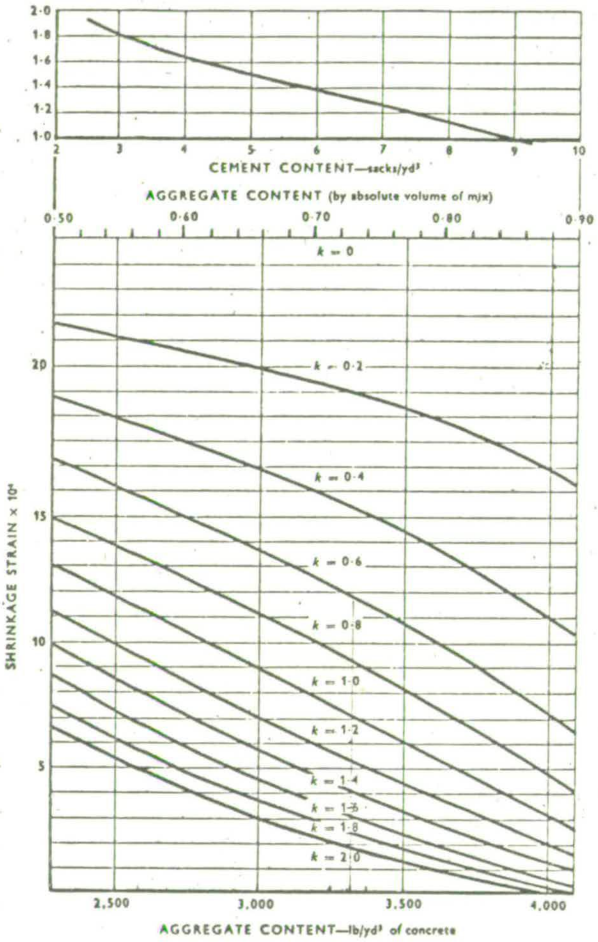


FIG. 1. Shrinkage at six month of concrete and mortar with a water/cement ratio of 0.5 cured at 70° F. and 50% relative humidity

1.3.3 Warping deflections of reinforced concrete due to shrinkage

Warping is alteration of shape caused by differential volume changes within a concrete element arising from unsymmetrical temperature distribution or moisture movement, the magnitudes of these changes in volume being governed principally by certain material properties. Through exposure to ambient conditions, setting, hardening and drying, concrete is subject to shrinkage movements. Introducing steel reinforcements in concrete results in these shrinkage movements being restricted and reduced but not entirely eliminated. When eccentric reinforcement is used the concrete elements are subjected to differential shrinkage strains due to the interaction of concrete shrinkage and steel reinforcement.

Warping due to shrinkage was considered by J.R. Shank(35) in the course of his notable treatment of plastic flow. Alfred L. Miller(10) studied the warping of reinforced concrete beams and emphasised that warping is not a function of f_c and E but is mainly due to interaction between the reinforcement and the concrete shrinkage. G.A. Maney(36) showed the importance of warping in connection with studies of long-time yield of loaded members.

In recent years, many cases of dished thin slab floors and sagging shallow beams, specially when shrinkable aggregate was used, have caused dispute and controversy among the structural Engineers, contractors and suppliers of material. These excessive deflections were sometimes attributed to faulty design, materials or workmanship, but in most cases tests have shown greater strength than anticipated and satisfactory elastic behaviour. It then becomes obvious that deflections which apparently indicate weakness and flexibility are warping deformations which are coincidently similar in magnitude.

In this thesis an investigation of deflection of thin beams due to shrinkage was tested for three different types of Scottish aggregates, Blairgowrie gravel, Eddleston gravel and Ratho-Whinstone. The following analytical methods were applied in checking the experimental data obtained to determine their validity when applied to structural members of concrete.

(a) The Geometry of warping

Warping is curvature of originally straight lines and plain surfaces. It may be expressed and measured in terms of either translational or rotational displacements. The former is preferable for physical description and measurements, and the latter is more suitable for mathematical purposes. The relation between the two methods of expression is derived in figure 2(a).

The following symbols and units will be used as notation:-

Δ = displacement, in inches.

L = length, in inches.

R = radius of curvature, in inches.

K = curvature in millionths of radians per inch.

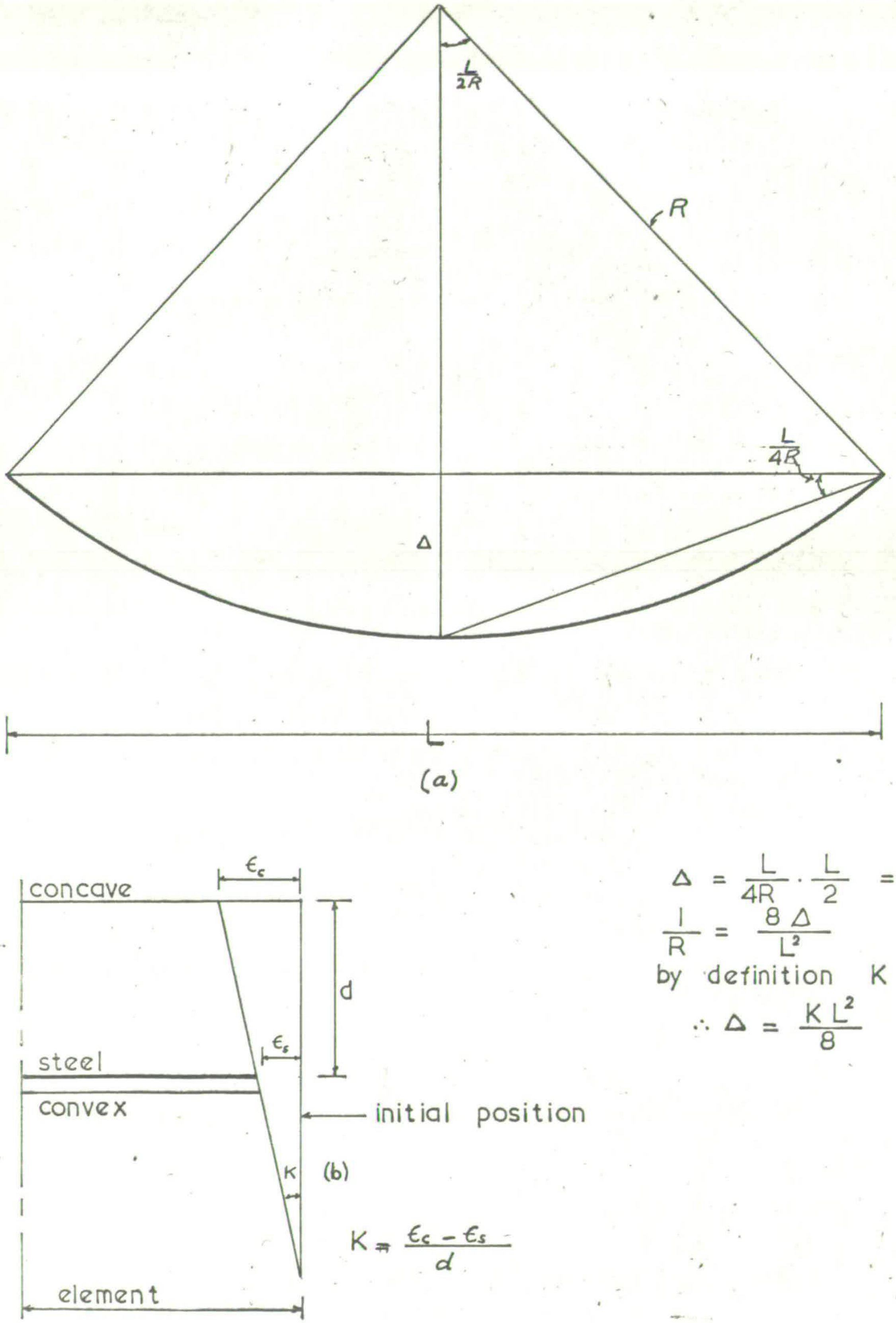
ϵ_a = concrete strain after bonding, inch/inch.

ϵ_s = steel strain, inch/inch

d = effective depth, in inches.

t = total depth, in inches.

e = eccentricity, in inches.



$$K = \frac{\epsilon_c - \epsilon_s}{d}$$

$$\Delta = \frac{L}{4R} \cdot \frac{L}{2} = \frac{L^2}{8R}$$

$$\frac{1}{R} = \frac{8\Delta}{L^2}$$

by definition $K = \frac{1}{R}$

$$\therefore \Delta = \frac{KL^2}{8}$$

FIG. 2 THE GEOMETRY OF WARPING

Curvature is the result of unsymmetrical volume changes expressed in terms of Linear strains. When an initially straight member becomes curved, parallel Longitudinal ~~transverse~~ sections become curved, parallel transverse sections become radial by rotational displacement. The amount of curvature can be found when the strains at any two points on the section are determined. Selecting one point on the reinforcement and the other point on the concave face of the concrete, the relationship between curvature and strains is depicted in figure 2 (b) for an element of unit length. All elements comprising the length of a straight member within which the material and sections are uniform will adopt identical curvatures and describe a circular arc. The equation of warping as derived from figures 2(a) and 2(b) is:-

$$\Delta = K \frac{L^2}{8} \quad \ldots\ldots\ldots\ldots (7)$$

$$\text{where } K = \frac{\epsilon_c - \epsilon_s}{d}$$

(b) Calculation of deflections from the induced force in steel reinforcement due to shrinkage.

When a concrete element shrinks due to setting, hardening and drying, the concrete shrinkage induces a compressive force in steel. When only tensile reinforcement is used, this force will tend to create a deflecting moment from which the warping deflections could be calculated as follows:-

Notations:-

L = effective length of the member, in inches.

Δ = centre deflection, in inches.

ϵ_s = steel strain due to shrinkage, in inch/inch.

E_c = modulus of elasticity of concrete, in lbs/sq.in.

A_s = area of steel, in square inches

I = the moment of inertia of the section, in inch^4.

e = the eccentricity, in inches. (measured from the centre of the beam)

E_s = modulus of elasticity of steel taken as 30×10^6 lbs/sq.inch.

Force in steel due to shrinkage = $\epsilon_s \cdot E_s \cdot A_s$, in lbs.

moment induced by the force in steel = M.

$$= \epsilon_s \cdot E_s \cdot A_s \cdot e, \text{ in lb.in.}$$

Applying the moment area method the deflection at the centre is equal to:-

$$\Delta = \frac{M L^2}{8 E_c I} \qquad \text{.......................} (8)$$

Hans Gesund(11) and Plowman (37) studied the deflections of reinforced concrete members over a long period and have suggested that a reduced modulus of elasticity for concrete E_c should be used in calculating the deflections. The reduction of the standard modulus of elasticity was mainly due to the effect of shrinkage and creep strains. Plowman(37) estimated the strains due to shrinkage and creep ~~by~~ to be as much as twice the elastic strains for the range of the working loads; the effective modulus of elasticity was chosen to be $\frac{1}{3} E_c$. Using the effective modulus of elasticity in calculating the shrinkage deflections, equation (8) could be rewritten as follows:-

$$\Delta = \frac{ML^2}{8 E_c' I} \qquad \text{.....................} (9)$$

where E_c' = the effective modulus of elasticity of concrete.

However, in this thesis the deflections were calculated by means of the three equations mentioned above (7),(8) and (9) in order to check their validity and adherence to the experimental results.

1.4 THE CODES OF PRACTICE AND SHRINKAGE

1.4.1 Shrinkage reinforcement

With regard to shrinkage reinforcement in concrete, the British Code of Practice CP114[(21)], clause 311.C specifies the following:-

Minimum reinforcement in slabs

In solid reinforced concrete slabs the reinforcement in each direction, expressed as a percentage of the gross-sectional area of concrete should not be less than:-

0.15 where plain bars are used or,
0.12 where high yield-bond bars, or high yield wire mesh are used.

The reinforcement is supposed to be sufficient to meet the requirements for concentrated loads, local shrinkage, and other secondary effects neglected in the design calculations.

The American Code of Practice[(29)], goes into further details, and recommends the following:-

Reinforcement for shrinkage and temperature stresses normal to the principal reinforcement shall be provided in structural floors or roof slabs where the principal reinforcement extends in one direction only. Such reinforcement shall provide at least the following ratios of reinforcement area to gross concrete area, but in no case shall such reinforcing bars be placed further apart than five times the slab thickness or more than 18 inches.

Slabs where plain bars are used 0.0025
Slabs where deformed bars with specified
Yield stress less than 60.000 lbs/□" are used 0.0020
Slabs where deformed bars with 60.000 lbs/□" specified yield
strength or welded wire fabrics having welded intersections
not further apart in the direction of the stress than
12 inches, are used 0.0018

not further apart in the direction of the stress than 12 inches, are used 0.0018

1.4.2 Loss of prestress due to shrinkage of concrete

The British Code of Practice CP115(22), clause 304.d recommends that the loss of stress in the prestressing of steel due to shrinkage of concrete should be calculated from the modulus of elasticity for steel given in clause 304.C on the assumption that:

(i) For pre-tensioning the ultimate shrinkage per unit length is 300×10^{-6}.

(ii) For post-tensioning at between two and three weeks after concreting the subsequent shrinkage per unit length is 200×10^{6}.

With regard to clause 304.a, the loss of prestress for pre-tensioning is 8400 lbs/□", and for post-tensioning is 5,600 lbs/□". ($300 \times 10^{-6} \times 28 \times 10^{6}$ and $200 \times 10^{-6} \times 28 \times 10^{6}$).

The shrinkage effect in prestressed concrete may result in permanent cracking. The prestress is imposed to give concrete in effect, an enhanced tensile strength. It is essential, when deciding the actual tensile stress to be allowed in the concrete, to make proper allowance for the losses of prestress which will reduce this effective tensile strength. The permissible tensile stresses recommended in CP115 range from 150 to 225 lb/in^2 corresponding to cube strengths at transfer of 3000 to 7500 lbs/in^2.

1.4.3 Allowable shrinkage limits for precast concrete blocks

The British Standard Specification B.S. 2028(30), deals with the following types of precast solid or hollow concrete blocks.

Type A, dense aggregate concrete blocks.

Type B, light weight aggregate concrete blocks for load bearing walls.

Type C, light weight aggregate concrete blocks for non-load bearing partitions.

The specification recommends that drying shrinkage of blocks should not exceed the following limits.

Type A blocks	0.04%
Type B blocks	0.06%
Type C blocks	0.08%

The average moisture movement for type B must not exceed 0.05%. The drying shrinkage has been defined as the difference between the length of the specimen cut from a block and its length when dried to constant length. The moisture movement was stated as the difference in length of a specimen when dried to constant length and that when subsequently saturated.

The B.S. 1881 - 1952(31) has laid down the procedures for testing the initial and drying shrinkage of dense concretes and described the appropriate device for the shrinkage measurements. The detailed description of the B.S. 1881 method for the initial shrinkage measurement is shown in Chapter 2.

1.4.4 The Building Research Station Recommendations

An extensive study of the shrinkage of various types of Scottish aggregates was carried out and several recommendations on the possible use of each type of aggregate were laid down in the Building Research Station, Digest No.35. They have recommended the suitability of aggregate giving 0.045% drying shrinkage for all concreting purposes. Special precautions were advised for any aggregate producing a higher value than the above mentioned.

1.5 THE SCOPE OF THE PRESENT INVESTIGATION

None of the codes of practice made any provision for design rules to control shrinkage effects and only recommended empirically the minimum reinforcement required to reduce the shrinkage strains.

Although the problems of shrinkage deformations and cracking have been studied by many investigators in different countries, the shrinkage of concrete remains as one of the most complicated problems in concrete technology.

The purpose of this investigation is to study the shrinkage properties of some Scottish aggregates, well known for their excessive shrinkage potentials. The experimental work is mainly directed towards the following objectives:-

(1) The determination of the shrinkage potentials for three types of Scottish aggregates, namely, Blairgowrie gravel, Eddleston gravel and Ratho Whinstone aggregate.

(2) The determination of the moisture movements for selected mixes.

(3) The warping of thin concrete beams due to the action of of reinforcing steel bars and its possible control.

(4) Elimination of shrinkage deflections and the detection of the internal shrinkage strains in reinforced and plain thin beams cast with Blairgowrie gravel and Ratho Whinstone aggregate.

(5) Comparison between the calculated and the experimental deflections.

Special emphasis is given to the interaction of reinforcement and concrete shrinkage. The presence of steel bars in a concrete element will disturb the expected shrinkage pattern in concrete by resisting the shrinkage tendency, and subsequently inducing tensile strains in concrete.

It is hoped that the resulting data would encourage further investigations in order to reveal valuable knowledge concerning the behaviour of reinforced concrete elements under the process of setting, hardening and drying.

CHAPTER 2

2.1 DRYING SHRINKAGE OF CERTAIN TYPES OF SCOTTISH AGGREGATES

Certain types of Scottish aggregates are known to produce concrete of high shrinkage. Among these types are the Ratho-Whinstone aggregate and the Eddleston gravel; the former produces concrete of medium shrinkage and the latter produces concrete of a very high shrinkage.

A series of experiments ~~were~~ was applied on the above mentioned types of aggregates to determine their effect on concrete shrinkage as a part of a general study of the influence of shrinkable aggregates on the structural properties of concrete.

The drying shrinkage of concretes cast with Ratho-Whinstone aggregate and Eddleston gravel were investigated in a series of experiments taking into consideration the effect of the water content, cement content and the aggregate content on the magnitudes of shrinkage.

A third type of aggregate, Blairgowrie gravel, considered to produce concrete of low shrinkage, was also investigated for its drying shrinkage to enable comparison between the three different types of aggregates.

Rapid Hardening Portland cement, complying with B.S.12, was used throughout.

Short descriptions of these types of aggregates are given hereafter.

(i) Blairgowrie gravel:

It is a mixture of different types of igneous rocks, reduced to different sizes by natural means, such as weathering and water attrition. It is an alluvial material which has a rounded shape and smooth surface. It produces a concrete of low shrinkage and comes from Castlehill Quarry.

(ii) Ratho-Whinstone:

It is a crushed dolerite aggregate, dark grey in colour and has an angular shape. It has a rough surface and comes from Craigpark Quarry, Ratho, Midlothian, and produces concrete of medium shrinkage.

(iii) Eddleston gravel:

It is a natural alluvial gravel, rounded in shape and has a smooth surface. It comes from Silverburn Quarry, Penicuik, and produces concrete of a very high shrinkage.

2.1.1 Classification of different mixes tested

Owing to the numerous factors that affect the shrinkage of concrete and the difficulty in getting reliable results with so many variables, it was decided to limit the testing for the initial drying shrinkage to the main three factors, i.e. the water content, the cement content and the aggregate content.

Six different mixes for each type of aggregate were tested for their initial drying shrinkage using different water/cement ratios of 0.4, 0.5, 0.6 and 0.7 successively. The cement content for each group of mixes varied between 1008 lbs/yd^3 for the richest mix and 448 lbs/yd^3 for the leanest mix. The aggregate content for the richest mix was 2880 lbs/yd^3 and it was increased by 112 lbs/yd^3 for every leaner mix. For each mix the aggregate content was supplied in the ratio of 2:1 coarse to fine aggregate.

It was at first intended to test 24 mixes for each type of aggregate, but some of them were cancelled, being either dry or very wet mixes. Table 1 shows the different mixes tested for each type of aggregate.

Water/cement ratio	Constituents of Mix	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
0.4	Cement lbs/yd^3	1008	896	784	672	dry mix	dry mix
	Aggregate lbs/yd^3	2880	2992	3104	3212		
	Water lbs/yd^3	403	358	313	269		
0.5	Cement lbs/yd^3	1008	896	784	672	560	dry mix
	Aggregate "	2880	2992	3104	3212	3327	
	Water "	504	448	392	336	280	
0.6	Cement lbs/yd^3	1008	896	784	672	560	448
	Aggregate "	2880	2992	3104	3212	3327	3432
	Water "	605	538	470	403	336	269
0.7	Cement lbs/yd^3	wet mix	wet mix	784	672	560	448
	Aggregate "			3104	3212	3327	3432
	Water "			549	470	392	314

Table 1 – The classification of mixes tested for the initial drying shrinkage.

2.1.2 Casting and curing procedures

The testing of the initial drying shrinkage for the three types of aggregate involved a total of fifty seven mixes. Batching was done by weight and the constituents were mixed by means of a Hobart mixer. After the concrete was mixed three specimens of dimensions 2" x 2" x 8" were cast in a steel mould. The fine aggregate was used as supplied from the source and sizes of the coarse aggregate were ranging between $\frac{3''}{16}$ and $\frac{3''}{8}$.

Vibration was evenly and carefully done by a Kango electric hammer type L. The surfaces of the specimens were smoothed by a trowel and covered with wet hessian for 24 hours.

After the first 24 hours, the specimens were demoulded and two reference points consisting of $\frac{5''}{16}$ diameter steel balls were cemented into the centre of each end of the specimens, after drilling a shallow depression. After fixing, the balls were wiped clean of cement, dried and coated with Lubricating grease to prevent corrosion.

The specimens were kept moist for another 24 hours in order to allow the Rapid Hardening Portland cement to harden. On the third day after casting, the initial lengths of the specimens and their weights were determined; and then the specimens were immersed in water at a temperature of 18°- 22°C (64° - 72°F) for a period of eight days.

2.1.3 Procedures for testing the initial drying shrinkage

Owing to the numerous mixes in the testing programme, and the limited time available to complete it, the author departed from the standard method specified by the B.S. 1881 - 1952(31).

For the test procedures, departures were as follows:-

(i) The water curing of the specimens was reduced to 8 days instead of 28 days.

(ii) One specimen, out of three for each mix, was dried in the standard oven recommended by the B.S.1881. The remaining two specimens were dried in the open air of the laboratory.

(iii) The oven drying was started at a temperature of 15°C and 50% relative humidity for a period of 20 days, allowing for a daily new specimen to be added to the oven, until it reached its maximum capacity of 20 specimens. Then, drying proceeded at the temperature and humidity specified by the B.S. 1881-1952(31). (50°C and 17% R.H.).

(iv) The initial length and weight of each specimen was determined before immersing the specimens in water for their wet curing. This permitted the calculations of the shrinkage movements as early as the third day after casting. and also made it possible to determine the expansion of the specimens due to saturation.

Apart from the previously mentioned points, the B.S. 1881: 1952(31), procedures of shrinkage testing were fully respected.

The total number of specimens cast for testing was 171 for the three types of aggregates. Fifty seven specimens were dried in the standard oven, and 114 specimens were left to dry for a period of six months in the laboratory and at a temperature of 18°- 22°C and a relative humidity of 10 - 40%. The changes in length and weight of the specimens were determined at convenient intervals until they reached approximately a constant length. Drying was considered as completed when the change of length between successive measurements with a period of two days in between did not exceed 0.0004 inch per length of specimen. The length measurements were all taken at the laboratory temperature of 18° - 22°C.

Table 2 shows the quantities of materials used for casting three standard specimens of 2" x 2" x 8" for the various mixes.

An average of twelve readings were taken for each specimen and the changes in length and weight were determined. The shrinkage strains for the specimens were calculated per unit length and then plotted in two series of graphs. (Shrinkage versus time graphs and the shrinkage versus loss of water). The experimental data obtained for the different types of aggregates were shown in figures 3,4,5,6,7,8,9,10 ...., 45, 46, 47, 48 and 49.

2.1.4 The moisture movement

To determine the moisture movement on subsequent drying and wetting, four specimens for each type of aggregate were chosen after being fully tested for their initial drying shrinkage. The four specimens had equal cement and aggregate contents but they were cast with different water/cement ratios of 0.4, 0.5, 0.6 and 0.7 successively.

The specimens were then immersed in water at 18° - 22°C, (65° - 72°F), in such a way that one of the larger faces of the specimens just breaks surface in water, and they were left so for four days after which the final wet measurements were

W/C	Mix No.	Water content in grams	Cement content in grams	Course Aggregate in grams	Fine Aggregate in grams
0.4	1	377	942	1939	969
	2	335	837	2009	1004
	3	293	732	2079	1039
	4	251	627	2149	1074
0.5	5	471	942	1939	969
	6	419	837	2009	1004
	7	366	732	2079	1039
	8	314	627	2149	1074
	9	262	523	2218	1109
0.6	10	565	942	1939	969
	11	502	837	2009	1004
	12	439	732	2079	1039
	13	376	627	2149	1074
	14	314	523	2218	1109
	15	251	418	2288	1144
0.7	16	512	732	2079	1039
	17	439	627	2149	1074
	18	366	523	2218	1109
	19	293	418	2288	1144

Table No.2 - Materials used for preparing three specimens 2" x 2" x 8" (19 mixes were cast for each type of aggregate).

determined.

The moisture movement was calculated as the difference between the dry measurement and the final wet measurement expressed as a percentage of the dry length.

Three cycles of drying and wetting of the specimens were performed, and the moisture movements obtained were shown in table No.3.

2.1.5 Strength and elasticity of selected mixes

The shrinkage testing covered a series of 57 different mixes. Selected mixes were chosen and control tests were prepared in accordance with the B.S.1881 - 1952(31). The mixing of the concrete was done by a liner mixer. The vibration was performed by means of a Kango Electric Hammer type L. The specimens were cured under water at a temperature of 18°-22°C. for 28 days.

(a) Compressive strength

Six inch cubes were tested in a 250 tons Denison testing machine. The compressive strength was found to be inversely proportional to the water content of the mix. The concrete shrinkage showed an opposite behaviour, the shrinkage increased in proportion with the water content.

(b) Tensile strength

The indirect tensile test was applied to determine the tensile strength of concrete. Eight inch cylinders were tested in a 250 tons Denison testing machine. The tensile strength for the different types of aggregate was found to vary from 590 lbs/sq.in. to 425 lbs/sq.in.

Type of Aggregate	Specimen No.	Particulars of Mix				Moisture movement %		
		W/C	water in grams	cement in grams	aggregate in grams	first cycle	second cycle	third cycle
Blairgowrie gravel	1	0.4	98	244	1040	0.0447	0.0315	0.0283
	2	0.5	122	"	"	0.0429	0.0335	0.0354
	3	0.6	146	"	"	0.0396	0.0396	0.0390
	4	0.7	171	"	"	0.0396	0.0339	0.0377
Ratho-Whinstone aggregate	1	0.4	98	244	1040	0.0465	0.0345	0.0326
	2	0.5	122	"	"	0.0493	0.0430	0.0379
	3	0.6	146	"	"	0.0570	0.0405	0.0386
	4	0.7	171	"	"	0.0639	0.0544	0.0500
Eddleston gravel	1	0.4	98	244	1040	0.0973	0.0821	0.0803
	2	0.5	122	"	"	0.0974	0.0804	0.0785
	3	0.6	146	"	"	0.0996	0.0801	0.0807
	4	0.7	171	"	"	0.1032	0.0856	0.0863

Table No.3 - The moisture movement of some selected specimens (constituents were given per specimen of 2" x 2" x 8")

cement content = 784 lbs/~~y~~d³
Aggregate " = 3104 " "
A/C ratio = 3.96

(c) The modulus of elasticity

Twelve inch cylinders were tested in a Losenhausenwerk testing machine. Lamb's extensometer was used in measuring the axial strains in a gage-length of six inches. The modulus of elasticity was found to vary with respect to the type of aggregate and the strength of the mix.

Table No.4 and figures 50,51 and 52 show the test results for the strength and elasticity of concrete.

2.1.6 Analysis and discussion of results

The experimental results covered a range of mixes with different water/cement ratios. For each water/cement ratio, the shrinkage values differed between a maximum and a minimum value which corresponded to the higher and lower cement content. Some of the specimens deviated from the regular pattern, i.e. the richer the mix the higher the shrinkage of concrete. This deviation could be attributed to the possible nonuniformity of vibration, uneven distribution of aggregate and paste between the three specimens of each mould, uneven circulation of air in the standard oven or differences in degrees of curing. In fact the exact reason for these deviations is not certain.

The shrinkage results for both methods of testing (oven and laboratory drying) provided reasonably coincident data. The laboratory drying results were more uniform and showed less deviations. The oven drying gave higher shrinkage for the concretes cast with Ratho-Whinstone aggregate and Eddleston gravel than those dried in the laboratory. The Blairgowrie specimens which were dried in the standard oven have shown a decrease (expansion) of

Type of Aggregate	W/C	Constituents of Mix				Concrete properties				
		cement. lbs/yd^3	coarse Aggregate lbs/yd^3	fine Aggregate lbs/yd^3	Water lbs/yd^3	Cube strength lbs/sq.in.	Cylinder strength lbs/sq.in.	Modulus of Elasticity lbs/sq.in.	tensile strength lbs/sq.in.	Shrinkage in/10^{-6}/in.
Blairgowrie gravel	0.4	1008	1920	960	403	8095	5152	3.76x10^6	457	650
	0.4	672	2144	1072	269	8415	5568	4.04x 10^6	502	400
	0.5	1008	1920	960	504	6650	5945	3.51x 10^6	421	660
	0.5	672	2144	1072	336	6755	6262	3.85x 10^6	504	405
	0.6	1008	1920	960	605	4878	4510	2.94x 10^6	424	705
	0.6	672	2144	1072	403	5306	4606	3.16x 10^6	441	430
Ratho-Whinstone aggregate	0.4	1008	1920	960	403	9444	9226	3.66x 10^6	590	890
	0.4	672	2144	1072	269	8836	8648	3.98x 10^6	502	900
	0.5	1008	1920	960	504	8556	6817	3.26x 10^6	464	980
	0.5	672	2144	1072	336	8585	6837	3.36x 10^6	497	860
	0.6	1008	1920	960	605	6362	5953	2.79x 10^6	392	970
	0.6	672	2144	1072	403	6462	6278	3.13x 10^6	490	840
Eddleston gravel	0.4	1008	1920	960	403	7933	7823	3.16x 10^6	457	1390
	0.4	672	2144	1072	269	7941	7850	3.63x 10^6	499	1300
	0.5	1008	1920	960	504	5467	5715	2.70x 10^6	455	1480
	0.5	672	2144	1072	336	5571	5811	2.83x 10^6	462	1100
	0.6	1008	1920	960	605	5413	5144	2.60x 10^6	432	1420
	0.6	672	2144	1072	403	5724	5367	2.88x 10^6	443	1210

Table No.4 - The strength and elasticity of selected mixes.

about 25% of its ultimate shrinkage and then gradually regained its value once more. This was a strange phenomenon and it was clearly shown in figures 27,29,31 and 33, drawn for the shrinkage versus the loss of water. This behaviour of the Blairgowrie specimens could be attributed to some sort of released internal surface tensions or an expansion due to invisible hair cracking that took place when most of the absorbed water had evaporated.

The Blairgowrie concrete produced shrinkage values ranging between 0.04% to 0.08% corresponding to a water/cement ratio of 0.6 and cement contents between 448 and 1008 lbs/yd^3. The Ratho-Whinstone and Eddleston concretes produced values between 0.07% to 0.1% and 0.1% to 0.14% respectively for the same w/c ratio and cement contents. Table No.5 shows the shrinkage values measured during the present investigation. Table 6 shows the specific gravity, water absorption and the bulk density of the different aggregates tested.

2.1.7 Conclusions

The following conclusions were drawn from the test results covered by this chapter:-

(1) The water content is probably the most important single factor affecting the shrinkage of concretes. Any condition which will permit the use of less mixing water will reduce the inherent shrinkage greatly and vice-versa.

(2) In cases of higher water/cement ratios, however, cracking is common during drying and the measurements may therefore be misleading.

(3) In general, extra cement increases shrinkage, but the effect varies considerably with the type of aggregate used. For

W/C	Cement content lbs/yd^3	Aggregate Content lbs/yd^3	Concrete Shrinkage %		
			Blairgowrie	Whinstone	Eddleston
0.4	1008	2880	0.064	0.088	0.116
	896	2992	0.051	0.0885	0.110
	784	3104	0.043	0.089	0.106
	672	3212	0.038	0.089	0.101
0.5	1008	2880	0.071	0.080	0.120
	896	2992	0.058	0.085	0.117
	784	3104	0.050	0.074	0.110
	672	3212	0.047	0.070	0.103
	560	3327	0.040	0.068	0.091
0.6	1008	2880	0.083	0.103	0.137
	896	2992	0.075	0.095	0.132
	784	3104	0.067	0.088	0.130
	672	3212	0.055	0.079	0.115
	560	3327	0.046	0.074	0.106
	448	3432	0.040	0.070	0.105
0.7	784	3104	0.068	0.081	0.133
	672	3212	0.056	0.077	0.137
	560	3327	0.047	0.070	0.116
	440	3432	0.034	0.060	0.109

mix 1:2:4 corresponds cement 555 lbs/yd^3 to aggregate 3333 lbs/yd^3

mix 1:1½:3 correspond cement 707 lbs/yd^3 to aggregate 3181 lbs/yd^3

mix 1:1:2 correspond cement 372 lbs/yd^3 to aggregate 2916 lbs/yd^3

Table No.5 - Shrinkage of concretes - made with Blairgowrie, Ratho-Whinstone and Eddleston aggregates

Type of Aggregate	Specific Gravity			Water Absorption %	Bulk Density	
	Oven dried	Saturated & Surface dry	Apparent		Course Aggreg. lbs/ft^3	fine Aggreg. lbs/ft^3
Blairgowrie	2.625	2.6580	2.7134	1.1	101	108
Whinstone	2.7416	2.8082	2.9576	2.4315	99	106
Eddleston	2.5736	2.6090	2.7190	2.5355	100	109

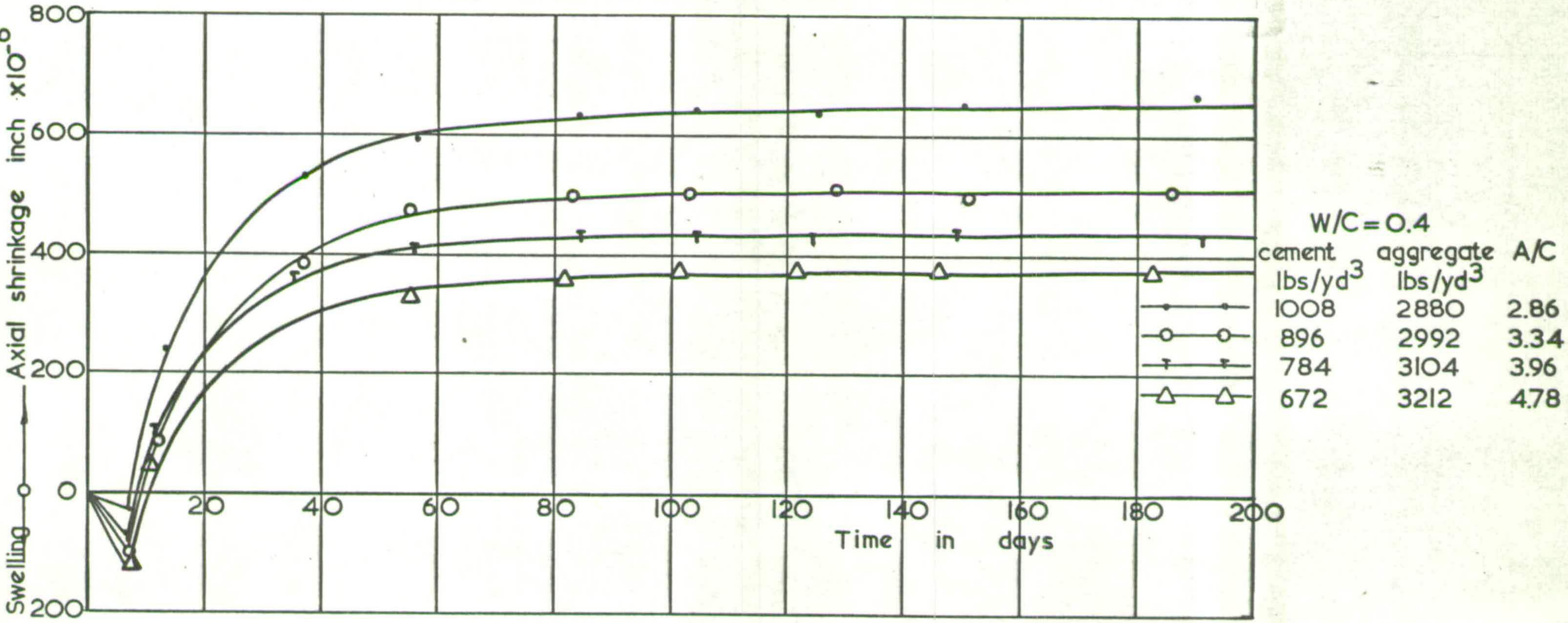
Table No.6 - Some of the properties of the different aggregates used.

aggregates which are noted for producing concrete of low shrinkage, higher shrinkage was observed for higher cement contents. For shrinkable aggregates, the effect of cement content is relatively small. (See figure 34, 36, 38, 46 and 48).

(4) Large differences in concrete shrinkage are obtained from different aggregates. Some difference results from the fact that one aggregate requires more mixing water than another, but the greater difference is probably due to the physical properties of the aggregate itself. The Ratho-Whinstone aggregate and Eddleston gravel were of these types which contribute towards the final shrinkage by as much as three times the shrinkage of the Blairgowrie gravel concretes.

(5) The increase in aggregate contents reduces the shrinkage of concrete provided that the water content and the cement content remain constant.

(6) The Ratho-Whinstone aggregate produces concrete of medium shrinkage and the Eddleston gravel produces concrete of high shrinkage.



IG. 3 SHRINKAGE TIME CURVES ——— BLAIRGOWRIE AGGREGATE DRYING IN LABORATORY CONDITION

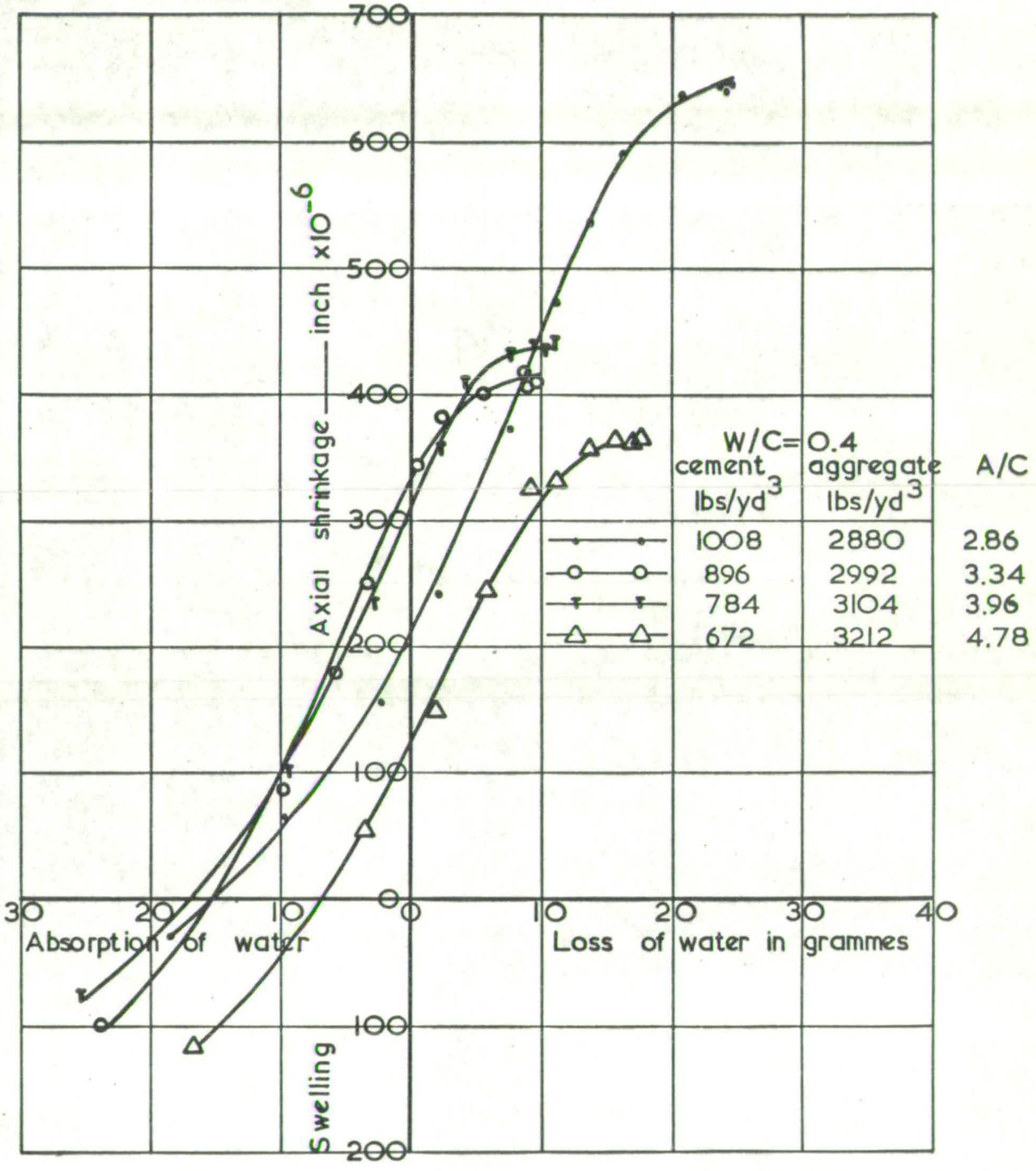


FIG. 4 RELATION BETWEEN SHRINKAGE & LOSS OF WATER —— BLAIRGOWRIE AGGREGATE

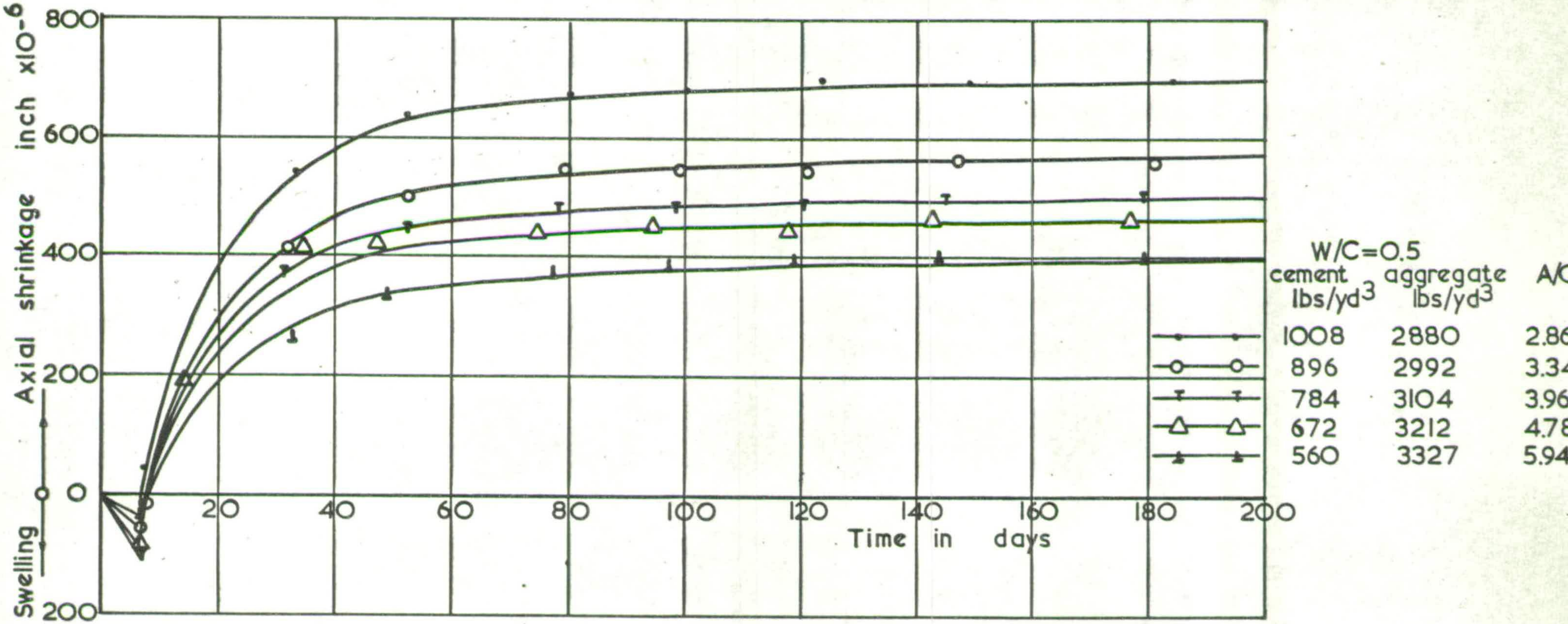


FIG. 5 SHRINKAGE TIME CURVES ——— BLAIRGOWRIE AGGREGATE DRYING IN LABORATORY CONDITION

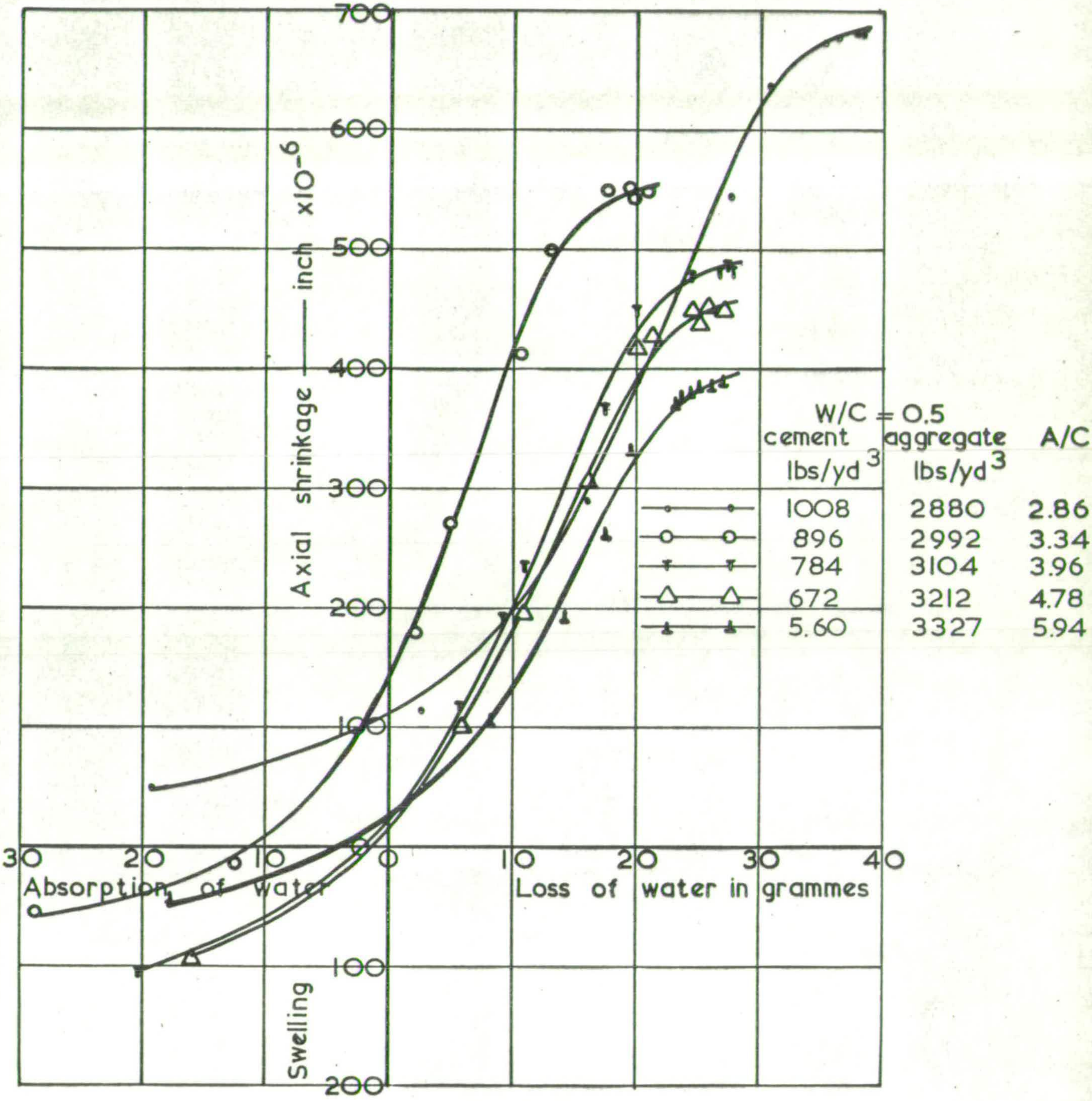


FIG. 6 RELATION BETWEEN SHRINKAGE & LOSS OF WATER——BLAIRGOWRIE AGGREGATE

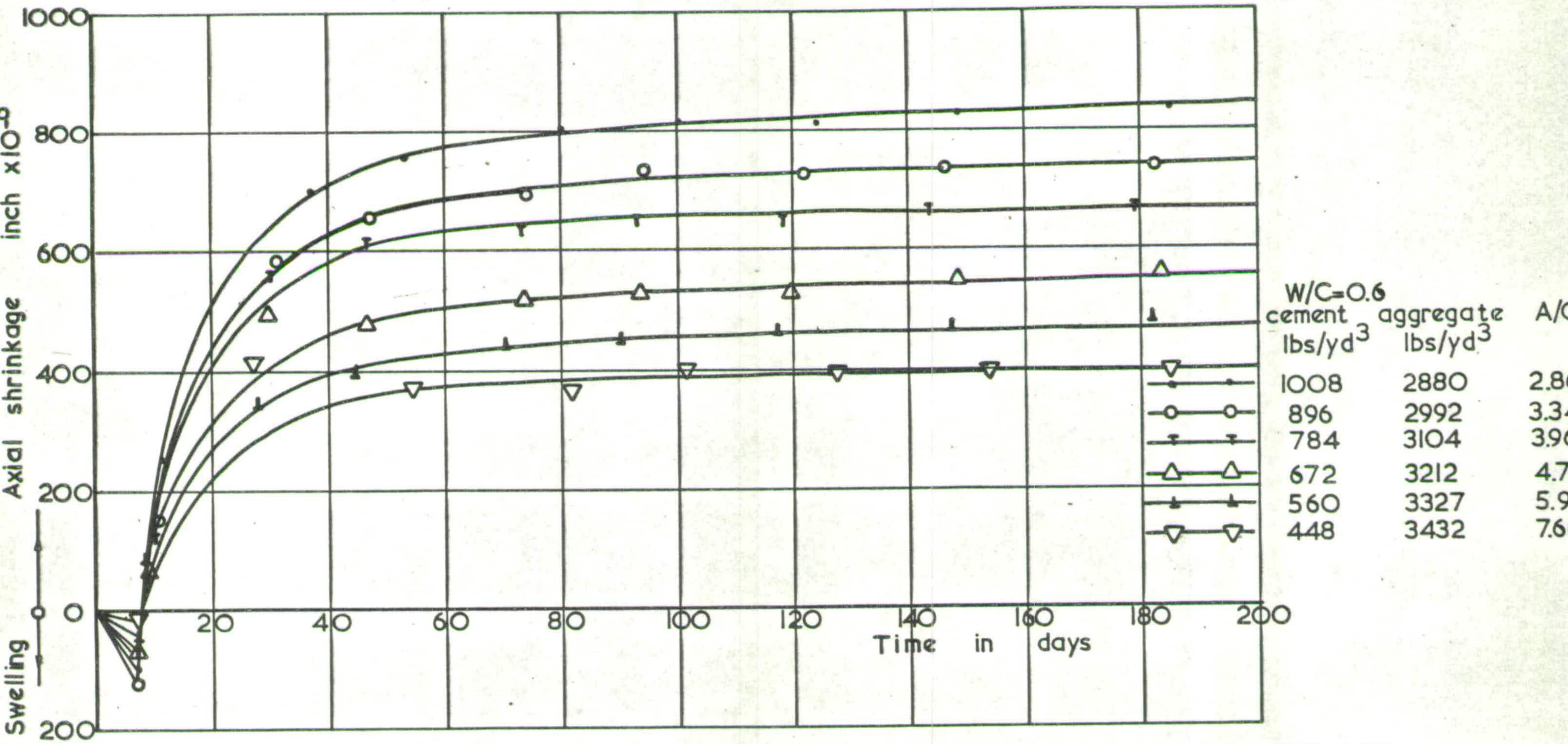


FIG. 7 SHRINKAGE TIME CURVES ——— BLAIRGOWRIE AGGREGATE
DRYING IN LABORATORY CONDITION

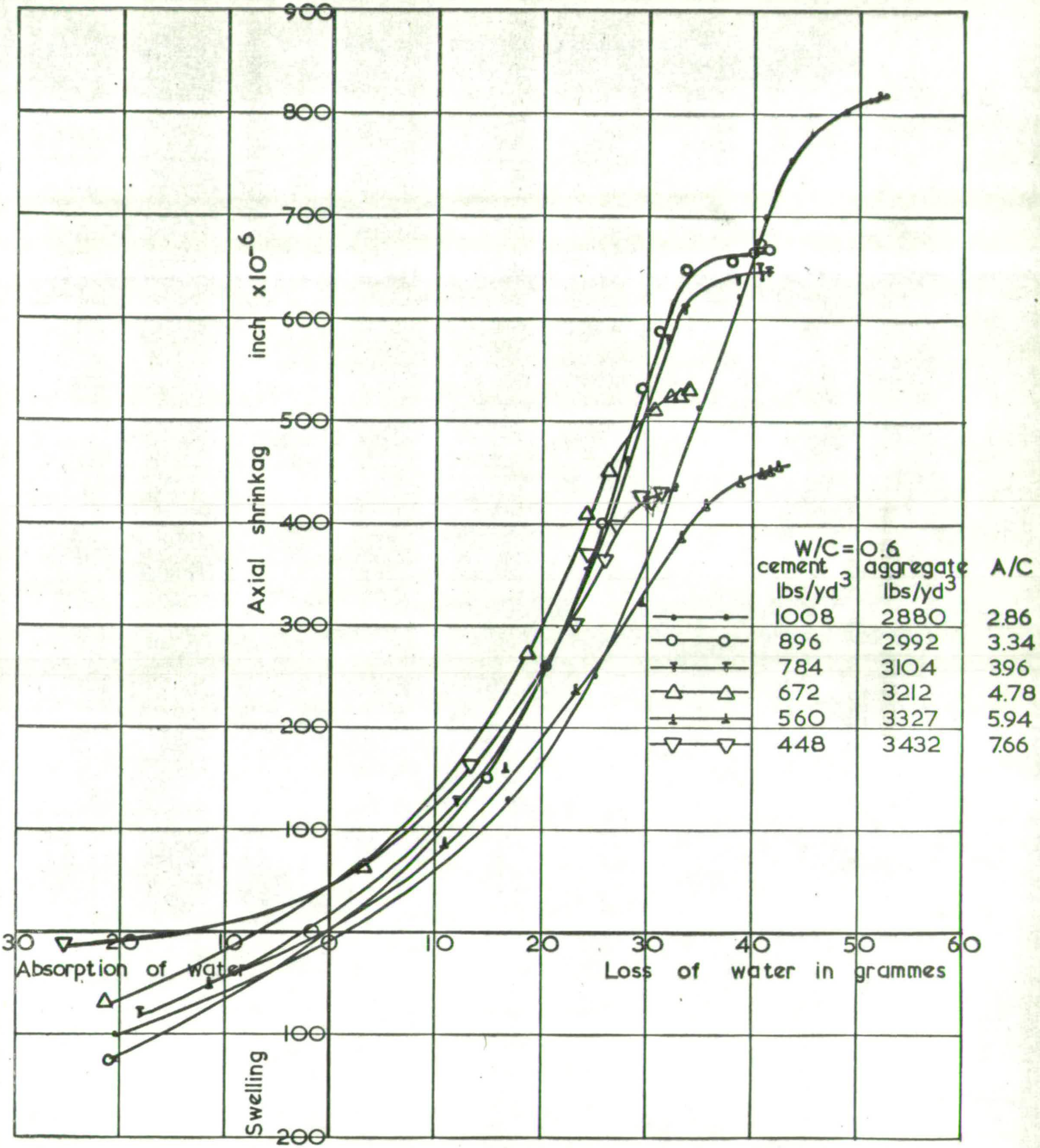


FIG. 8 RELATION BETWEEN SHRINKAGE & LOSS OF WATER ——BLAIRGOWRIE AGGREGATE

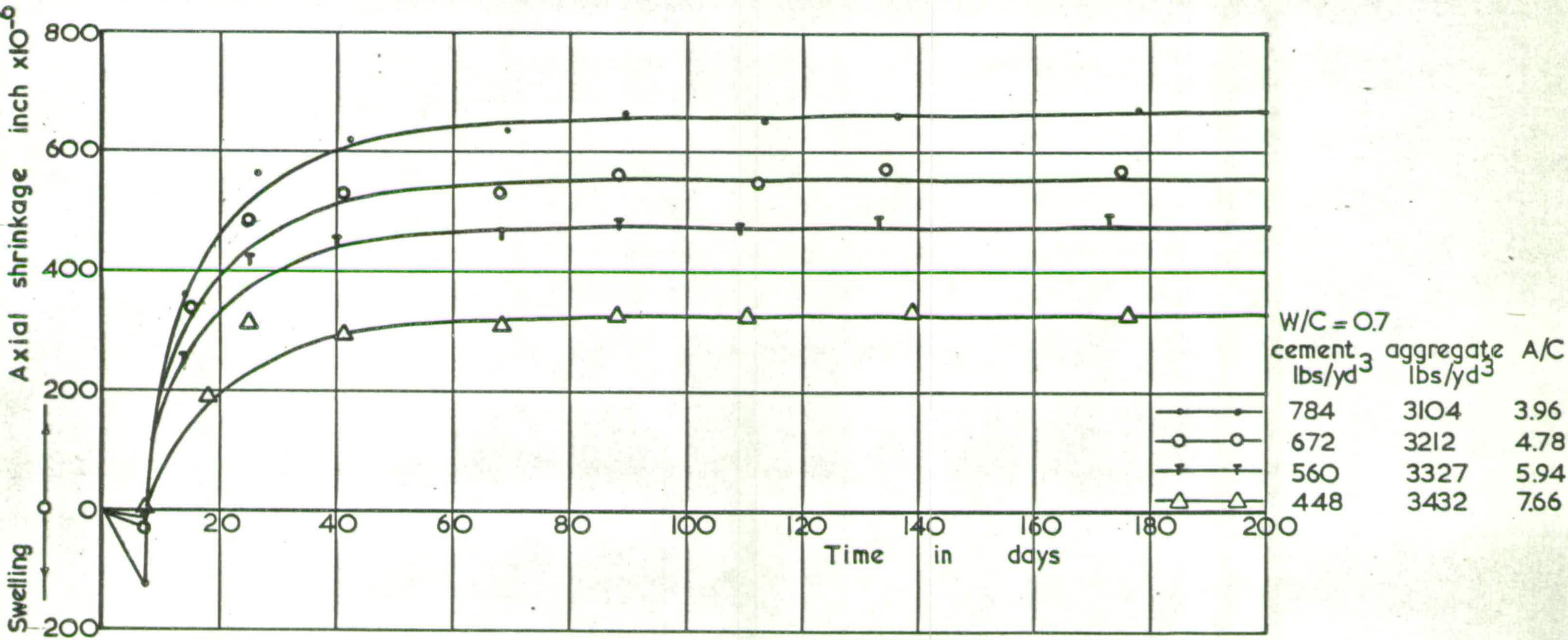


FIG. 9 SHRINKAGE TIME CURVES — BLAIRGOWRIE AGGREGATE DRYING IN LABORATORY CONDITION

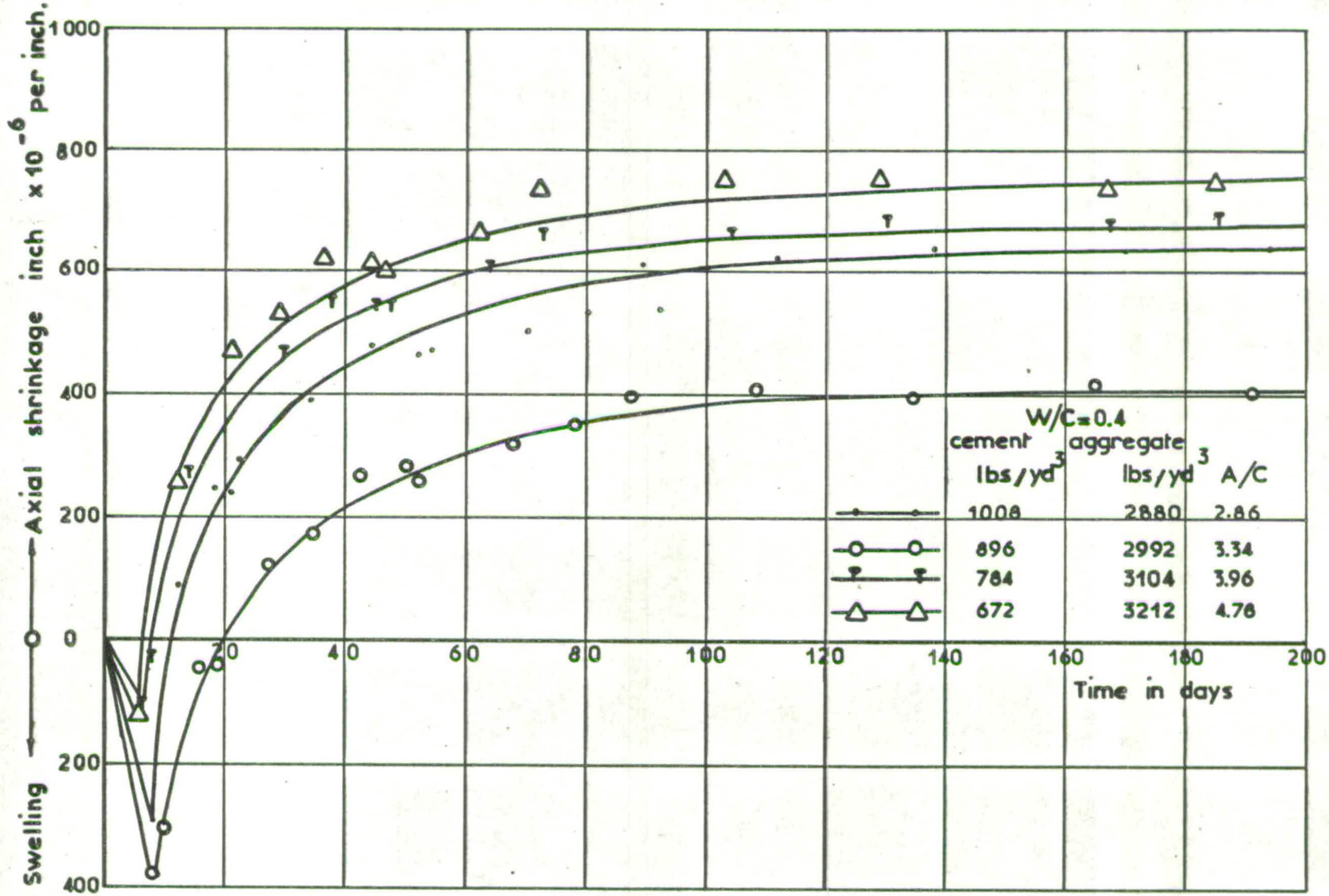


FIG.10 SHRINKAGE TIME CURVES___WHINSTONE AGGREGATE.
DRYING IN LABORATORY CONDITION

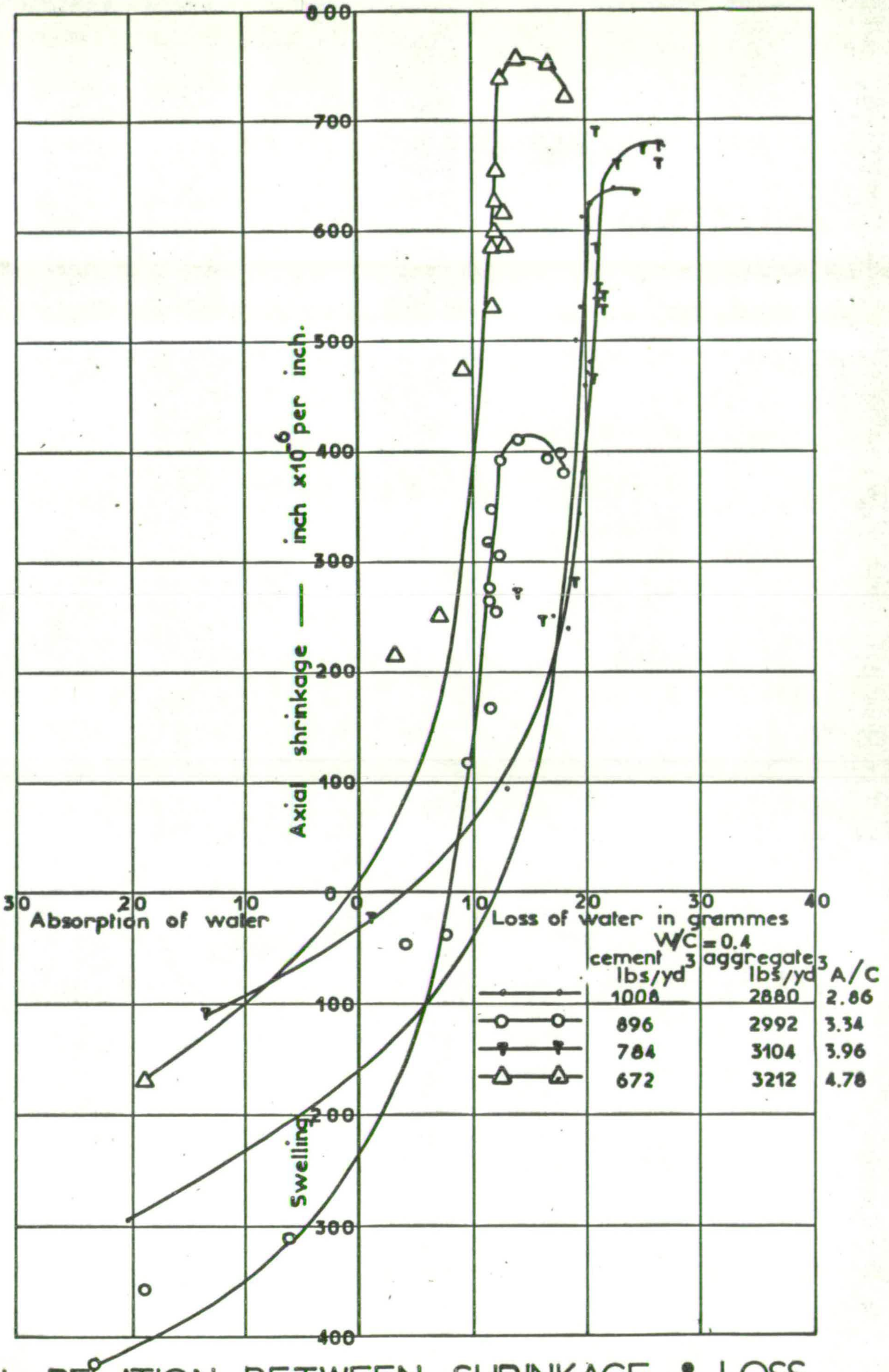


FIG.11 RELATION BETWEEN SHRINKAGE & LOSS OF WATER —— WHINSTONE AGGREGATE

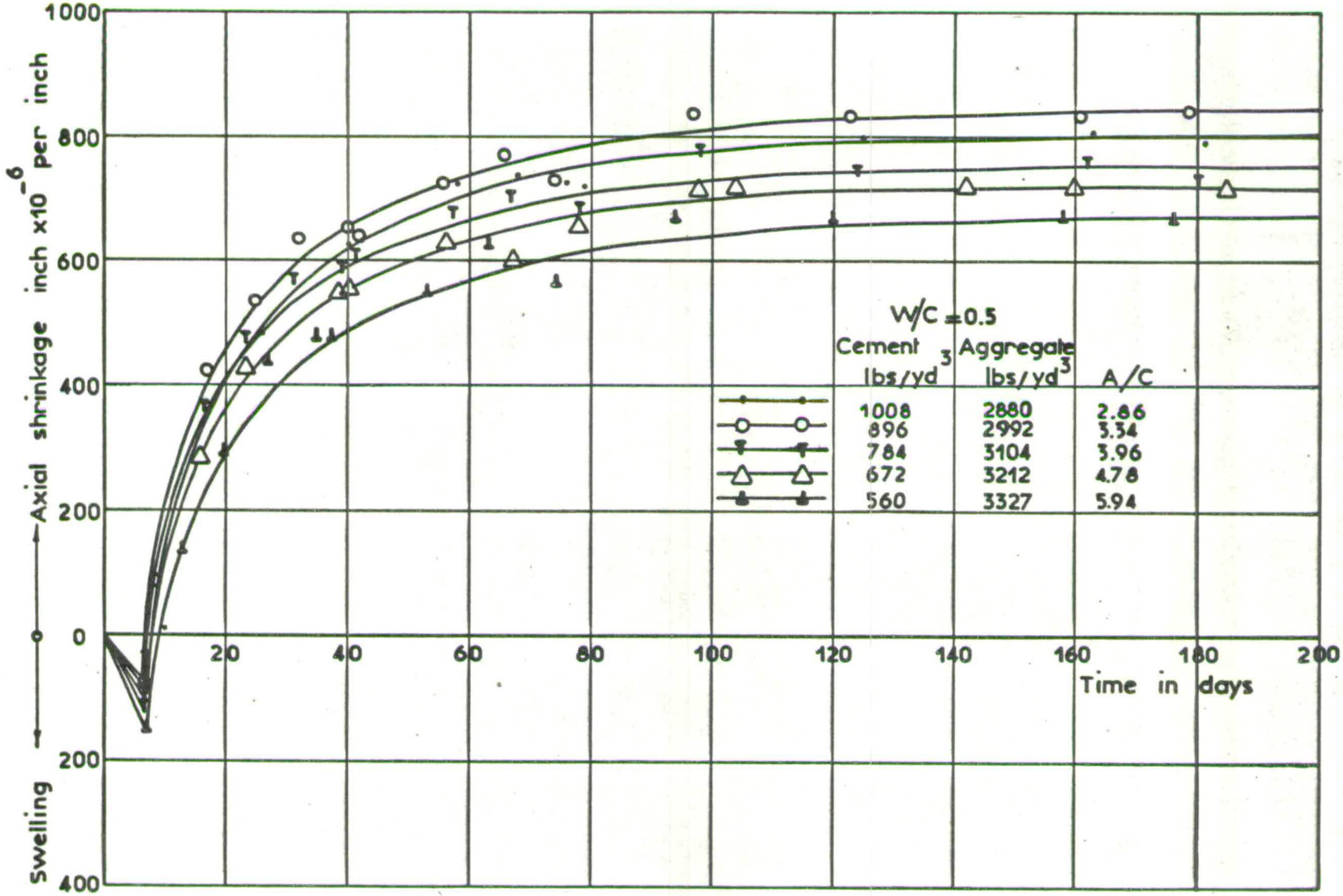


FIG.12 SHRINKAGE TIME CURVES ____ WHINSTONE AGGREGATE DRYING IN LABORATORY CONDITION

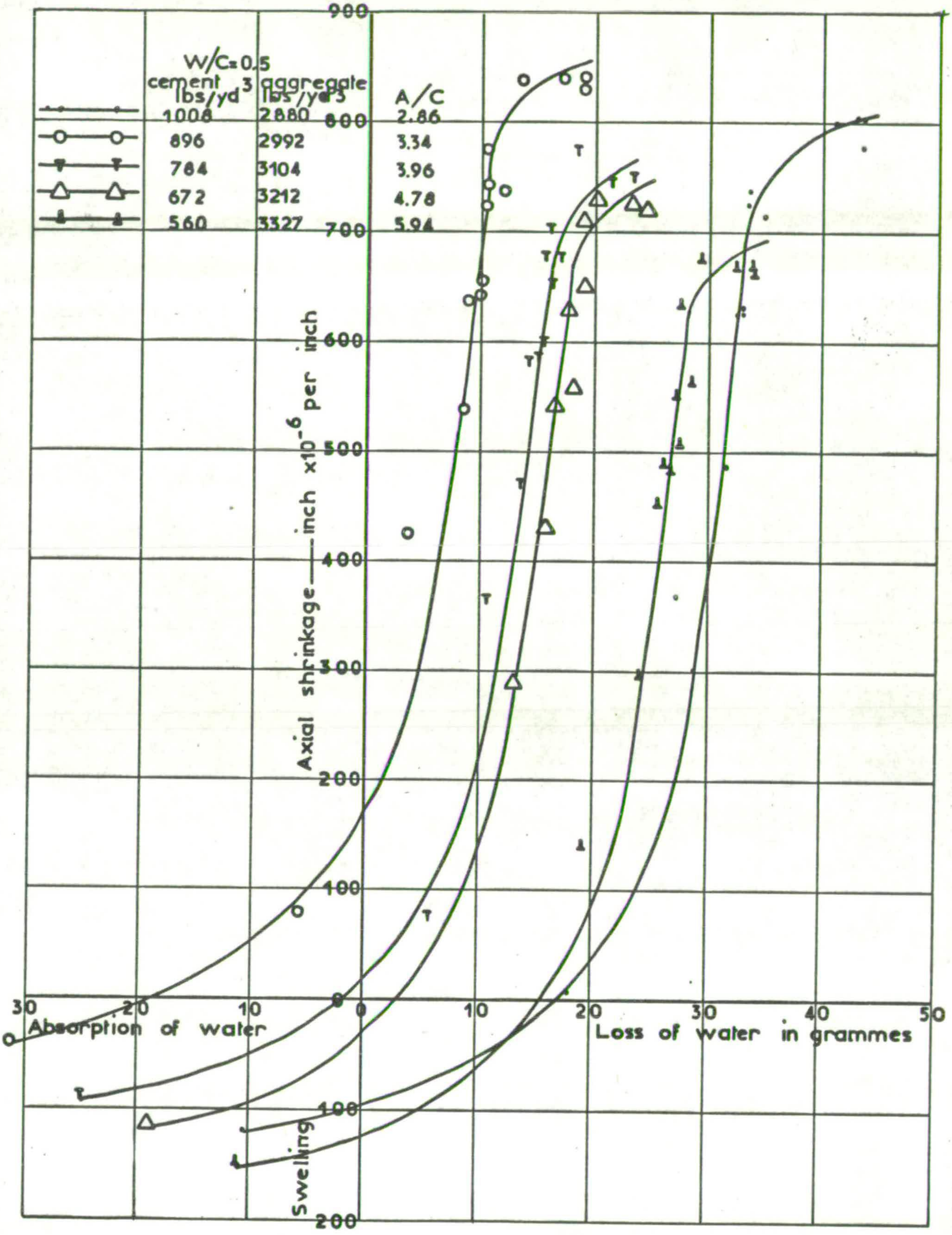


FIG. 13. RELATION BETWEEN SHRINKAGE & LOSS OF WATER —— WHINSTONE AGGREGATE

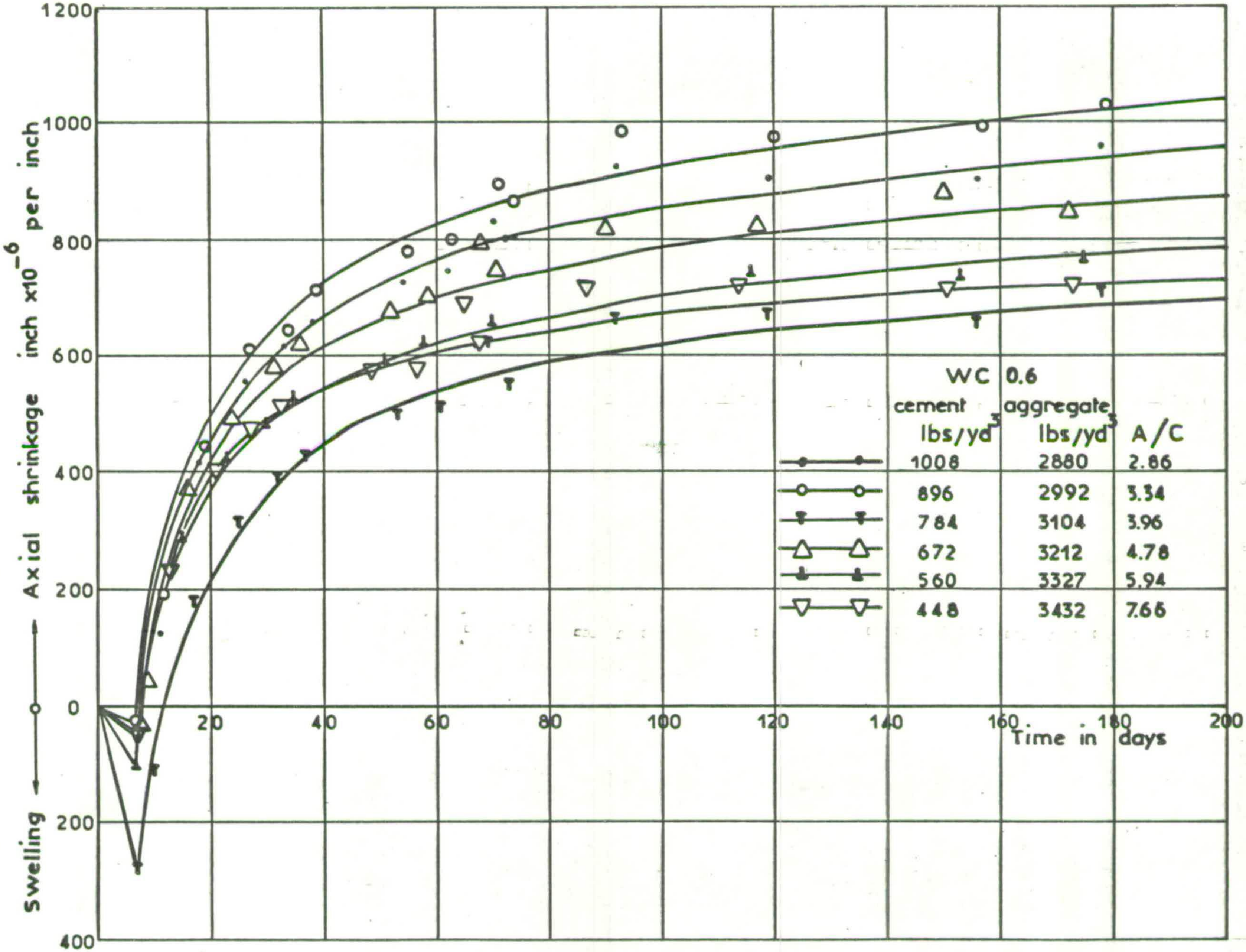


FIG.14 SHRINKAGE TIME CURVES ____ WHINSTONE AGGREGATE DRYING IN LABORATORY CONDITION

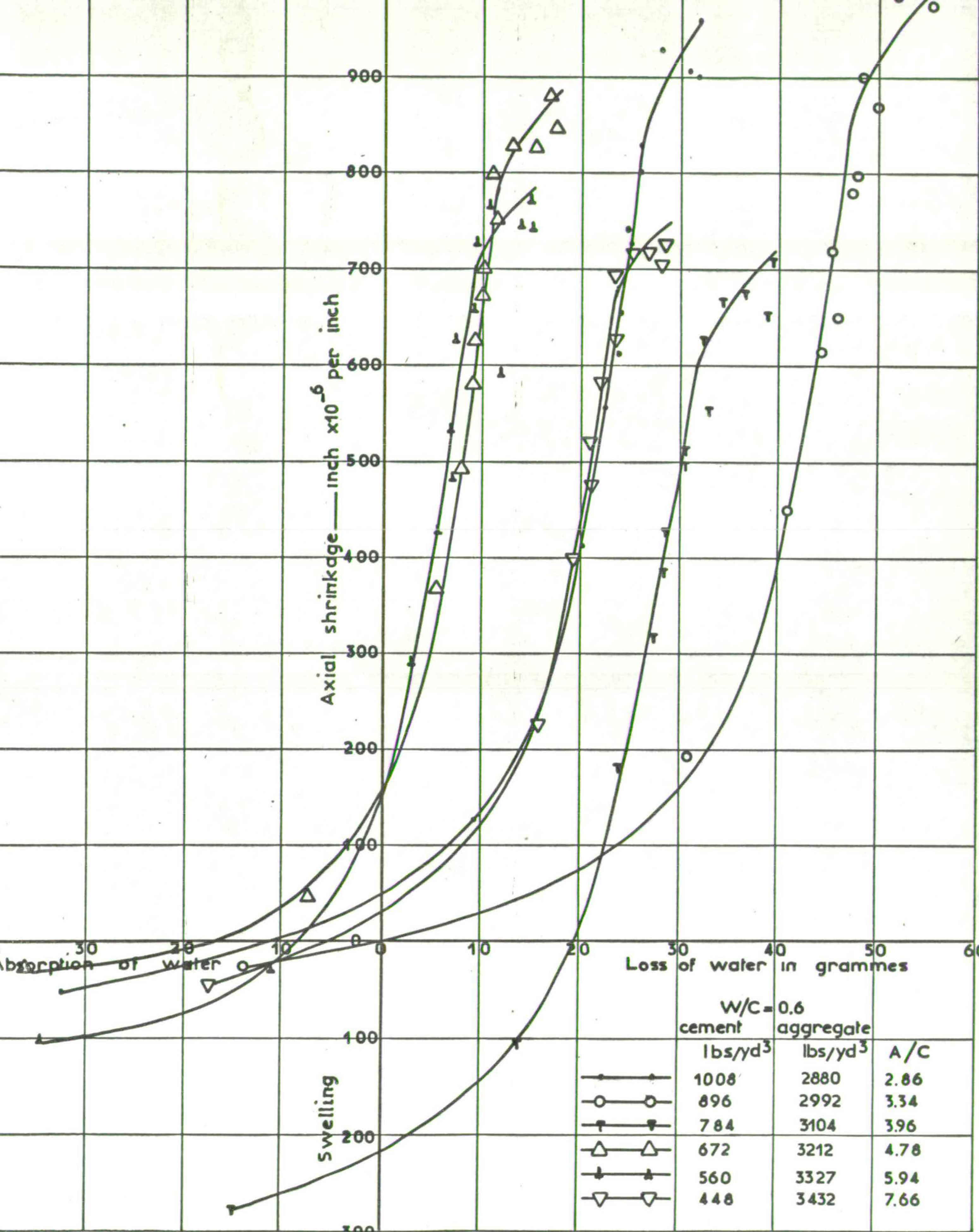


FIG. 15 RELATION BETWEEN SHRINKAGE & LOSS OF WATER —— WHINSTONE AGGREGATE

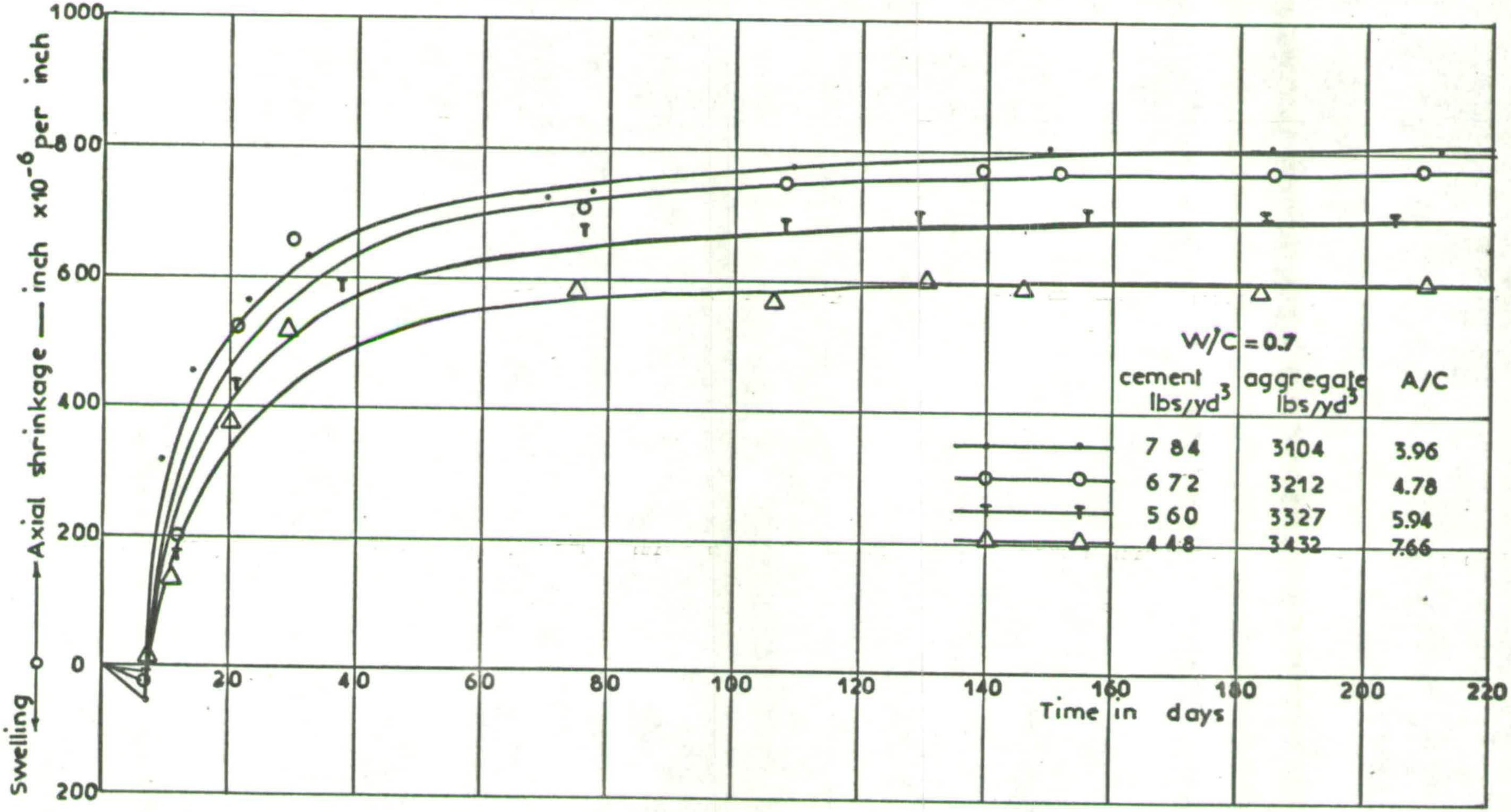


FIG.16 SHRINKAGE TIME CURVES —— WHINSTONE AGGREGATE DRYING IN LABORATORY CONDITION

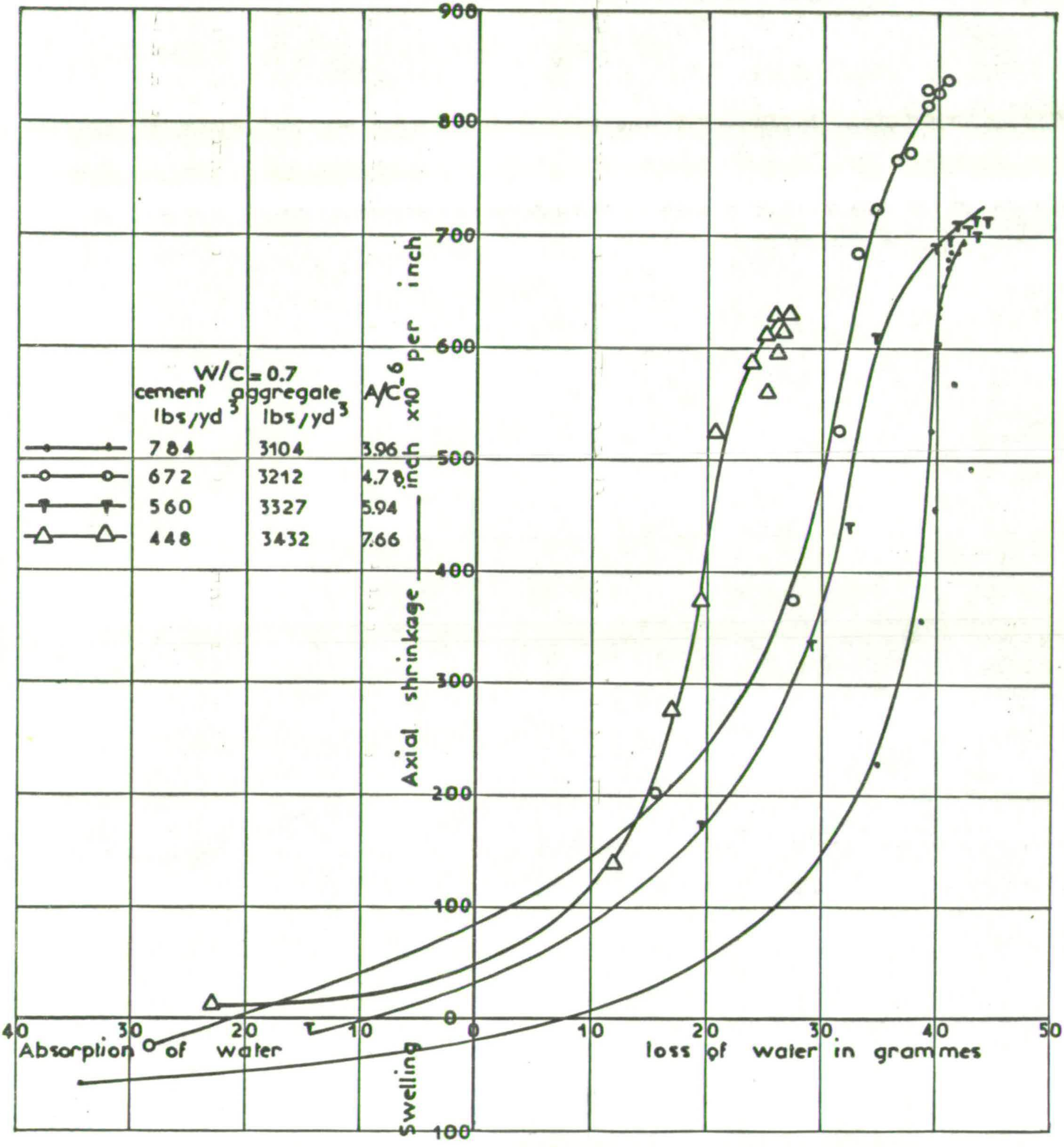


FIG.17 RELATION BETWEEN SHRINKAGE & LOSS OF WATER —— WHINSTONE AGGREGATE

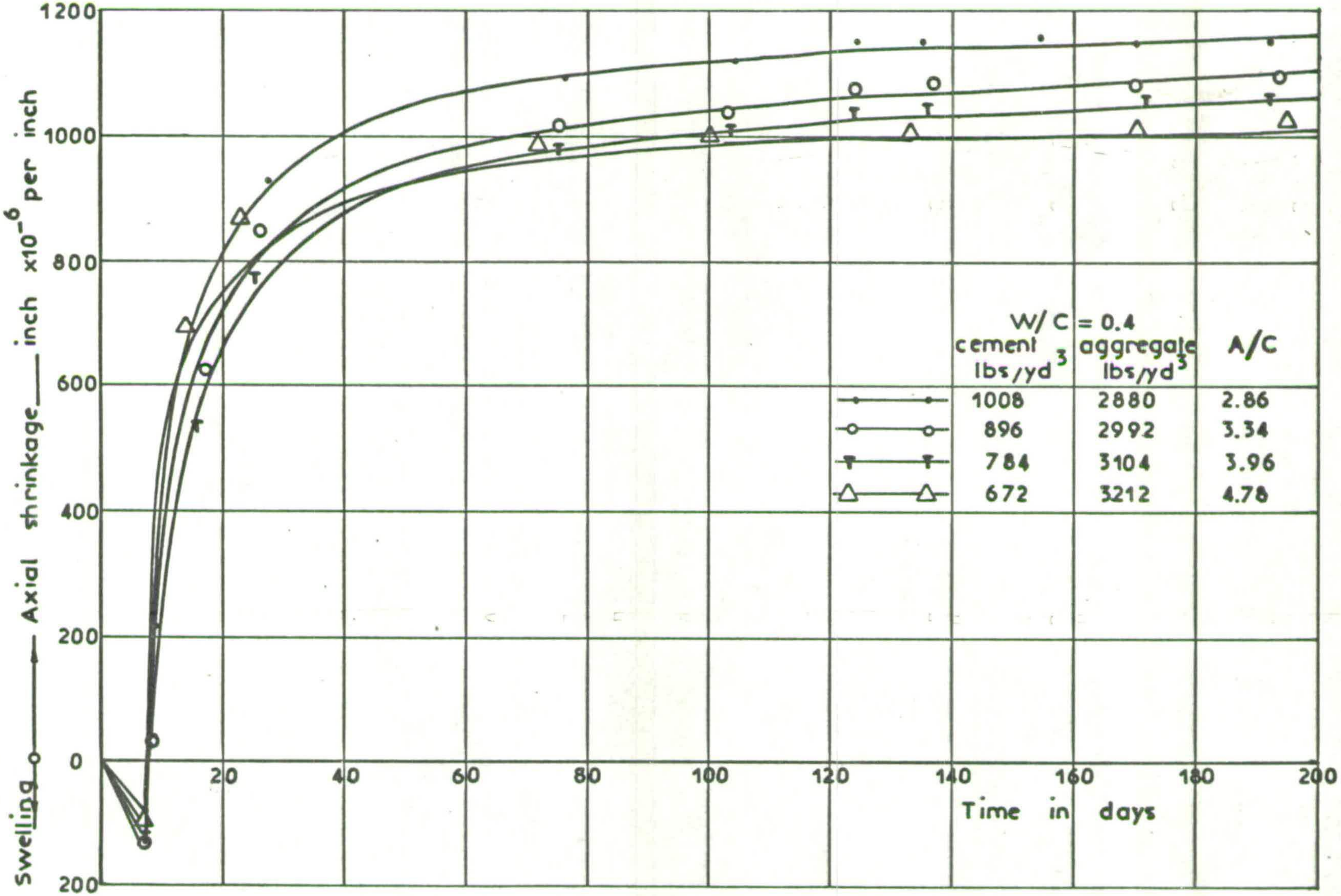


FIG.18 SHRINKAGE TIME CURVES —— EDDLESTON AGGREGATE DRYING IN LABORATORY CONDITION

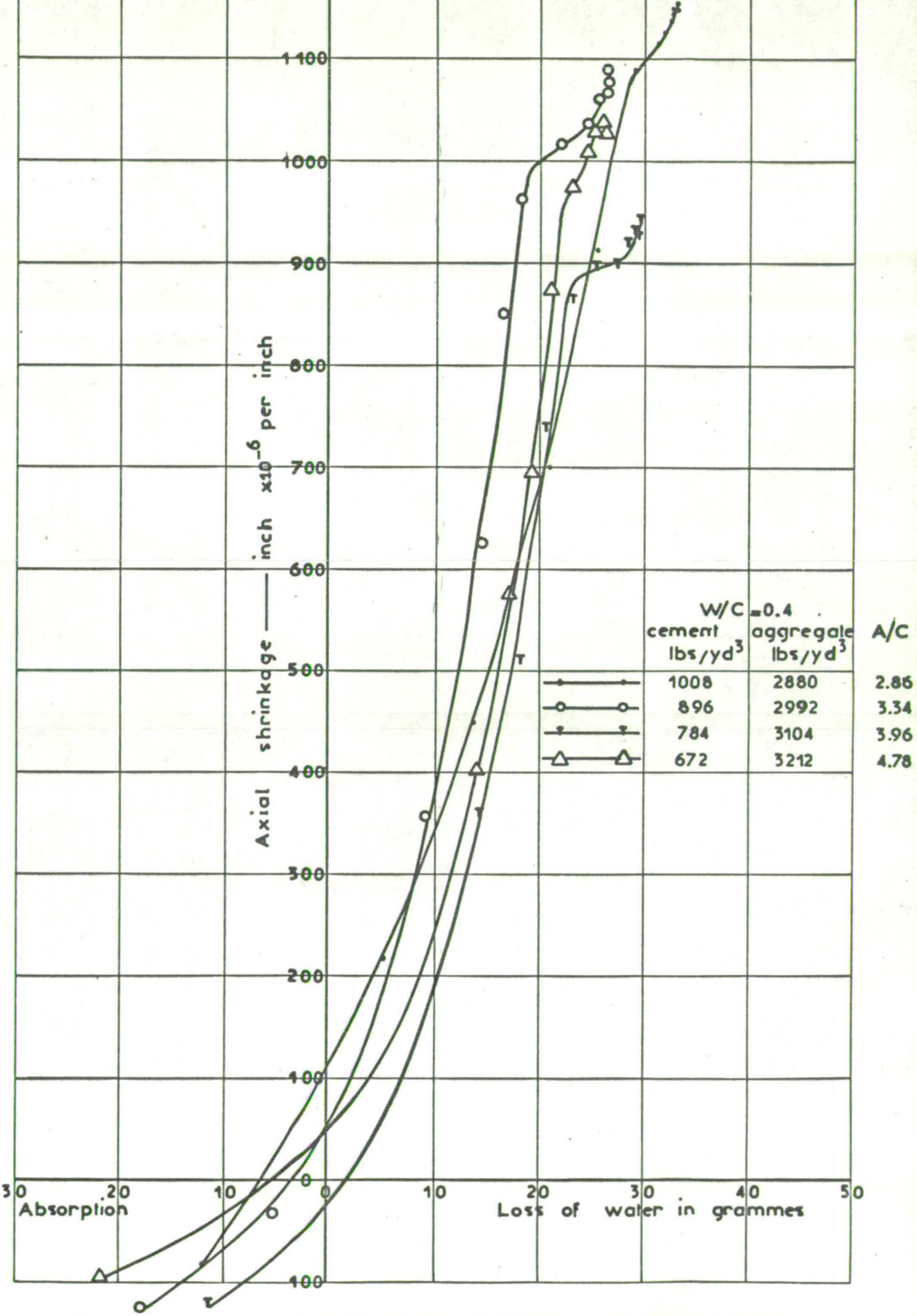


FIG.19 RELATION BETWEEN SHRINKAGE & LOSS OF WATER — EDDLESTON AGG

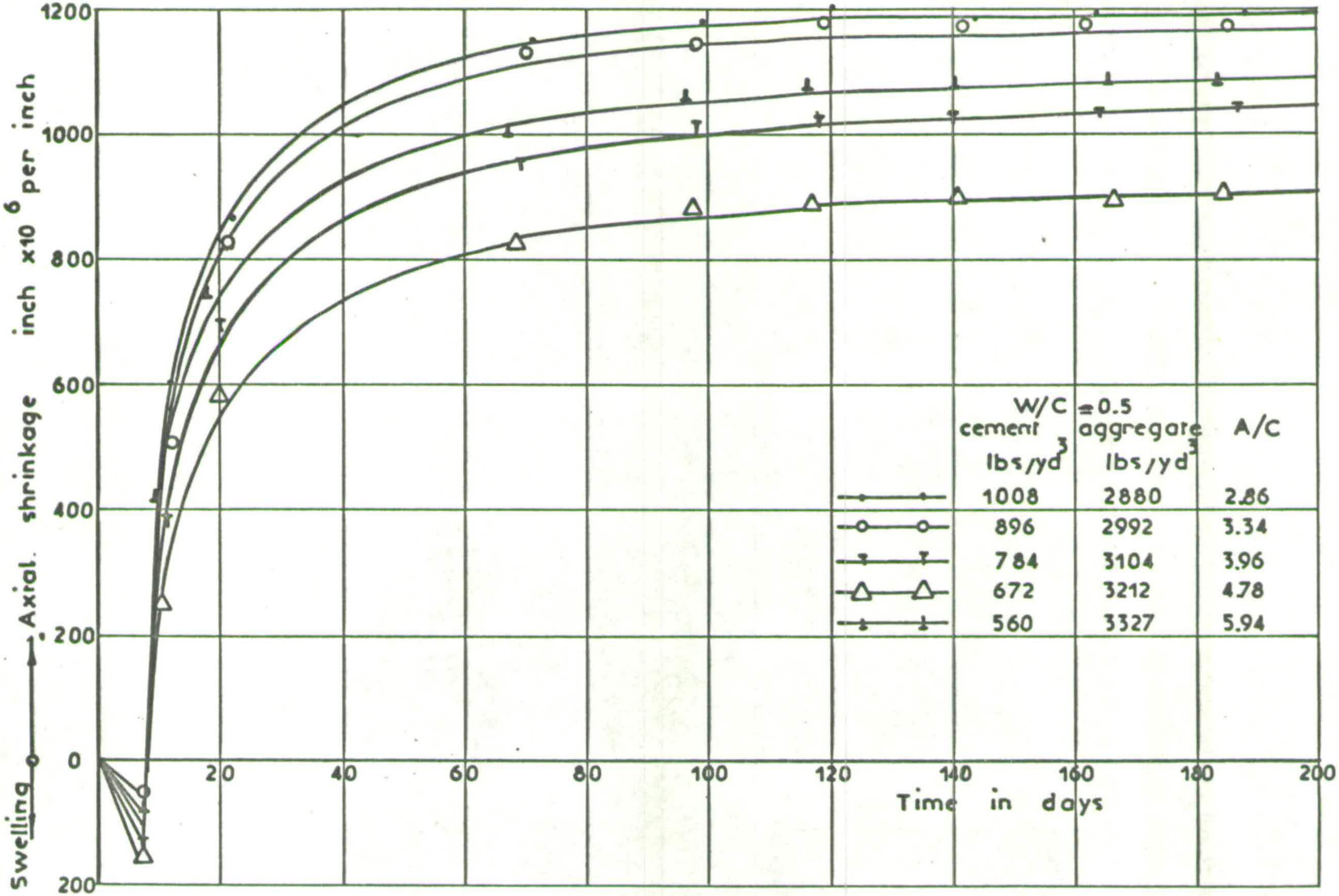


FIG.20 SHRINKAGE TIME CURVES —— EDDLESTON AGGREGATE DRYING IN LABORATORY CONDITION

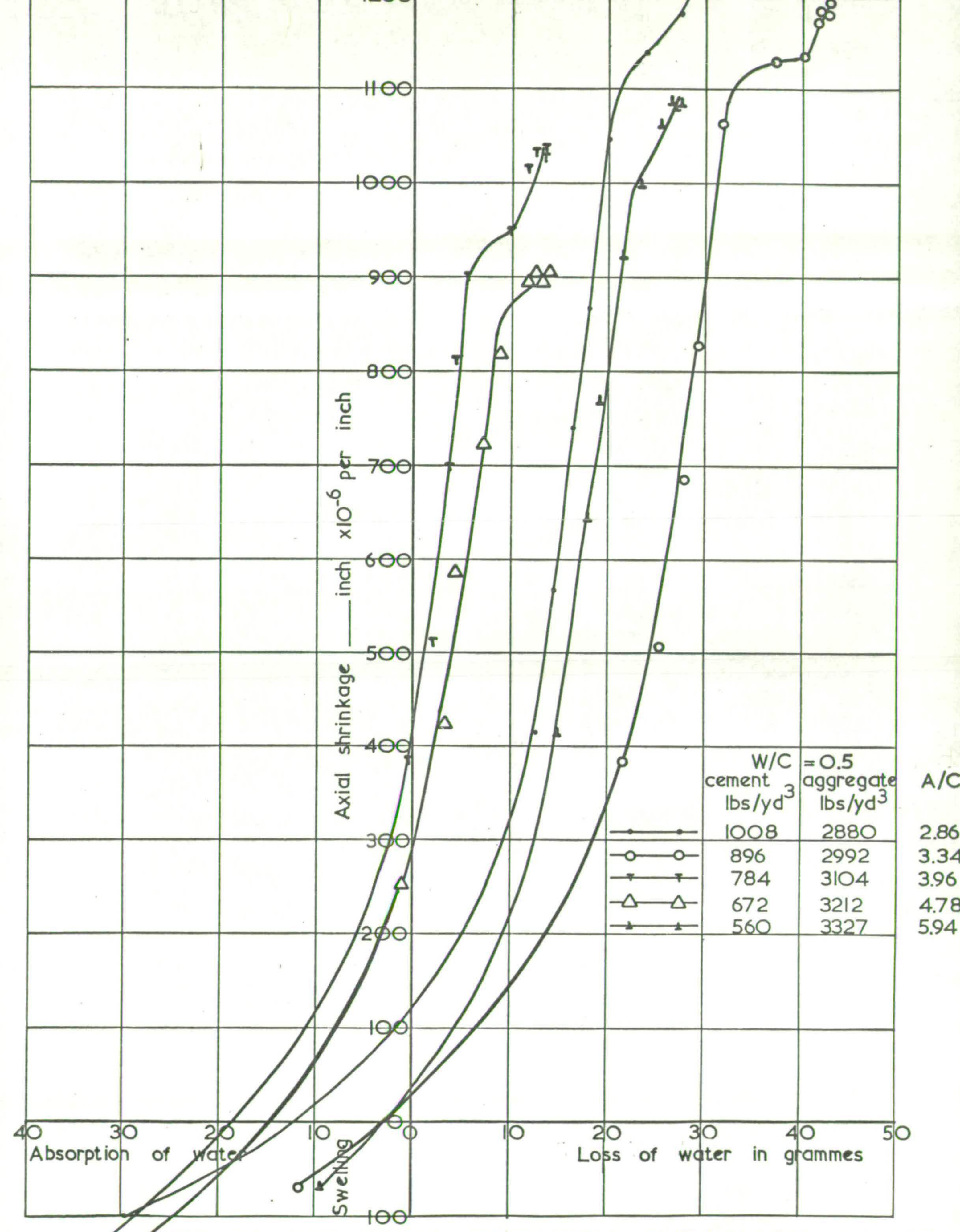


FIG. 21 RELATION BETWEEN SHRINKAGE & LOSS

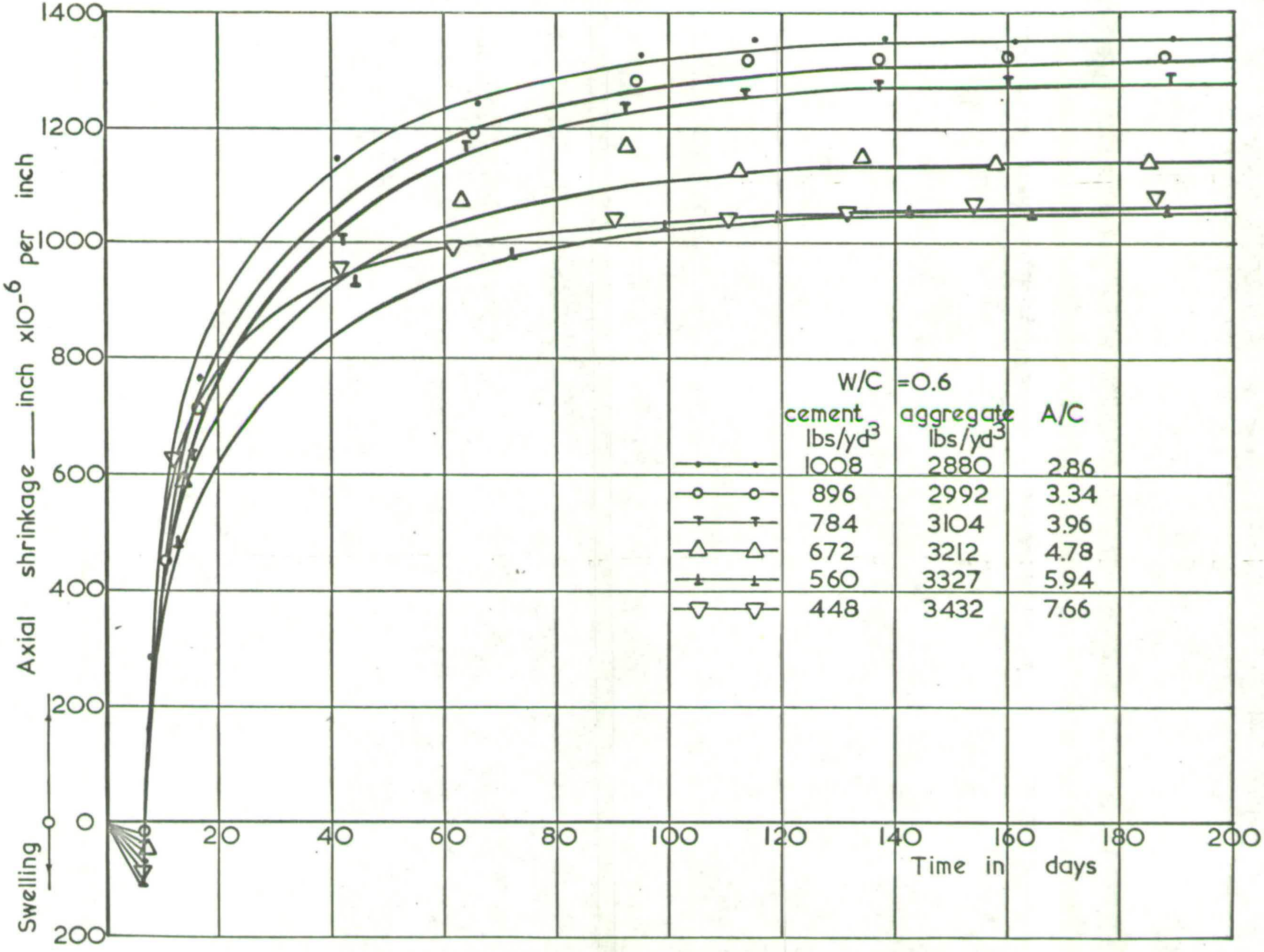


FIG.22 SHRINKAGE TIME CURVES —— EDDLESTON AGGREGATE DRYING IN LABORATORY CONDITION

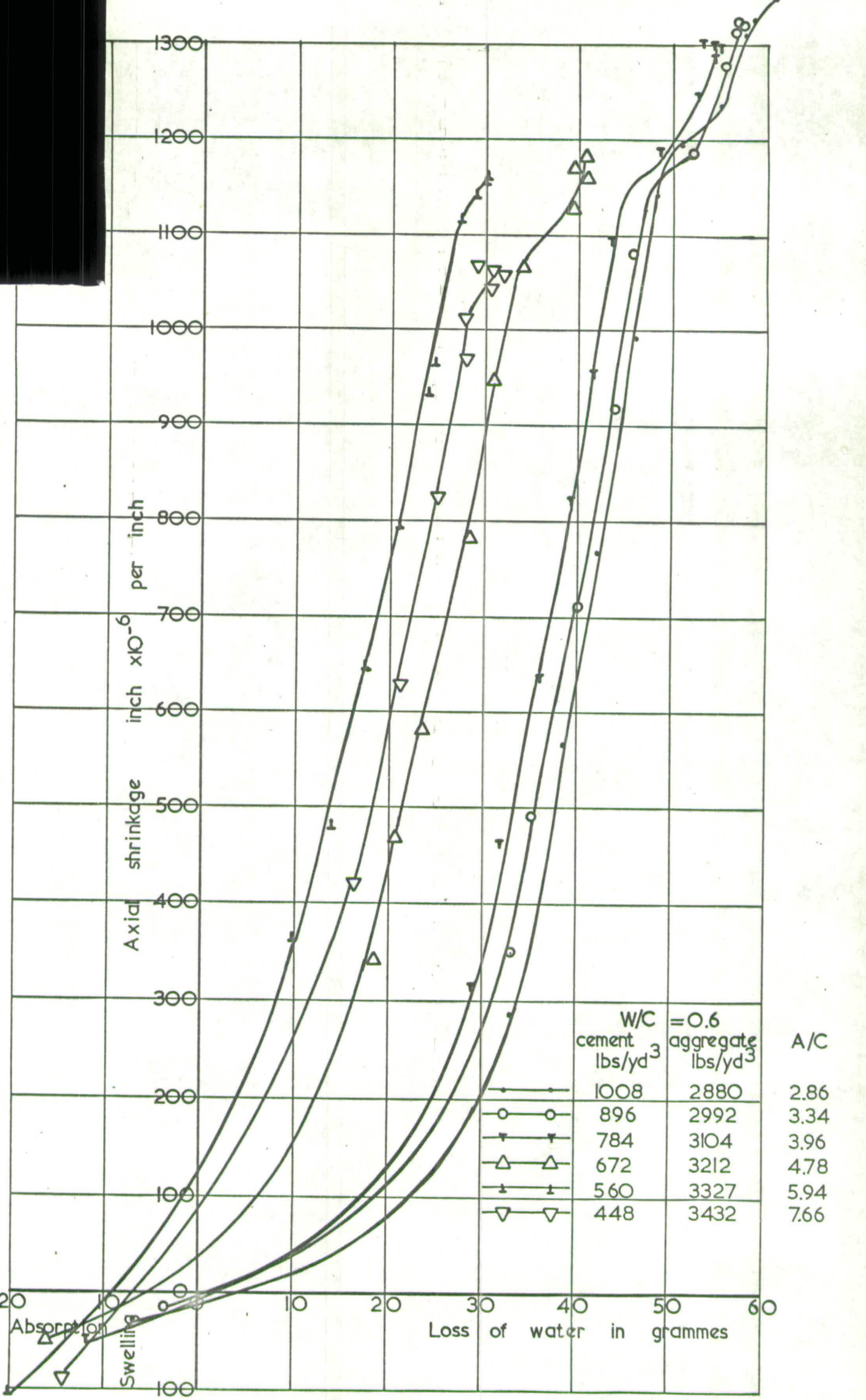


FIG. 23 RELATION BETWEEN SHRINKAGE & LOSS OF WATER—EDDLESTON AGG.

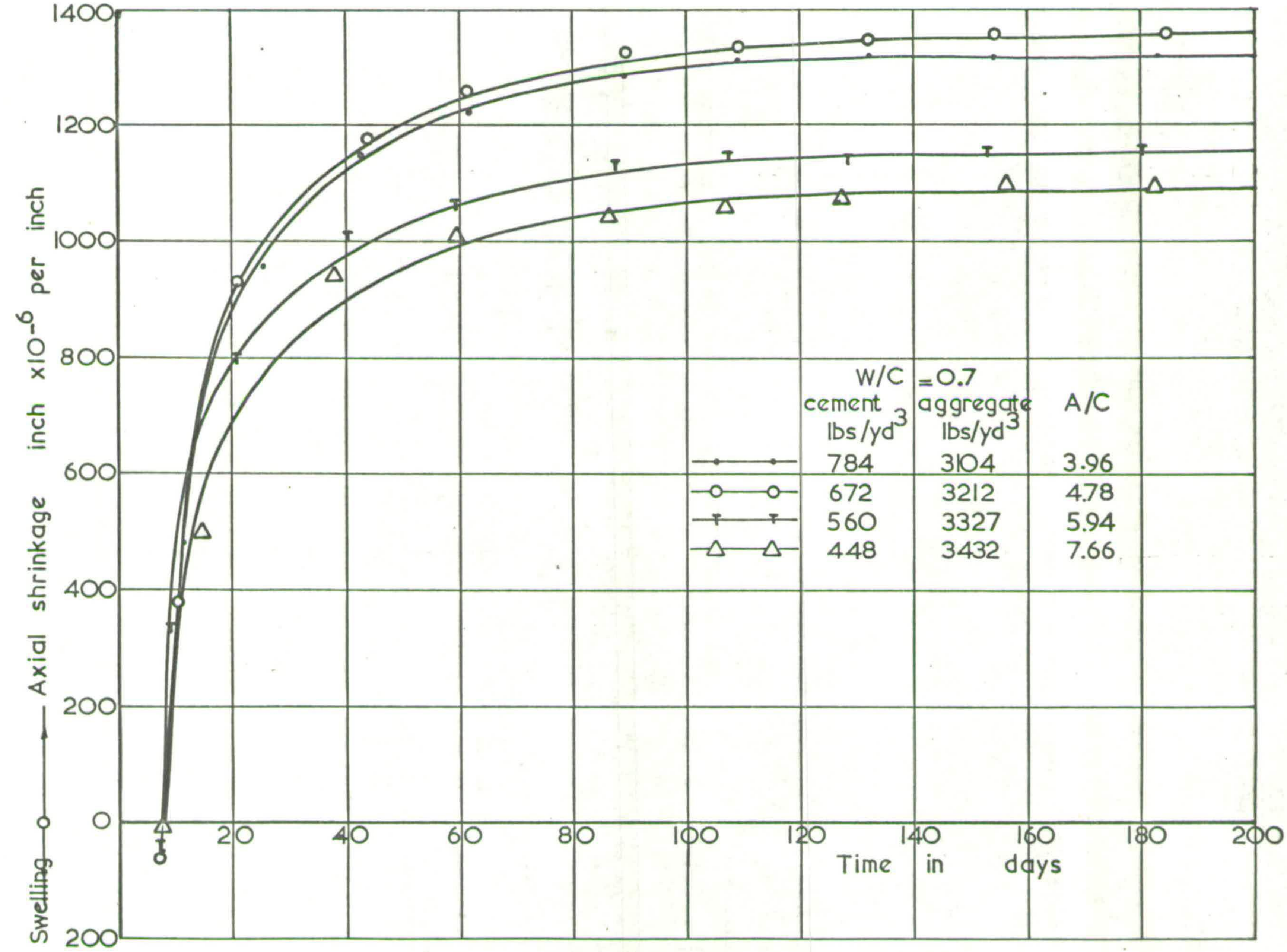


FIG.24 SHRINKAGE TIME CURVES — EDDLESTON AGGREGATE DRYING IN LABORATORY CONDITION

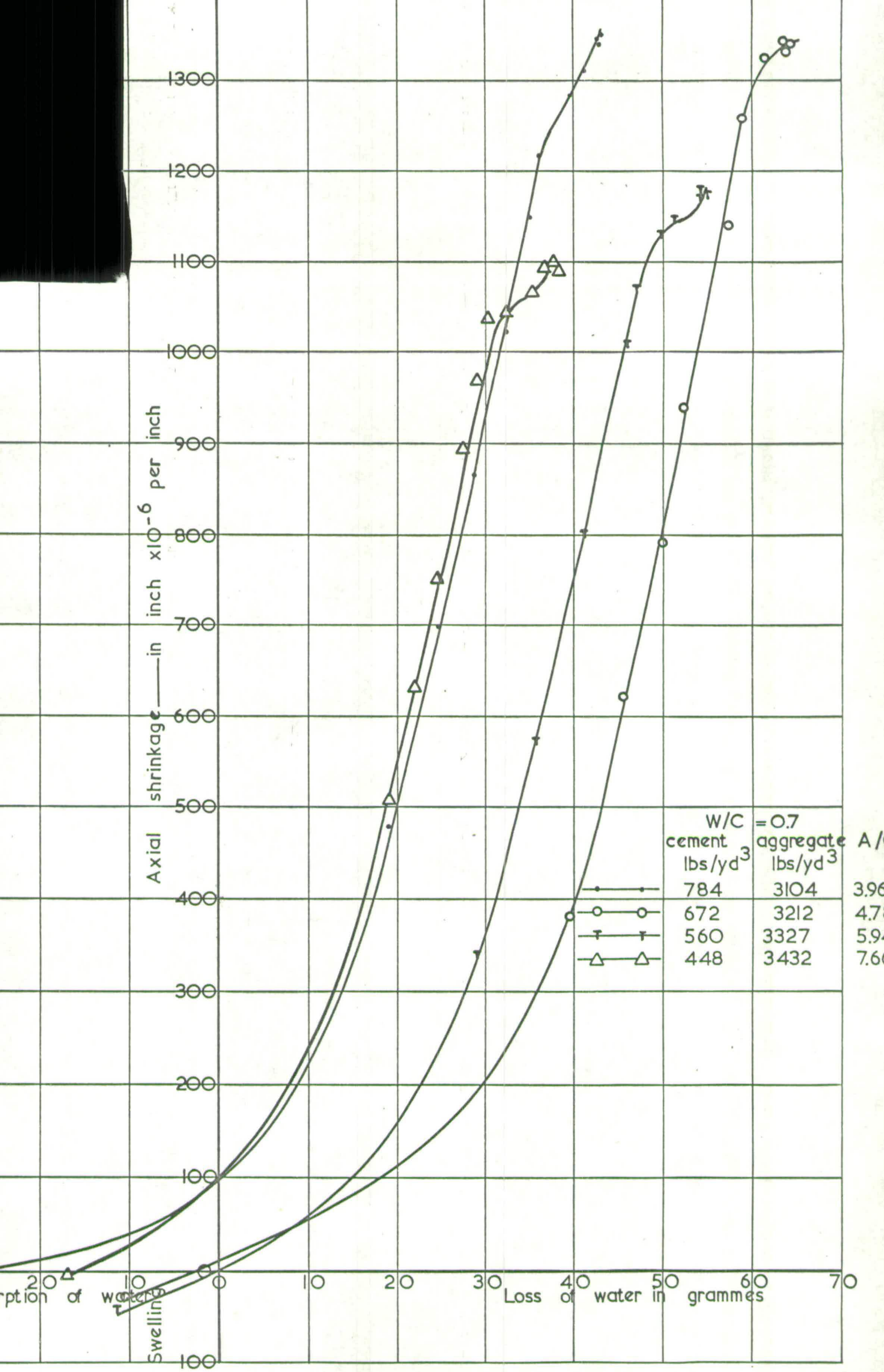


FIG.25 RELATION BETWEEN SHRINKAGE & LOSS

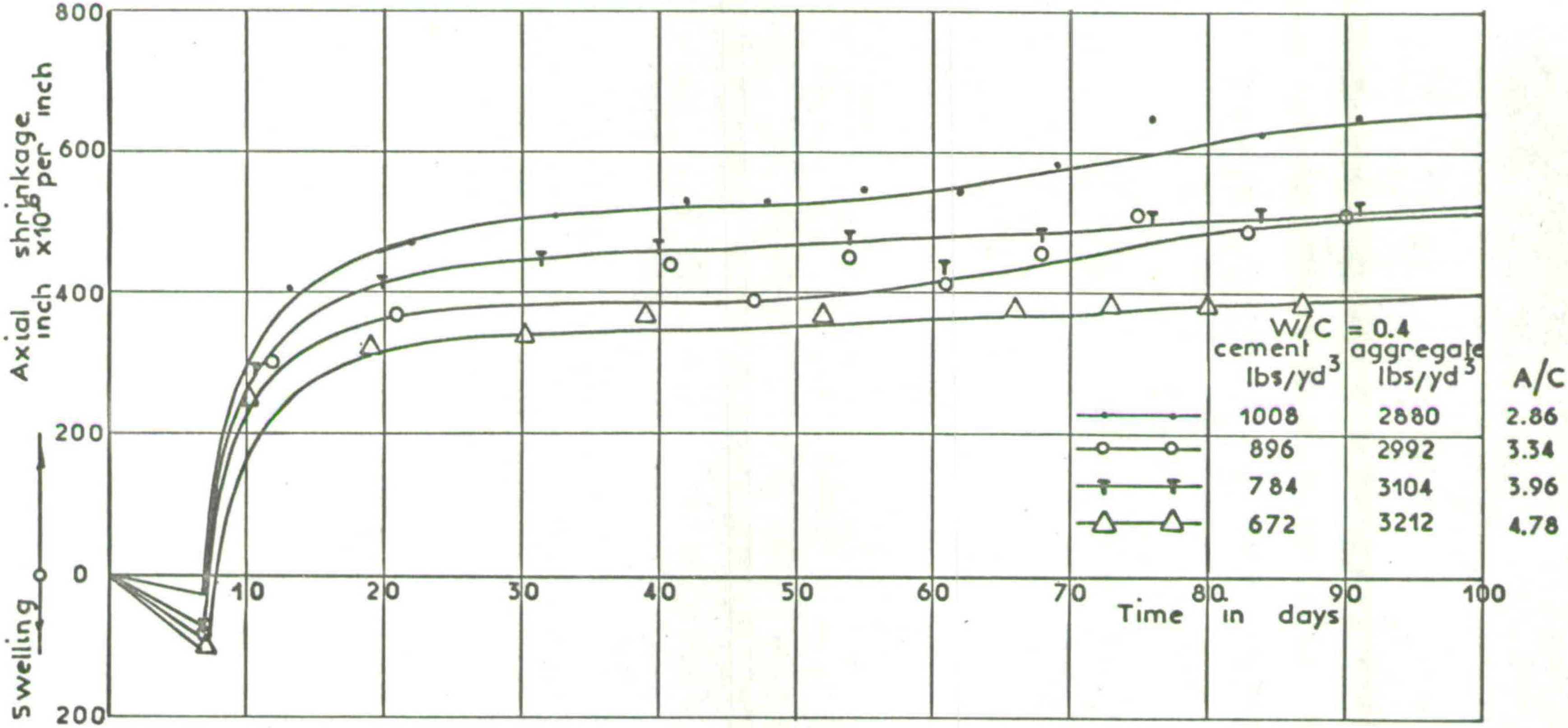


FIG.26 SHRINKAGE TIME CURVES ——BLAIRGOWRIE AGGREGATE OVEN DRYING

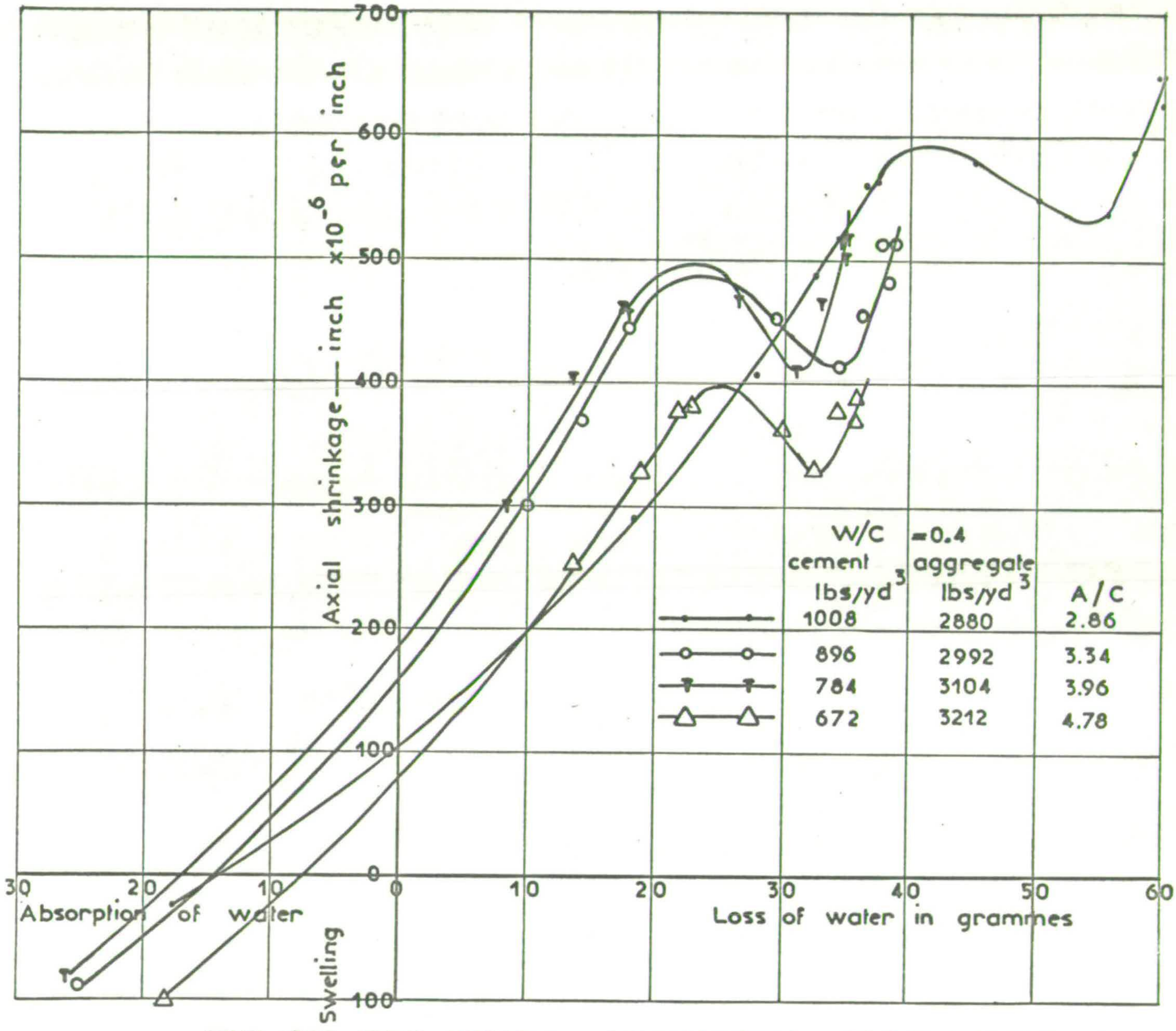


FIG. 27 RELATION BETWEEN SHRINKAGE & LOSS OF WATER — BLAIRGOWRIE — OVEN DRYING

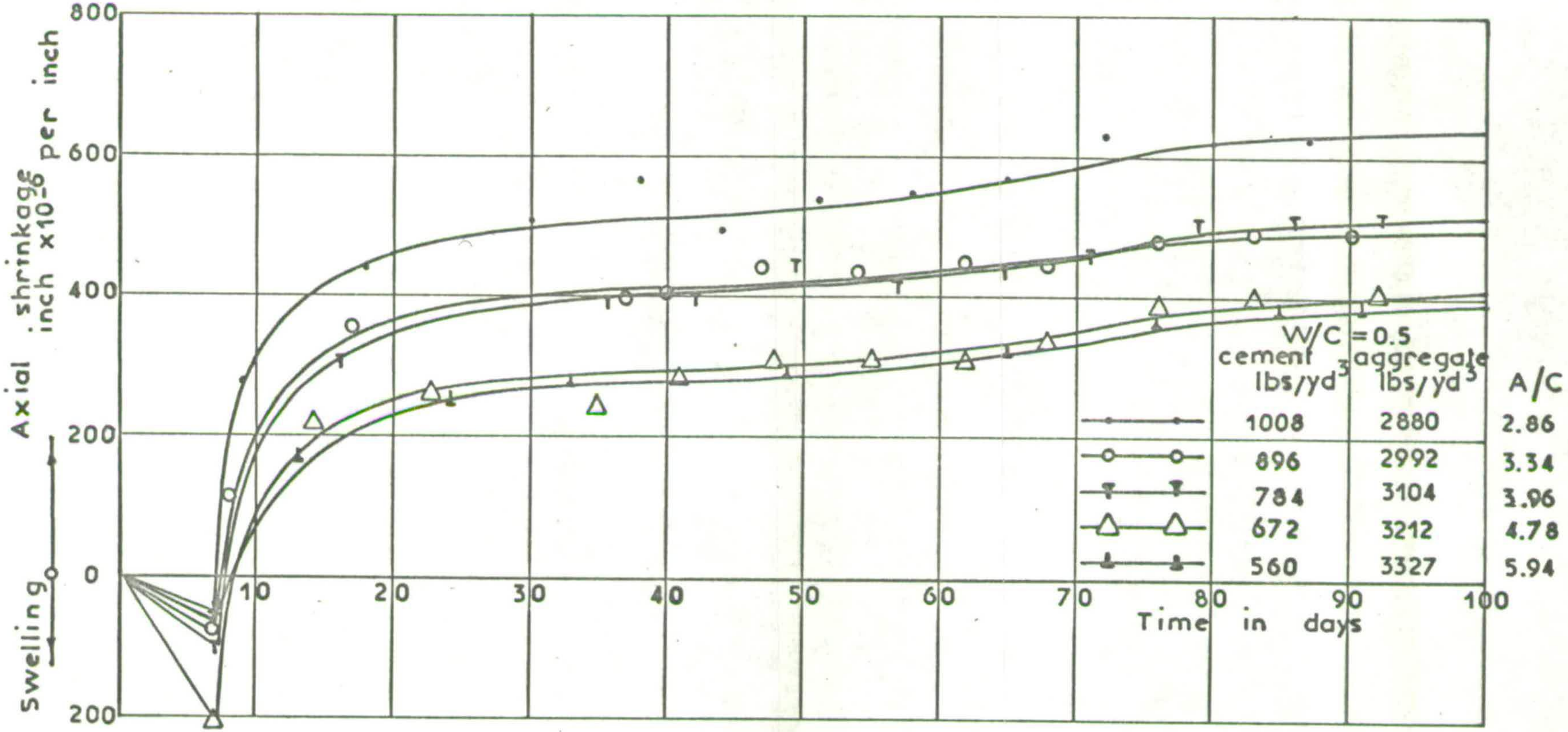


FIG. 28 SHRINKAGE TIME CURVES —— BLAIRGOWRIE AGGREGATE
OVEN DRYING

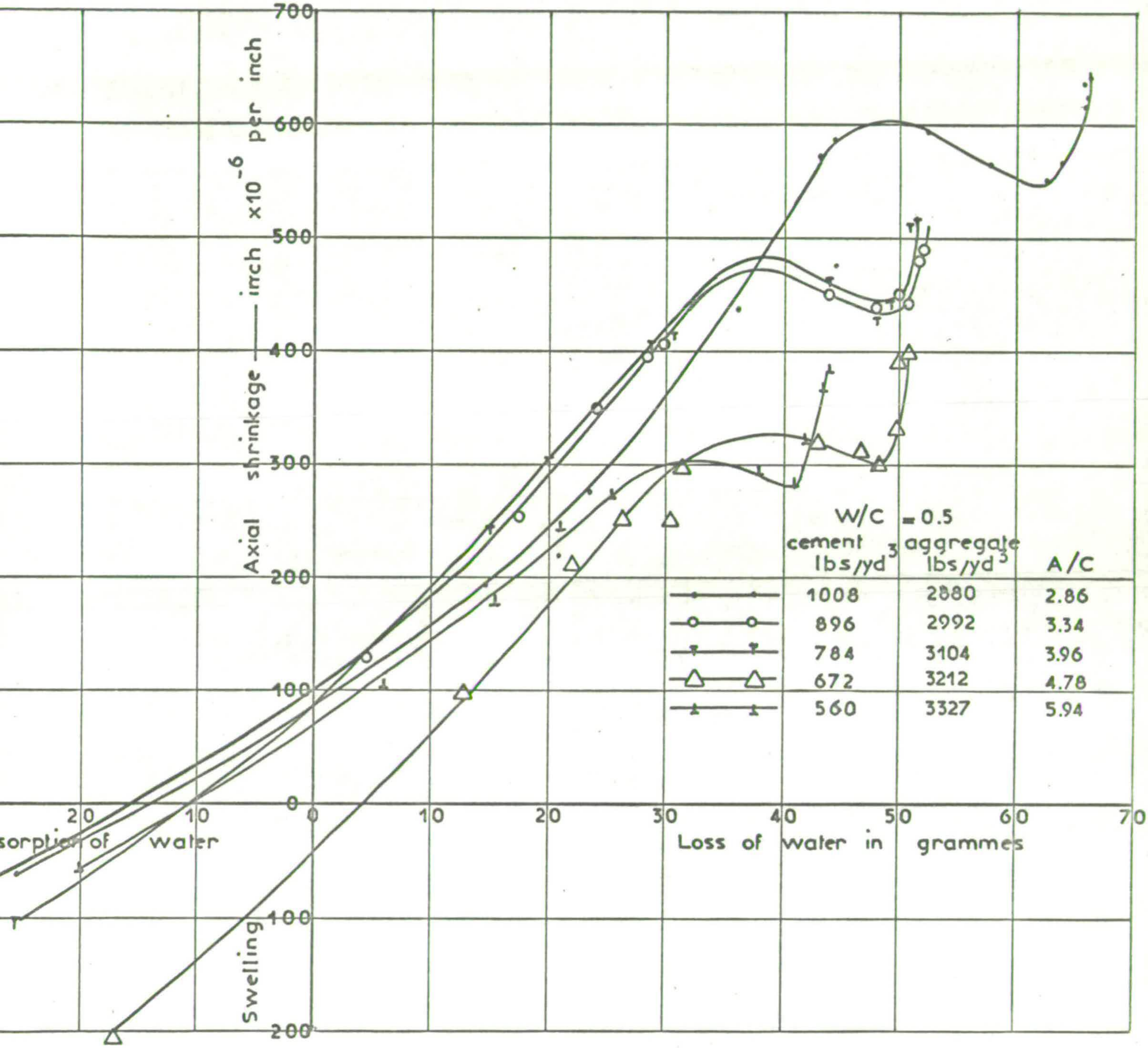


FIG.29 RELATION BETWEEN SHRINKAGE & LOSS OF WATER —— BLAIRGOWRIE —— OVEN DRYING

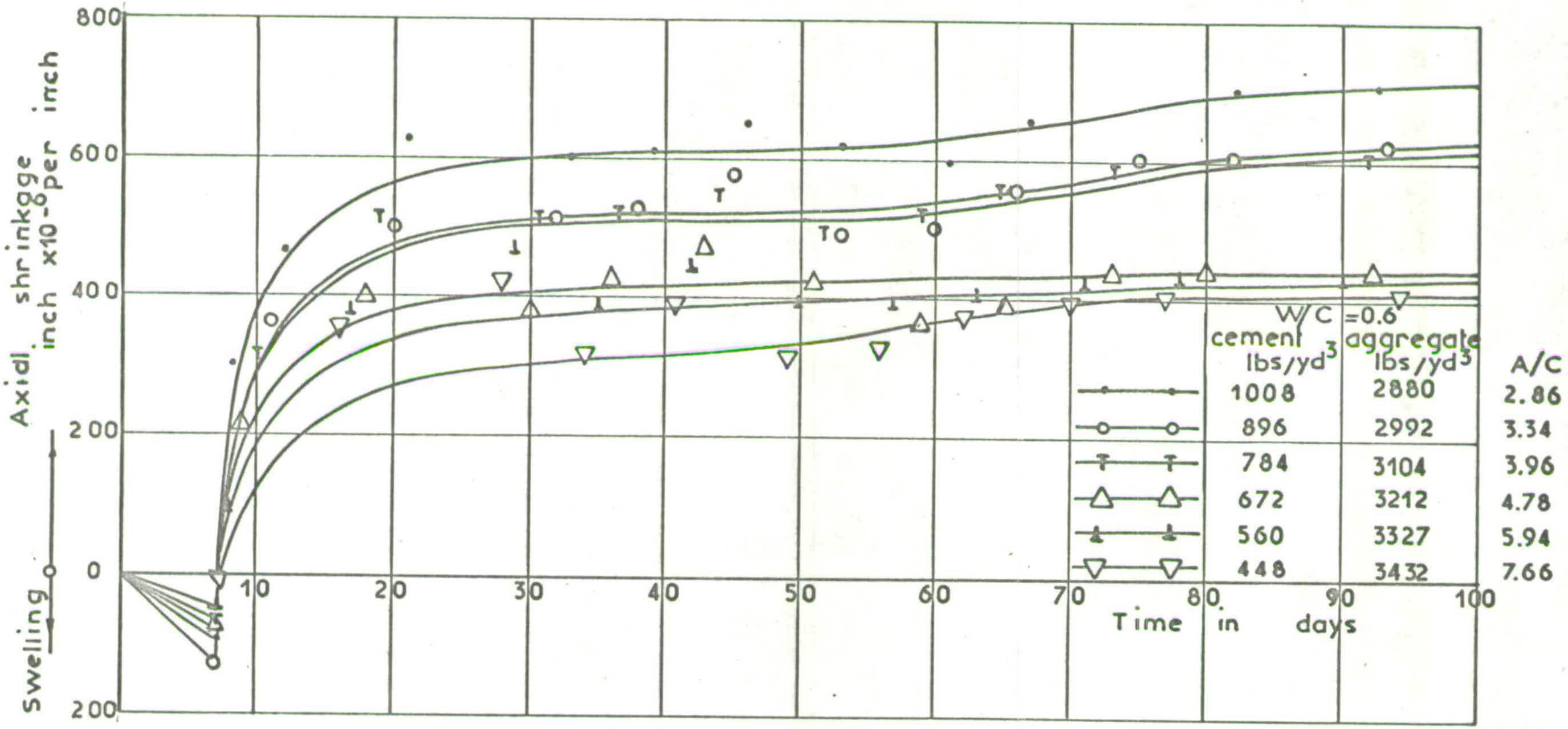


FIG.30 SHRINKAGE TIME CURVES —— BLAIRGOWRIE AGGREGATE
OVEN DRYING

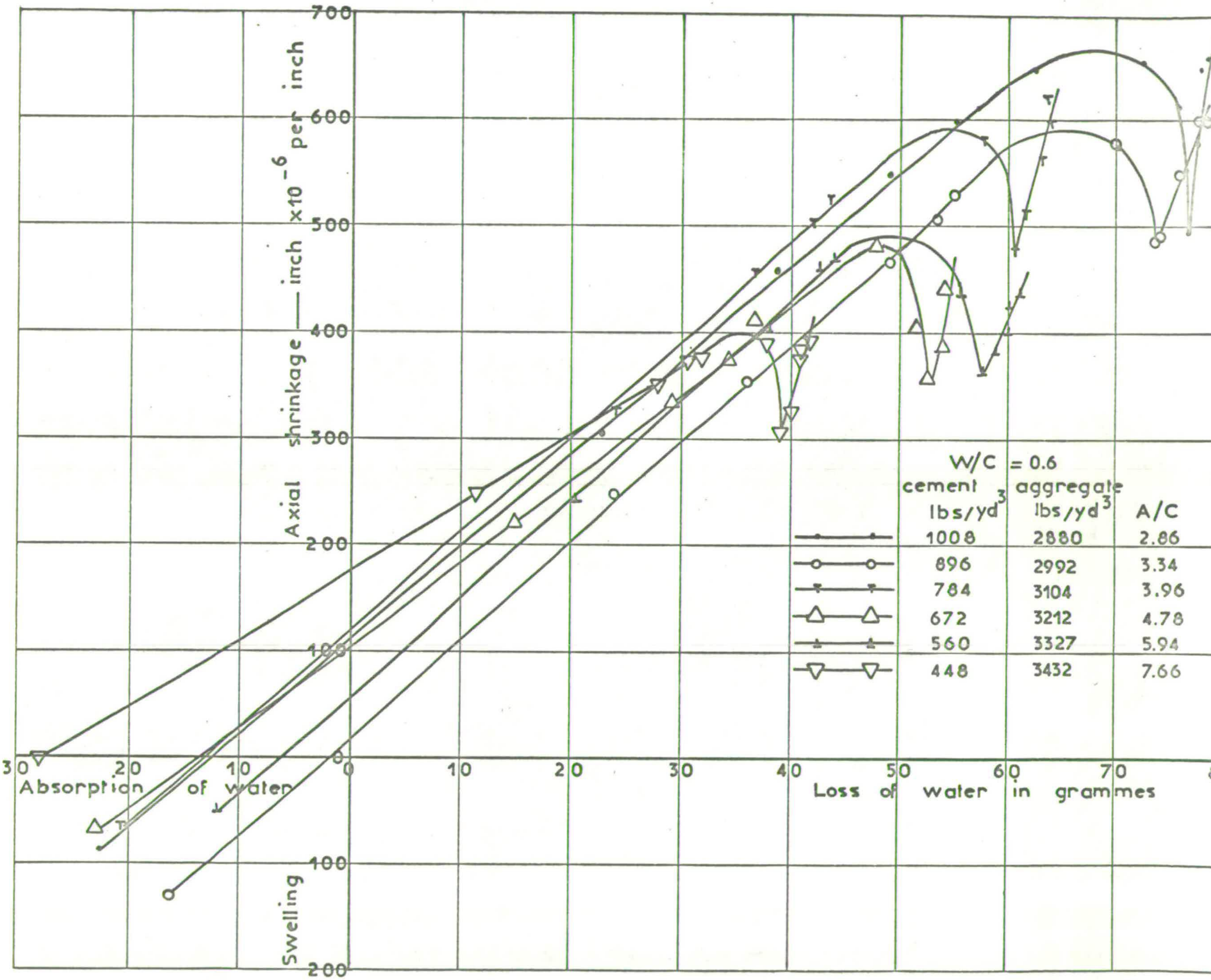


FIG. 31 RELATION BETWEEN SHRINKAGE & LOSS OF
WATER —— BLAIRGOWRIE —— OVEN DRYING

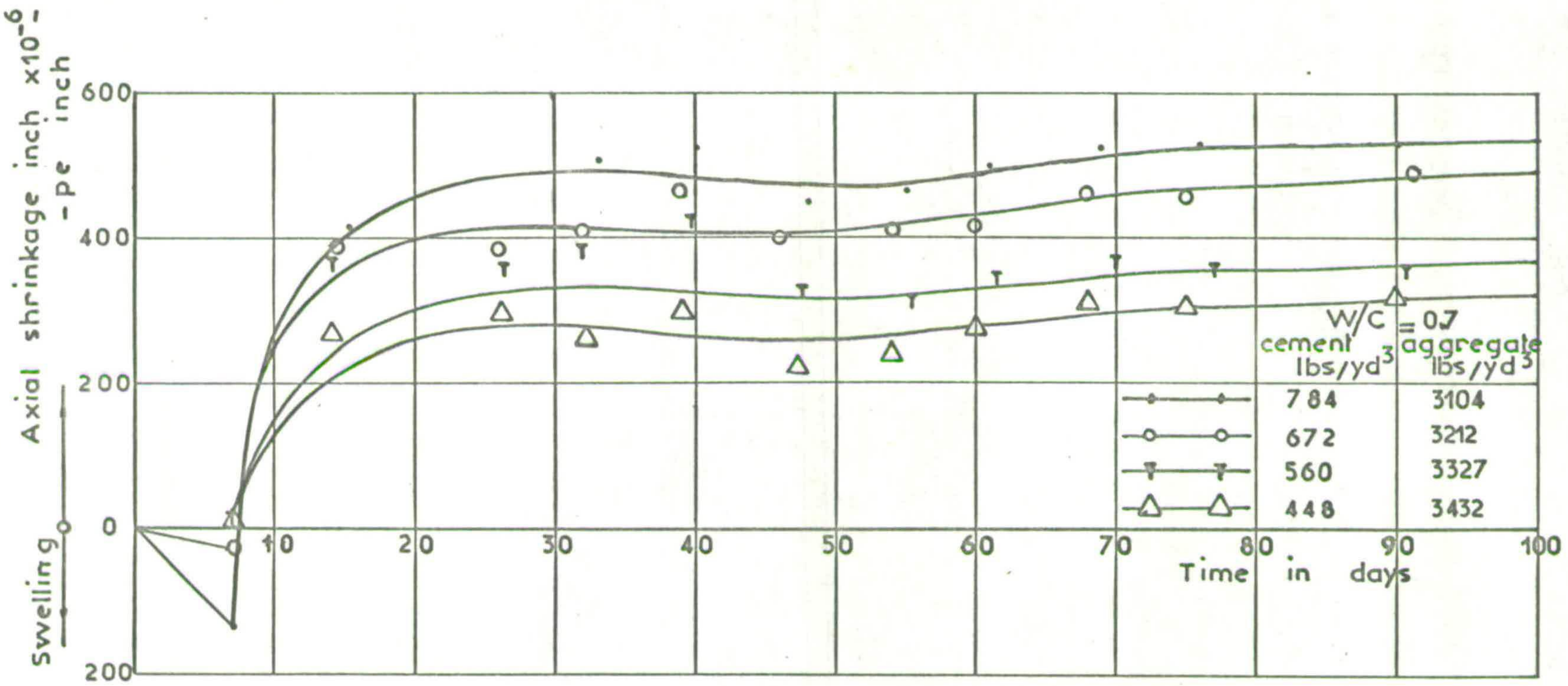


FIG.32 SHRINKAGE TIME CURVES——BLAIRGOWRIE AGGREGATE
OVEN DRYING

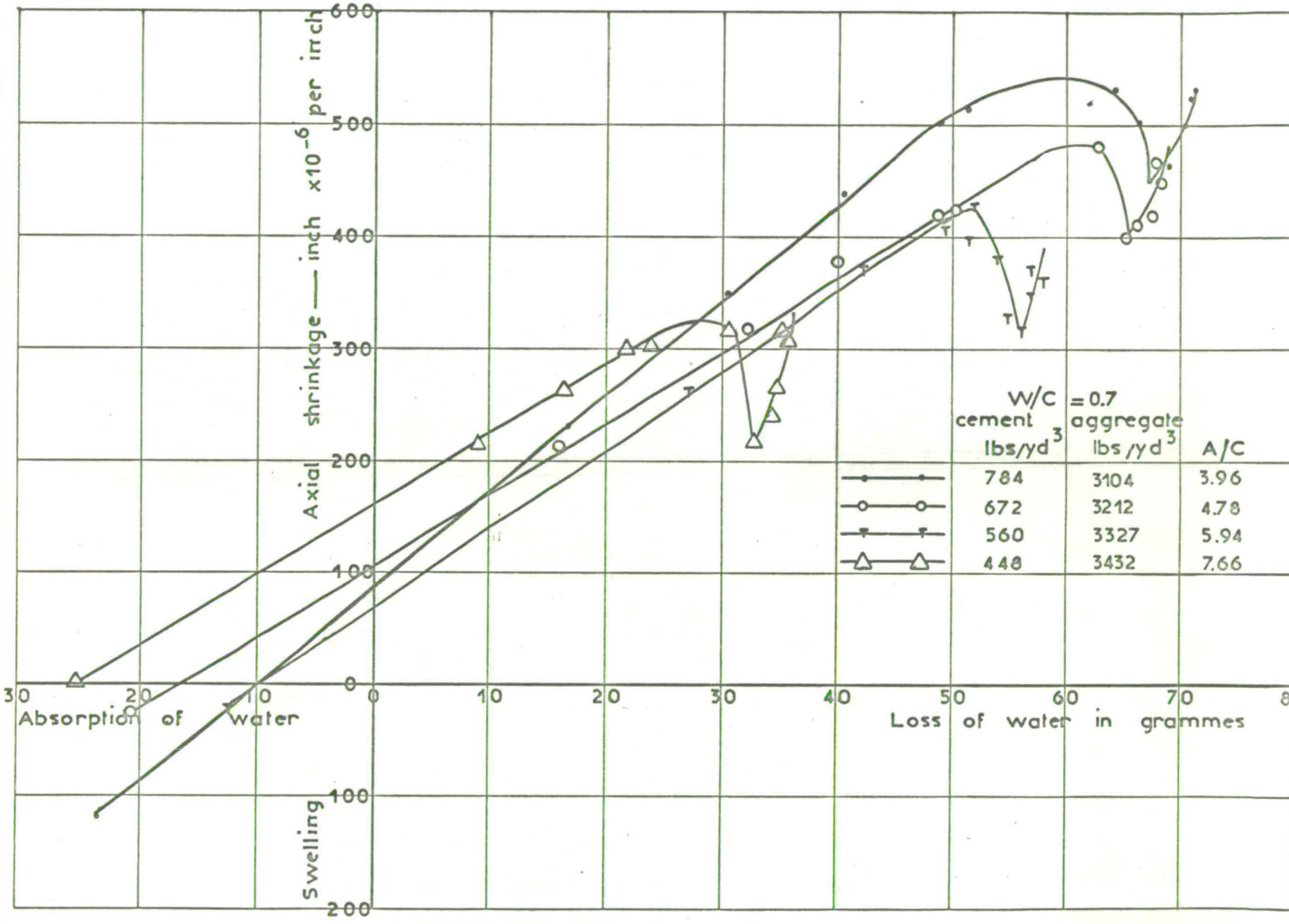


FIG.33 RELATION BETWEEN SHRINKAGE & LOSS OF WATER ____ BLAIRGOWRIE ____ OVEN DRYING

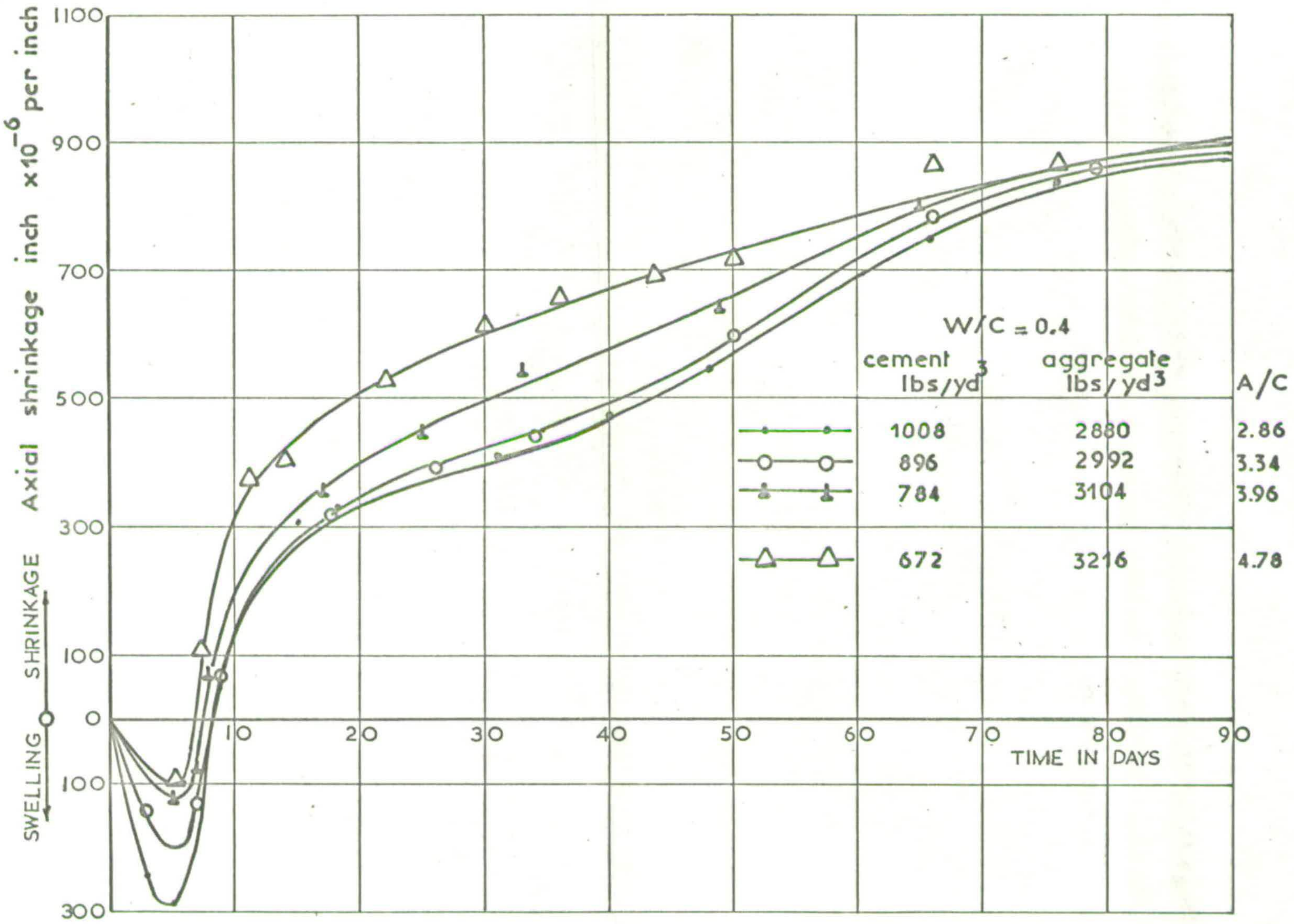


FIG. 34 SHRINKAGE TIME CURVES—WHINSTONE AGGREGATE OVEN DRYING

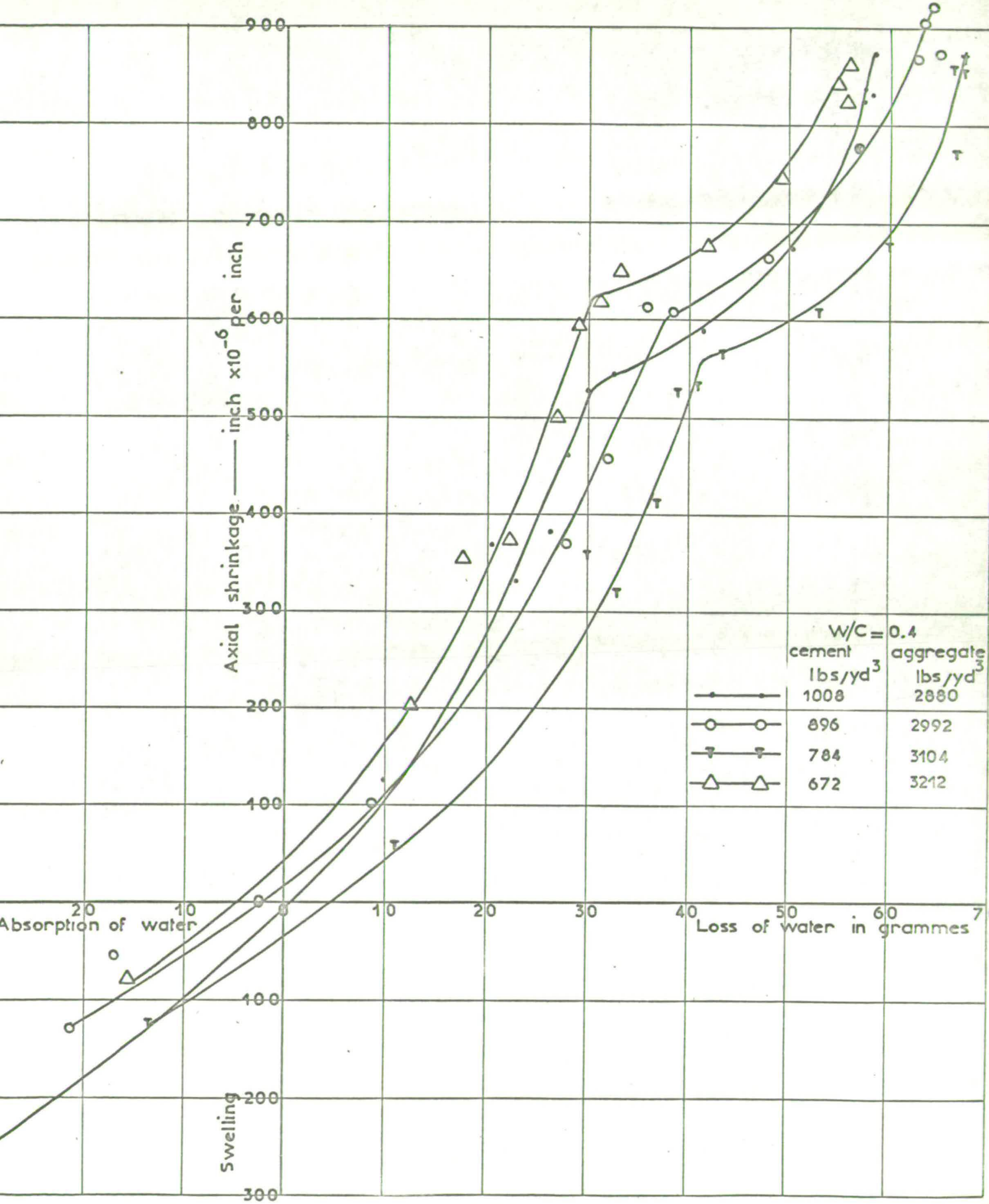


FIG.35 RELATION BETWEEN SHRINKAGE & LOSS OF WATER — WHINSTONE — OVEN DRYING

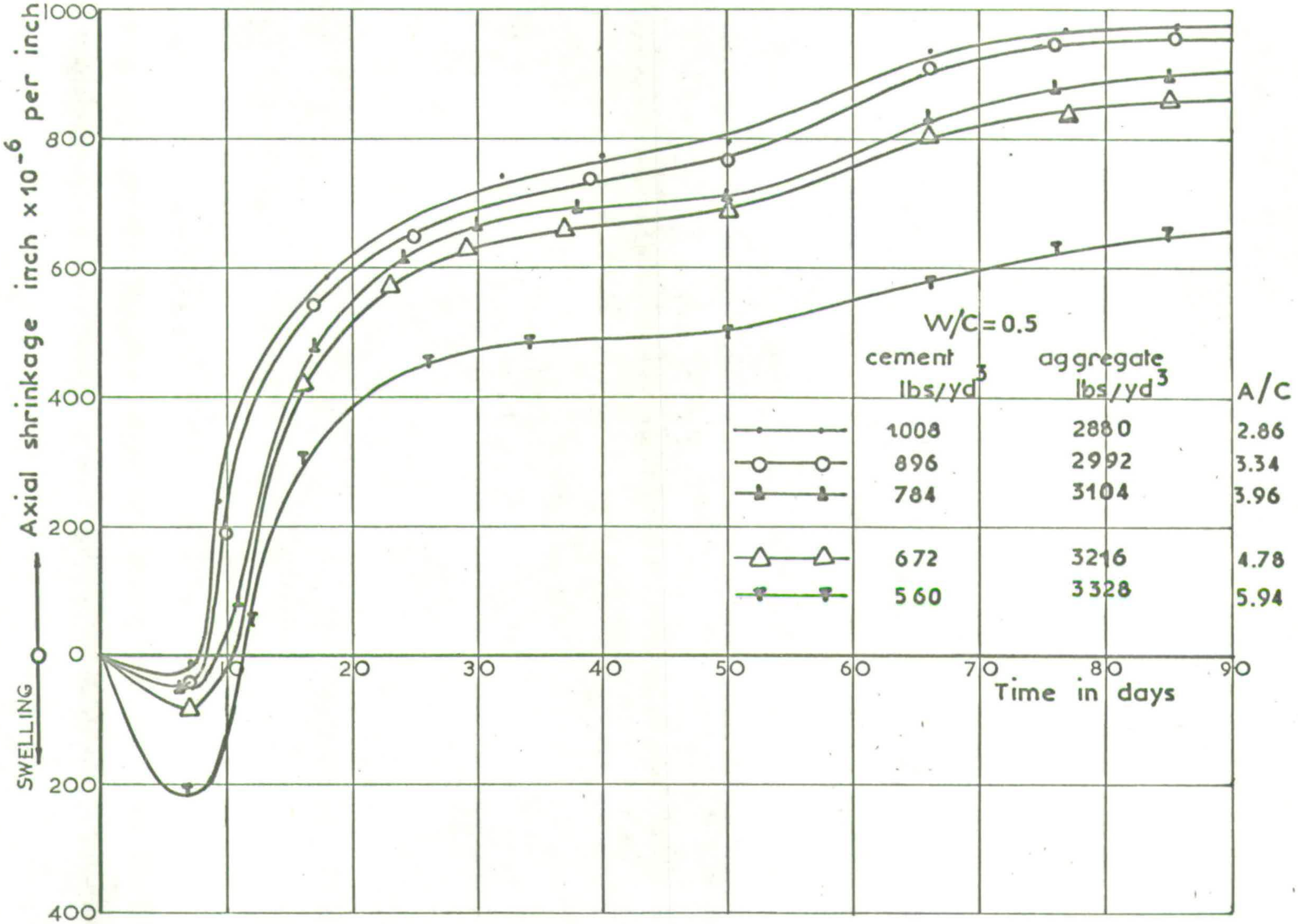


FIG 36 SHRINKAGE TIME CURVES WHINSTONE AGGREGATE

OVEN DRYING

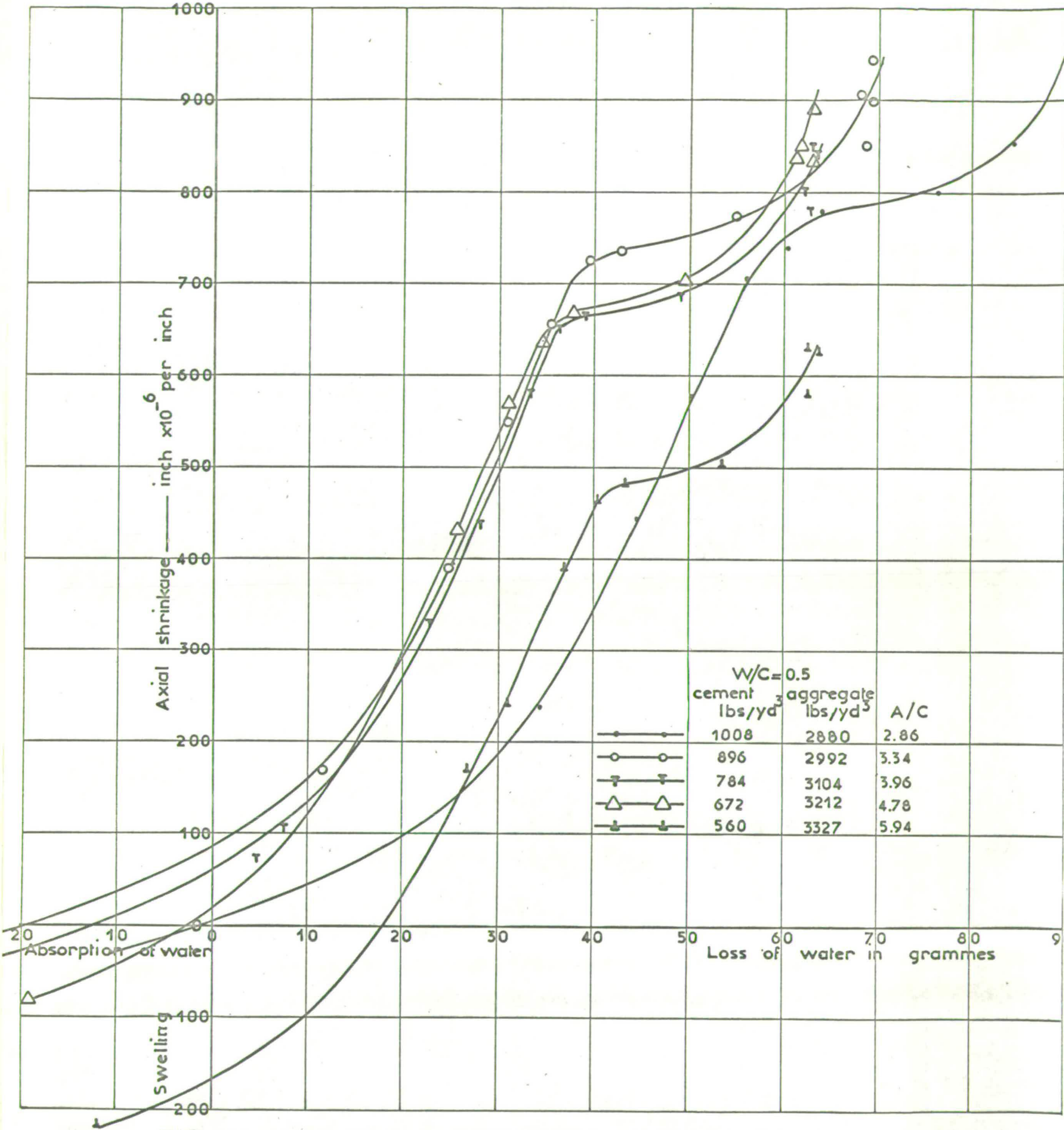


FIG. 37 RELATION BETWEEN SHRINKAGE & LOSS OF WATER —— WHINSTONE —— OVEN DRYING

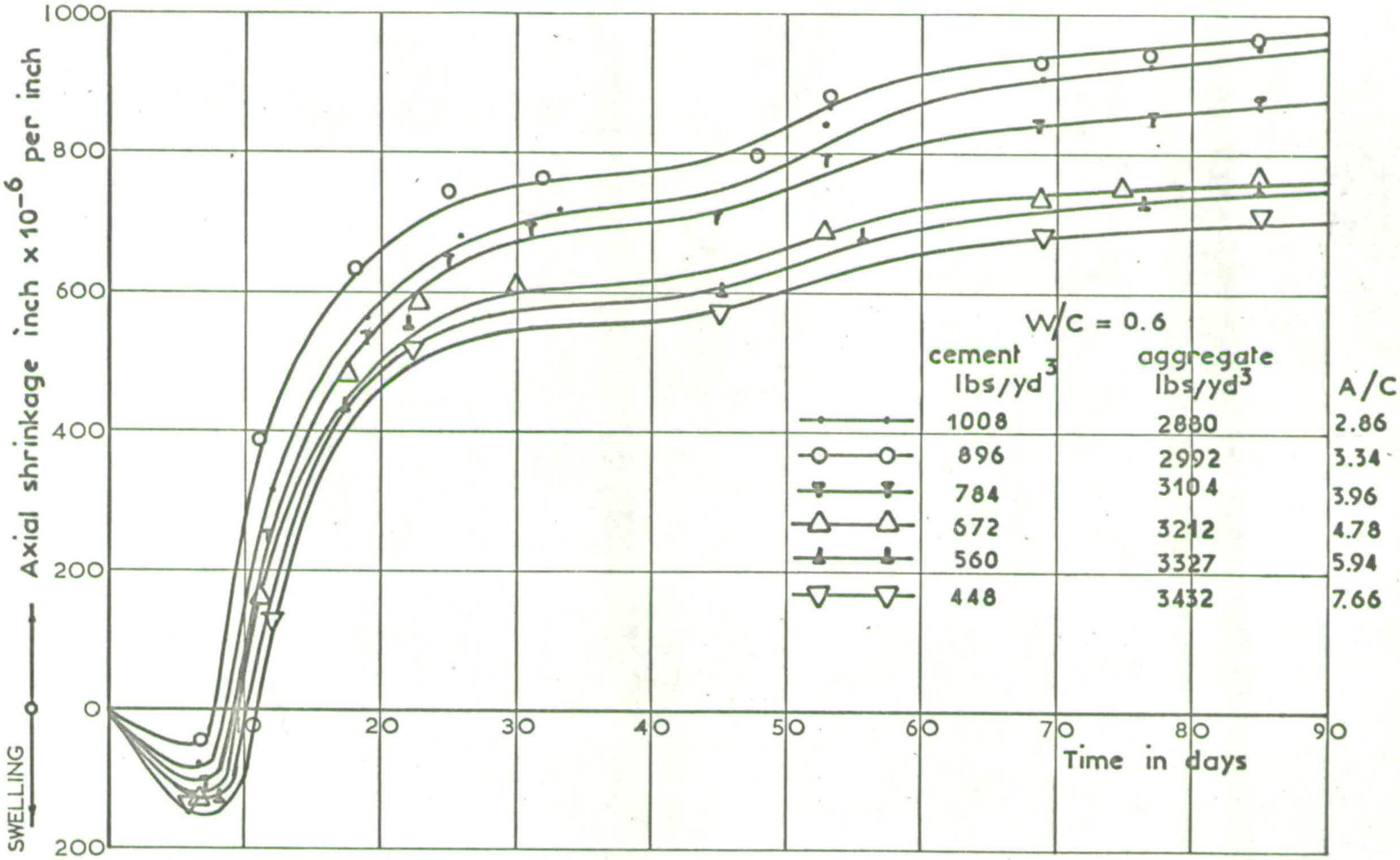


FIG.38 SHRINKAGE TIME CURVES — WHINSTONE AGGREGATE OVEN DRYING

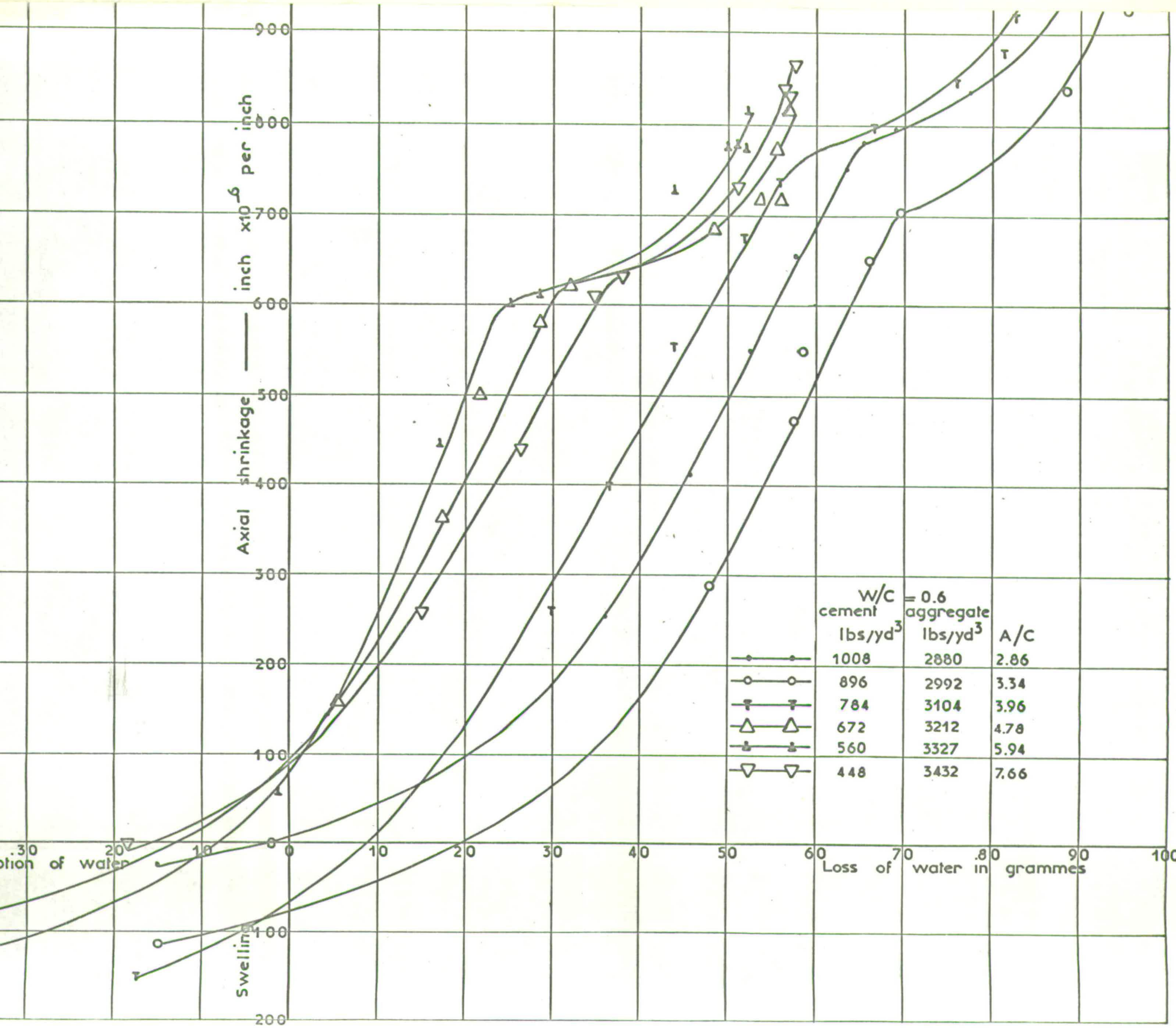
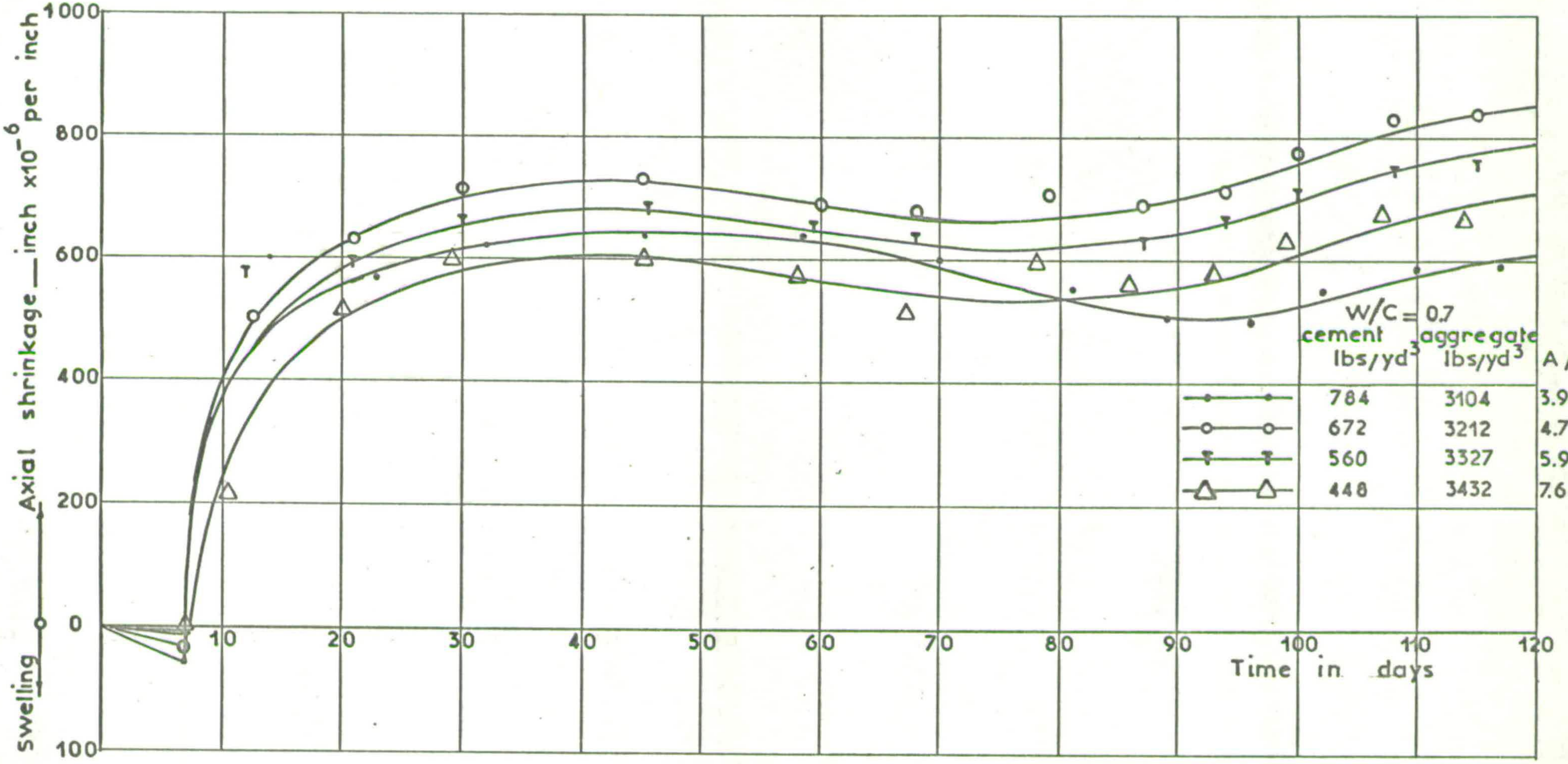


FIG.39 RELATION BETWEEN SHRINKAGE & LOSS OF WATER

WHINSTONE AGGREGATE — OVEN DRYING



IG.40 SHRINKAGE TIME CURVES —— WHINSTONE AGGREGATE — OVEN DRYING

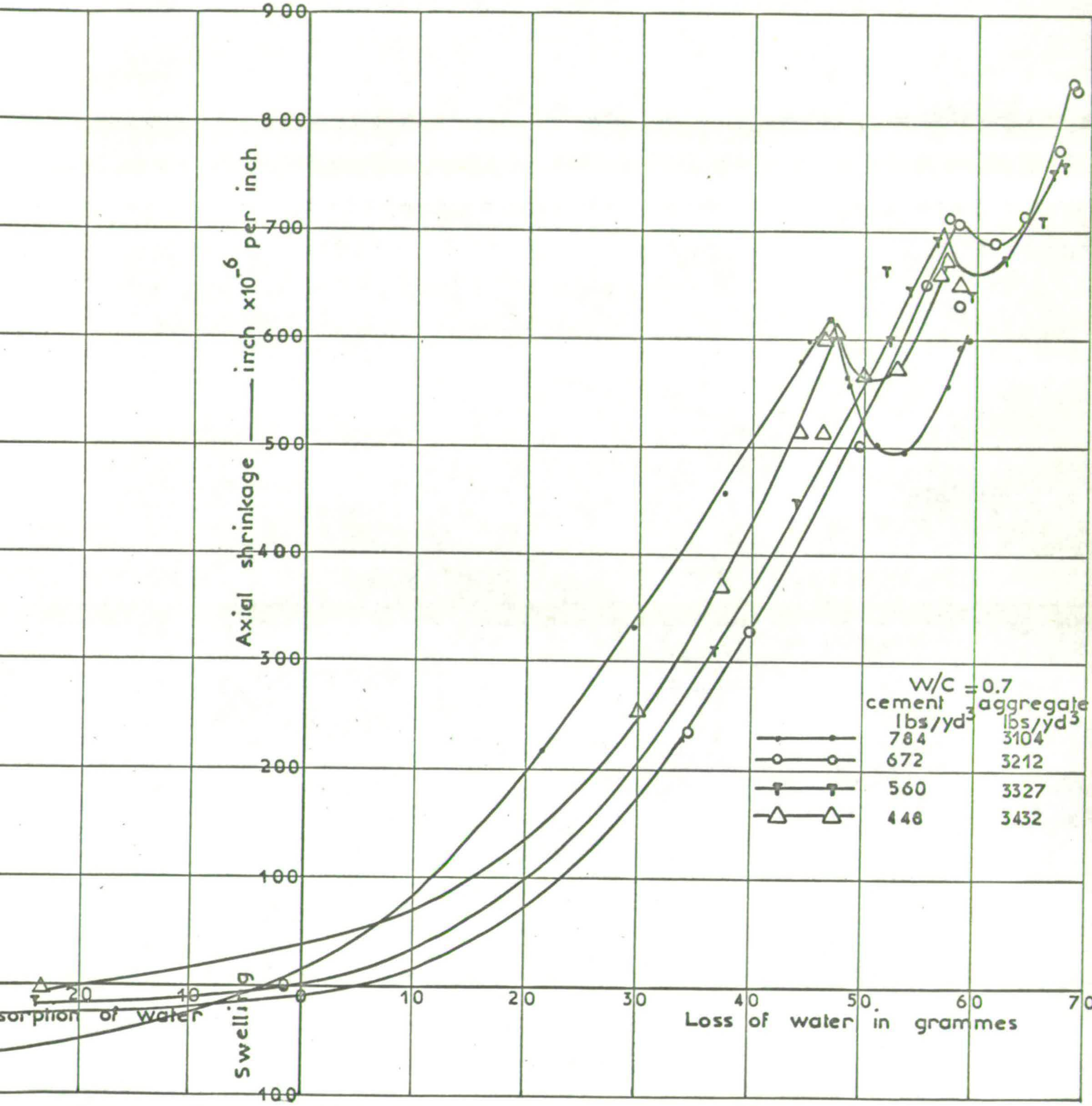


FIG.41 RELATION BETWEEN SHRINKAGE & LOSS OF WATER WHINSTONE OVEN DRYING

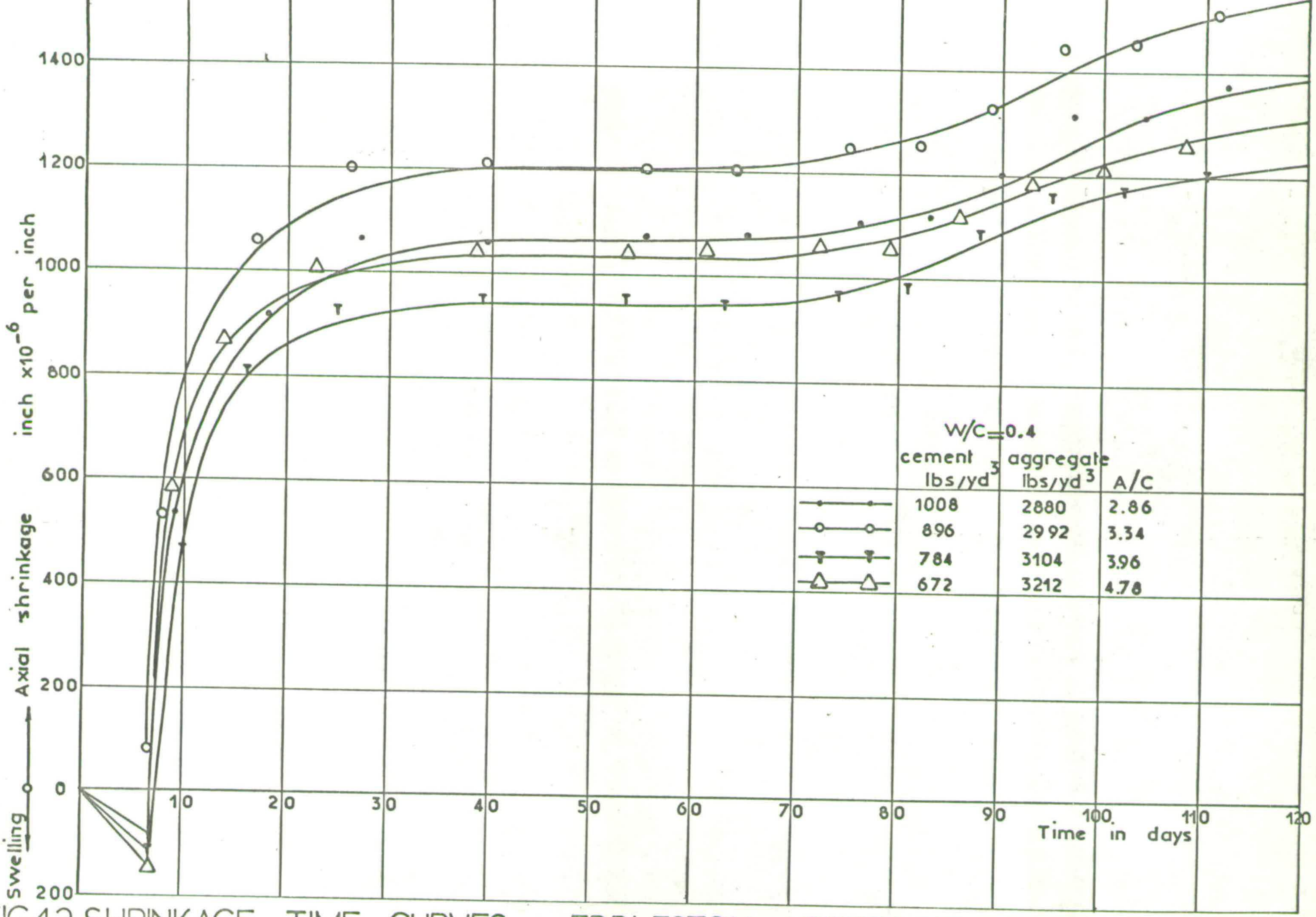


FIG.42 SHRINKAGE TIME CURVES — EDDLESTON AGGREGATE — OVEN DRYING

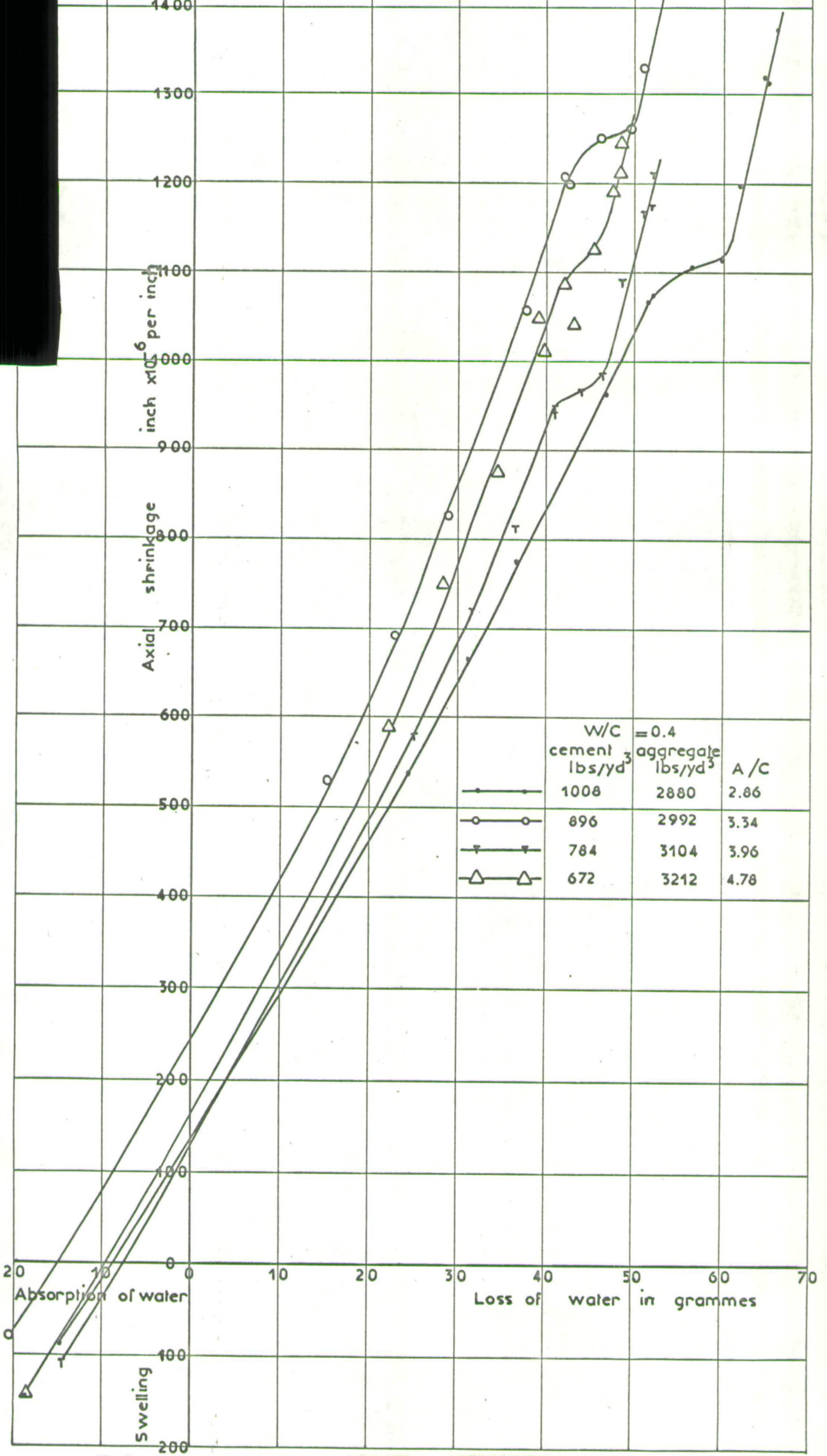


FIG.43 RELATION BETWEEN SHRINKAGE & LOSS OF WATER — EDDLESTON — OVEN DRYING

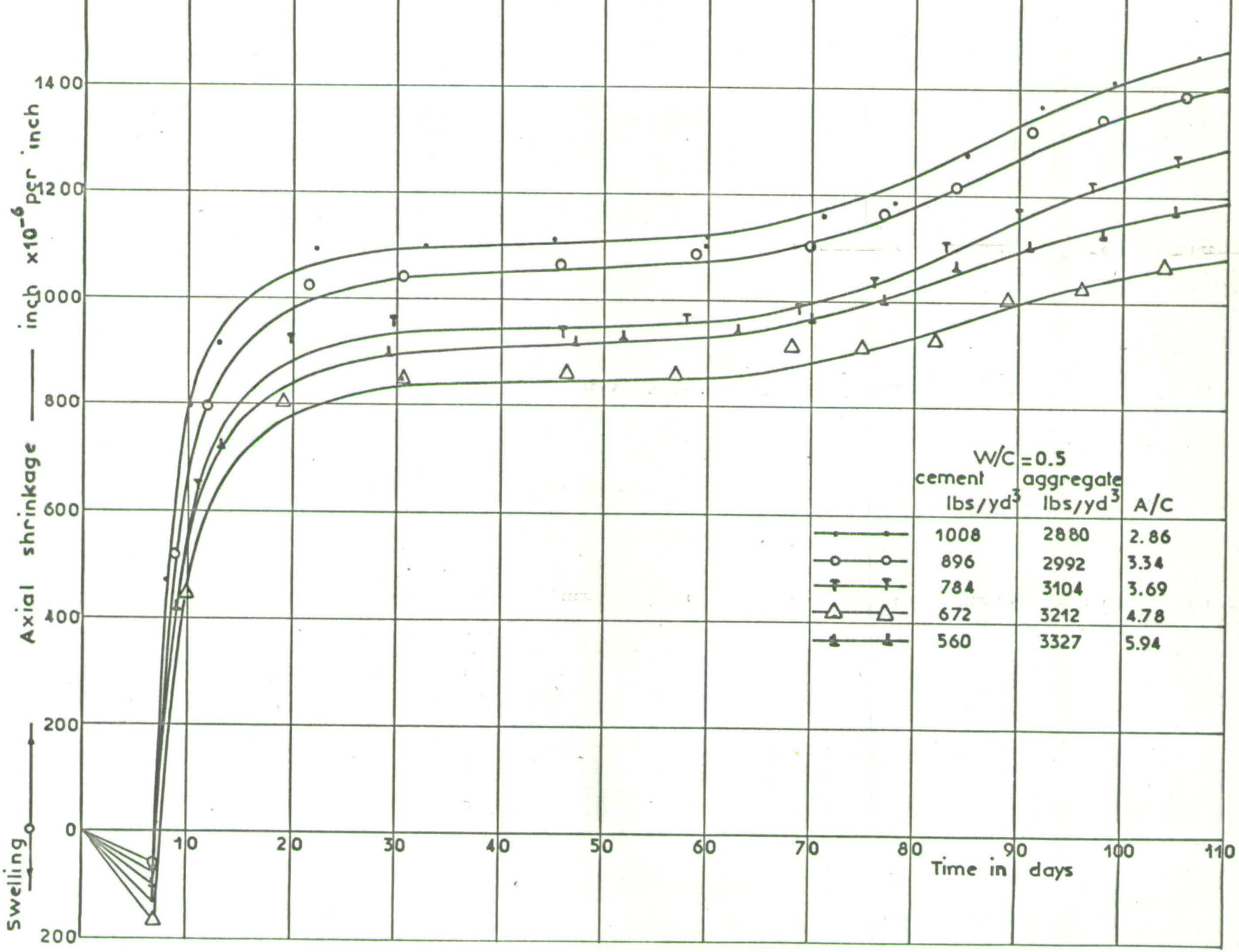


FIG.44 SHRINKAGE TIME CURVES — EDDLESTON AGGREGATE — OVEN DRYING

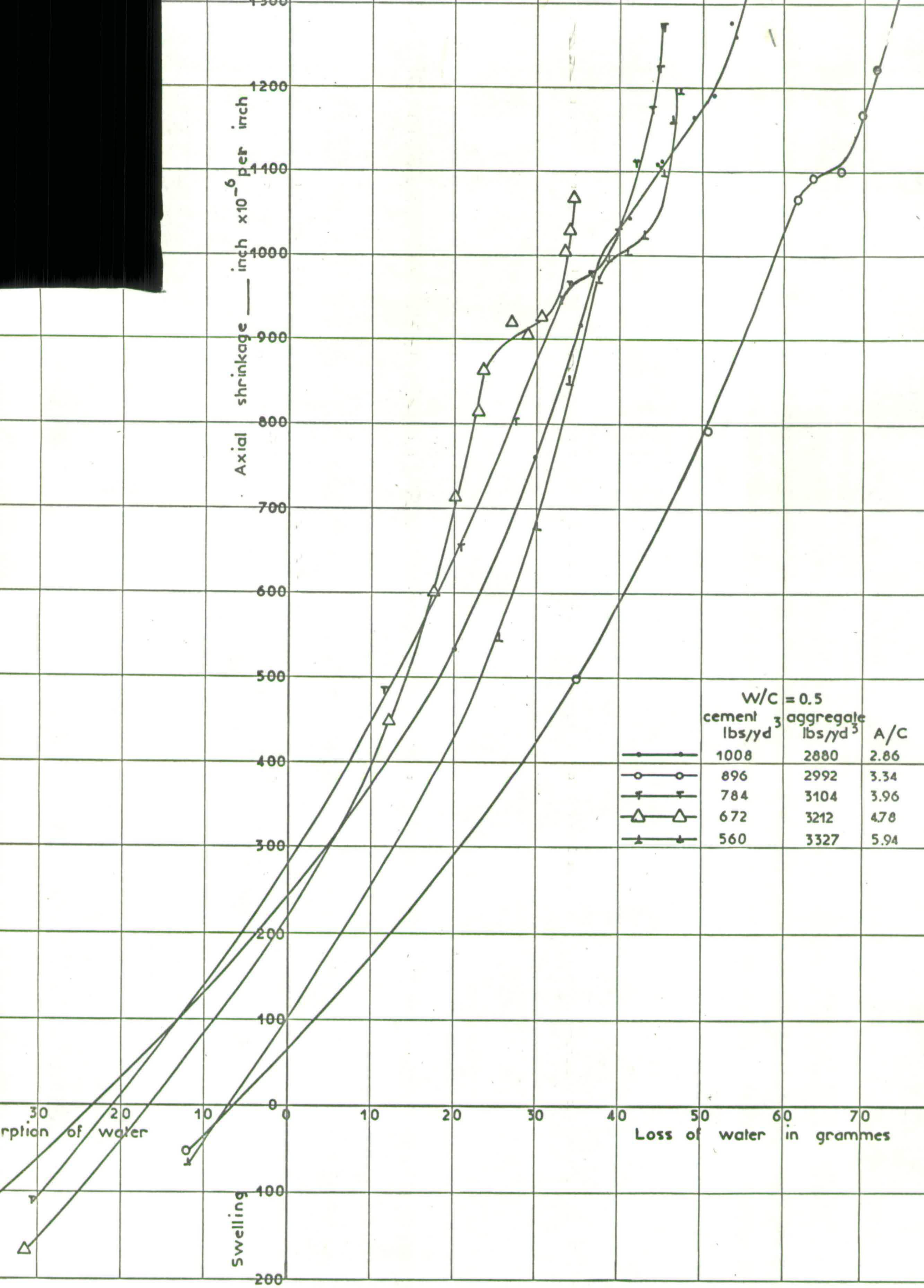


FIG.45 RELATION BETWEEN SHRINKAGE & LOSS OF WATE
EDDLESTON — OVEN DRYING

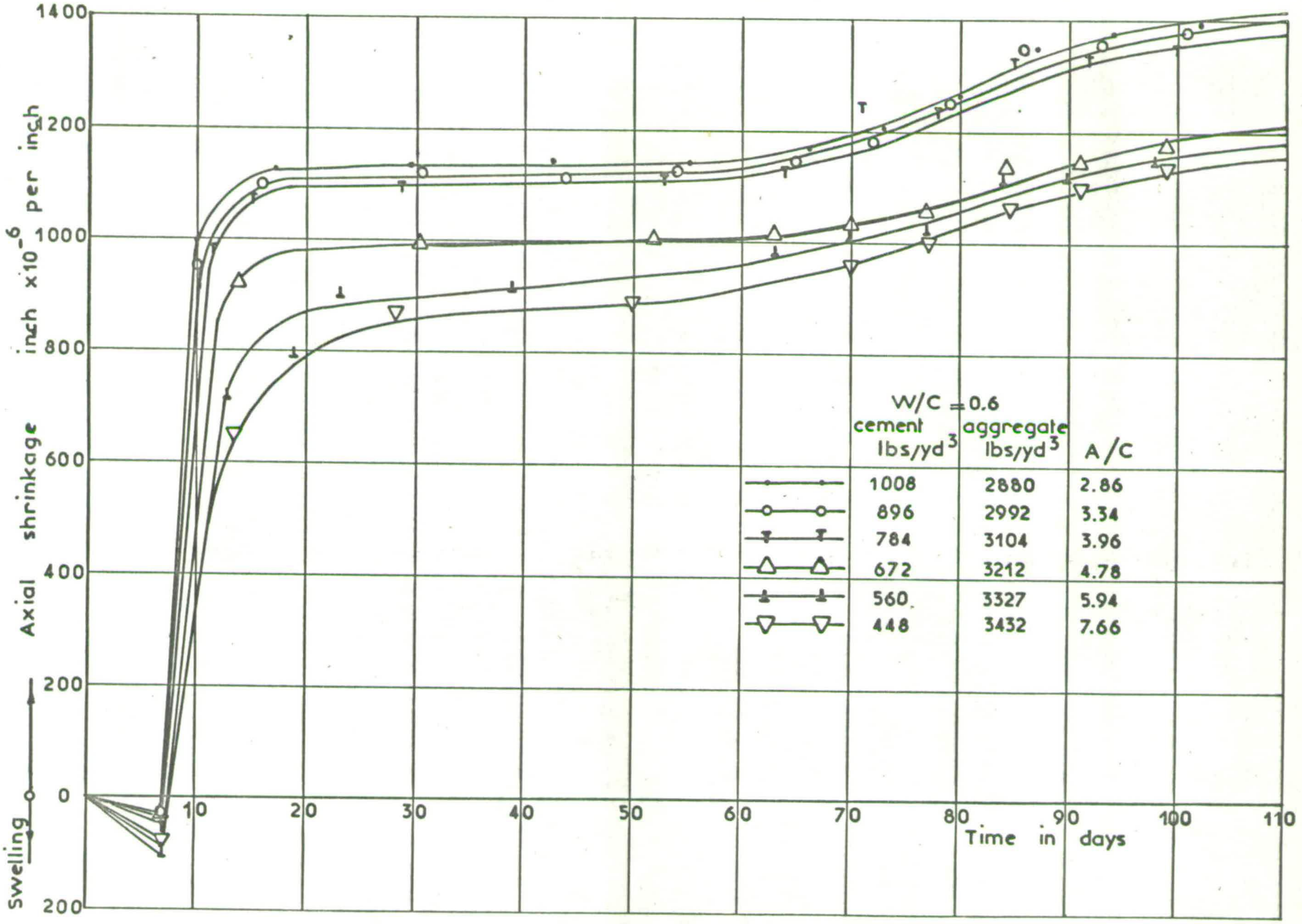


FIG. 46 SHRINKAGE TIME CURVES — EDDLESTON AGGREGATE — OVEN DRYING

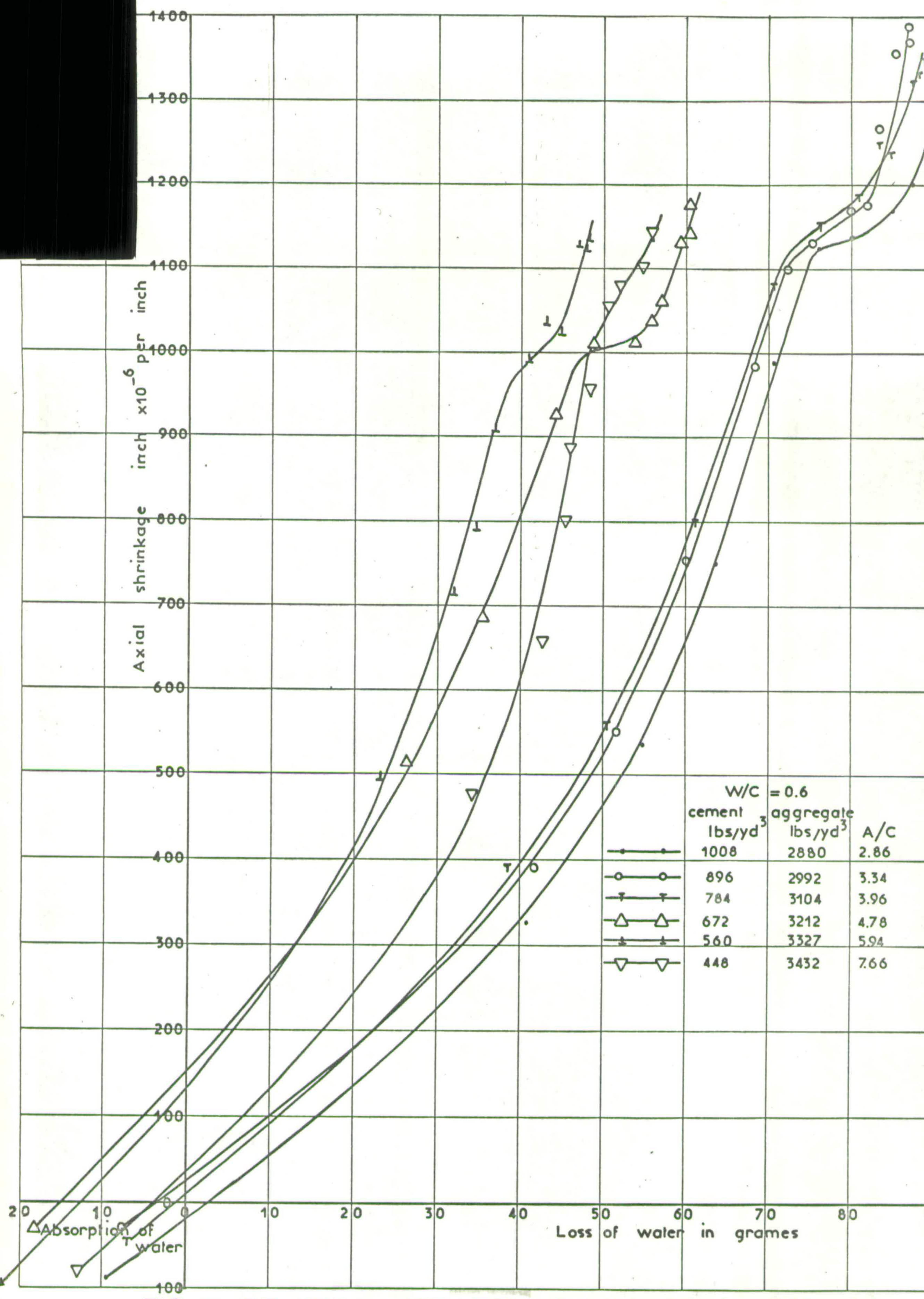


FIG.47 RELATION BETWEEN SHRINKAGE & LOSS OF WATER —— EDDLESTON —— OVEN DRYING

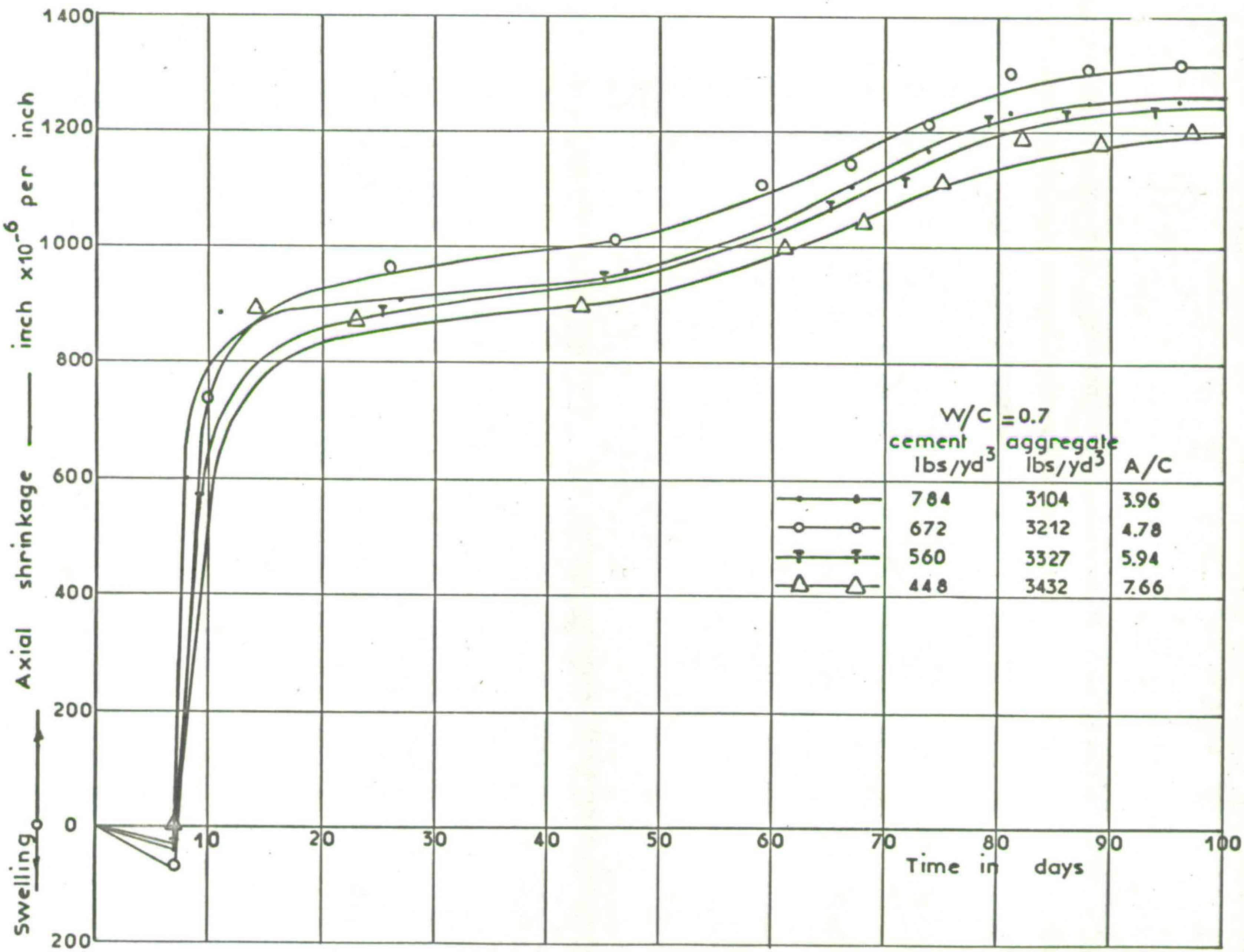


FIG.48 SHRINKAGE TIME CURVES—EDDLESTON AGGREGATE
OVEN DRYING

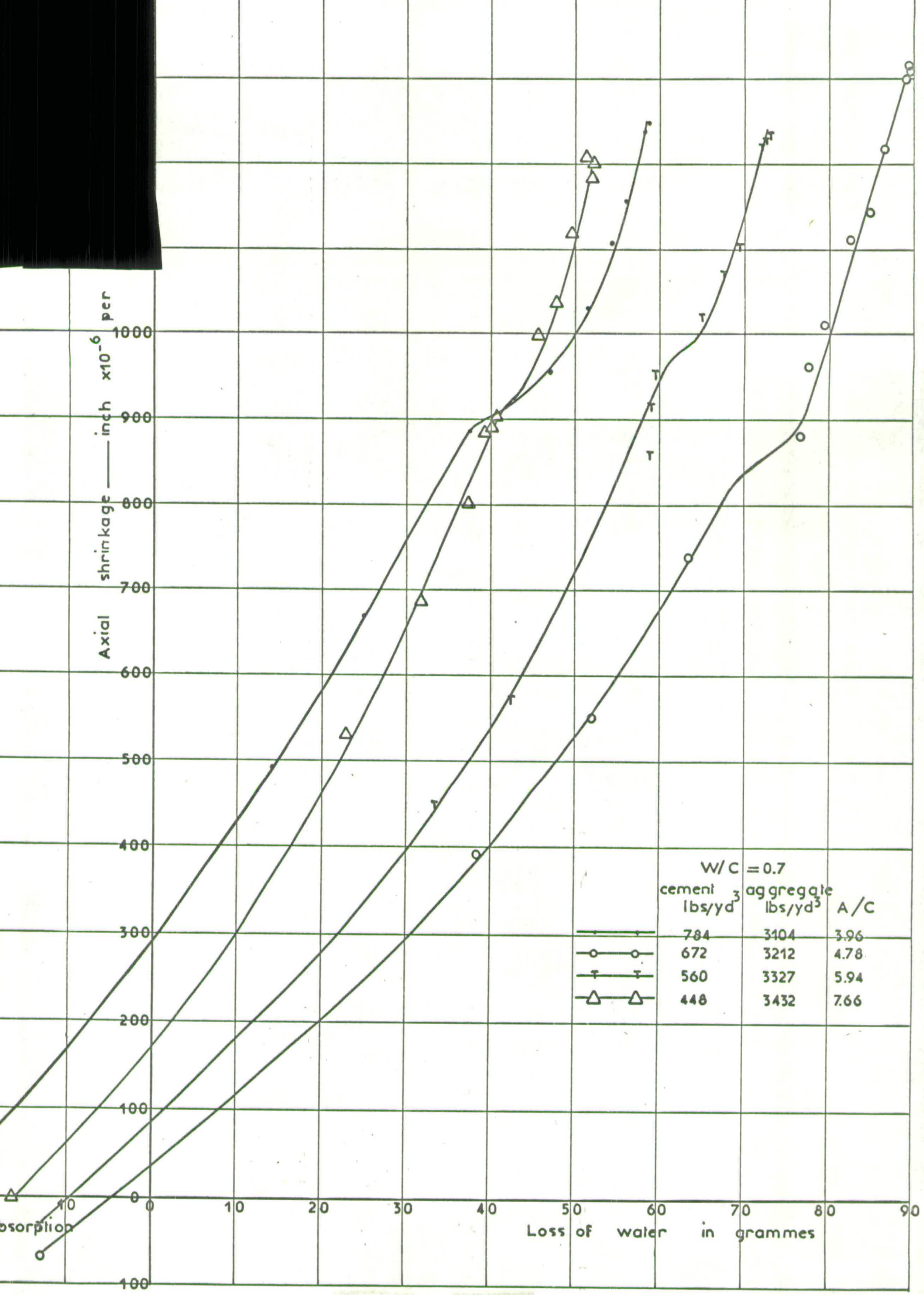


FIG.49 RELATION BETWEEN SHRINKAGE & LOSS OF WATER —— EDDLESTON —— OVEN DRYING

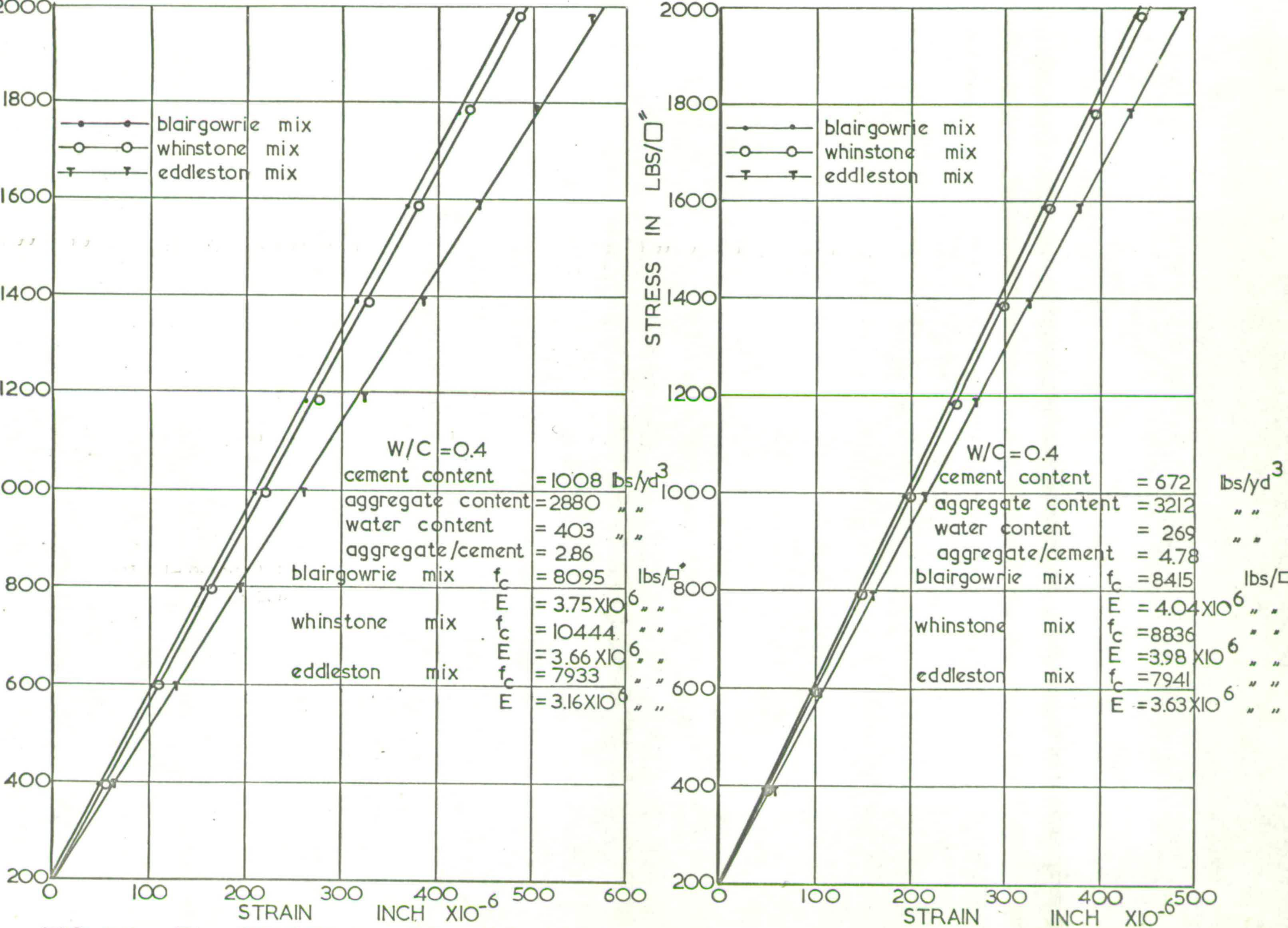


FIG. 50 ELASTICITY OF CONCRETES IN DIFFERENT TYPES OF AGGREG

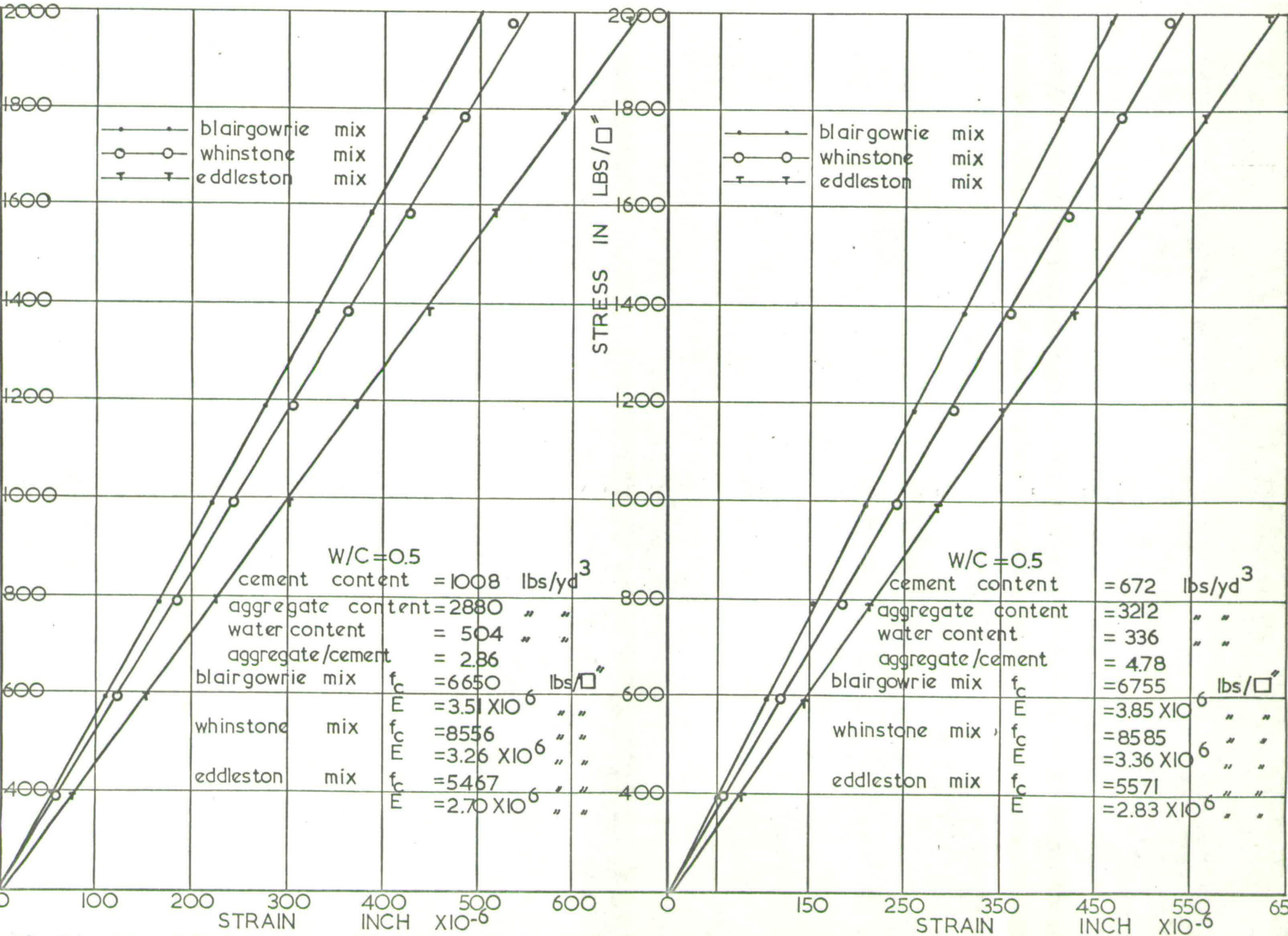


FIG 51 ELASTICITY OF CONCRETES IN DIFFERENT TYPES OF AGGREGATE

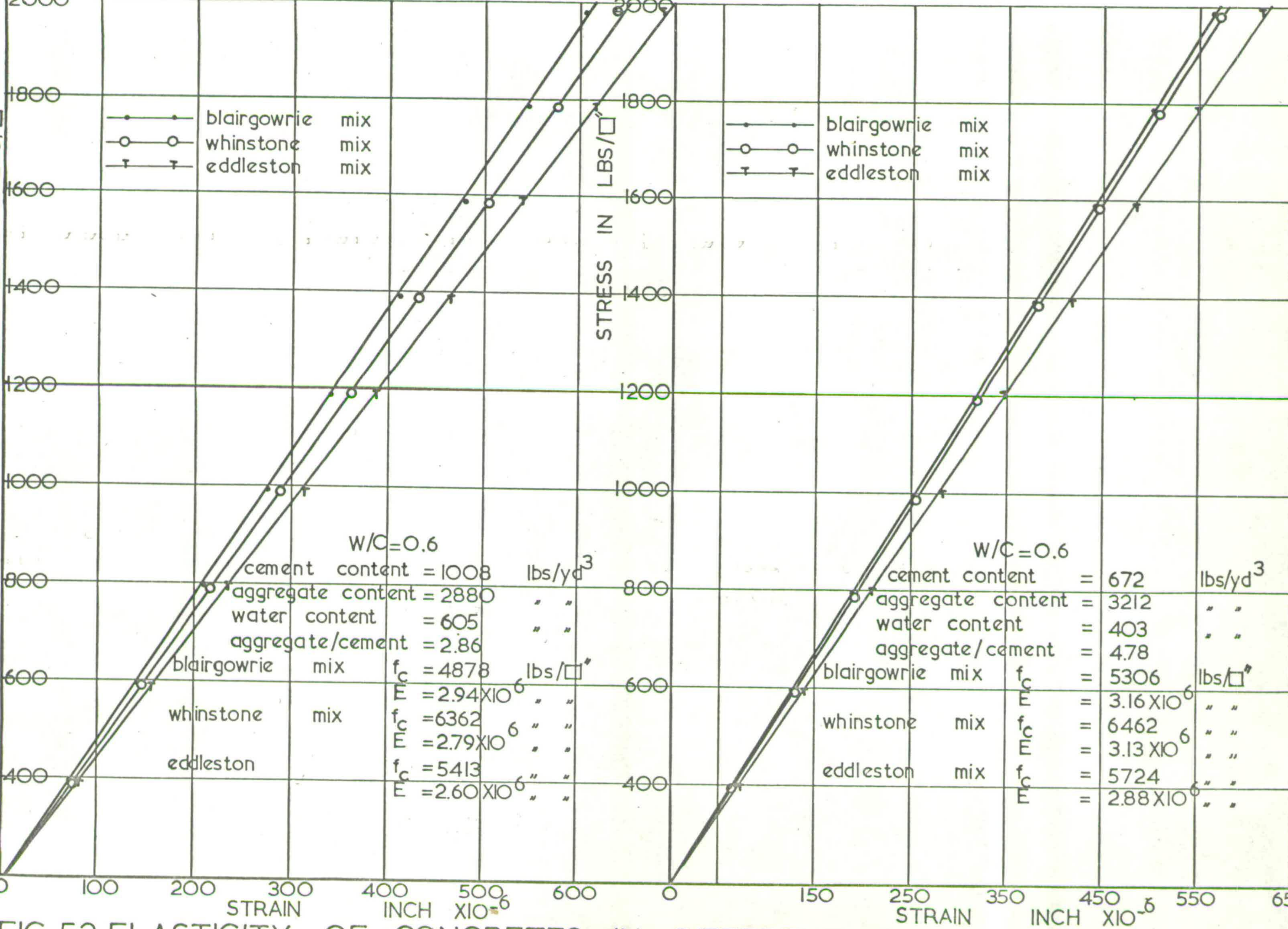


FIG. 52 ELASTICITY OF CONCRETES IN DIFFERENT TYPES OF AGGREGATE

CHAPTER 3

3.1 DEFLECTION OF SHALLOW BEAMS DUE TO SHRINKAGE

The shrinkage of plain concrete has been widely covered and supposed to give no deflections assuming that the shrinkage strains are uniformly distributed.

When steel reinforcement is used, it restricts, but does not prevent, shrinkage in its effective direction. It prevents free shrinkage of concrete immediately adjacent to the steel to which it bonds, thereby inducing tension in the concrete and compression in the steel. The amount of concrete that participates in this interaction determines the compressive effect on the steel reinforcement. When the interaction between steel reinforcement and concrete shrinkage is eccentric with respect to the cross section, unsymmetrical strains cause warping.

3.1.1 Classification of test specimens, casting of specimens and curing conditions

As a part of the present investigation a series of nine beams were tested for warping deflections. Test specimens, 42 inches long and 5"x6" in cross-section were used. Three beams were cast for each type of aggregate, having tensile reinforcement composed of two bars $\frac{3}{8}$", $\frac{1}{2}$" and $\frac{3}{4}$" diameter respectively. Figure 53 shows the cross-sectional dimensions and position of reinforcement.

A mix of 1:2:4 by weight and 0.6 water/cement ratio was used in casting the beams. The concrete was mixed by means of a Liner mixer and then placed in the mould in four successive layers having thicknesses of ½", 2", 2" and ½". Vibration of concrete was performed by means of a Kango electric hammer type L. The first layer was cast, vibrated, and levelled with a wooden trowel. The first bar was placed in position carefully with a clear cover of ½". The second and third layers were cast and vibrated and the second bar was placed in position. The fourth layer was then cast, vibrated and the concrete was levelled and the surface smoothed with a trowel. Control specimens composed of 12" cylinders and 6" cubes were prepared for each type of aggregate to determine the crushing strength, the tensile strength and the modulus of elasticity of the concrete.

Two days of moist curing were permitted in the laboratory (18° - 22°C) before starting the warping tests. The constituents of each mix were as follows:-

Water = 10.2 lb.
cement = 17 lb.
coarse aggregate = 68 lb.
fine aggregate = 34 lb.

3.1.2. Measurement of warping deflections

After two days of moist curing, the beams were raised over steel trustles, supported on two rollers at 10.5" from each end to eliminate dead load bending moment at the centre.

The beams were left to dry in the laboratory for six months at a temperature of 18°-22°C and 10 - 40% relative humidity. The beams were kept in position by introducing a wooden wedge at one of the supports to prevent the beams from rolling off the trustles.

The warping deflections were measured by a three-point gauge on a length of 38 inches between two metal points and a dial gauge at midpoint. The dial gauge and means of support were shown in plate 3.1.

The gauge was manufactured locally in the department workshops and was used to measure the deflections at the centre of the beams as well as the longitudinal shrinkage strains at the top and bottom fibres of the beams. Reliable readings were obtained for the warping deflections, but the readings of the longitudinal shrinkage strains were incorrect. The failure of the gauge in measuring the longitudinal shrinkage strains was due to the instability of the screws which support the gauge when the readings were taken. The warping deflections were observed for a period of six months at convenient intervals and the collected data was plotted and shown in figure 53.

3.1.3 Analysis and discussion of results

Figure 53 shows the deflection-time curves for the series.

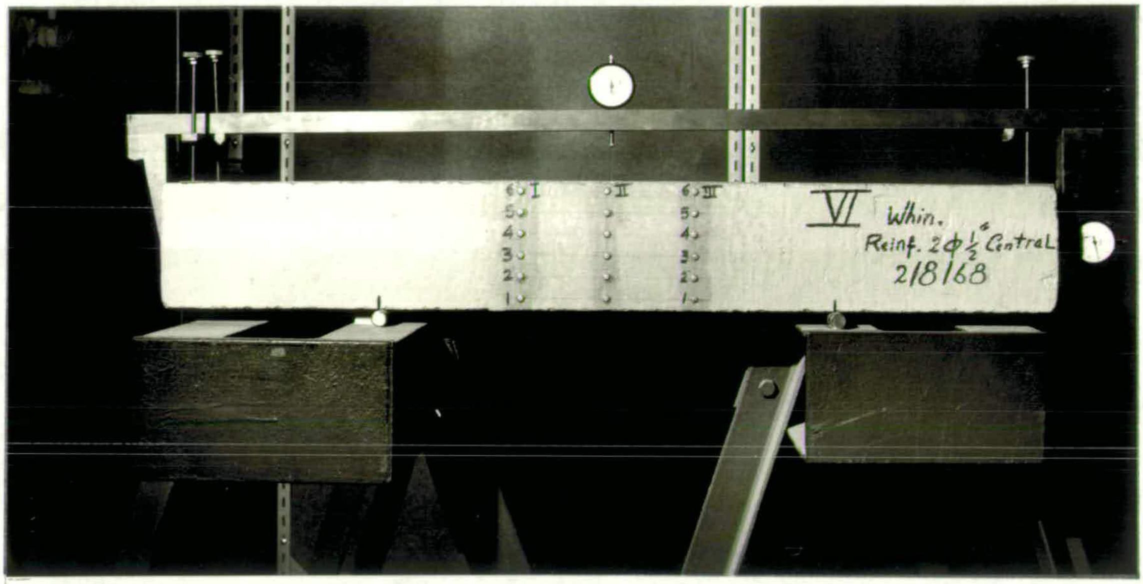


PLATE. 3.1 — Device for measuring the deflections, and means of support to eliminate dead load ~~deflections~~ bending moment.

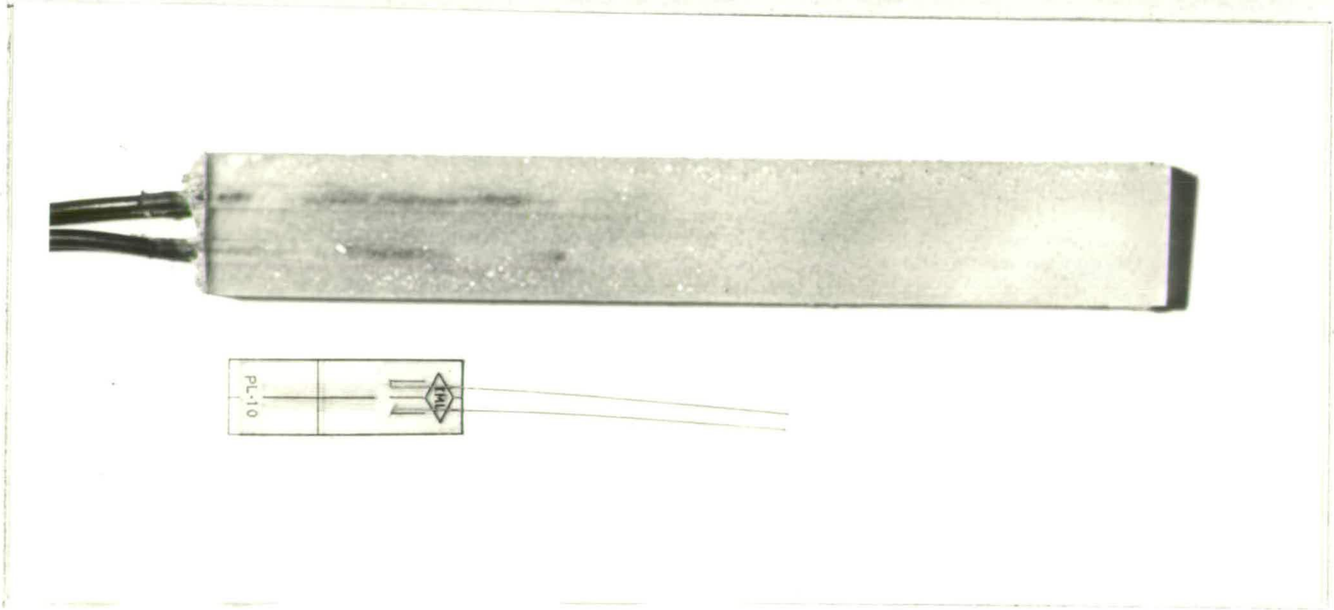


PLATE. 3.2 Types of electric strain gages. PLM 30 & PL 10.

	PLM 30	PL 10
gage length	30 m.m.	10 m.m.
gage factor	2.17	2.07
resistance	120 ± 1 Ω	120 ± 1 Ω

of beams cast with different aggregates and variable reinforcement. All the deflections were measured at the centre of the beams to the nearest 0.0001 inch. The results were consistent and gave smooth curves.

The Blairgowrie gravel beams attained their maximum deflection in about a hundred days and then maintained their stable condition till the end of the test.

The Ratho-Whinstone aggregate and the Eddleston gravel beams showed greater deflections ranging from two to three times the deflections demonstrated by the respective Blairgowrie gravel beams. Moreover, the former beams have undergone a sudden increase in deflection after a hundred days of drying which was peculiar behaviour and had no obvious explanations. It might be that cracking in such types of concretes was mainly responsible for the excessive deflections observed.

Within the first five days no considerable deflections were observed. This phenomenon could be attributed to the fact that the interaction between steel and concrete requires a certain period of time for bond to become effective and the reaction of the steel to materialise.

The warping of the beams was attributed to the eccentric interaction between the steel and the concrete, principally due to bond between the two elements. During the first few days, the development of the bond forces becomes sufficient to transfer the shrinkage compressive effect to the steel which reacts creating a deflecting moment. After the warping - shrinkage relationship is established, undoubtedly interaction between steel and concrete shrinkage includes regular adjustments of the internal stresses and maintenance of equilibrium. It is also to be expected that creep will act simultaneously with shrinkage and tend to minimise the intensity of the shrinkage stresses. The following table No.7 shows the maximum deflections observed for the different series of beams.

diameter of bars in inches	A_s/A_c %	Deflections in inches		
		Blairgowrie gravel	Ratho-Whinstone aggregate	Eddleston gravel
$\frac{3}{8}$	0.74	0.015	0.040	0.045
$\frac{1}{2}$	1.32	0.025	0.0435	0.049
$\frac{3}{4}$	3.04	0.045	0.048	0.054

Table No.7 Deflections of shallow beams cast with different Scottish aggregates.

The results shown in table No.7 indicate the role of shrinkable aggregates in producing excessive deflections irrespective of the steel ratios used. This fact makes the use of such types of aggregates undesirable for shallow beams and floor slabs.

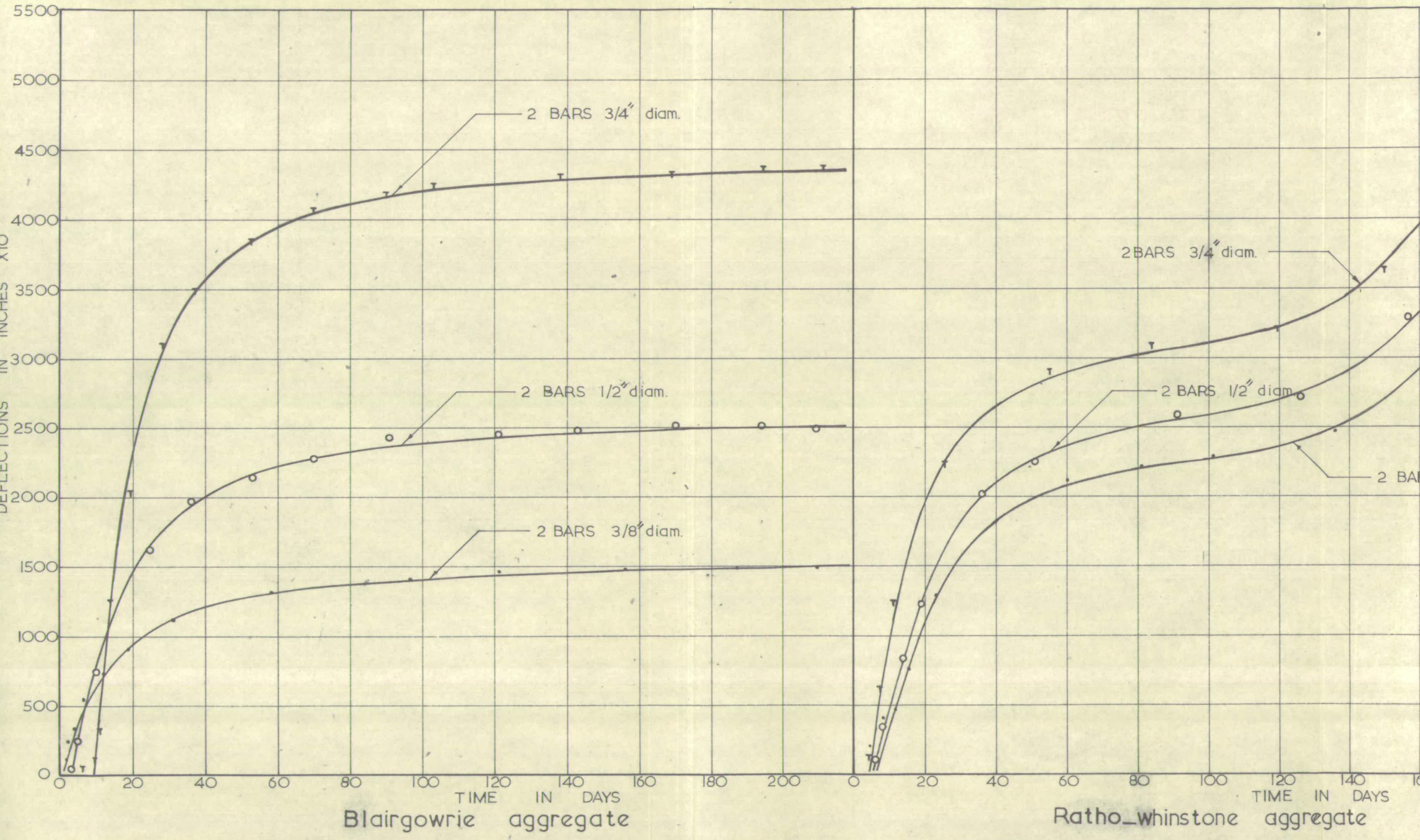
3.1.4 Conclusions

The following conclusions are drawn from the test results detailed in this chapter:-

(1) Concrete elements cast with shrinkable aggregate exhibit excessive deflections amounting to about three times the deflections observed for similar elements cast with sound aggregate.

(2) Under the application of the working loads these deflections might be detrimental to the structural elements. They might cause obvious sagging of thin beams and floor slabs, destruction of internal panels and external claddings, and redistribution of moments and stresses in case of continuous elements.

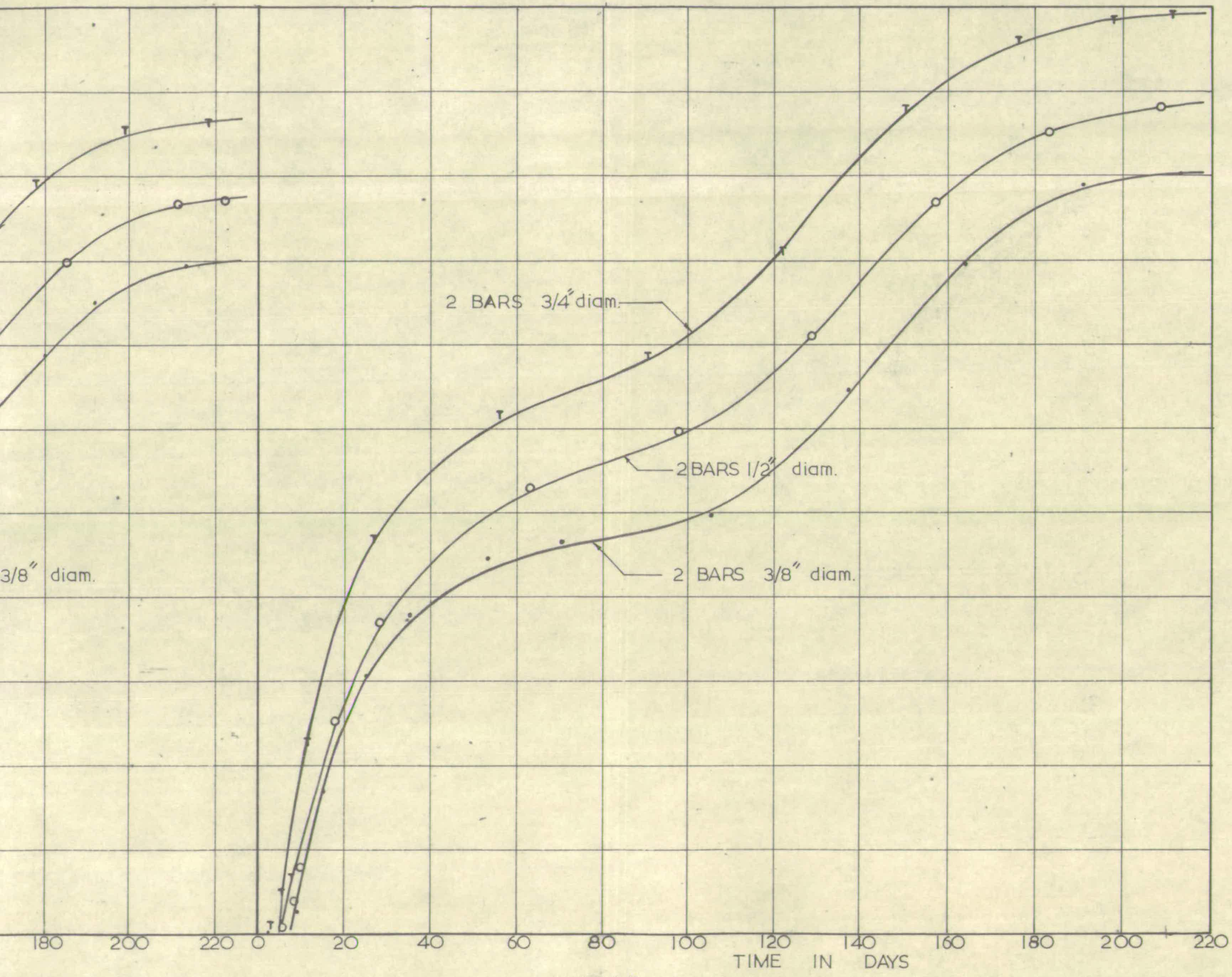
(3) It is advisable to avoid using shrinkable aggregate especially for reinforced concrete. If the use of such types of aggregates was unavoidable, precautions should be taken to reduce their objectionable deflections. Proposals for certain precautions are discussed in the following chapter.



Blairgowrie aggregate

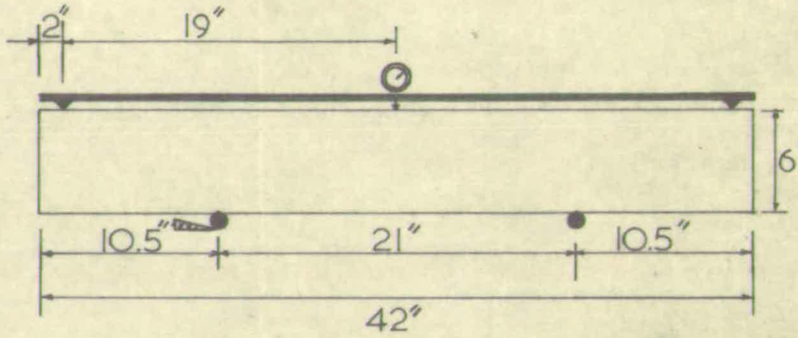
Ratho_whinstone aggregate

FIG. 53 RELATION BETWEEN TIME AND WARPING DEFLECTION DUE TO SHRINKAGE

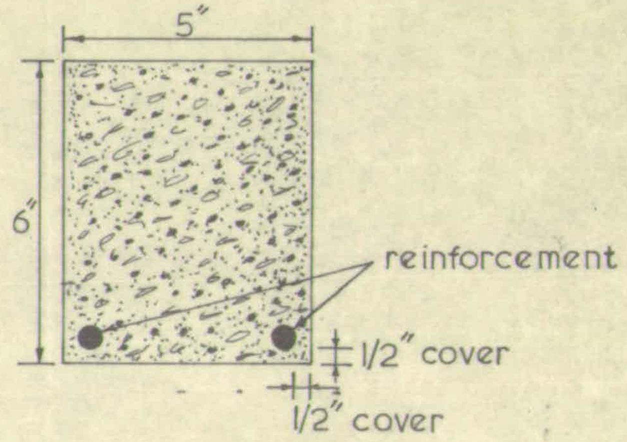


Eddleston aggregate

UNSYMETRICALLY REINFORCED CONCRETE BEAMS



DETAILS OF SUPPORTS & MEASUREMENT GAGE



CROSS SECTION OF BEAM SHOWING DIMENSIONS & POSITION OF REINFORCEMENT

Note:- further investigation is necessary to check the behaviour of Blairgowrie aggregate beams with 3/4" reinforcement.

CHAPTER 4

4.1 Control of deflections and the distribution of internal shrinkage strains

During the process of setting, hardening and drying, concrete undergoes a volumetric change accompanied by an adjustment in the state of internal balance of the concrete elements. The cement gel, shrinking or swelling, introduces internal shrinkage strains which will tend to increase or decrease the strains already built up by the hydration process and the chemical bond between the aggregate and the hardened cement paste.

In the present investigation several series of beams were tested to detect the distribution of shrinkage strains in plain and reinforced concrete. Failing to get correct external measurements of the shrinkage strains along the longitudinal direction of the beams by the available gauge shown in plate No.3.1, the author thought of using electric strain gauges to measure the internal shrinkage strains at the central cross-section of the beams.

The warping deflections at the centre of these beams were also measured and then checked analytically. One beam was cast with equal top and bottom reinforcement to investigate the effect of balancing the internal forces in reducing the warping deflections to an acceptable limit.

The procedures of batching, mixing, casting, and curing were the same as mentioned in Chapter 3. The same dimensions of beams and system of support to eliminate the dead load effect were used. The warping deflections were measured by dial gauges that read accurately to 0.0001 of an inch.

4.1.1 Technique of applying electrical resistance strain gauges to shrinkage measurements

Electric resistance strain gauges have been widely used to measure the strains induced in any element of a structural member under the action of an instantaneous or a sustained load. These gauges have been used also to measure thermal movements due to temperature changes. No reliable technique had been established to measure shrinkage strains inside a concrete structure satisfactorily. The detection of the internal shrinkage strain distribution in concrete remained for a long time a matter of mystery and speculation.

A series of experiments, on 12 inch. cylinders and 42 x 6 x 5 inch beams were carried out to measure the internal shrinkage strains using the embedded gauges PML-30. The dummy gauges were sometimes attached to a dry similar specimen and other times cast together with the active gauges in an identical specimen. The first method presented fluctuating data which was very much affected by the changes in the temperature of the laboratory. Investigations which were previously done in Sheffield University, in the same way, in a controlled temperature and humidity room have also shown irregular results. The author believes that identical conditions does not exist if the active gauge was cast inside a specimen and the dummy gauge fixed or placed in a drilled hole inside a dry specimen.

The second method of casting both the active and the dummy gauges identically at the same time was also found unsatisfactory. The dummy gauges, being under the action of approximately equal shrinkage stresses, have nullified most of the readings of the active gauges. In fact, this method was misleading because strains up to 400 x 10^{-6}in/in. were recorded for some of the gauges. Moreover the results appeared to be more uniform and increasing steadily.

As a result of the numerous investigations carried out, the author found that both the previous methods were unsatisfactory and that the following method could be considered the most reliable technique for measuring the shrinkage strains by means of the strain gauges:-

(1) To measure the internal shrinkage strains in any element the position of the required strain measurements should first be decided.

(2) Two identical specimens should be cast, one for the embeddment of the dummy gauges and the other for the active gauges.

(3) The dummy gauges must be cast inside the first specimen in positions identical to those proposed for the active gauges.

(4) The first specimen with the dummy gauges inside should be kept to dry in the same conditions decided.upon for the active specimen.

(5) The period of drying should be long enough to ensure that the shrinkage strains induced upon the dummy gauges should reach their ultimate values and no further considerable shrinkage proceeds with time. The dummy gauges at this stage could be used satisfactorily to eliminate the effects of temperature variations in the laboratory.

(6) The second specimen for which the measurements of the internal shrinkage strains are required should be cast with the active gauges embedded in identical positions to their respective dummy gauges.

(7) The active and the dummy gauges should be connected, immediately after casting the active gauges, to the selected strain recorder.

(8) Strain measurements should then be taken at convenient intervals and as usual.

(9) If the effect of the chemical reactions and hydration was not required in the measurements, gauges could be connected after about 24 hours when this effect could be eliminated by the initial balance of the active and dummy gauges.

4.1.2 Types and preparation of gauges used for the present investigation

The measurements of the internal shrinkage strains in the present series of tests were performed by using two types of electrical resistance strain gauges. These types were the polyester mould gauges, PML-30 and the wire wound gauges, PL-10. They were manufactured in Japan by Tokyo Sakki Kenkyujo company.

The polyester gauges PML-30 were provided for direct use in concrete. They were fitted between two perspex plates, waterproofed and completely protected from ambient conditions. These gauges were buried at the intended sites of measurements at the moment when the concrete was poured.

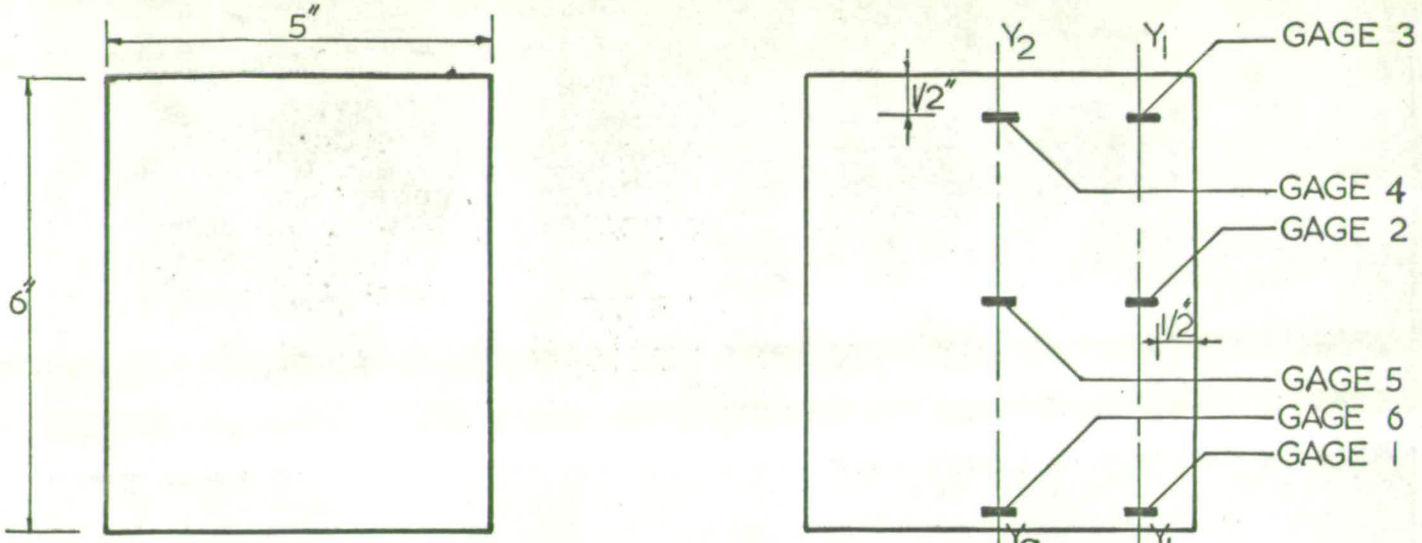
The gauges PL-10 were of wire wound types bonded with cellulose to a paper backing. They were provided for strain measurements on the steel reinforcements.

In order to fix the PL-10 gauges on the steel bars, the intended areas were first well polished to present even surfaces and then cleaned with acetone. The gauges were immersed in a prepared P.2 adhesive and then plastered on the intended surfaces. The gauges were immersed in a prepared P.2 adhesive and then plastered on the intended surfaces. The gauges were then covered with cellophane, pressed under cushions, like sponge or rubber and left for 24 hours to adhere to the reinforcement bars. Then, the cellphane was peeled off, lead wires connected and the gauges were covered totally with a P.S. adhesive for protection and water-proofing. After these procedures, the gauges and the steel bars on which they were attached were buried in concrete at the required positions. Plate No.3.2 shows the two types of gauges used.

4.1.3 Procedures of casting the test specimens and the embedment of strain gauges

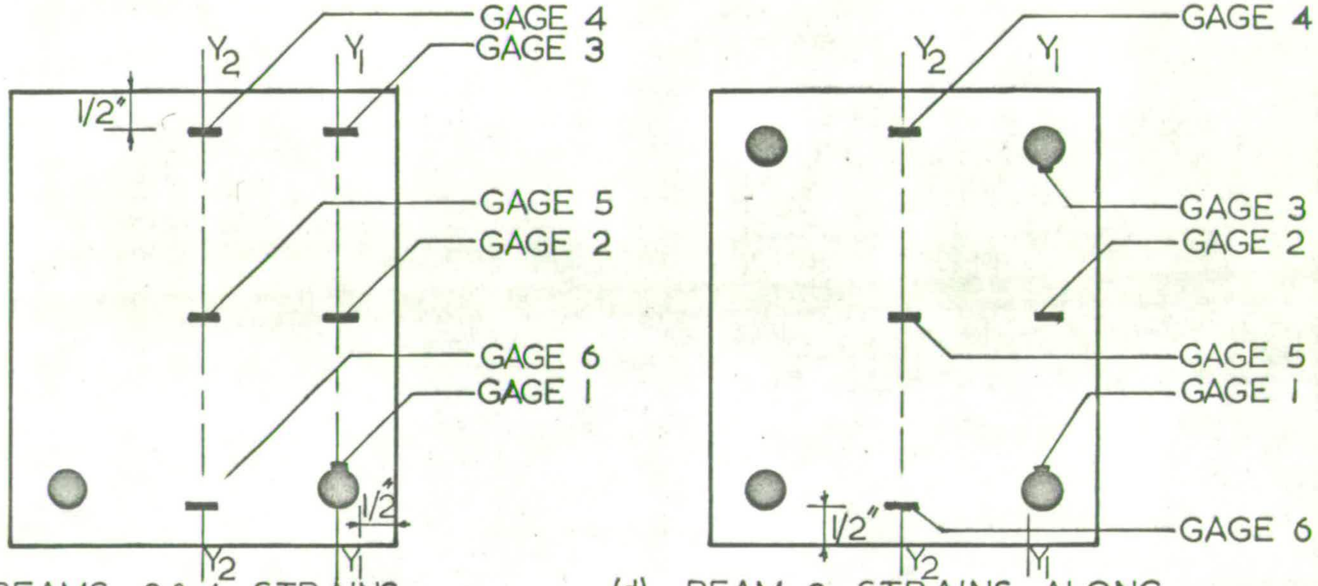
Four test specimens consiting of 42 x 6 x 5 inch beams were cast to investigate the internal shrinkage strains in plain and reinforced concrete. These tests were designed in such a way as to enable measurements to be made of the shrinkage strains in reinforcements and concrete at six points, along two axis $y_1 - y_1$ and $y_2 - y_2$ as shown in figures 54 (b), 54(c) and 54(d). The arrangement of these gauges was chosen in order to show the measured data in the usual stress and strain distribution pattern. All the gauges were embedded with their axes coinciding with the central cross-section of the beam.

The behaviour of concrete plain and reinforced during hydration, setting, hardening and drying was to be studied with respect to time. The beams No.1, 2 and 3 were cast using the Ratho-Whinstone aggregate (shrinkable aggregate) and beam No.4 was cast with Blairgowrie gravel. Beam No.1 was cast in plain concrete, beam No.2 reinforced with two half inch bars as bottom reinforcement and beam No.3 was cast with balanced reinforcement of two half inch bars top and bottom. Beam No.3 was cast to investigate the effect of balancing the reinforcement on the magnitude of shrinkage deflections and internal strains.



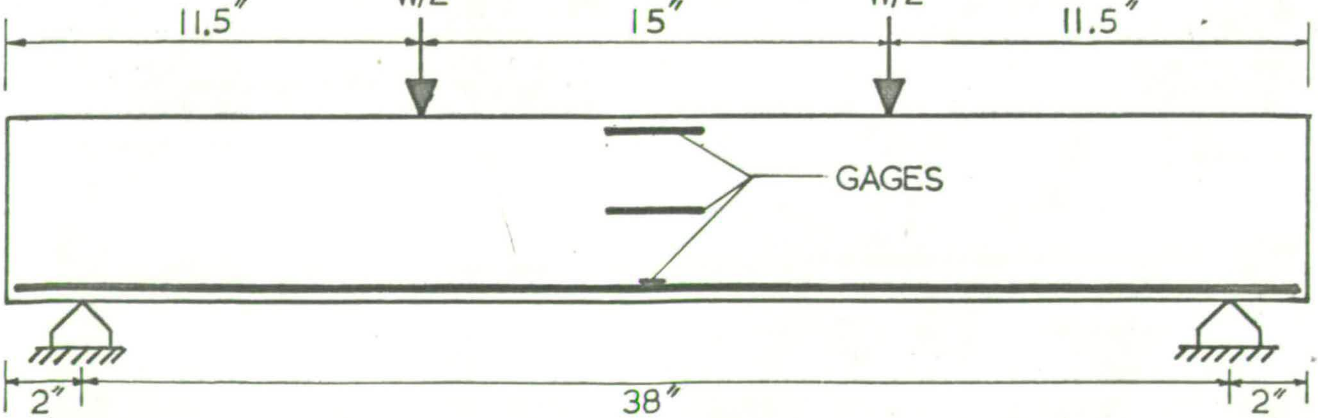
(a) BEAMS CROSS SECTIONAL DIMENSIONS

(b) BEAM_1 —— STRAINS ALONG Y_1-Y_1 & Y_2-Y_2 plain concrete



(c) BEAMS_2 & 4 STRAINS ALONG Y_1-Y_1 & Y_2-Y_2 reinforced con. 2 bars 1/2" dia.

(d) BEAM_3 STRAINS ALONG Y_1-Y_1 & Y_2-Y_2 reinforced con. 4 bars 1/2"



(e) THE TWO POINT LOADING ARRANGEMENT

FIG.54 POSITION OF GAGES & LOADING SYSTEM

Beam N$_o$.4 was cast with Blairgowrie gravel and with tensile reinforcement of two half inch bars. This beam was cast for comparison between the behaviour of the non-shrinkable and the shrinkable aggregate in concrete structures.

The active gauges were prepared for embedment and given their indicative numbers following their position in the beam. The concrete was batched by weight, mixed and poured into the mould in four layers as follows:-

(1) Half an inch layer of concrete was first laid, vibrated and levelled by means of a wooden trowel. The first bar (two bars for beam No.3) was then put in position maintaining half an inch cover from each side of the mould. (For beam No.1 half the height of the mould was filled with concrete and surface prepared for gauges).

(2) A concrete layer of $1\frac{7}{8}$ inches was poured, vibrated and levelled. Three gauges, PML-30 No.4, 5 and 6, were carefully placed and held in position by means of two wooden spacers as shown by plate No.4.3. More concrete was poured to cover the gauges, vibrated thoroughly to ensure that the gauges would not be displaced or titled. The two wooden spacers were pulled out cautiously and the gauges were checked to ensure no displacement.

tilted

(3) More concrete was poured to make up a total thickness of four inches, vibrated and surface prepared for the remaining gauges. The steel bar with gauge No.1 attached was put in position followed by gauges No.2 and 3 (PML.3), held in position by another wooden spacer. (In case of beam No.1 three gauges PML-30 were located in position and for beam No.3 two bars with gauges No.1 and 3 attached were placed in the required position). These gauges were covered

with concrete and wooden spacers removed after proper vibration.

(4) The mould was then topped with concrete, vibrated, levelled and smoothed with a trowel. Plates No.4.1, 4.2, 4.3 and 4.4 show the different steps of casting and embeddment of gauges.

The beams being cast, all the active gauges were attached to a fifty-way strain recorder (Savage and Parsons) together with their respective dummy gauges. The dummy gauges were identically embedded in similar beams and were kept to dry for six months. In fact these dummy gauges had been previously prepared for the test beams which were cancelled and now used as dummies for the new test beams after approximately complete drying. The plates No. 4.5, 4.6 and 4.7 show the 50-way strain recorder and the proper connections of the gauges.

4.1.4 Method of strain measurement

The usual method of measuring the strains in a test specimen is by measuring the change of resistance in each gauge by means of a Wheatstone bridge. The stress analysis requires strain readings to be taken at a large number of points in the test specimen. This is achieved simply by adding a strain gauge, apex resistance and dummy gauge circuit for each point to be measured. The moving arms of the apex resistances are then connected to a selector switch so that the galvanometer can be connected to each gauge circuit in turn and the reading for the change in resistance taken.

A device of this kind manufactured by Savage and Parsons Ltd., comprising connections for fifty strain gauges, apex resistances and dummy gauges circuits, was used for measuring the internal shrinkage strain gauges, apex resistances and dummy gauges circuits, was used

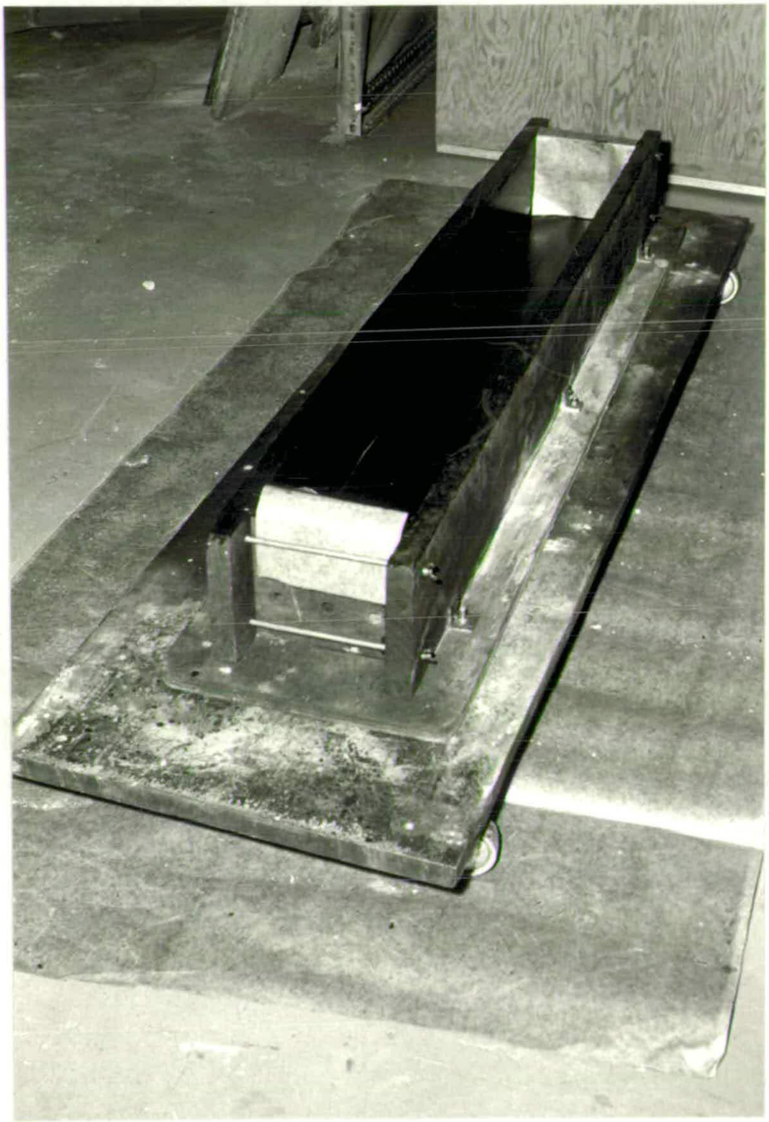


Plate 4.1—The mold oiled and prepared for casting.

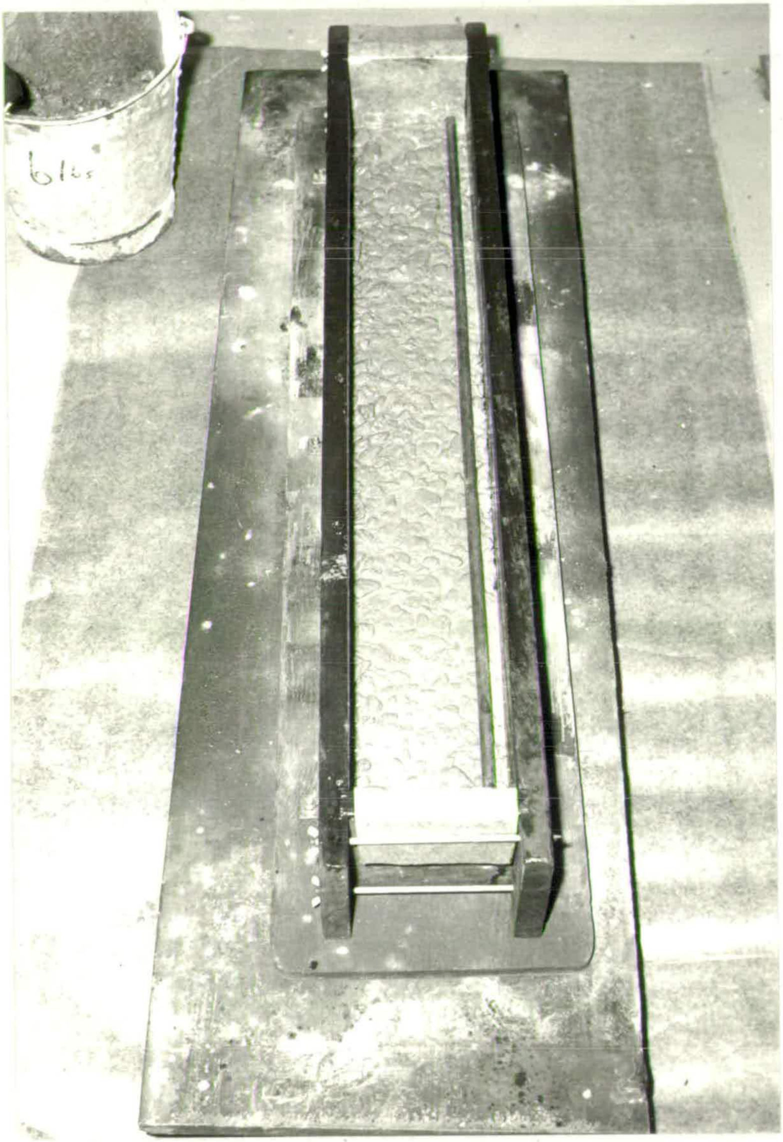


Plate 4.2 — First layer cast, vibrated, leveled & steel bar placed.

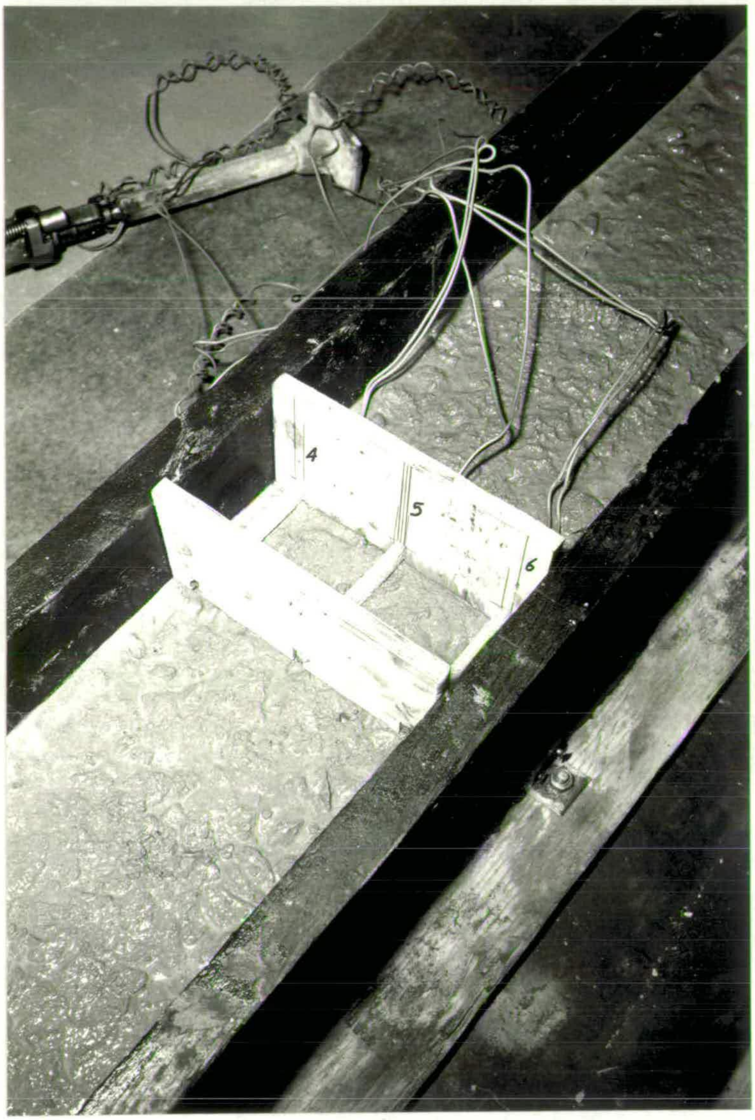


Plate 4.3 — Second layer cast, vibrated and gages 4, 5 & 6 placed at the intended sites of strain measurements.

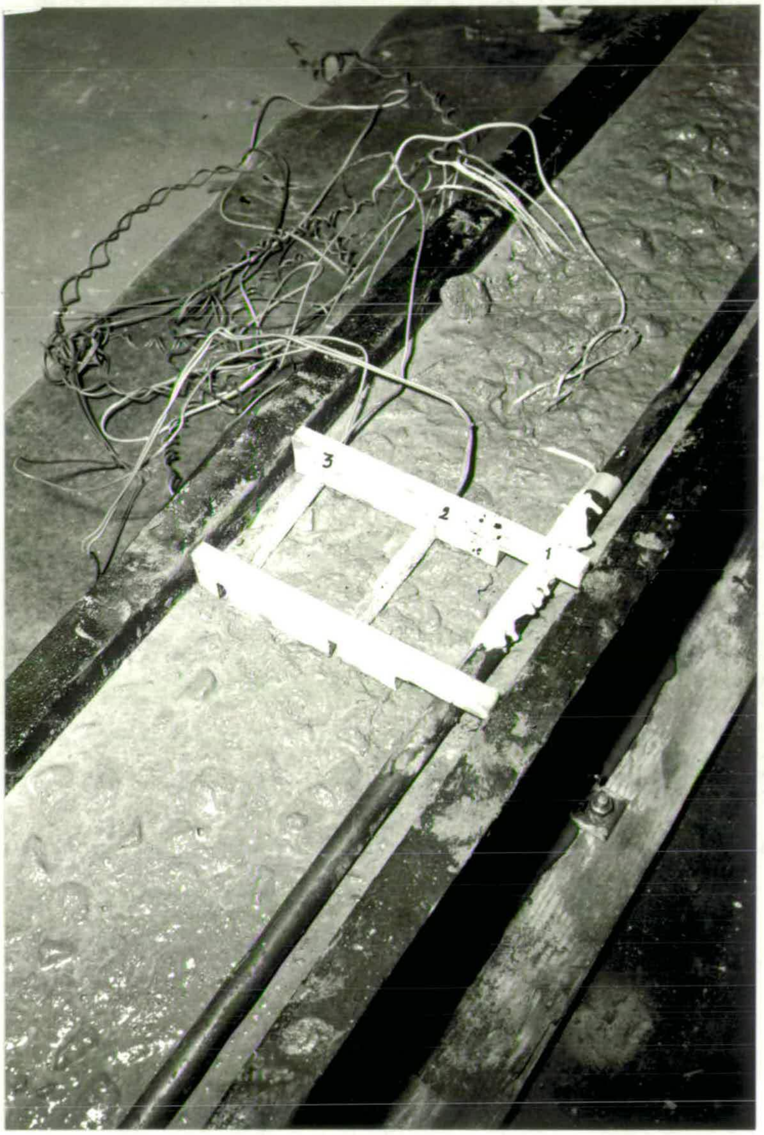


Plate 4.4 — Third layer cast, vibrated and gages 1, 2 & 3 placed at the intended sites of strain measurements

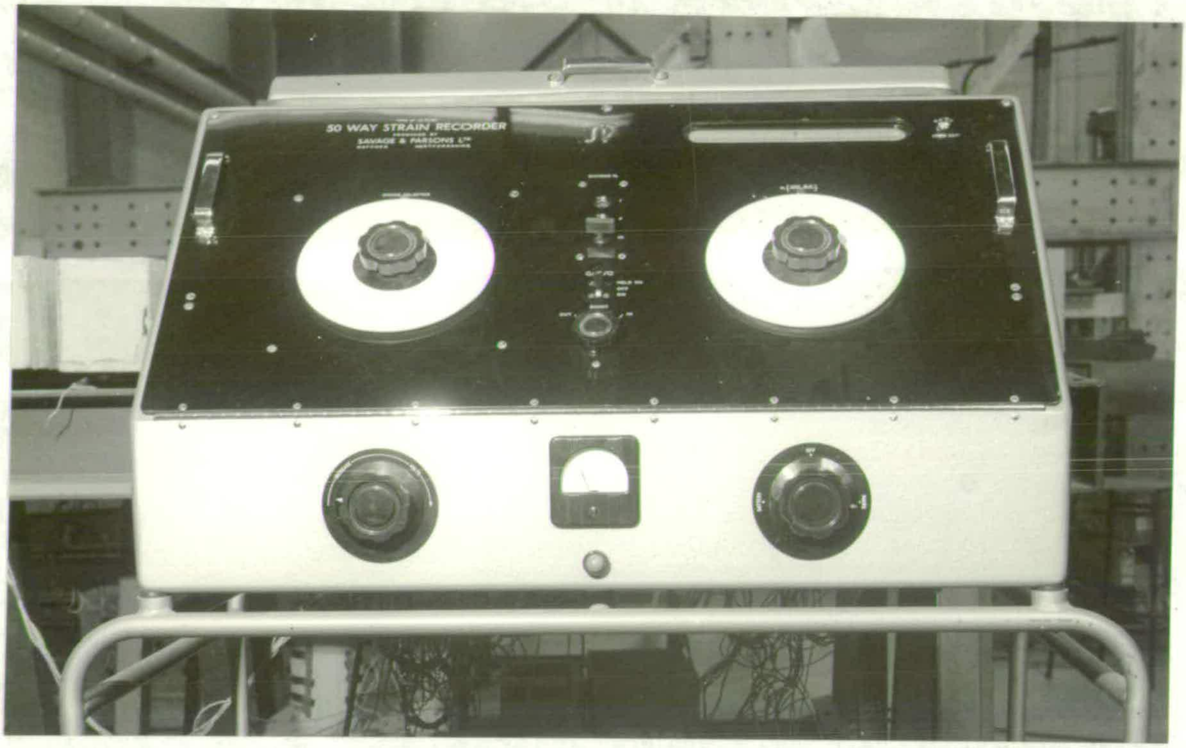


Plate 4.5 — The 50 way strain recorder.

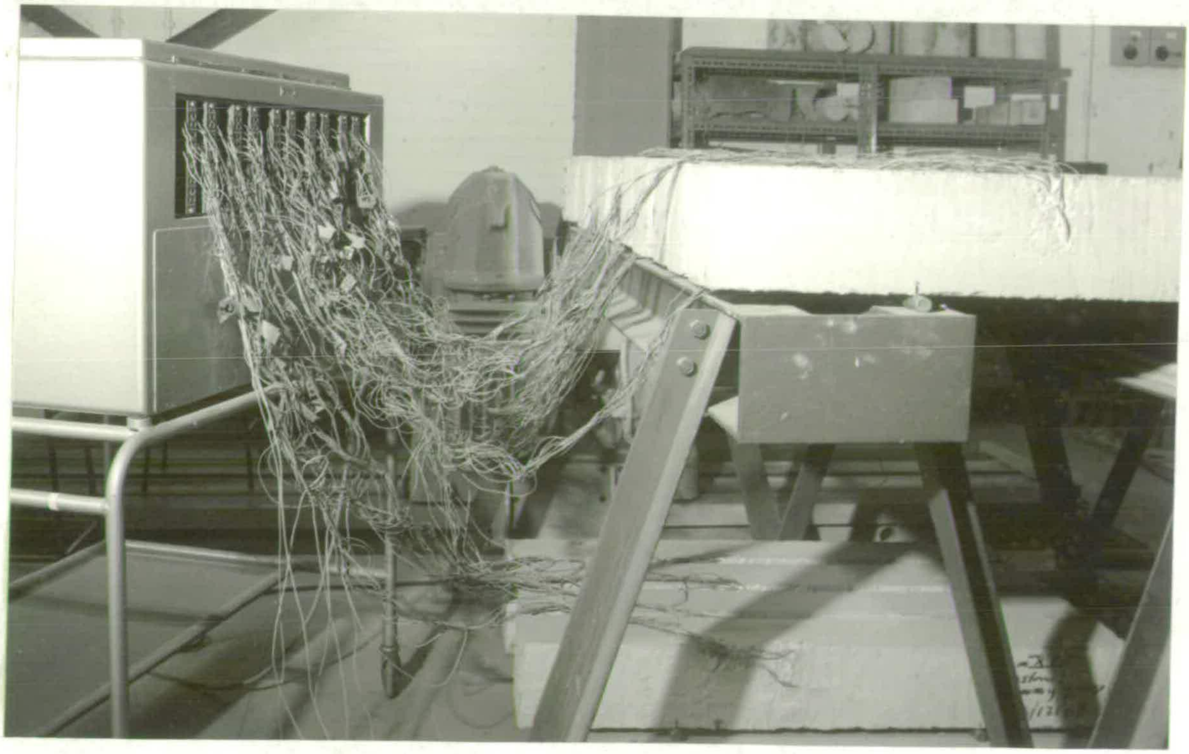


Plate 4.6 — Connection of gages to strain recorder.

Plate 4.7 Beams under test for internal shrinkage strains.

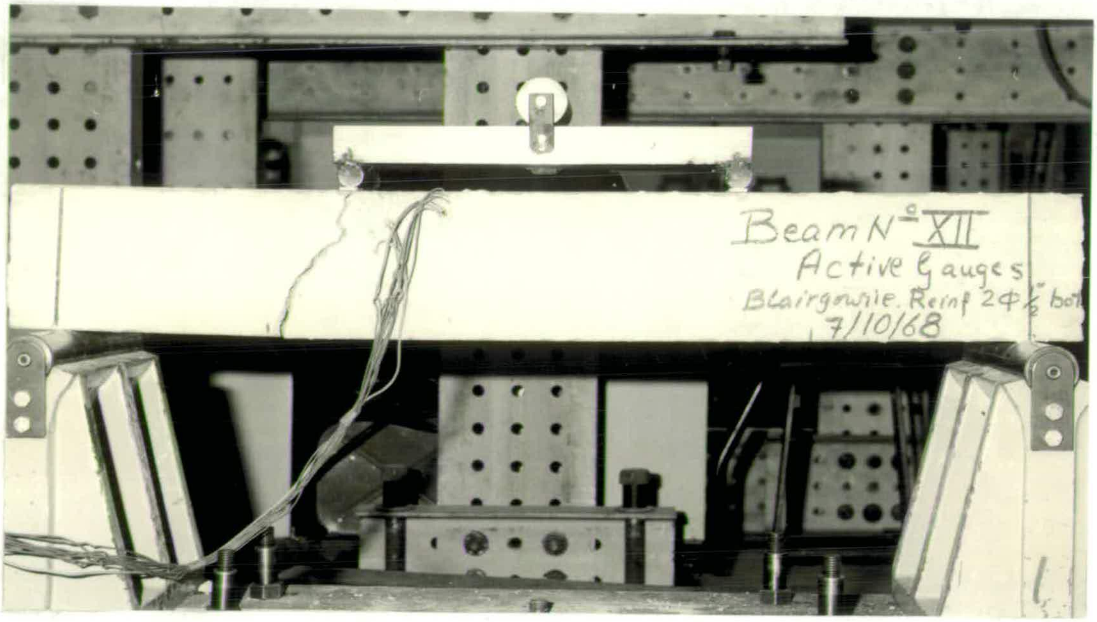


Plate 4.8 The two point load arrangement.

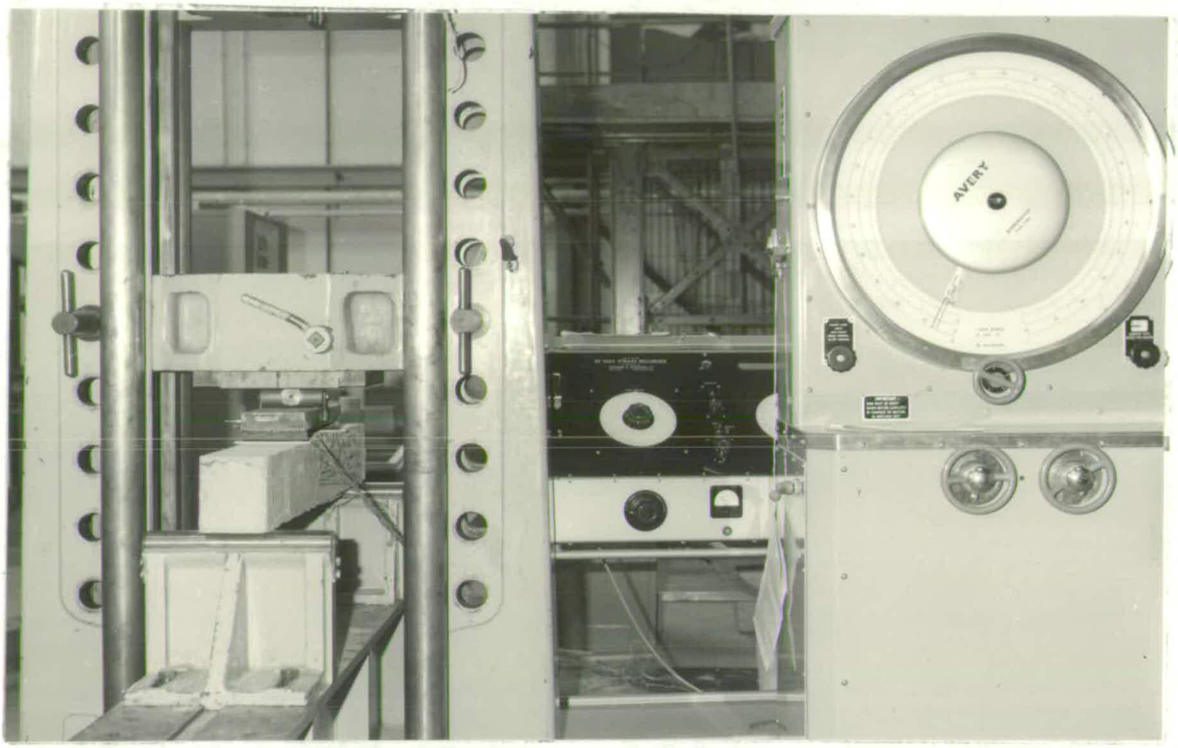


PLATE. 4.9 Test specimen under load

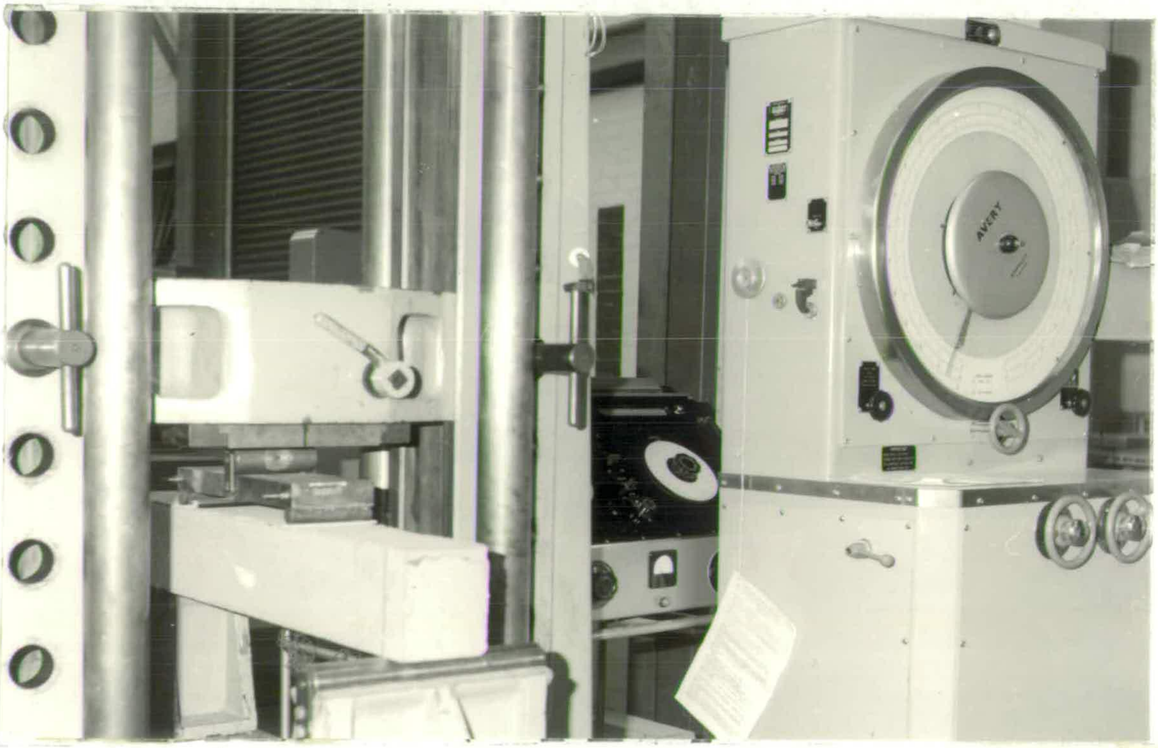


PLATE. 4.10 The Avery testing machine

for measuring the internal shrinkage strains of the test specimens. It has slide wire bridges, adjustable voltage, gauge selector and a galvanometer. The readings of the galvanometer are evaluated to $n\left(\frac{100.\Delta R}{R}\right)$, where n is a constant that varies between 10, 2 and 1. This constant is always registered from the strain recorder when the readings are taken. Plate 4.5 shows the device used. The strain measurements are calculated as follows:-

$$\epsilon = \frac{1}{K} \cdot \frac{\Delta R}{R} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where ϵ = the strain in/in

K = the gauge factor

ΔR = the change of resistance

R = the original gauge resistance

The galvanometer reading $= \phi = \left(\frac{100 \cdot \Delta R}{R}\right) n$

$$\therefore \quad \Delta R/R = \frac{\phi}{n \times 100} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

substituting from (2) into (1)

$$\epsilon = \frac{\phi}{n \times 100 \times K} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

The strains at the required points were calculated by substituting the galvanometer reading ϕ in equation (3).

For the present investigation the twenty four gauges and their respective dummies were connected to the 50-way strain recorder, each in position. The zero reading of the galvanometer was set up and all the gauges were initially balanced by means of the controls provided for this process.

As the setting, hardening and drying proceed the active gauges were subjected to increasing shrinkage strains. These strains were time dependent and they were measured for a period of fifty days. The first reading for each gauge was taken four hours after casting and successively every four hours for the first three days. Then the readings of the gauges were taken regularly once every three days for the remaining period of the test. The shrinkage strains for all the gauges were calculated carefully and plotted versus time for each beam separately. Figures 55, 56, 58 and 60 represent the measured strains for the different beams tested. The measured deflections of the four beams were also plotted against time and shown in figure 62.

4.1.5 Testing of the specimens under load

Having measured the internal shrinkage strains for the four beams, it was found necessary to test them under load for the following purposes:-

(i) To determine Young's modulus in compression due to bending in order to check Hans Gesund(11) and Plowman's(37) suggestions. (The two gauges No.3 and 4 situated in the compression zone were used for this purpose).

(ii) To calculate the shrinkage stresses.

(iii)To determine the combined strains and stresses due to shrinkage and the applied load. (Maximum safe load was considered to be half the failure load).

To achieve these targets, the beams were subjected to a two point load in an Avery testing machine as shown in figure 54(e). The beams were tested to failure and the internal strains developed at each increment of load were measured. The distribution of strains and stresses due to shrinkage, applied load and the combined action of shrinkage and load are shown in figures 57 and 59 for beams No.2 and 4. The stress-strain relationships for the gauges No.3 and 4 were drawn and Young's modulus determined. The results of the modulus of elasticity in compression due to bending were shown in figures 61

Control tests composed of 6 inch cubes and 12 inch cylinders were also prepared and tested according to B.S.1881-1952. Table No.8 shows the control tests results.

Type of Aggregate	crushing strength lbs/□"	tensile strength lbs/□"	Modulus of elasticity lbs/□"
Ratho-Whinstone aggregate	5080	420	3.37×10^{6}
Blairgowrie gravel	5970	480	3.78×10^{6}

Table No.8 control tests results.

4.1.6 Analysis and discussion of results

The experimental work covered by this chapter revealed a good deal of information which reflects to a certain extent the internal movements in plain and reinforced concrete. As soon as concrete is mixed with water, a series of chemical reactions takes place and the concrete after an apparent dormant period starts to set and harden. The concrete as a result of hydration undergoes a reduction in volume of what is known as the pre-set shrinkage - (Intrinsic shrinkage). In the same time, the cement on passing into cement gel expands to more than double its original volume. For instance, one could expect to see that the internal gauges will reflect this action by reading compressive strains. In fact the results shown in figures 55, 56, 58 and 60 showed that all the gauges, embedded in concrete, indicated tensile strains ranging between 200×10^{-6} to 320×10^{-6} in/in within the first twenty four hours of the age of concrete. The author explains this phenomenon as follows:-

(i) The gauges are affected by the heat of hydration of cement which showed an increase of about $11^{\circ}F$. above the normal laboratory temperature. Considering a coefficient of thermal expansion of paste to be 9×10^{-6} per $^{\circ}F$, the expected expansion could be about 100×10^{-6} in/in which is far less than that measured experimentally.

(ii) The gauges themselves were embedded in the mortar paste which contracts as a result of hydration, thus inducing compressive stresses in the surrounding coarse aggregate particles. These particles in return will react giving additional tensile strains to the mortar paste.

(iii) It is most probable that the tensile strains which were indicated by the gauges within the first 24 hours are the combined action of both item (i) and (ii).

The experiments proved that the concrete undergoes substantial tensile strains along its longitudinal axis during the first 24 hours and then starts to shrink almost in a uniform pattern for the plain concrete. The presence of steel reinforcement restricted the free shrinkage in the neighbourhood of the bars and created an interaction between the two different elements. The shrinkage of concrete initiated the bond forces between the steel and concrete through which the steel bars received compressive strains due to the action of shrinkage of concrete. In spite of the presence of reinforcement the shrinkage of concrete proceeded uniformly for several days before the interaction between the steel and concrete shrinkage came into action. Then, the gradual adjustment between the two opposing internal forces, the shrinkage of concrete and the restriction offered by steel, produced a redistribution of the shrinkage strains. The concrete around the bars had taken tensile strains which increased with time and propagated vertically and horizontally. When only tensile reinforcement was used, the interaction between steel and concrete shrinkage created a bending action leading to warping of the concrete beams as well as cracking.

The use of shrinkable aggregate in concrete structures having only tensile reinforcement resulted in exessive deflections and more cracking as shown in figures 56,57 and 62 and plate 4.11. These objectionable effects may endanger the utility of the concrete element especially in restrained floor slabs, thin beams and continuous structural members.

A reduction in the value of Young's modulus of elasticity was also proved experimentally by loading the specimens and finding its value in compression due to bending as shown in figures 61. These values were emphasized when used in calculating the shrinkage deflections and compared to the measured data as shown in table No.9. The author believes that the reduction in the value of E_c which was determined experimentally for beams No.3 and No.4 was mainly due to the nonuniform distribution of shrinkage strains.

Beam Nº	Type of Aggregate	Period of drying in days	measured deflections in inches	ϵ_c in/in	ϵ_s in/in	Calculated deflections in inches		
						$\Delta = K \frac{L^2}{8}$	$\Delta = \frac{ML^2}{8 E_c I}$	$\Delta = \frac{ML^2}{8E'_c I}$
4	Blairgowrie gravel	10	0.0048	101×10^{-6}	65×10^{-6}	0.00137	0.00161	0.0046
		20	0.0086	133×10^{-6}	92×10^{-6}	0.00194	0.00228	0.00651
		30	0.0110	178×10^{-6}	130×10^{-6}	0.00183	0.00323	0.00921
		40	0.0118	176×10^{-6}	161×10^{-6}	0.00023	0.00340	0.0114
		50	0.0120	173×10^{-6}	182×10^{-6}	–	0.00452	0.01289
2	Ratho-Whinstone Aggregate	10	0.0080	195×10^{-6}	100×10^{-6}	0.00362	0.00279	0.00831
		20	0.0138	245×10^{-6}	132×10^{-6}	0.00431	0.00368	0.01100
		30	0.0174	315×10^{-6}	185×10^{-6}	0.00495	0.00515	0.01540
		40	0.0198	325×10^{-6}	239×10^{-6}	0.00328	0.00666	0.01988
		50	0.0230	345×10^{-6}	278×10^{-6}	0.00255	0.00774	0.02310

Table No. 9 Experimental and calculated shrinkage deflections.

Beam 2

$I = 70.675$ inch^4

E_c = standard young's modulus = 3.37×10^6 lbs/□"

E_c = experimental modulus in bending = 1.128×10^6 lbs/□"

Beam 4

$I = 70.675$ inch^4

$E_c = 3.78 \times 10^6$ lbs./□"

$E_c = 1.328 \times 10^6$ lbs/□"

It was also found that the shrinkage strains beside their warping and cracking effect led to the loss of the tensile strains provided in the steel bars due to load and increased the compressive strains in the compression zone. The combined strain and stress distribution are shown in figures 57 and 59.

To eliminate or reduce the shrinkage warping it was proved that the provision of reinforcement in the compression zone could be satisfactory as shown in figure 62. Still the use of a balancing reinforcement had an adverse effect of increasing the restriction to shrinkage and promoting more shrinkage cracking in cases where shrinkable aggregate was used as shown by Plate No.411.

4.1.7. Conclusions

The following conclusions are drawn as a result of the experimental work covered by this chapter:-

(1) Unsymmetrically reinforced sections exhibit permanent deflections due to nonumiform shrinkage of concrete. These deflections are independent of the load action and their values depend greatly on the properties of aggregate used. The shrinkable aggregate is compressible and contributes to shrinkage of concrete. Excessive warping deflections could be mainly attributed to the role of the shrinkable aggregate in concrete shrinkage.

(2) Warping of concrete elements cast with shrinkable aggregate could be greatly minimised by using an equal amount of reinforcement near the concave face.

(3) Shrinkage and creep produce large, though gradual, redistribution of stresses due to interaction between the steel and concrete

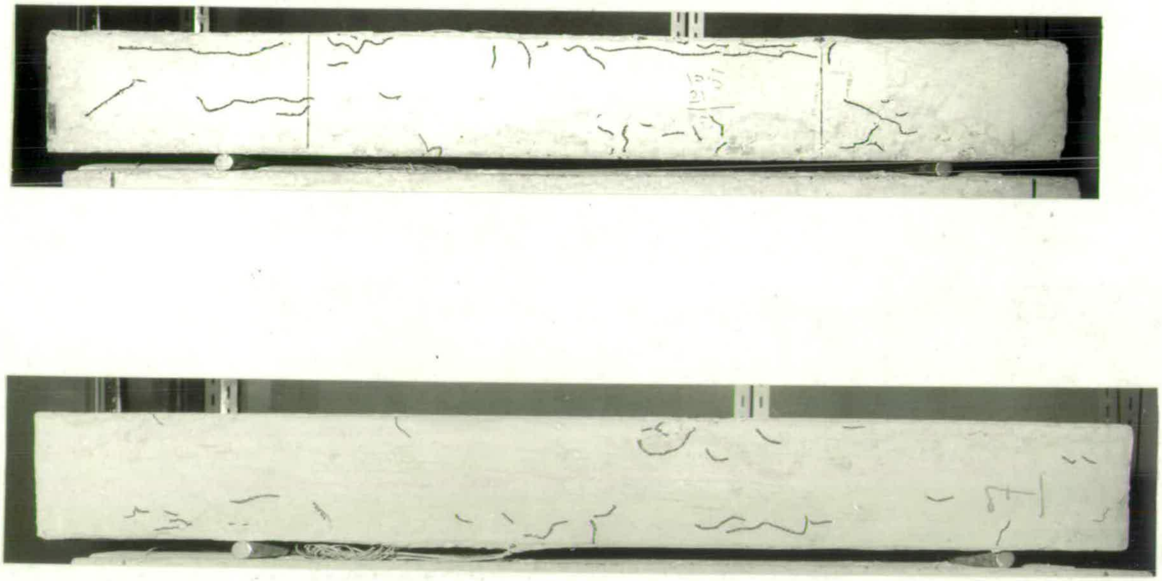


Plate 4.11 Cracking due to shrinkage observed in one of the beams cast with shrinkable aggregate

shrinkage.

(4) Drying shrinkage imposes compressive stresses on the steel which by itself reacts against them putting the adjacent concrete in tension. The shrinkage stresses which are induced in steel and concrete have a considerable effect on the stresses developed due to load. The steel in the tension side loses part of its load stresses while the concrete in compression receives additional compressive stresses due shrinkage.

(5) It is advisable to avoid the use of shrinkable aggregates in major structures to ensure their safety, efficiency and durability.

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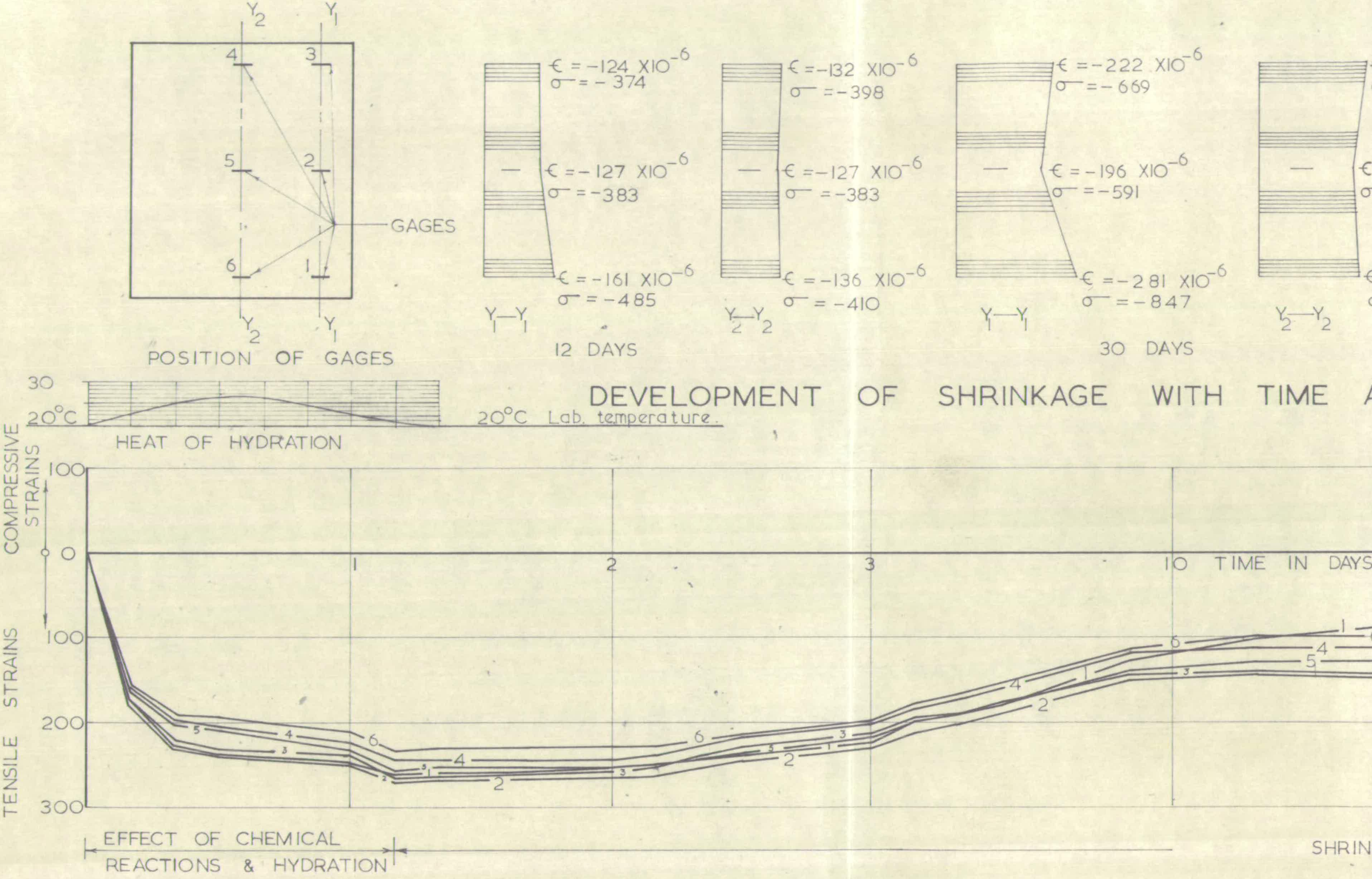
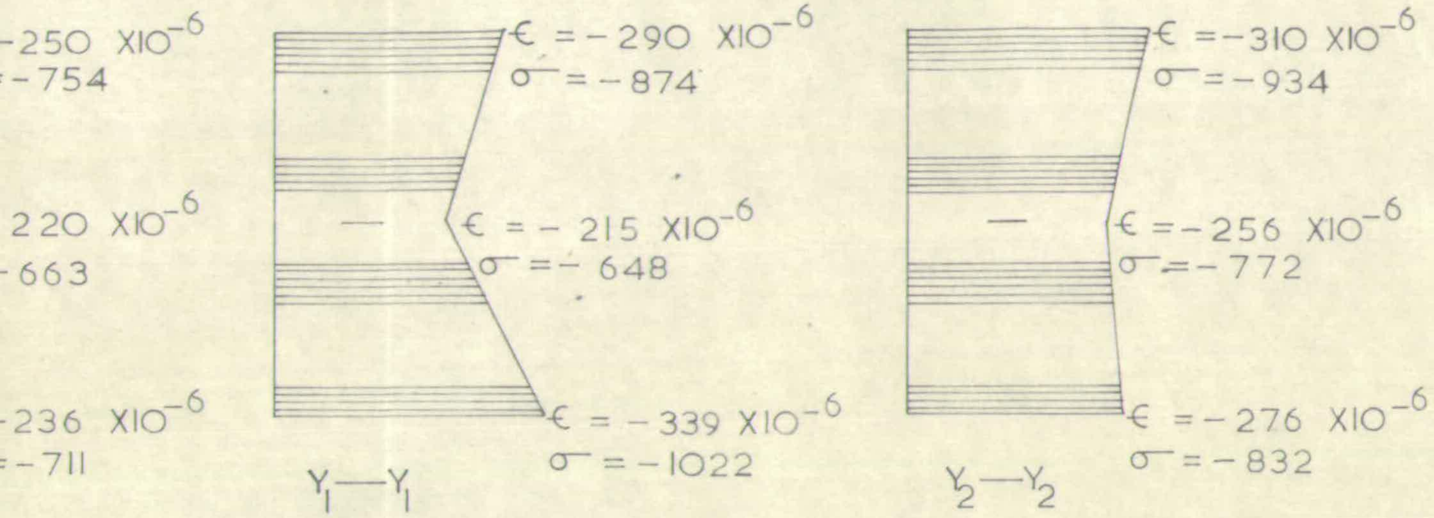


FIG. 55 INTERNAL STRAINS —— PLAIN CONCRETE BEAM NO.

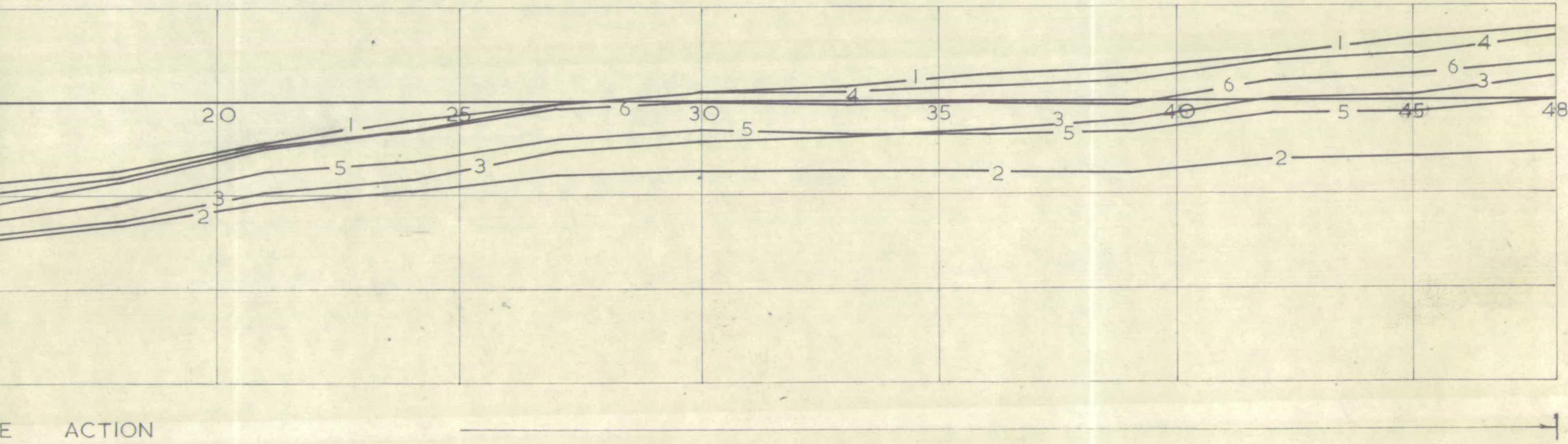
(15)



48 DAYS

UNITS
- STRAINS in XIO^{-6}/in
- STRESSES lb/sq. in

ONG THE AXES $Y_1 - Y_1$ & $Y_2 - Y_2$



E ACTION

——— RATHO — WHINSTONE AGGREGATE

Ⓐ

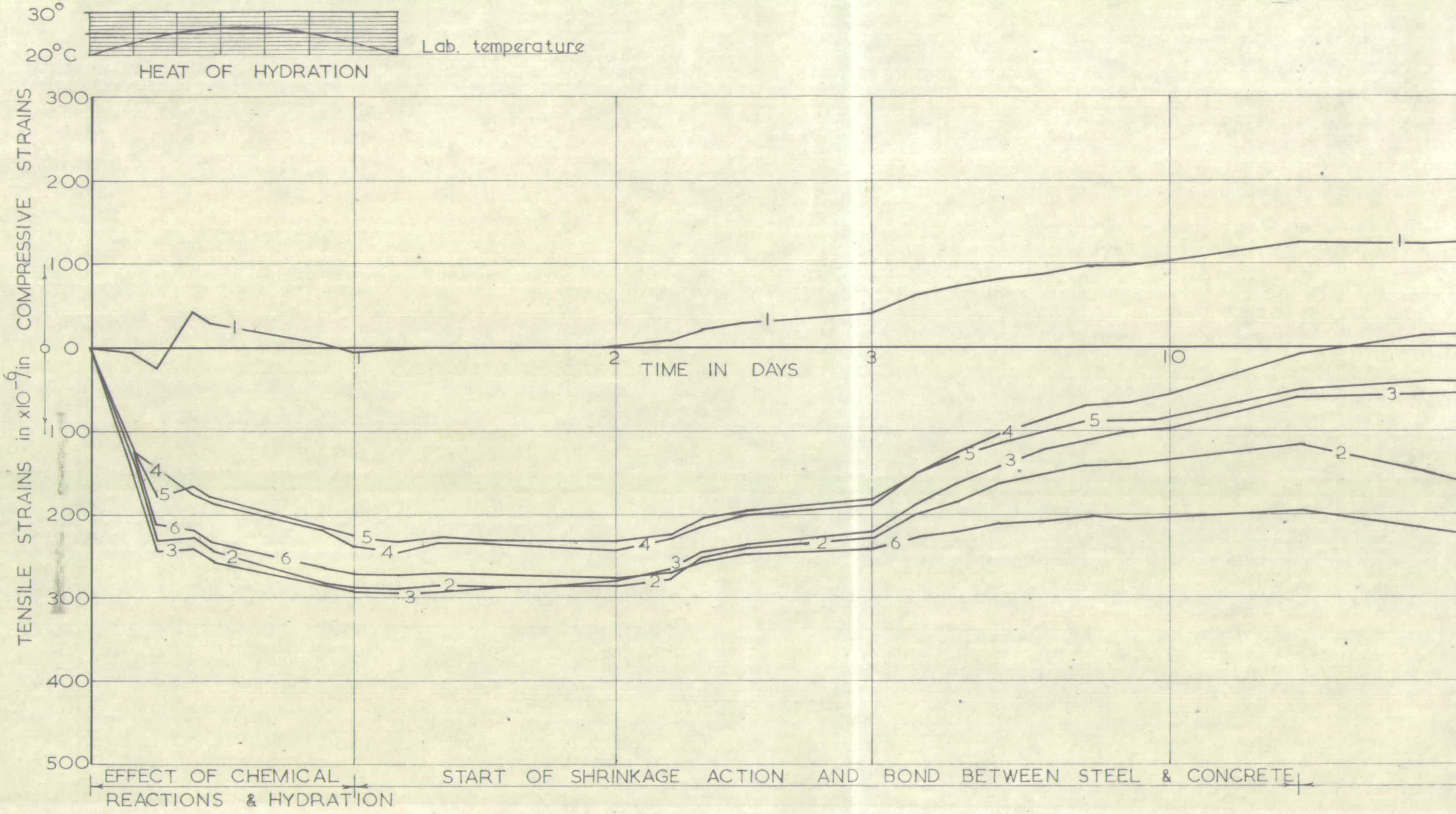


FIG. 56 INTERNAL STRAINS —— REINFORCED CONCRETE BEAM NO. 2 —— F

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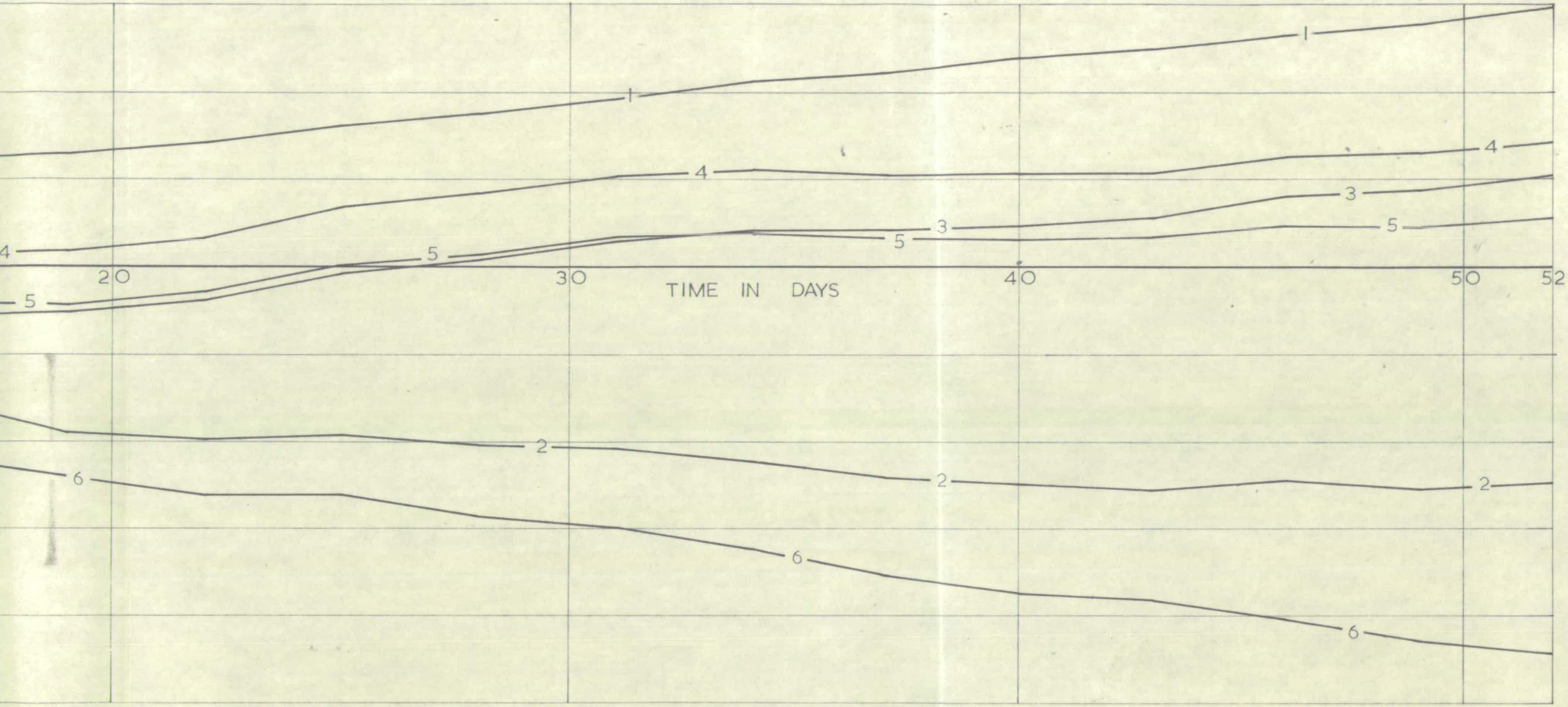
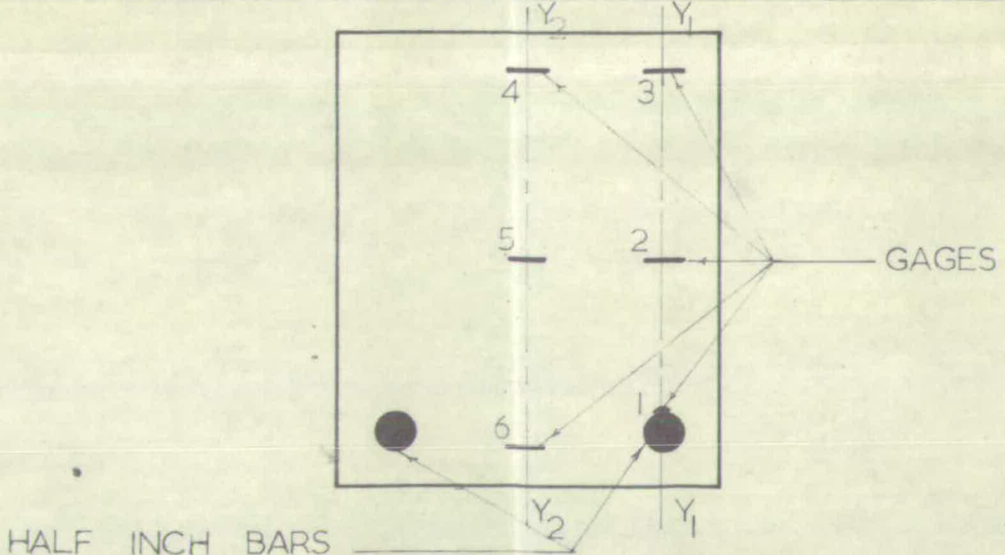
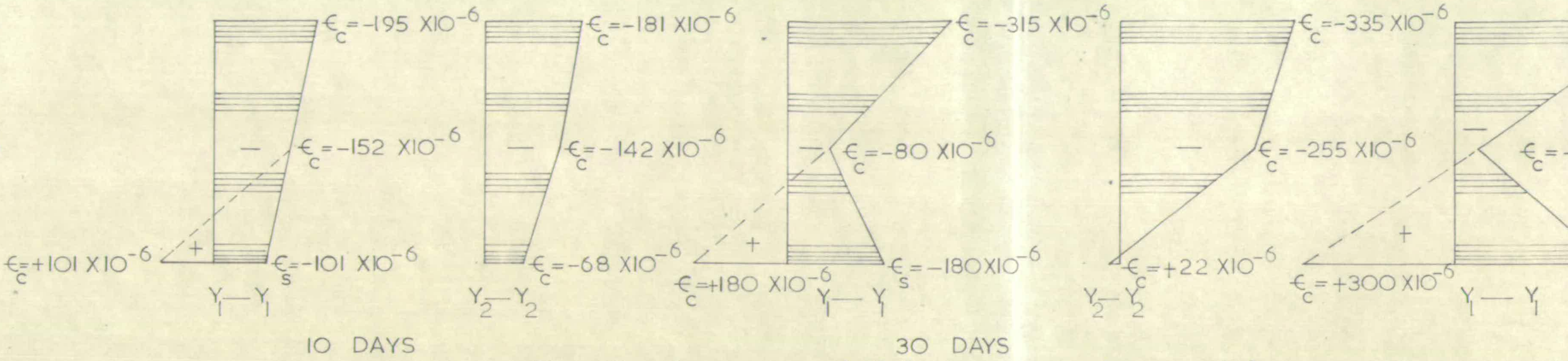


GAGES 2 & 6 TAKING TENSILE STRAINS DUE TO INTERACTION BETWEEN STEEL & CONCRETE SHRINKAGE

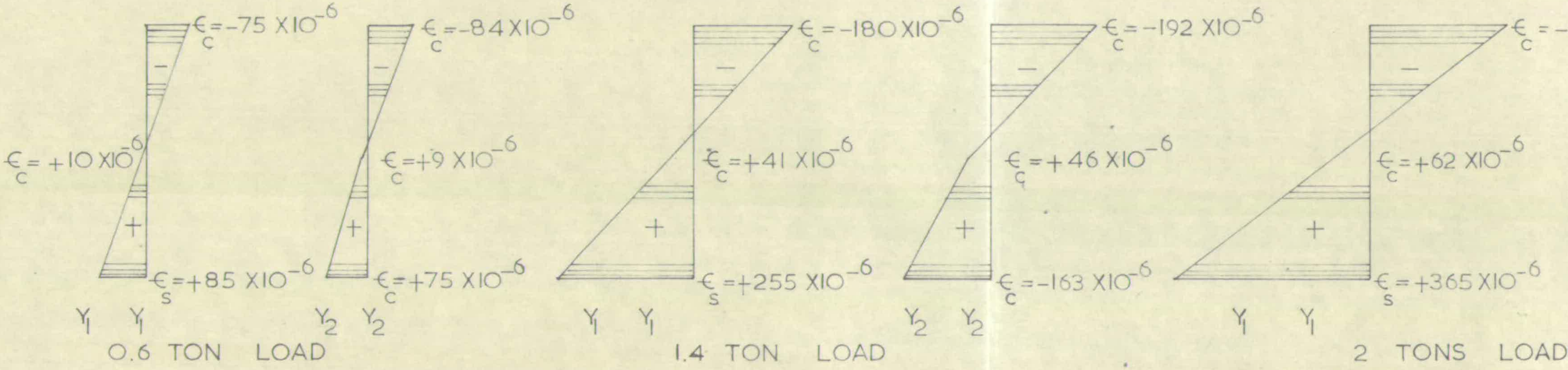
THO WHINSTONE



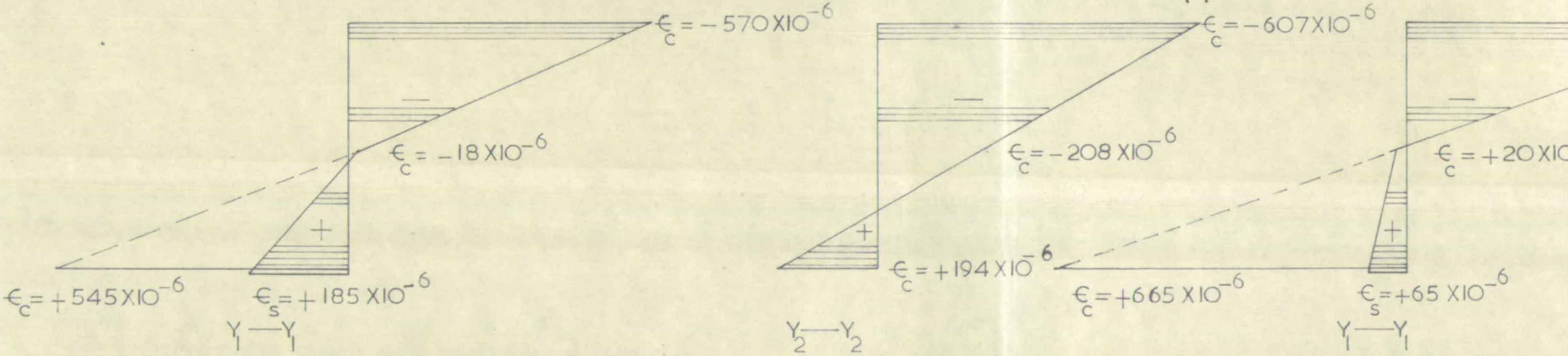
(A·)



distribution of shrinkage strains with respect to t

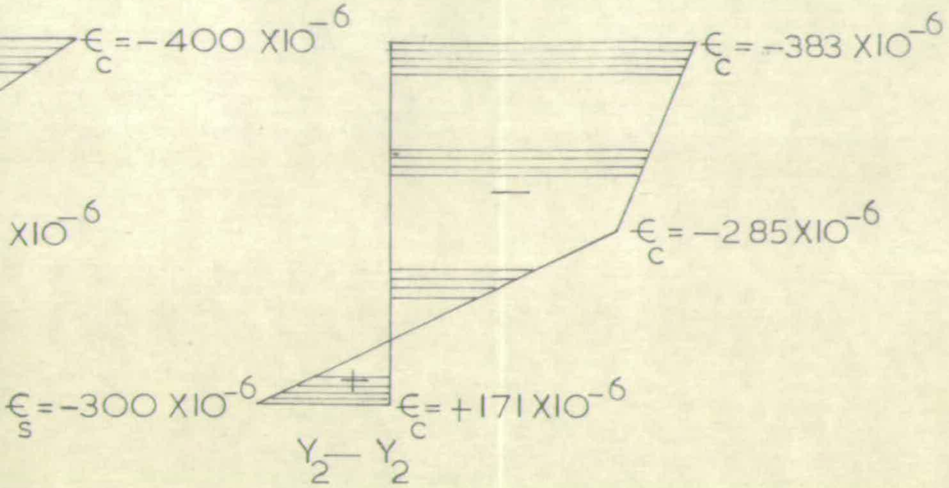


distribution of strains due to applied load

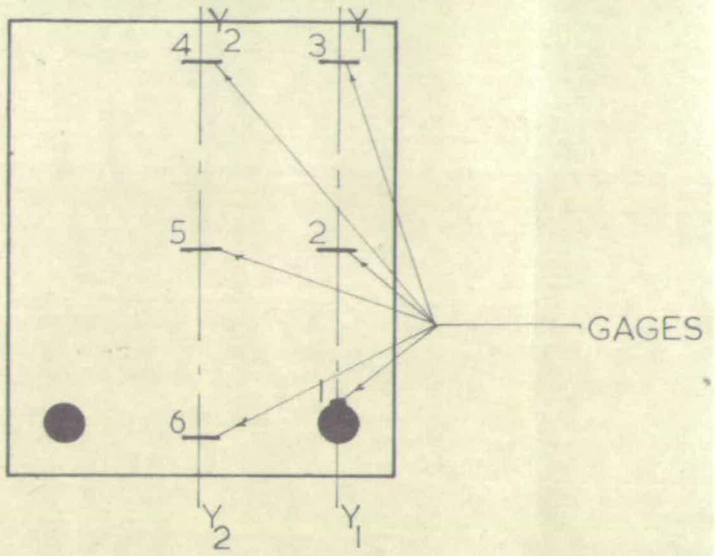


combined strain distribution ___ 2 tons + 30 days shrinkage & 2 tons + 52 days

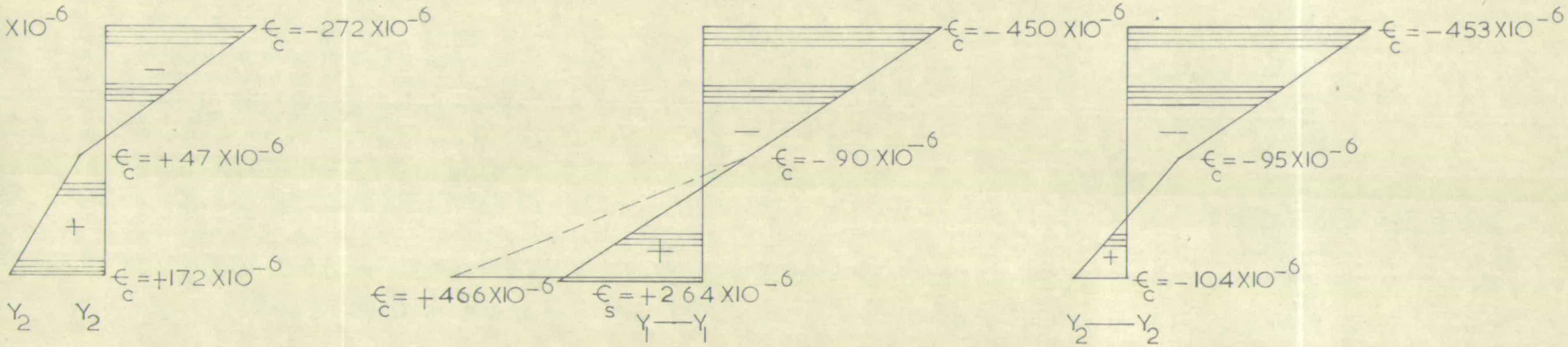
FIG. 57 INTERNAL STRAINS DUE TO SHRINKAGE AND APPLIED



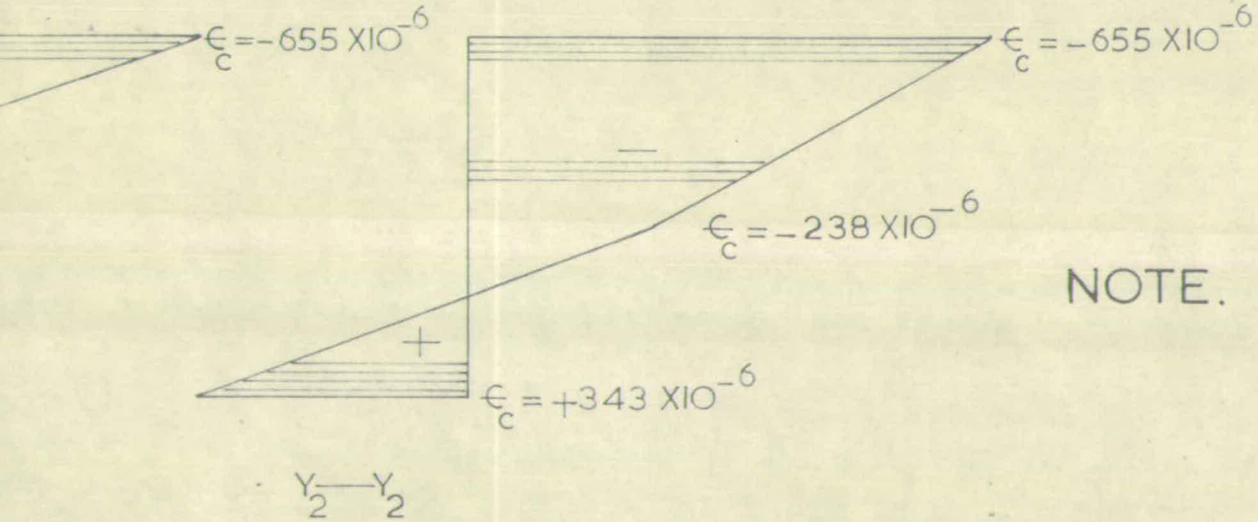
2 DAYS



CROSS SECTION OF BEAM & GAGES



combined strain distribution — 2 tons + 10 days shrinkage



NOTE. Cracks in concrete are expected for tensile strains around 200×10^{-6} in/in

rinkage

LOAD ——— BEAM NO. 2 —— RATHO_WHINSTONE AGGREGATE

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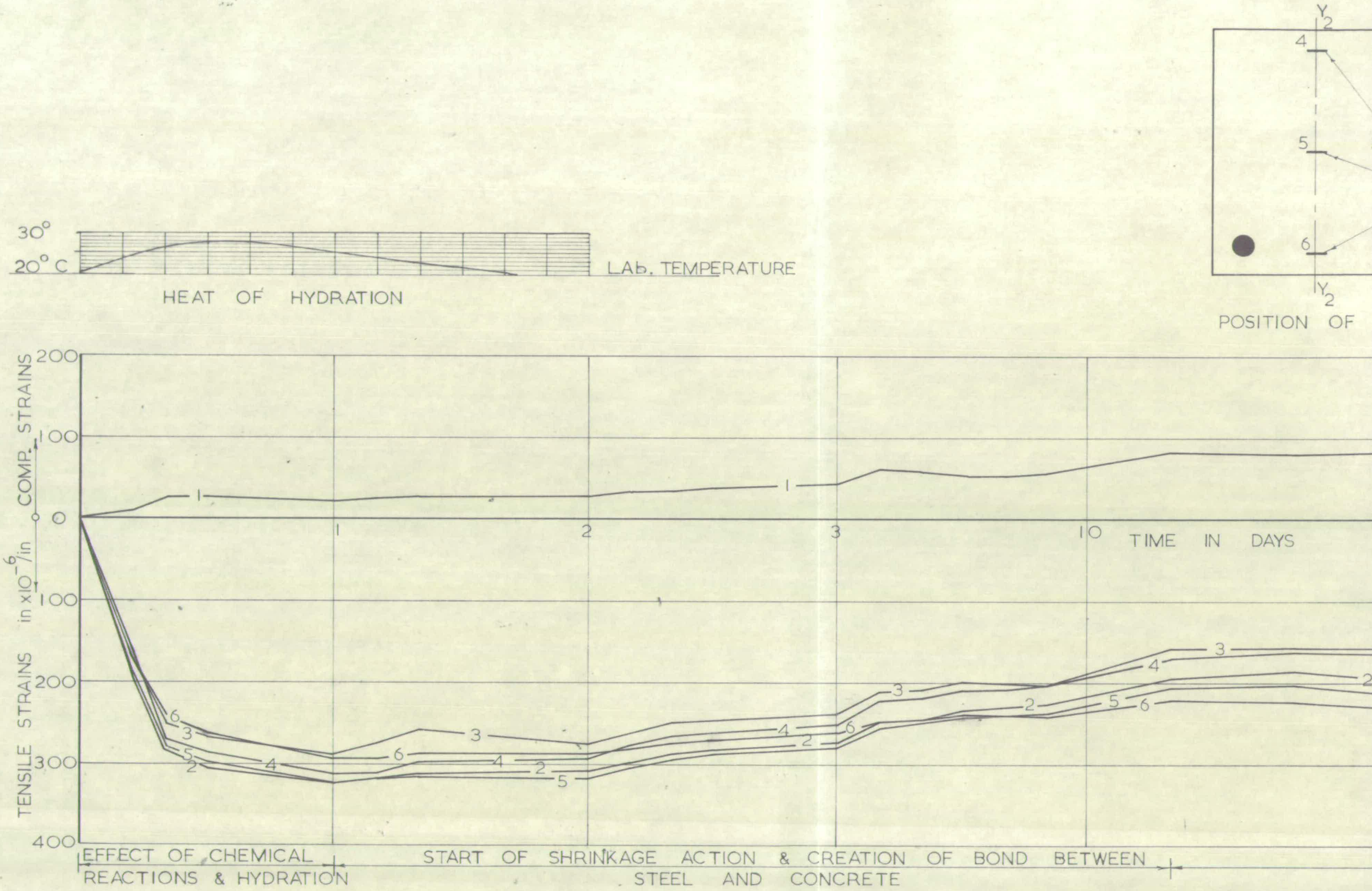
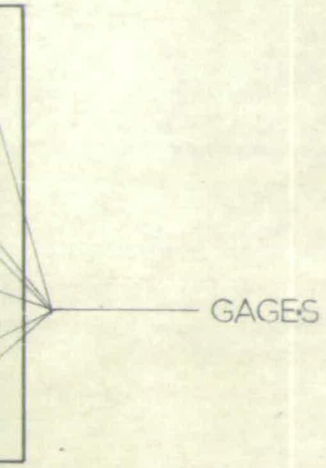
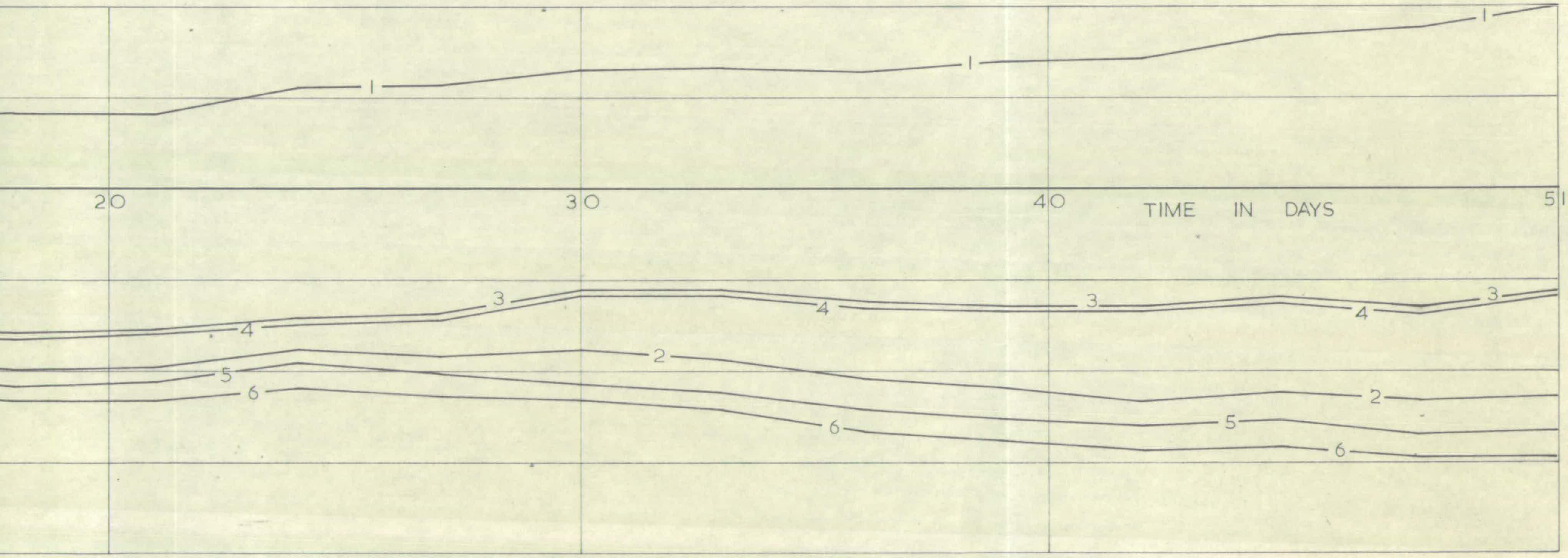


FIG. 58 INTERNAL STRAINS REINFORCED CONCRETE BEAM



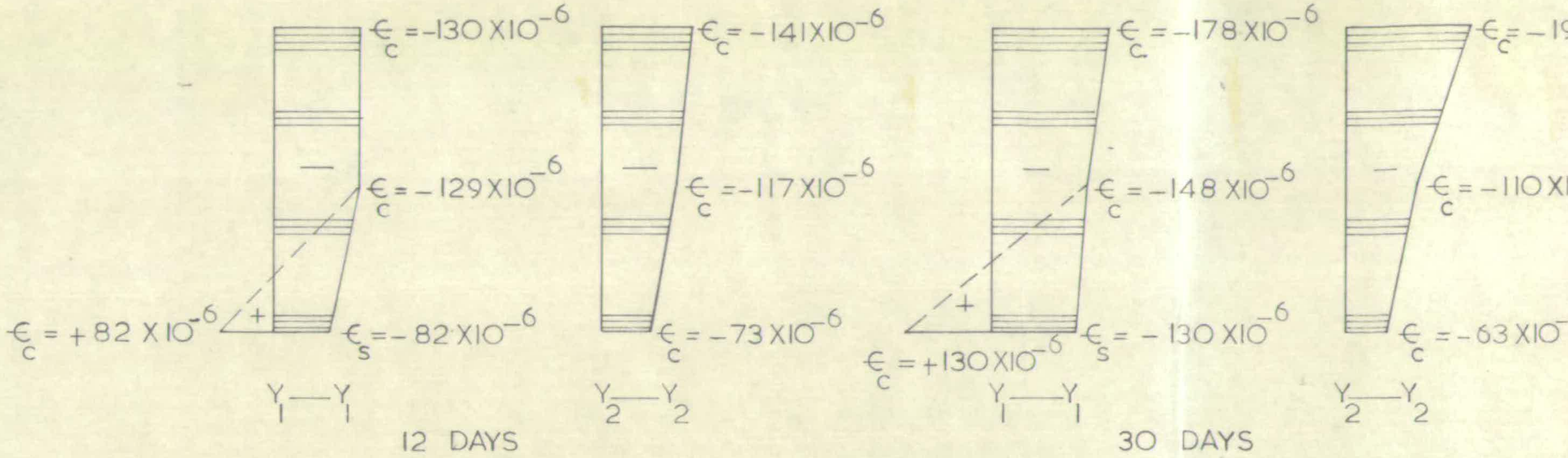
GES



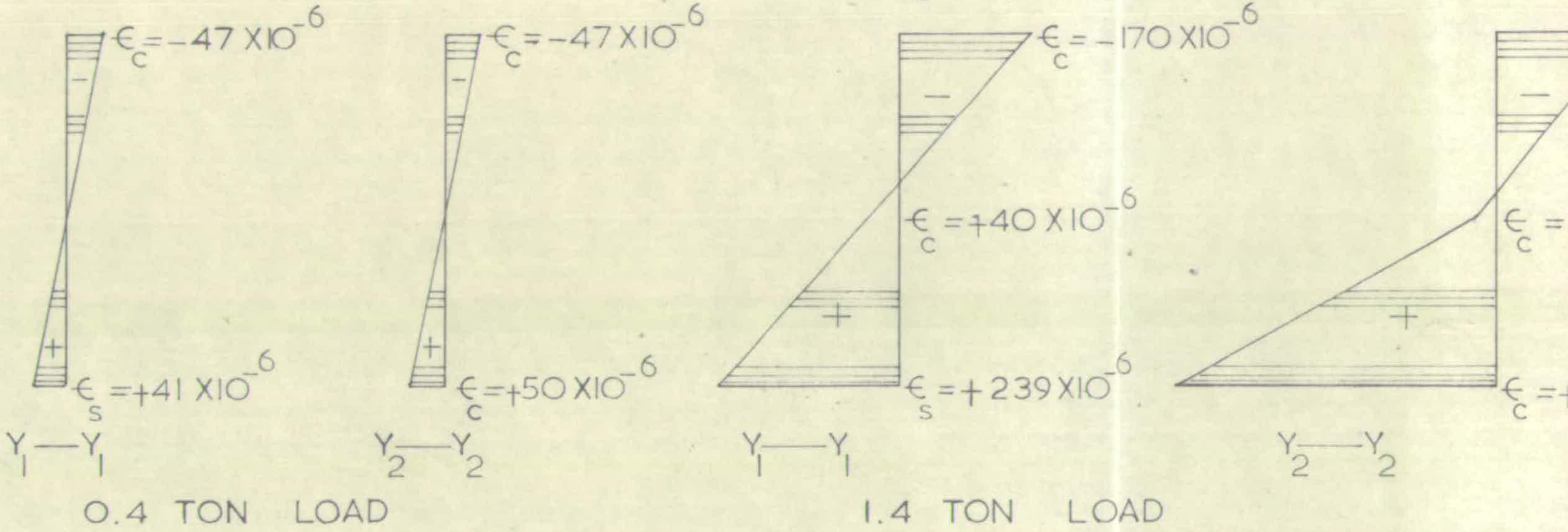
GAGES 2, 5 & 6 TAKING TENSILE STRAINS DUE TO INTERACTION BETWEEN STEEL & CONCRETE SHRINKAGE

NO. 4 BLAIRGOWRIE GRAVEL

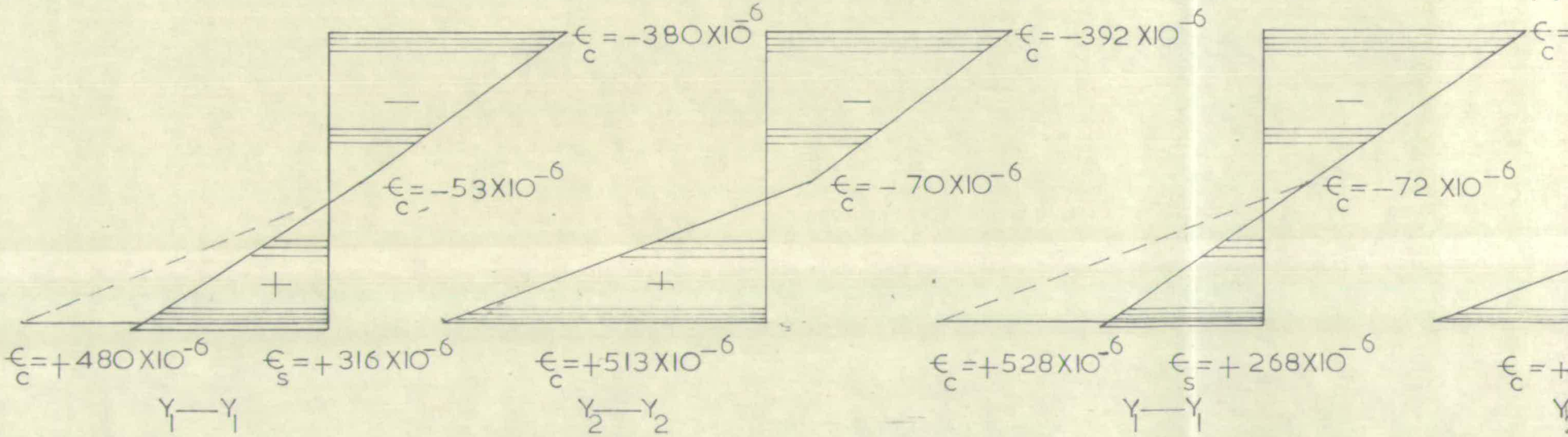
A.



distribution of shrinkage strains with respect



distribution of strains due to app

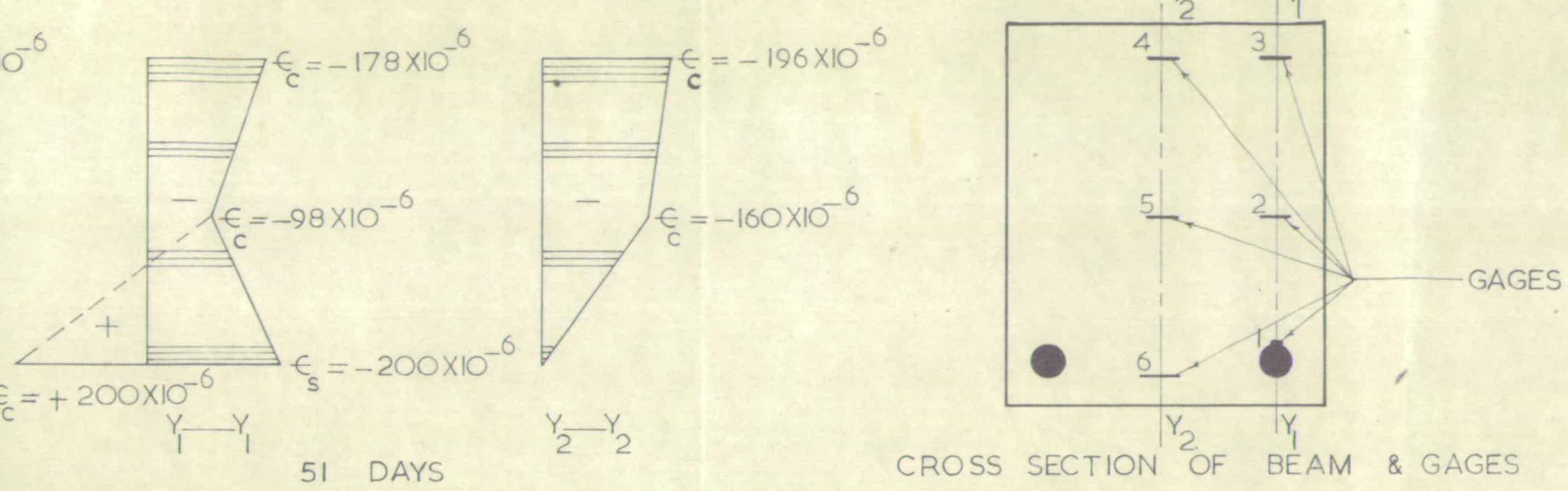


combined strain distribution ——— 2 tons applied

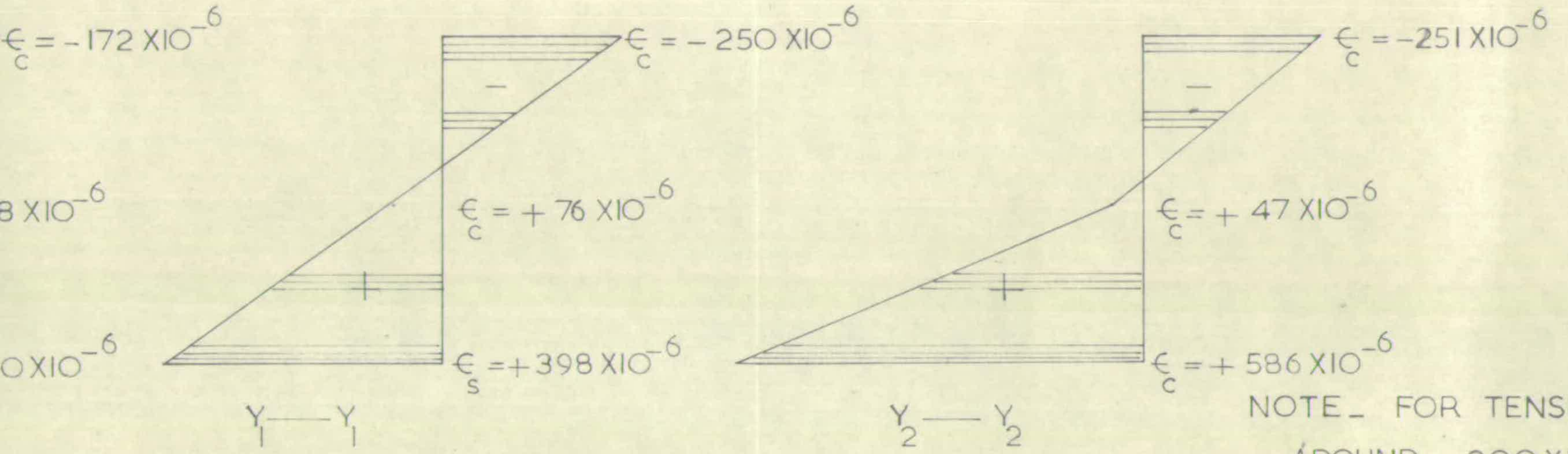
FIG. 59 INTERNAL STRAINS DUE T

BEAM NO. 4 ——— BLAIR

(B.)



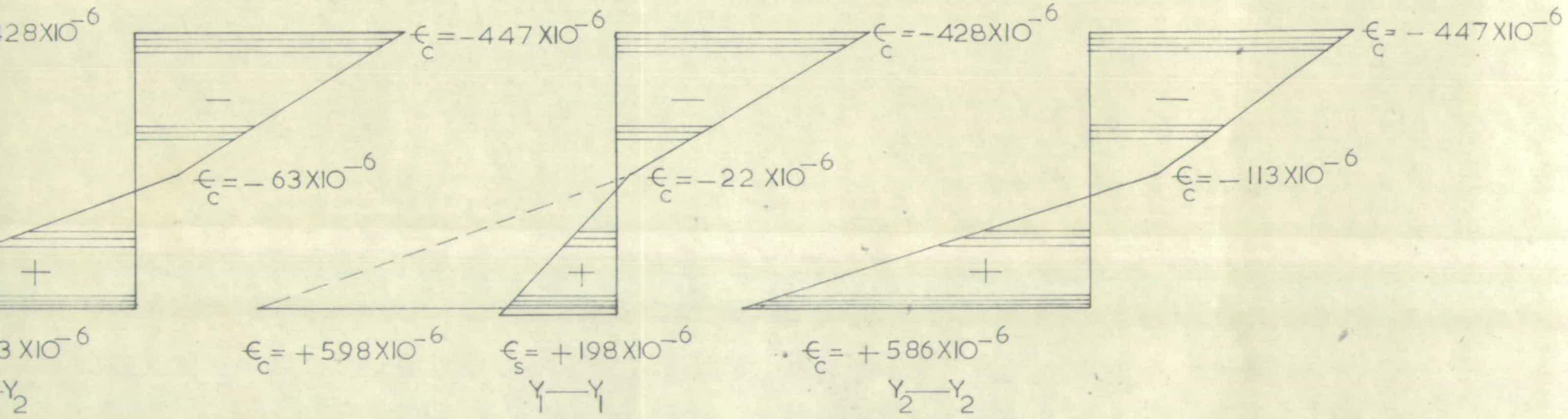
to time



2 TONS LOAD

NOTE_ FOR TENSILE STRAINS AROUND 200×10^{-6} in/in CRACKS IN CONCRETE ARE EXPECTED

d load



ad + shrinkage strains developed at 12, 30 & 51 days

SHRINKAGE AND APPLIED LOAD.

OWRIE GRAVEL

Ⓐ

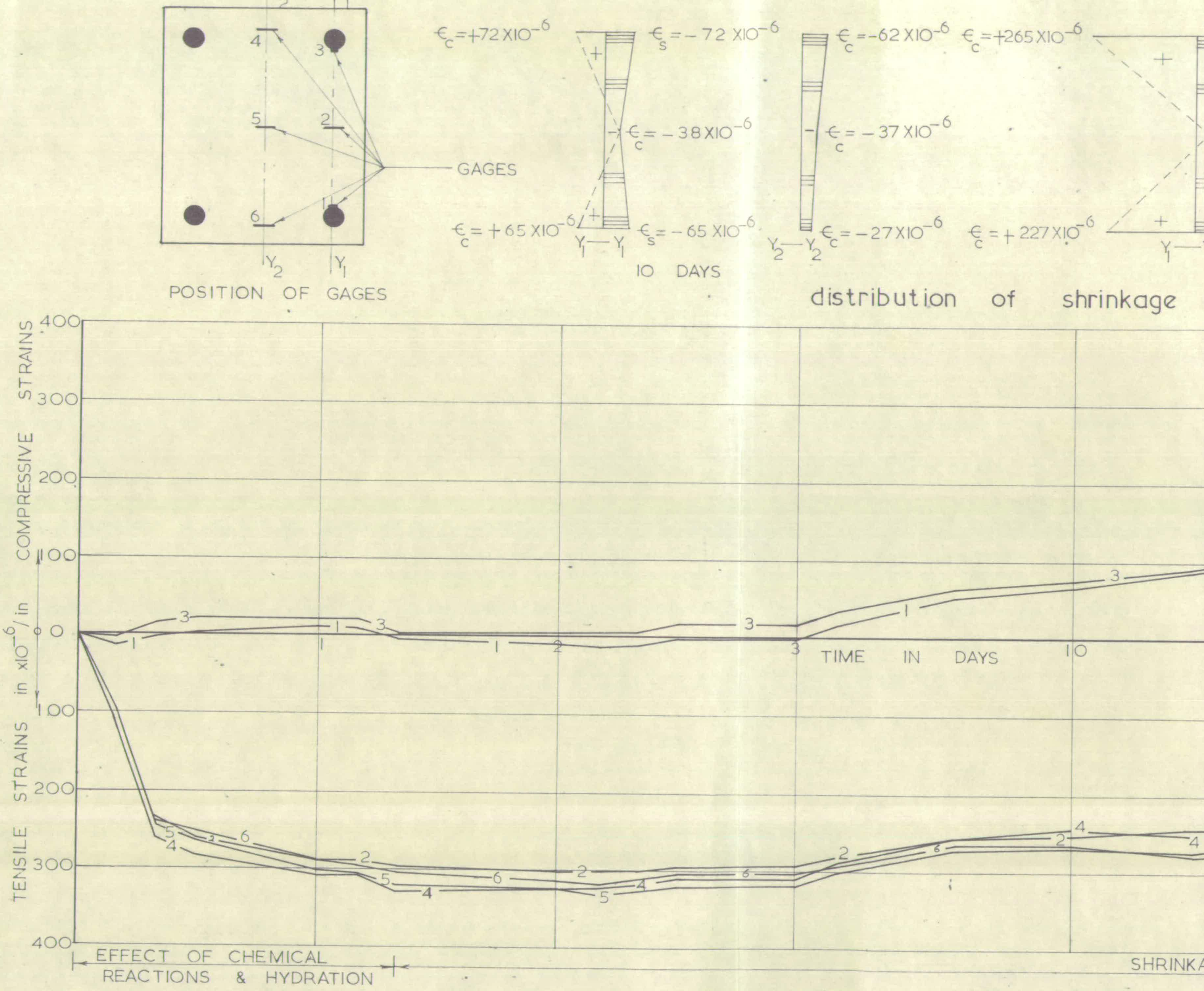
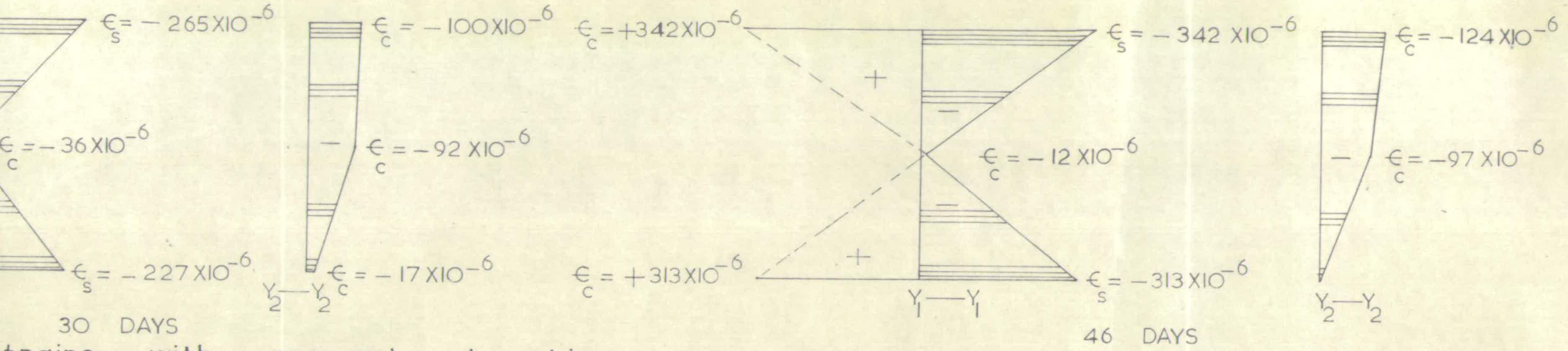
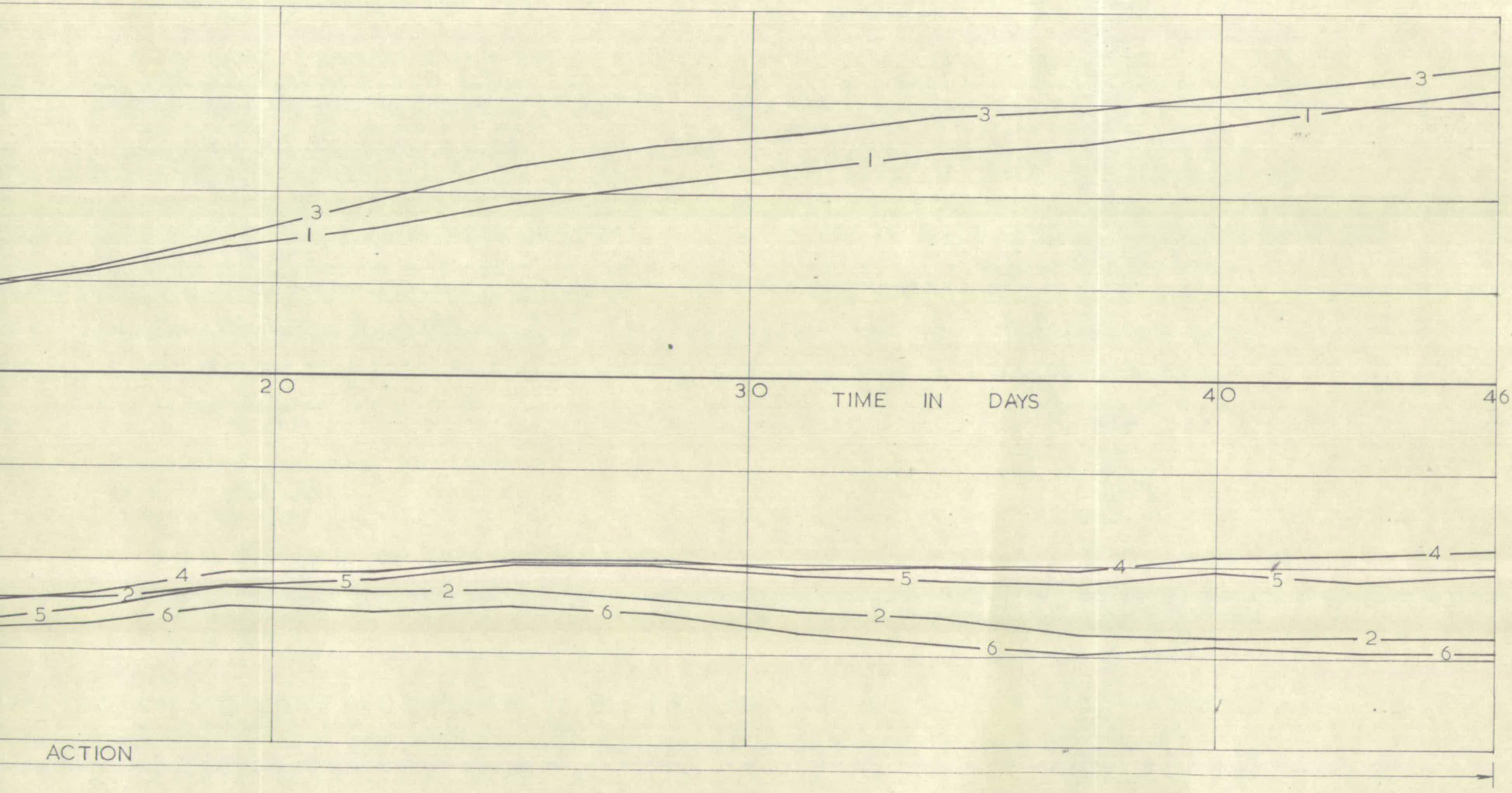


FIG. 60 INTERNAL STRAINS —— REINFORCED CONCRETE

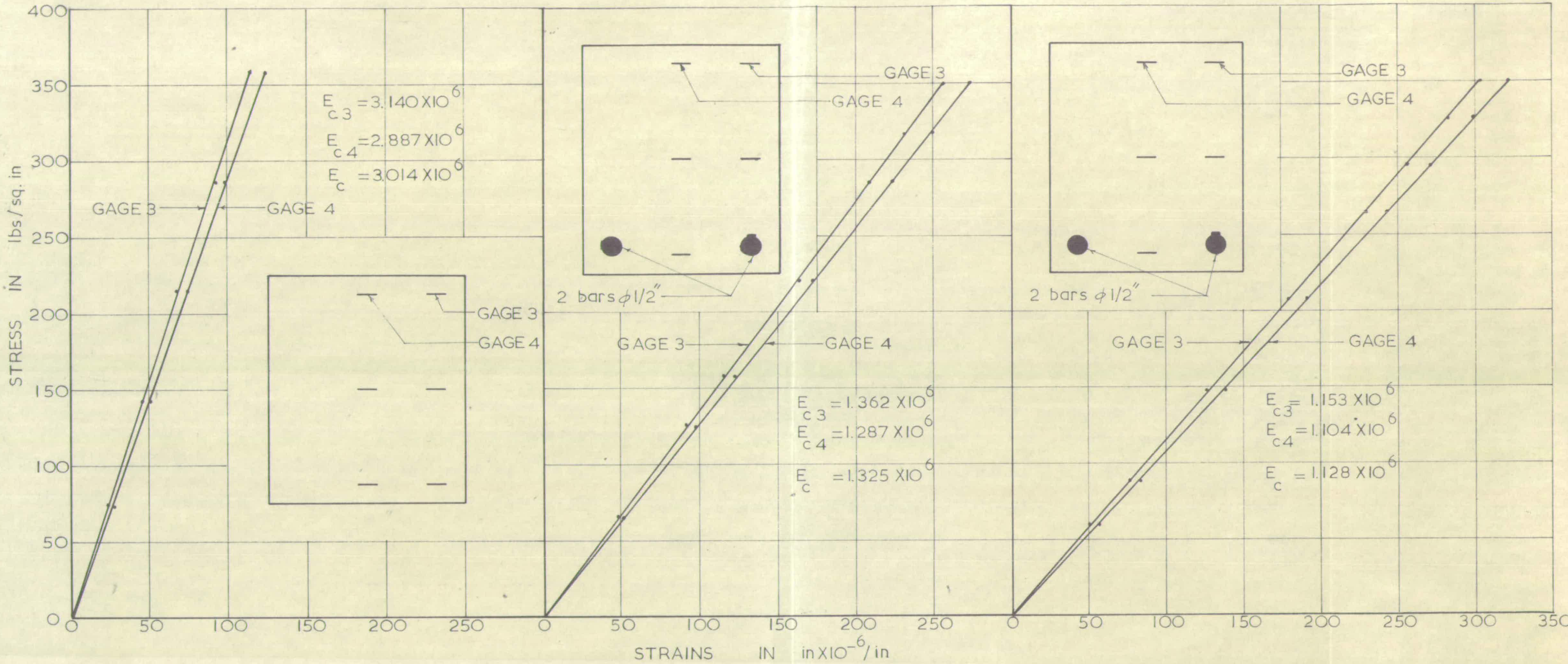
(B)



trains with respect to time



BEAM 3 ——— RATHO — WHINSTONE AGGREGATE



beam 1 ratho_whinstone

beam 4 blairgowrie gravel

beam 2 ratho_whinstone

FIG. 61 MODULUS OF ELASTICITY IN COMPRESSION DUE TO BENDING

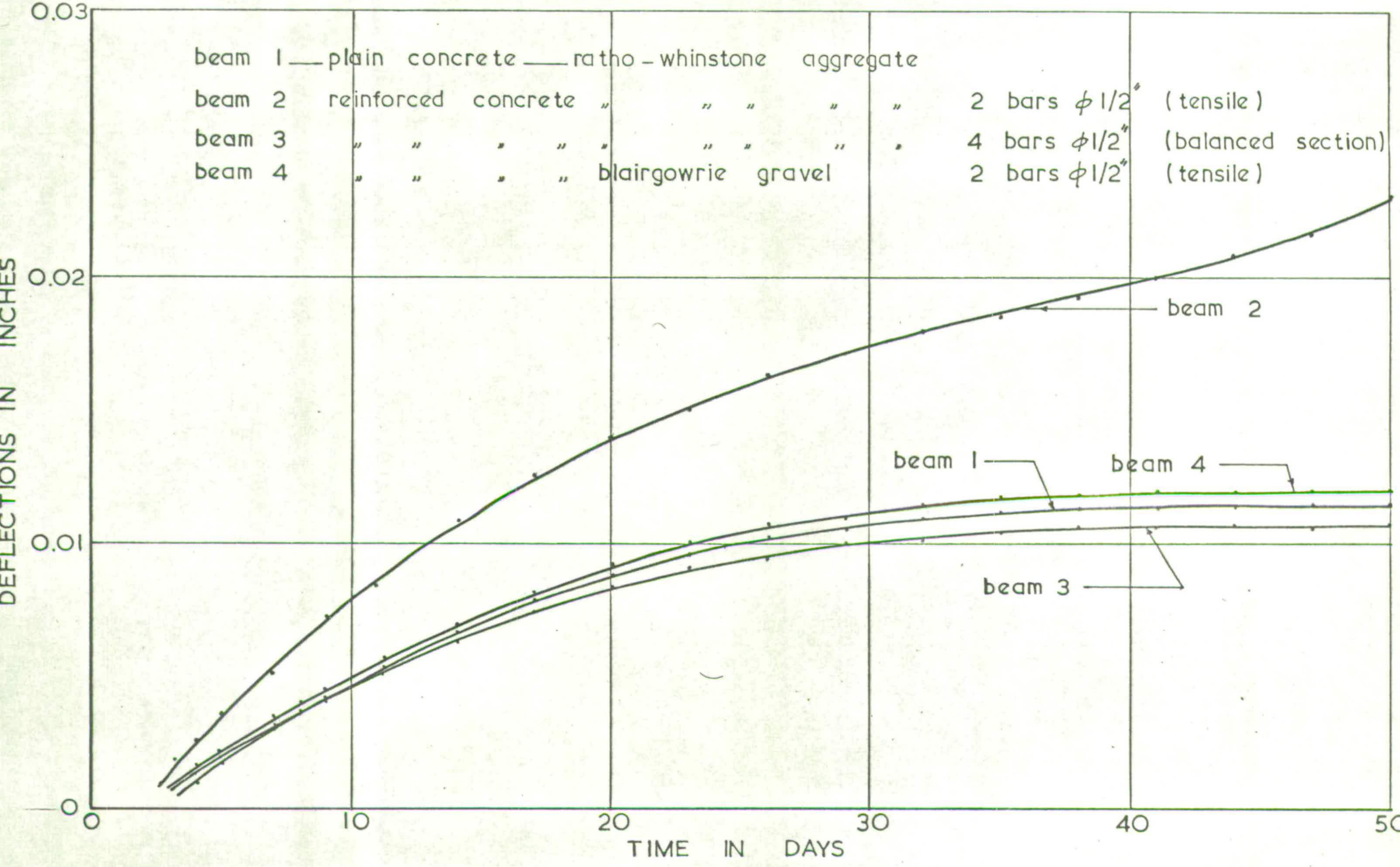


FIG. 62 WARPING DEFLECTIONS DUE TO SHRINKAGE

CHAPTER 5

5.1 GENERAL CONCLUSIONS

The consequences of using shrinkable aggregate in cement-bonded products are important and interesting. The most notable of these are the deflections of structural members, shrinkage cracking and deterioration of concrete surfaces.

Reinforced concrete contains steel to provide the tensile strength required in a structure. Normally, such steel is introduced near the base of the member and when excessive shrinkage of concrete takes place, the effect of the steel is to reduce the shrinkage of concrete in the immediate proximity of the steel. Further away from the steel much greater shrinkage takes place and the resultant warping of the concrete could be mainly attributed to nonumiform shrinkage distribution in the member. The restriction that the steel exerts on the free shrinkage also initiates tensile strains in concrete which may exceed its tensile strength and lead to cracking.

The deflections of thin beams and their internal shrinkage strains are dealt with in this thesis and the results shown in the previous chapters. In practice, structures such as bridges, buildings, water tanks and frames would suffer damaging effects which manifest themselves as deflections in the spans, cracking of the members and deterioration of the exposed surfaces. Deflections of two inches have been found in beams 30 ft. long. Severe leakage due to shrinkage cracking was experienced recently in a newly built filtration plant in Edinburgh. The deflections in roof slabs and beams in buildings have secondary affects such as cracking of partition walls, distortion of door frames and buckling of ceilings. In prestressed structures the excessive shrinkage of concrete may lead to total loss of prestress and hence permanent cracking.

Since all such defects result from the excessive shrinkage of concrete and essentially when shrinkable aggregate is used, it is advisable that the use of such types of aggregates should be entirely avoided. Engineers should pay utmost attention to the adverse effects of the shrinkable aggregates and should insist on using normal types of aggregates irrespective of their initial cost to save all the troubles that might be encountered when the shrinkable aggregate is used. The author believes that the recommendations laid down by the Building Research Station in Digest 35 are valuable and should be followed to ensure the efficiency of the concrete structures and their safety.

REFERENCES AND BIBLIOGRAPHY

1.	T.L. Webb	Shrinking aggregate in the construction industry in South Africa. Industrial review of Africa, April 1959.
2.	Torben C. Hansen and Allan H. Mattock	Influence of size and shape of member on the shrinkage and creep of concrete. A.C.I. Journal, February 1966.
3.	Gerald Pickett	Shrinkage stresses in concrete A.C.I. Journal, January, February 1946.
4.	Thomas T.C. Hsu	Mathematical analysis of shrinkage stresses in a model of hardened concrete, A.C.I. Journal, March 1963.
5.	E.P. Evans and B.P. Hughes	Shrinkage and thermal cracking in a reinforced concrete retaining wall. Proceedings, Institution of Civil Engineers, August, 1968.
6.	Roy W. Carlson	Drying shrinkage of concrete as affected by many factors. Proceedings, A.S.T.M., V.38, No.11-1938.
7.	Torben C. Hansen and Knud E.C. Nielsen	Influence of aggregate properties on concrete shrinkage. A.C.I. Journal, July 1965.

8. Roy W. Carlson Drying shrinkage of large concrete members. A.C.I. Journal, February 1937.

9. A.D. Ross Shape, Size and Shrinkage. Constructional and Engineering, August 1944.

10. Alfred L. Miller Warping of reinforced concrete due to shrinkage. A.C.I. Journal, May 1958.

11. Hans Gesund Shrinkage and creep influence on deflections and moments of reinforced concrete beams. A.C.I. Journal, May 1962.

12. George L. England Methods of estimating creep and shrinkage strains in concrete from properties of constituent materials. A.C.I. Journal, November 1965.

13. W. Kinniburgh Comparison of drying shrinkage of autoclave and air cured concrete at different humidities. Rilem Symposium on lightweight concrete, Gothenburg, June 1960.

14. K.M. Alexander Factors affecting drying shrinkage of concrete. Constructional review, March 1964.

15. F.S. Fulton — A co-ordinated approach to the shrinkage testing of concretes and mortars. Magazine of concrete research, Vol.13, No.39, November 1961.

16. Gerald Pickett — Effect of aggregate on shrinkage of concrete and hypothesis concerning shrinkage. A.C.I. Journal, January 1956.

17. Ulf Bjuggren and A.M. Neville — Effect of aggregate on shrinkage of concrete and hypothesis concerning shrinkage. Discussion, A.C.I. Journal, December 1956.

18. A.M. Neville — Properties of concrete. Pitman, London.

19. W.T. ~~Marchal~~ Marshall — Shrinkage and temperature stresses in reinforced concrete sections. Civil Engineering, Vol.56, No.665, December 1961.

20. F.K. Garas — The control of shrinkage cracking in concrete slabs. Ph.D. thesis submitted to Sheffield University, 1965.

21. Scott, W.L. and Sir W. Glanville — Explanatory handbook of the B.S. Code of practice for reinforced concrete, C.P.114, 1957.

22.	F. Walley and S.C.C. Bate	A guide to the B.S. Code of practice for prestressed concrete. C.P.115: 1959.
23.	O. Faber	Plastic yield, shrinkage and other problems of concrete and their effects on design. Inst. of Civil Engineers, Proceedings, November 1927.
24.	W.H. Glanville	Studies in reinforced concrete shrinkage stresses. Building Research Station, Technical Paper No.11.
25.	F.M. Lea	The chemistry of cement and concrete.
26.	D.F. Orchard	Concrete technology. Vol.1, Properties of Materials.
27.	Boley and Weiner	Theory of thermal stresses
28.	Building Research Station	Shrinkage of natural aggregates in concrete. Digest (2nd series) No.35, July, 1963.
29.	American Code of Practice	A.C.I. Journal No.318-1963.
30.	British Standard Institution	B.S. 2028-1968. Precast concrete blocks.
31.	British Standard Institution	"Methods of testing concrete" B.S. 1881: 1952.
32.	D.F. Orchard	Concrete technology, Volume 2, Practice.

33.	A.W. Hendry	Elements of experimental analysis
34.	Snowdon, L.C. and Edwards, A.G.	The moisture movement of natural aggregates and its effects on concrete. Magazine of concrete research Vol.14, No.41, July 1962.
35.	T.R. Shank	The mechanics of plastic flow of concrete. A.C.I. Journal, November-December 1935. Proc. V.32
36.	G.A. Maney	Warping of Non-Uniform shrinkage over cross-section found to be source of all time yield in loaded concrete members. Studies in Engineering, No.1, North Western University Technological Institute, Feb. 1941.
37.	R.A. Sefton Jenkins, J.M. Plowman and B.A. Haseltine	Investigation into the causes of the deflection of heated concrete floors, including shrinkage. The Structural Engineer, Vol.43, No.4, April 1965.
38.	W.Czernin	Cement chemistry and physics for civil engineers