LINEAR SHRINKAGE OF CEMENTS DURING SETTING.

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There has been relatively little investigation into the conditions arising in the cement, from the time water has been added to its usually adopted setting time according to Vicat needle, largely owing to the difficulty of measurements and if this technical obstacle could be surmounted, then it would appear that much valuable information could be obtained at the earlier stage.

Hardening of Portland Cement has been generally explained either by the crystal or gel theory. Crystal theory raises the question whether there is enough water in a concrete for the solution and crystallization. Gel theory assumes that a body of gel does not remain similar to itself during swelling and shrinkage, but suffers considerable deformations. In a conservative system in which water neither entered nor left a mass of concrete and neglecting thermal effects, the concrete would shrink continuously till all the cement has hydrated, all the water used up or all movement of water rendered impossible.

In view of these conflicting opinions, an attempt has been made in this dissertation to obtain information about linear changes in cement during the first six hours after water has been added. Blue Circle Portland Cement and Ferrocrete neat

as well as 1:3 mortars with standard sand according to the British Standard Specifications have been investigated upon. A technique has been developed after careful trial which enables measurements to be taken and data recorded of the linear changes arising during the period of the initial set.

The data thus obtained is analysed and discussed in relation to previously accepted explanation on the results indicated. The results obtained indicate that the usually adopted ideas about shrinkage seem rather untenable.

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This investigation was carried out in the Laboratory of the Civil Engineering Department of the City and Guilds College, Exhibition Road, London, S.W. 7., during the Sessions 1934-35 and 1935-36, under the direction of Professor R.G.H. Clements, M.C., M.Inst.C.E.

The author has to thank Professor Clements for his valuable suggestions, constant help and guidance throughout the whole period.

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PART I.

CHAPTER I.

THE HISTORY OF CEMENTS AND CONCRETES.

CHAPTER I.

Definition of Cements.

Cements[1] may be defined as adhesive substances capable of uniting fragments or masses of solid matter into a compact whole. Such a definition embraces a large number of widely different substances, having little in common with one another but their adhesiveness, and the very unequal technical and scientific importance has tended to bring about a restriction of the designation to one group of adhesive substances, namely to the plastic materials employed to produce adhesion between stones, bricks, etc., in the construction of buildings and engineering works. Cements of this kind also bear a chemical relationship to each other, consisting as they do, at least in modern technical practice, of mixtures which contain compounds of lime as their principal constituents. The term "cements" in this restricted sense then becomes equivalent to "calcareous cements", but it may be allowed to include certain allied compounds of magnesium.

The History of Cements and Concretes.

A brief historical sketch of the use of cements and concretes may not be considered out of place.

The use of cement in buildings is not met with below a relatively advanced stage of civilisation. The prehistoric megalithic structures as well as

the cyclopean masonry of Greece are all made up by ramming successive layers of earth one over another or of stone blocks, set one above another without the aid of cementing materials. Babylonians and Assyrians were perhaps the first people to have used a layer of Bitumen as a cementing material between successive layers of stones. Bitumen was available there in natural deposits. The use of bitumen did not spread as it was not then available in natural deposits elsewhere. In the sense of using a calcareous cementing material for their construction works, Egyptians were perhaps the first. The use of burnt lime as a cementing material is generally attributed to them, though chemical examination in buildings as old as the Great Pyramid shows that they never used lime until the Roman period and that they always obtained cementing material by burning gypsum. The reason[2] for using gypsum instead of lime, although limestone was more abundant and more accessible than gypsum, was probably the scarcity of fuel, lime requiring a much higher temperature and consequently more fuel for its calcination. Romans must have borrowed it from Greeks who in their turn must have adopted it possibly from Persia. Greeks prepared their mortar by slaking the lime and mixing it with sand. Perhaps they started the use of concretes, an artificial conglomerate of gravel or broken stone with sand and lime or cement

which the Romans in their turn used very widely for their constructions. Vitruvius has described concrete, and Pliny[3] thus refers to the construction of cisterns - "Cisterns should be made of five parts of pure gravelly sand, two of the very strongest quicklime, and fragments of silex (not true silex, or flint, but a hard lava from the Alban Hills) not exceeding a pound each in weight; when thus incorporated bottom and sides should be well beaten with iron rammers". The art of making mortars and concretes reached a very high degree of perfection with the Romans. The still existing Roman brickwork and concrete is a sufficient testimony to the excellence of the material and workmanship. The great vaults of the Thermae and of the Basilica of Constantine are cast in concrete.[4] The most famous ofRoman buildings erected in concrete is the Pantheon[1], the walls of which, 20 ft. thick, are of tuffa and pozzolana concrete, thinly faced with brick, whilst the dome, 142 ft. 6 inches in span, is cast solid in concrete containing pumice and pozzolana. The remarkable hardness of Roman workmanship puzzled many engineers and has sometimes led to the assumption that some skill was possessed by the workmen which is now lost, but a comparison of the analysis of the mortar with the descriptions of the method by ancient

authors gives no ground for such a supposition. It was mainly due to the thoroughness of mixing and ramming.

A gradual decline in the quality of the mortar used in buildings set in after Roman times due to various reasons and continued throughout the middle ages. Much of the concrete used in early medieval buildings is of very inferior quality.

From[1] the twelfth century onwards, the quality has steadily improved, the lime being well burnt and well sifted. After the fourteenth century, excellent mortar is found, and precaution was evidently taken of washing the sand free from adhering dirt or clay.

During recent times, the investigation carried out by John Smeaton[5] in 1756, when called upon to erect a new lighthouse on Eddystone Rock is the most important. As the results with the usual mixture of mortar which used to be composed of "two measures of quenched or slaked lime, in the dry powder, mixed with one measure of Dutch Tarras, and both very well beat together to the consistence of a paste, using as little water was possible" were not always satisfactory, he investigated different types of limes and found that those which gave the best results contained a considerable proportion of clay.

This was the first time that the properties of hydraulic lime were recognised. In spite of the success of Smeaton's experiments, the use of hydraulic lime made little progress and the old Roman mixture of lime and pozzolana retained its supremacy for a long time.(6)

The investigations of L.J. Vicat(7) on hydraulic limes led him to prepare an artificial hydraulic lime by calcining an intimate mixture of limestone (chalk) and clay, ground together in a wet mill. This process may be regarded as the principal forerunner of the manufacture of Portland cement, which is not a material of great antiquity. It was discovered only a little over a century ago and quite by accident. Hydraulic limes then were usually manufactured by heating argillaceous limestones to temperatures not greatly above that at which the carbon dioxide would be liberated. This process was carried out in a stack furnace and the conditions were such inside it that some(8) parts of the material were heated to temperatures which produced sintering. As it was much more difficult to grind these hard sintered materials they were usually discarded and the rest ground and used as hydraulic lime. However, Aspdin(9) in 1824 ground some of these hard lumps and in confirmation of a report of Vicat, found

that they produced a cementing material far superior to any of those formerly produced by the old process. To this the name "Portland Cement" was given because of a fancied resemblance of the colour of the cement after setting to Portland stone.

Essentially,[10] the making of cement consists in combining the oxides of calcium, silicon, iron and aluminium into crystalline compounds by the application of heat.

For half a century the amounts of this new material produced were very small, and even up to the beginning of the twentieth century there was only a suggestion of the tremendous industrial importance which Portland cement was destined to attain in building construction.

The invention of reinforced concrete, a material in which the resistance to compression of well-mixed and hardened concrete is combined with the tensile strength of steel has given a great impetus to the use of concrete and has also had a far-reaching effect in bringing about a steady improvement in the quality of cement.

Versatility of Concrete Construction.

It has placed in the hands of the architect a plastic and versatile material with which he can fashion the substance of his dreams, may fabricate

the most massive monoliths of which he may mould into the most delicate tracery of ornamentation and to which he may impart any tone or tint of the rainbow. R.H. Bogue[8] sums it as follows:- "The most delicate forms of adornment can be produced by its use. One of the most beautiful of all modern shrines is the remarkable lacelike Bahá'i Temple in Chicago as conceived by its creator, 'shelter of cobweb interposed between earth and sky', struck through and through with light'. This was done in concrete by the master craftsman Earley, who made one of the first great statues ever to be built of concrete, the "Fountain of Time" in Chicago. It has played an important part in the development of an incomparable network of modern highways, great and inspiring edifices and economical homes which are durable and secure abodes of lasting beauty".

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CHAPTER II.

CRACKS IN CONCRETE.

CHAPTER II.

Scientific Study of Cements.

The scientific study of cements is of quite recent date, though the earliest authors, Vitruvius and others, dealt with the theory of setting even. Their explanations were naturally of an extremely hypothetical character. The use of Portland cement after the invention of reinforced concrete has grown beyond dreams and the requirements of engineers have called for a more perfect material. So various associations were established in most of the countries either under voluntary organisation of engineers or under official auspices to control or study the quality of the product. As the use of cement grows from day to day, these specifications have to be revised, alterations made being almost invariably in the direction of the stringency of the requirements. The cement[1] produced to-day is far superior to that produced some years back due to the improvements in kilns and mechanical appliances of the industry, and the improved knowledge of the limits of composition within which a satisfactory product can be obtained. There is no reason to suppose that the limit of improvement has been reached, as quite a lot about cement is still unknown.

Some properties of cements, such as grading of

mixtures, water content, admixtures, etc., as well as strength, creep, elasticity, bond of cement, have received a good deal of attention from the investigators. Some work has been done about its constitution, shrinkage, etc. as well, but it still remains to formulate a basic theory which would account for all - creep, shrinkage, plastic flow, setting, etc.

Cracks in Concrete.

Some people have still the idea that concrete is one of the few structural materials which crack. Whereas reinforced concrete[2] is normally monolithic in character, other constructions in masonry or marble are discontinuous and jointed. The result is this - that the cracks produced by movement in an ordinary jointed structure are dissipated and spread over numerous beds and joints of construction, but in a concrete construction they are apt to concentrate themselves in well-defined and sometimes ugly openings, unless the steel reinforcement is sufficient and properly disposed.

Building materials[3] as far as cracks due to shrinkage are concerned could be classified into three main groups:- (1) Impervious materials - such as metals and to a certain extent marble and granite.

They shrink or expand slightly on change of temperature or stress beyond the elastic limit, the movements are proportional to the change of conditions and are reversible. Group (2) Porous but seasoned timber, mature concrete and brickwork, are subject to the same movements as are those in Group (1), but also to expansion or shrinkage due to change of humidity. The Group (3) consists of unseasoned timber and immature concrete which are subject to reversible movements due to the three causes already mentioned and in addition, to shrinkage on seasoning which is irreversible as well as plastic yield. The movements due to different causes may be opposed, a piece of concrete, for example, will expand when warmed, but it may at the same time tend to shrink through abstraction of moisture, so that only the difference between the two movements becomes apparent. Timber will shrink as much as $\frac{1}{4}$" to the foot across the grain during seasoning, and will not expand again to its original size even when immersed. Concrete shrinks on hardening. These latter movements are irreversible and must not be confused with the shrinkage caused by drying.

Most of the failures in concrete could be attributed to poor workmanship. The reasons[4] for poor concrete have been proportioned as being 90% due to poor workmanship, 8% due to poor aggregate, and 2% to poor cement.

Concrete cracks due to internal stresses [5] set up within it due to

(A) Loading;

(B) Chemical reaction;

(C) Changes in Moisture Content;

(D) Changes in Temperature.

The first two will now be briefly discussed.

(A) Cracks due to Loading may be due to:-

(i) Settlement of the supports or foundations;

(ii) Too high a stress in the reinforcement resulting in excessive deformation;

(iii) Too thick a covering of concrete, in particular where the effective depth of the beams is very small.

(iv) Too early removal of forms.

(v) Defective design of forms, with inadequate allowance for contraction and expansion due to variation of moisture.

(vi) Careless removal of forms.

(vii) Forms not being rigid, resulting in deficient adhesion and excessive deflection.

(viii) Insufficient allowance for continuity, fixity and general monolithic nature of concrete work done in situ.

(ix) Applied loads in excess of those allowed for in the design.

(x) Impact.

(B) Cracks due to chemical reaction may be due to:-

(i) Use of unsuitable aggregates;

(ii) Use of unsound cement;

(iii) Action of applied acids, etc.

(iv) Corrosion of reinforcement due to passage of moisture through porous concrete;

(v) Inclusion of impurities in the concrete such as plaster, etc.

(vi) Crazing. This will be explained later. (See page 26).

(C) and (D). - Changes in moisture content and temperature cause expansion and contraction of concrete and mortar. This shrinkage sets up tensile stress in a specimen and the concrete cracks when such stress passes a certain point. This will now be discussed in detail as being one of the most important factors about concrete about which still little is known; the data available is still contradictory and unless this problem of shrinkage is fully solved, the concrete cannot be put to its full use.

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CHAPTER III.

SHRINKAGE STRESSES.

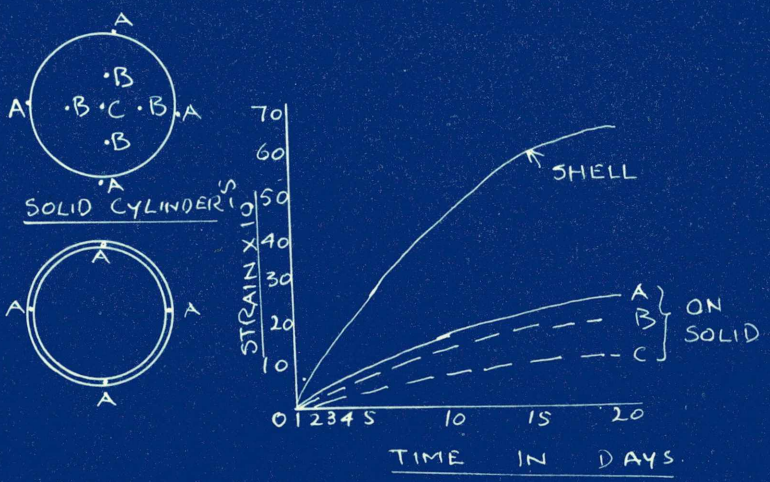


FIG. 1 — SHRINKAGE IN HOLLOW AND SOLID CYLINDERS.

CHAPTER III.

Shrinkage Stresses.

A shrinkage strain [1] is the prevention of a movement, and causes stress which somewhat resembles temperature stress. In a sphere, the skin would tend to contract more than the bulkier core would allow; and the prevention of this movement would put the skin in tension and the core in compression. In a cylinder, induced shrinkage would cause circumferential hoop tension in the exterior, and a corresponding compression in the interior. In an axial direction, the tendency of the skin to shorten would be partially restrained by the moister concrete inside; and the skin would be put into longitudinal tension, and the core into longitudinal compression. Maney's [2] tests have shown this very clearly. He cast two cylinders, 8 x 32 inches, one solid, and one hollow with walls $\frac{3}{4}$" thick; and measured the longitudinal shortening in air at several points. Fig. 1 shows the result. The free shrinkage of the hollow shell is 420×10^{-6} times more than the restrained skin shrinkage of the solid cylinder. Maney calculated that, assuming $E = 4 \times 10^{-6}$ lbs., the skin tension in the solid cylinder was 1600 lbs./sq.in. Lynam [1] has rightly pointed out that this conclusion does not take account of the fact that the water in the shell has only a very

short distance to travel to the surface, and the surface/mass ratio is so large as to lead to rapid evaporation. The surface of the solid cylinder is probably always more moist than that of the shell as it can call on large reserves of water during hydration from the interior; the surface/mass ratio is small; and in such a large mass thermal effects may be important. It is possible that the skin shrinkage of the cylinder may approach that of the shell; but it is doubtful whether the core of the cylinder will ever come to a level with the skin unless other agencies come into action.

R.W. Carlson[3] also measured the shrinkage of prisms of 6 ins. square cross-section, with lengths 22 ins., at different distances from the exposed surface. Shrinkages were measured with a 5-inch strain gauge on two opposite surfaces, in two directions at right angles, and at different distances from the exposed surface. There were 26 gauge lines. He found that the gauge line nearest to the exposed surface but perpendicular to it showed no shrinkage but rather a slight expansion up to the age of three months, which he attributes to an abrupt change in shrinkage from the exposed face inward. His results are discussed on page 66 and are given in Table XVI.



INTERNAL STRESS
NO LOAD.



INITIAL TENSION JUST ELIMINATED.



DISTRIBUTION COMMONLY ASSUMED.

FIG. 2 — EFFORT OF INTERNAL STRESS.

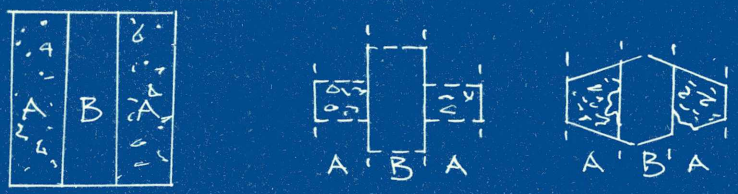


FIG. 3 — UNEQUAL SHRINKAGE OF TWO GELS.

Maney[2] has given a sketch of the distribution of internal stress in the cylinder (Fig. II); and points out that, when it is loaded, P/A is always less than the maximum stress by an amount dependent on the initial skin tension. The skin of the cylinder shrank 140% more than the axis. Obviously, shrinkage coefficients and other strains will vary enormously in value according to the plane on which measurements are taken; and the phrase "overall movement" is meaningless unless it is averaged over the cross section.[1]

Shrinkage stress can neither be compared to the stress caused by loading a bar nor can it be compared to that caused by cooling a bar whose ends are fixed, though it resembles temperature stress in some respects. Its analogue[1] is the stress caused by welding two metals with different coefficients of thermal expansion, and cooling them. Fig. III shows an element of a cylinder composed of two types of gel, A having a greater coefficient of shrinkage than B. Their positions of ease are shown dotted, and A is prevented by its cohesion to B from contracting to a state of ease. The longitudinal compression in B exerts a bursting tension on A. If this tension grows too high, A can relieve itself

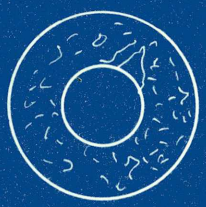


FIG. 4 — RADIAL FAILURE THROUGH SHRINKAGE.

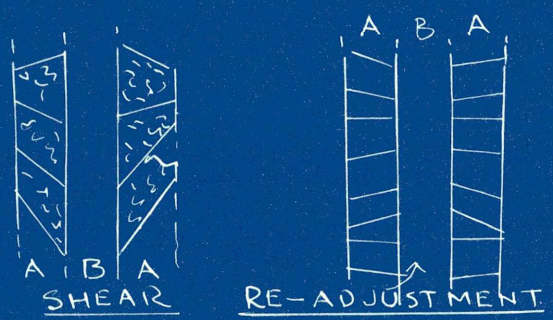


FIG. 5 — INTERNAL STRESS. — MIDDLE CONDITION.

by tearing transversely or by failing in cohesion with B, or both. In cross-section, the shrinkage hoop tension of A will be intensified by the lateral expansion of B under longitudinal compression; and it can relieve itself by tearing radially (Fig.IV). In an axial direction, the contraction at the outside of A will be greater than at the inside, and the section will be prismoidal as shown. The second element (Fig. V a), being attached to the first, will be distorted; and in addition to the bursting tension caused by B, shear will exist due to the cohesion of the two elements of A and the resistance of B. This second element of A can relieve itself by failure as in the first case, and also by tearing at the outside. In a cylinder of infinite length, this distortion would keep on growing; but it is probable that microscopic failure of the type mentioned above would occur frequently; and the distribution of stress would resemble that sketched in Fig. V.b. This may be called the middle condition.

If now the cylinder be reduced to finite length, the conditions are altered; for moisture can be lost from the ends as well as the sides. The rate of loss of moisture - and therefore the induced shrinkage - is some function of the ease with which water can escape. In Fig. VI.a, the concrete at A - having

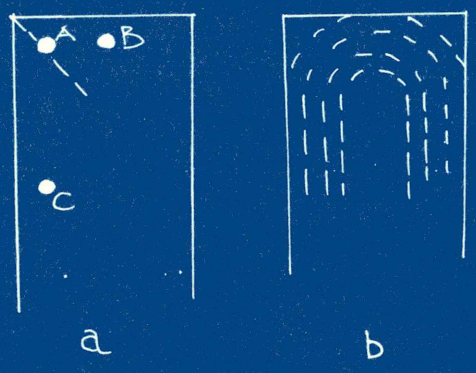


FIG 6 — END CONDITION — EFFECT OF EVAPORATION FROM END OF CYLINDER.

two surfaces through which to lose moisture - will shrink more rapidly than that at B or C. Surfaces of equal shrinkage may be conceived as shown diagrammatically in section by the curves in Fig. VIb. Considering the figure as a solid of revolution, the end effect results in a heavy concentration of tensile stress where the axis passes through the end. The resultant of this which tends to axial shortening is resisted by direct compression in the moister concrete beneath, without the intermediate shear which intervenes in the middle condition. If the tension increases sufficiently, the gel will relieve itself by tearing radially. These radial contraction cracks are a common occurrence in cement pats, and are occasionally visible in cylinders of a rich mix which have dried out rapidly; but they may often occur unnoticed in the middle of the concrete.

The relative importance of end and middle conditions will vary with the shape of a specimen; and in a sphere (which is absolutely symmetrical) there would be no end condition, and the distribution of stress would resemble that sketched in Fig. Vb. Though gels A and B are sharply differentiated in the diagrams for the sake of clearness, there is, of course, no such rapid transition in practice.

LEGEND

— TENSION

---- COMPRESSION

—·—·— ZERO STRESS

ALL STRESSES ARE SHOWN IN LBS. PER SQ. INCH.

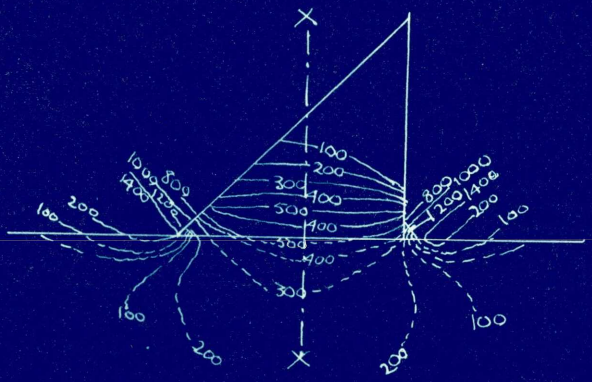


FIG.– 7

STRESSES IN A GRAVITY DAM AND ITS FOUNDATIONS DUE TO A UNIFORM SHRINKAGE OF 0.0016 IN. PER INCH.

Shrinkage stresses in large works such as masonry dams are of very great interest and importance, but the determination of these stresses is complex and difficult. Photo-elastic method has been suggested for determining them. But, in practice, the large masses of concrete used in gravity dams are not homogeneous; nor are they isotropic, as the structure is poured in blocks which present many planes of discontinuity. The indeterminate factors on these planes of discontinuity present such formidable difficulties that an accurate determination of shrinkage stresses is impossible. If the problem is idealised, however, by assuming a homogeneous, isotropic, simple gravity dam subject to uniform shrinkage, it becomes possible to predict these stresses with some assurance. Although this idealised case is not truly consistent with actual practice, it creates a philosophical "picture", nevertheless, of the strained condition that should be of value to the judgment of the designing engineer.

Under the above theoretical conditions, Howard G. Smits[4] carried out a photo-elastic determination of shrinkage stresses in a gravity dam. His results are shown in Fig.VII. In this way points of high stress as well as a general 'feeling' for the behaviour of shrinkage stresses can be obtained. Of special

interest is the high unit stress between the dam and the ground at the heel and the toe of the dam. In general, the larger the fillets at these points, the lower will be shearing stress.

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CHAPTER IV.

VOLUME CHANGES IN CONCRETE.

CHAPTER IV.

Volume changes in concrete may be due to stress, temperature, or moisture.

Volume changes due to stress.

These will be discussed very briefly as being beyond the scope of this investigation. They can be divided into elastic and plastic movements. When concrete is subjected to stress, there is a corresponding strain. Immediately after the load is applied the whole of the strain may be considered as 'elastic deformation', but under a sustained load it will be found that there is a further movement known as 'plastic deformation'. This property possessed by concrete of yielding very gradually under a sustained load is quite distinct from the shrinkage caused in concretes while hydrating or curing in air. Because of the complexity of the structure of concrete it is not known just what internal actions produce this phenomenon.(1)

In general there appears to be three ways in which continuous yielding may take place. First, there may be a movement of particles one over the other, as in the flow of oil, asphalt, glue or wet clay; this may be called viscous flow. Second, in a mass composed of crystals, slips may occur along

planes within the crystal. This type of yielding which in metals is called 'creep', will be termed crystalline flow. The third way in which yielding may occur is by an actual loss of liquid from a mass composed of a liquid and a finely divided solid; this action will be called 'seepage', the term used to describe the phenomenon in colloidal systems.[2]

That the yielding of concrete may involve all the three kinds of flow is apparent from a consideration of the elements that make up a concrete mass. The major portion of the mass is composed of relatively chemically inert aggregate, usually a crystalline material surrounding each piece of aggregate is the chemically active cement-water paste which in the hardened state binds the mass together. The majority of modern opinion seems to favour the view that the setting of cement is best explained by the theory that its physical structure is based on an amorphous, or gel silicate mass.

Davis[2] and his co-workers came to the conclusion that the major portion of the plastic flow or time yield in concrete under sustained compressive stress is apparently due to seepage of colloidal water from the cement gel. So far as gain or loss of moisture

is concerned, plastic flow and shrinkage are intimately related. The moisture content of the cement gel has a marked effect upon the seepage and hence upon the time yield of concrete. The flow of a totally dry cement is of a very small magnitude.

Lynam[3] has also come to a similar conclusion and states that the greater part of plastic flow comes about from the gel is evidenced by the fact that the plastic flow slows down as the concrete ages, when the gels become more solid and more or less crystalline. Concretes loaded at greater ages show less plastic flow than those loaded younger.

Volume Changes due to Temperature.

Concrete like other structural materials, expands when heated and shrinks on cooling. It is frequently considered[4] that the thermal coefficient of expansion for concrete is not greatly different from that of carbon steel (0.0000065 per °F.), 0.000005 per °F. being a commonly accepted value which is regarded as constant for all concretes within the ordinary ranges of temperature. Recent tests, however, indicate that there is a wide range in the value of the coefficient.

Volume Changes due to Moisture.

Matsumoto[5] has shown that the volume of the aggregate in concrete is not altered by moisture

conditions - all movements must take place in the cement paste. Set cements change their volume with variations in mositure conditions in the same way as clays and mortars and concretes are affected similarly. These dimensional changes occur not immediately after setting, but throughout the life of a specimen. The change in volume that takes place in concrete until all the cement is hydrated is known as the "autogeneous shrinkage", to distinguish it from that which is due to thermal causes or to loss of moisture.

A further movement can take place due to the action of the carbon dioxide from the atmosphere reacting with the hydrated cement. It is this further movement which is the major cause of 'crazing', and like troubles. 'Crazing' is the name given to the 'hair cracks' which are formed on the surface of mortar and concrete. It can be shown by adding suitable reagents like phenol-phathalein that the chemical composition of the outer skin of a block of concrete which has been exposed for some time, is quite different from that of the rest. This is due to the carbonation of the skin. Recent investigations at the Building Research Station have shown that crazing is due to the carbonation

of the outer skin and that shrinkage due to it is of the order of two-thirds of the initial shrinkage, wet to dry of the mortars. Crazing is perhaps the biggest problem of all those engaged in the concrete products industry. The best method known at present of overcoming crazing is steam curing.[6] Investigations about the changes in temperature and moisture content that occur while concrete is setting (about which little is known), might discover a better method than that.

A pictorial representation of these movements due to moisture changes and carbonation has been suggested by Dr. Stradling[7] as follows:- Suppose a specimen of concrete had not been allowed to dry out from the time of mixing until one is ready to take measurements of length changes. Now on first drying, suppose the specimen shrinks an amount represented by 2 units. Then on wetting again it expands by an amount represented by 1 unit. On redrying it contracts by about 1 unit, thus reaching the same length as on first drying out. Rewetting and redrying now only cause a length change represented by 1 unit. If, however, the specimen be exposed to carbon dioxide until it is carbonated right through, a shrinkage now takes place equivalent to about 1.4 units, and this is, like half of the first

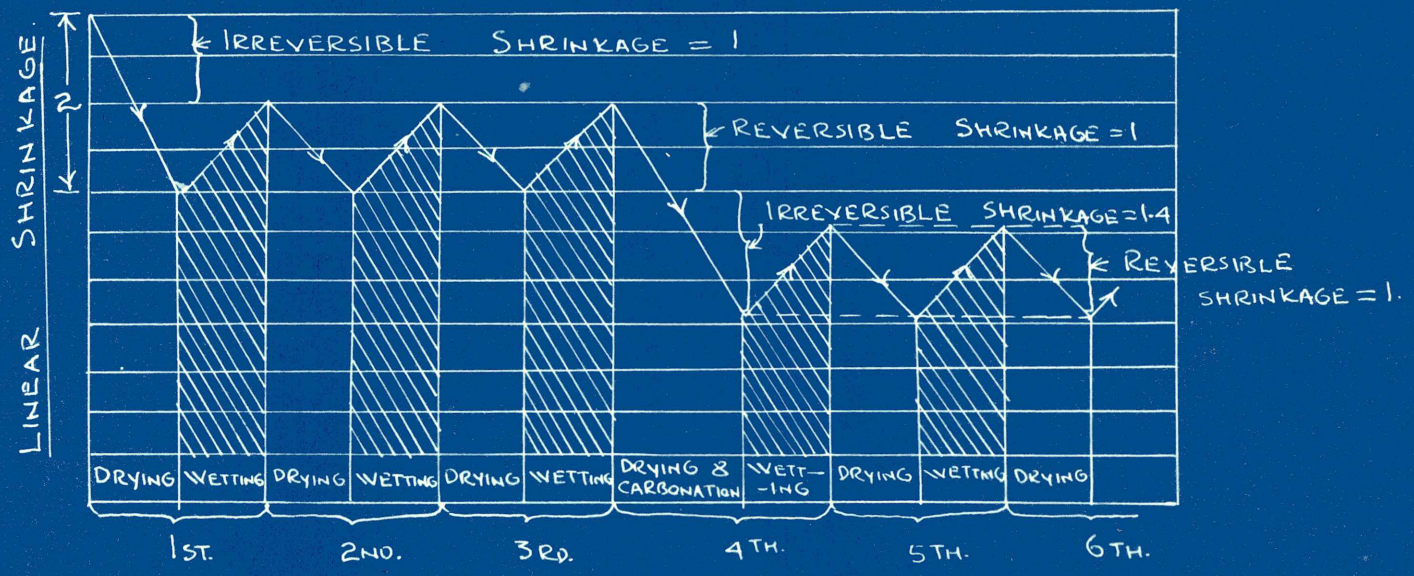


FIG. 8— DIAGRAM OF MOVEMENTS OF CEMENT PRODUCTS DUE TO MOISTURE CHANGES AND CARBONATION.

drying out irreversible. After this has happened the specimen will still expand and contract with wetting and drying by about the same amount as before, i.e. unity. In Fig. VIII these movements are represented diagramatically. It must be realised, of course, that the actual relative values given are only approximate ones.

Besides these attendant circumstances such as fineness of cement, water/cement ratio, difference of movements on core and skin, and temperature and humidity of surrounding air, affect shrinkage. Their effect will be considered in the next chapter in the critical survey of the existing literature.

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CHAPTER V.

CRITICAL SURVEY OF EXISTING LITERATURE.

CHAPTER V.

Critical Survey of Existing Literature.

The volume changes in neat cement pastes, mortars and concretes had not received the same amount of attention as other problems connected with concretes such as bond, strength, creep, etc., from the early investigators, mainly due to the difficulty in taking measurements of the actual movements which are very small. But as time elapsed, it was generally realised that this was one of the major problems connected with concretes and which would go a long way not only in throwing considerable light on the setting of concretes and such other allied complex problems, but also from the practical constructional point of view, such as cracking, crazing, etc. Once this was clearly realised, quite a number of investigators have given attention to it. Quite a lot of work has been done after the development of the strain gauges which made the taking of the measurements possible. They were followed by dial and screw micrometers and optical comparators.(1)

No attempt has been made to present the existing data in a chronological order, but it is given under the following heads. (A) Moisture; (B) Temperature;

It has now been established that the swelling and shrinking of concrete with changes in moisture is

far greater than its expansion and contraction with changes in temperature[2]. So data regarding moisture has been given in detail. No literature re plastic flow has been considered, as being beyond the scope of the present investigation.

(A) Moisture.

The data re, moisture has been given under the following heads:-

(1) Cements;
(2) Proportions;
(3) Aggregates;
(4) Admixtures;
(5) Consistency;
(6) Moisture Conditions;
(7) Age at first observation;
(8) Duration of test;
(9) Size and shape of specimen;
(10) Mixing and Placing;
(11) Reinforcement.

(B) Temperature.

(A.)(1) Cements.

Quantitative measurements of the change of volume of cements while hardening commence with the classic experiments of Bauschinger[3] who in 1879 reported on the

volume changes of eight different cements made into small cubes of neat cement and 1 :3 and 1:5 mortars. One set of cubes was kept in water and one in air and the changes in length of one side observed for 16 weeks. The most important study of the subject was made by Schumann[4] in 1881 who measured expansions not only of neat cement and cement mortars, but also of blocks of building stone. Toniëi[5] did some work in 1893 and Gary[6] in 1899 carried out some measurements of neat cement as well as 1:3 mortar specimens. Campbell and White in 1906 presented a study of 56 expansion bars of neat cement which had been under observation for five years. A number of these were pathological specimens of unsound cement containing free lime and magnesia, but their experiments showed as much as 0.19% expansion with sound neat cement cured in water for five years and a shrinkage as high as 0.39% with bars of sound neat cement cured in air. They were perhaps the first investigators to devise a reliable and inexpensive micrometer and a satisfactory method of inserting glass plates in the specimens.

Table I presents the condensed data of the investigators mentioned above.

Table No. I.

% change in Volume of Bars of Neat Cement and Cement Mortar.

(a) Expansion after lying continuously in water.

Authorities.	Neat Cement.	1:3 Cement and Sand Mortar.	1:5 Cement and Sand Mortar.	Duration
(1) Bauschinger - average of 8.	+0.046	+0.009	+0.001	16 weeks
(2) Schumann - average of 7.	+0.150	+0.028		1 year.
		+0.029		2 years.
		+0.027		5 years.
(3) Toniĕi - average of 8.	+0.025	+0.027		90 days.
(4) Considére (7)	+0.079	+0.028		63 days.
(5) Gary,- average of 10.	+0.063	+0.008		1 month.
	+0.078	+0.013		3 months.
	+0.094	+0.012		1 year.
	+0.092	+0.020		2 years.
(6) Campbell & White.	+0.190			5 years.

(b) Contraction after lying continuously in air.

Authorities.	Neat Cement.	1:3 Cement and Sand Mortar.	1:5 Cement and Sand Mortar.	Duration.
(1) Bauschinger, average of 8.	-0.214	-0.132	-0.124	16 weeks.
(2) Schumann, average of 4.		-0.042		1 week in water; then 3 weeks in air.
(3) Toniéi, average of 8.	-0.201	-0.094		90 days.
(4) Considére	-0.132	-0.050		63 days.
(5) Campbell & White	-0.390			5 years.

P.H.Bates[8] investigated about ten cements and found that the volume changes varied considerably among them from 0.057 to 0.120% for the normal neat cement specimens, and from 0.005 to 0.024% for the normal 1:3 mortars. He also found that the expansions of normal cement were only about 90% of the expansions of reground cements both for neat cement and 1:3 mortar bars.

W.K. Hatt[9] carried out his tests for as long a period as four years. His specimens were all of neat cement, stored in water for ten days and then in

air for about 4 years. He observed maximum contractions from 0.12 to 0.23% after one year. Subsequent changes due to variations in humidity of the air were approximately alike for the several brands. A second series of tests by Hatt indicated that the cements which exhibited the greater net expansions under water, also developed the lesser net contractions in air. Thus it appears that an immersion test by itself is not a true measure of the volume changes which may be anticipated for a given cement.

A.H. White[10] measured the volume changes of many neat cements and 1:3 mortars made into 1" x 1" x 4" bars. The observations were made over a period of many years. His conclusions for the several cements were:-

(1) Neat Cement Bars hardening under water:- After one year, expansion 0.07 to 0.15%; on drying 65 days in air after 3 years in water, total contraction 0.13 to 0.15%; on wetting again for 1 month, total expansion 0.13 to 0.17%.

(2) Neat Cement Bars hardening in Air:- Contraction after 3 months, 0.14 to 0.28%; after one year, 0.18 to 0.34%, with a slight increase to 4 years.

(3) Mortar bars of 1:3 mix hardening under water:-

Expansion 0.01 to 0.05% at one year; the more rapid changes occurring during the first few weeks.

(4) Mortar Bars of 1:3 mix hardening in air:-

Contraction 0.06 to 0.09% at one year, most of the contraction being in the first three months.

Messrs. Shoichiro Nagais, Keima Matsuoka and Konji Nomi[11] carried out tests on specimens of mixed Portland Cement and common Portland Cement. The specimens were all water cured. Their results are given in Table II. From the results, it seems that the mixed Portland Cements have the same rates of expansion and contraction as common Portland Cement. This seems rather doubtful, unless it is a special property of the Japanese cements under observation.

TABLE II.

No. of sample.	Type of Cement.	Expansion(+) or contraction(-) mm./10m.					
		4 weeks water-curing to 1 day hardening	Water-curing to 4 weeks hardening.				
			4 wks.	8 wks.	21 wks.	32 wks.	52 wks.
85	Common Portland Cement.	+5.4	-3.7	-4.4	-2.2	-2.2	-0.7
86	Spent shale mixed Portland Cement.	+1.9	-1.5	-2.9	-1.5	-1.5	-2.2
87	" "	+1.4	-1.4	-2.1	-1.4	-1.4	-1.4
90	Keisanhakudo	+2.5	-2.9	-3.7	-1.4	-1.4	-0.7
91	Kayohakudo	+4.8	-2.2	-3.6	-2.2	-2.2	-2.9
92	Yokeihakudo	+3.3	-2.2	-3.6	-3.6	-2.9	-2.2
93	Blast-furnace Slag cement.	+2.6	-1.4	-1.4	+0.7	+0.7	+0.7
101	Common Portland cement.	+5.6	-2.9	-2.9	-2.9	-2.6	-3.6
102	Yokeihakudo	+2.2	-1.4	-2.1	-1.1	-0.7	-2.4
103	"	+1.4	-1.4	-3.1	-2.1	-1.8	-2.9
104	Kayohakudo	+2.0	-1.4	-2.5	-0.7	-0.7	-2.8
105	"	+1.4	-2.1	-2.8	-1.4	-1.4	-3.2
108	Calcined green shale mixed Portland cement	+2.6	-1.4	-2.8	-1.4	-1.4	-2.9
109	" "	+1.9	-1.4	-2.5	-0.4	-0.4	-3.5

Fineness of Cement Grains.

As regards the fineness of cement grains, the general opinion amongst investigators is that fine cement has larger volume changes, especially at early ages. O. Graf[12] in a recent publication warns against generalising this too much and points out that though this is generally true there are rough cements which shrink a lot and fine cements which shrink little, as shrinkage is not only dependent on fineness but on other properties of cements as well. To safeguard against shrinkage due to too fine cement grains, Reichautobahnen in Germany[13] specify a cement which retains at least 5% on Sieve Din 70 (Mesh 4900/cm.^{2})

Dr. H. Nitzche[14] measured the volume changes of several cements with Bauschinger apparatus and his results are given in Table III. He used 1:4 mortars and cured his specimens for 2 days in moulds, 7 days in water, 10 days in room temperature; and finally dried to constant weight at 50° C.

TABLE III.

Cements.	Volume changes in water - Percentage.
Finest Slag Cement	0.0275
" " "	0.0204
Finest Portland Cement	0.0347
Coarsest Slag Cement	0.0224
Coarsest Portland Cement	0.0255
Iron Portland Cement	0.0204

The following values of expansion tests with Le Chatelier apparatus are taken from "Le Ciment", 1923. The author remarks that finer grinding reduces the expansion provided the cement is well-burnt. Also airing of cement would tend to lessen expansion.

TABLE IV.

Cement.	Residue.		Expansion. Le Chatelier apparatus.
	Sieve 900.	Sieve 4900.	
Cement A.	3%	28%	6 mm.
	2%	20%	3 mm.
	1%	16%	1 mm.
Cement B.	2%	25%	2 mm.
	1.5%	20%	2 mm.
	0.5%	14%	0.5 mm.

Dr. Abrams[15] reported in 1919 in connection with an investigation into the effects of fineness of cement, that he finds no appreciable difference in volume changes due to fineness, but laconically adds that his

measurements were not precise.

M. Ross[16] investigated three cements and found increase in shrinkage with fineness. The % retained of the cements on Sieve Din 70 (4900 meshes/sq.cm.) were 15%, 5%, 0%.

Storing of Cements.

M.Ross[16] found that fresh Portland cement when used straight after manufacture shrinks more than that which has been stored for a long time.

A.H. White[17], however, could not find any effect due to storage on shrinkage when cement was stored for 1 month, 1 year, and 2½ years. Possibly the cement did not contain any free lime.

Hans Kuhl[18] also found that long storage reduces the tendency to shrink even in completely dry air,, in which cements shrink the most.

Free Lime.

While little is known how the lime content of cement affects the shrinkage, the results are fairly consistent as far as the free lime in cement is concerned.

Messrs. O. Goffin, G. Musgnug[19], Bogue[20], and White[17] have all come to the conclusion that free lime diminishes the shrinkage of cement in air and increases the expansion in water. The influence is greatest during the first month of the observation.

Its hydration should be finished in a year and if the amount of free lime is small, the volume changes beyond that time should be normal.

Magnesia.

The effect of magnesia in cement has been studied by several investigators. A.H.White[17] states that magnesia in combination as silicate is entirely harmless no matter how much there may be in the cement. Most of the American investigators believe that magnesia is present in cement as free magnesia. Recent researches of Brownmiller, Bogue, and others, have shown that magnesia is present in the free condition at least in part. Free magnesia[17] hydrates slowly and causes slight additional expansion during the first 3 years in water, but if much magnesia is present, it causes marked expansion during the period from the third to the tenth year in water. Magnesia does not give trouble through expansion if the cement products are kept continuously in air.

Bogue[20] states also that over 5% may cause great swelling but has no effect on shrinkage.

(2) Proportions.

The general trend of the research as far as propertions go seems to show that rich mixes have greater volume changes than lean, especially in expansion. This seems in agreement with what could have been expected. Matsumoto[21] has shown that the volume of the aggregate in concrete is not altered by moisture conditions - all movement must take place in the gel formed by the hydration of cement paste. For a rich mix a larger fraction of the mass is gel and hence the movement is multiplied there. More cement means more and richer gel, which can take up more water andswell more. On drying, a weak gel soon fractures and ceases to move; but a rich gel is stronger and continues to shrink.

F.R.McMillan[22] conducted tests on 4"x5"x24" bars of limestone concrete of varying proportions. The bars were cured for 2 weeks under wet burlap and were then stored in air for 430 days. The net % contractions after the first observations at 1 day are given in Table V.

TABLE V.
Proportions and Contractions.

Mix.	Contraction.
1:1½:3	0.066%
1 :2 : 4	0.064%
1:2½:5	0.060%
1: 3 : 6	0.055%

Davis and Troxwell[23] also came to a similar conclusion that richer mixes show greater volume changes than lean ones.

Matsumoto[21] found that a direct relationship exists between the cement ratio and the expansion in water as well as contraction upon oven drying. His specimens were 2"x3"x24" bars which were kept wet first for 60 days and then dried in an oven at 200° F. His results are shown in Table VI.

TABLE VI.

Proportions and Dimensional Changes.			
Mix	Percentage Expansion. Wet-60 days.	Percentage Net Contraction. Air -58 days.	Percentage Net Contraction Oven -29 days.
1:1	0.0124	0.046	0.157
1:2	0.0100	0.049	0.124
1:3	0.0101	0.050	0.108
1:1:2	0.0091	0.036	0.081
1:2:4	0.0055	0.033	0.064
1:3:6	0.0019	0.036	0.062

The net contractions of the last two columns are based upon the first observation after casting. The contractions after 58 days in air do not bear a consistent relationship to cement ratio, indicating that the results of a short-time test are not always a criterion of values which would ultimately obtain.

Goldbeck[24] on the other hand, found that a wet or a dry mix of 1:2:4 or 1:3:6 concrete varies but little in contraction when exposed to air for one year. His results are given in percentages in Table VII as scaled from his diagrams.

TABLE VII.

Type of Concrete.	30 days. (in percentages)	60 days.	1 year
1:3:6 Mixed (very wet) 10-12% water	0.023	0.033	0.053
1:3:6 Mixed (Very dry)- 8.5% water	0.034	0.045	0.055
1:2:4 Mixed very wet	0.023	0.034	0.058
1:2:4 Mixed very dry	0.035	0.040	0.055

His specimens were 8 inches square in cross section and five feet long moulded as columns so that one end would be absolutely free to expand and contract.

The measurements were taken by a Brown and Sharpe micrometer. Specimens which were allowed to dry out immediately after moulding began to shrink almost from the day they were made, although the very wet mixes, for the first 10 days showed tendency towards slight expansion amounting to about 0.00005 ins. He came to the conclusion that the amount of contraction of air-cured concrete is influenced very little by the proportions of the mixture.

(3) Aggregates.

Evidence as to the effect of mineral aggregates is rather contradictory. Matsumoto[21] found that a sandstone and a limestone concrete have volume changes of the same order; but that in the same conditions the actual sandstone expanded much more than the concrete and the limestone did not expand or contract at all. He tested 3"x4"x24" bars of sandstone and limestone. They were first oven-dried for 6 days and then soaked for 13 days. The sandstone absorbed 5.75% of water and expanded 0.080% or somewhat more than ordinary concrete. Of this amount 0.070% expansion occurred the first day. Limestone treated in a similar way expanded only 0.001%, but it absorbed 6% of water. Other authorities maintain that the character of the aggregates exercises a great influence on the shrinkage. Their results show small contraction of granite and limestone concretes in comparison with similar gravel and sandstone concretes, and also that the magnitude of expansion of concrete in water is no indication of what the shrinkage would be when the concrete is exposed to dry air. This seeming discrepancy[25] in views may be due to the presence or absence of water absorbed in the aggregate, or to neglect of some important variable.

Schumann[4] observed the expansion and contraction of various building stones when alternatively wetted and dried and his results are shown in Table VIII.

TABLE VIII.

Volume Changes in Building Stones.

Kind of Stone.	% change in two weeks.	
	In Water.	In Air.
Sandstone - red, fine grained	+0.006	-0.018
- red, coarse	+0.016	-0.023
- green, fine grained	+0.050	-0.050
- red, fine grained	+0.050	-0.050
- red, very fine grained	+0.206	-0.178
Limestone - white	+0.004	-0.008
- Lothringer lias	+0.007	-0.008
- chalk	+0.011	-0.009
- dense, containing clay.	+0.026	-0.026
Granite.	+0.006	-0.015
Basalt (a)	+0.026	-0.027
(b)	+0.041	-0.050
(c)	+0.048	-0.057
(d)	+0.023	-0.057

Cloyd M. Chapman[26] made several tests on 2"x2"x24" bars to determine the effect of the type of fine aggregate on the contraction of 1:2 mortars and 1:2:4 concretes.

The fine aggregates were all of the same gradation and the coarse aggregates for all the concrete specimens

was ¾ inch gravel. The contractions after 7 days in water and 1 year in air are shown in Table IX.

TABLE IX.

Effect of fine aggregate upon Air shrinkage.		
Fine Aggregate (Screenings)	Percentage Contraction.	
	1:2 Mortar.	1:2:4 Concrete.
Conglomerate	0.21	0.075
Trap Rock	0.21	0.093
Slag	0.14	0.068
Granite	0.13	0.068
Limestone	0.13	0.062

R.E.Davis[23] investigated the effect of the type of aggregate upon the volume changes of 3"x3"x40" specimens of concrete made of a 1:2:3 mix by volume and using a water-cement ratio of 0.90. For all the specimens, except those employing gravel, the fine aggregate was obtained by crushing some of the coarse aggregate to the proper size. The gradation of the mixed aggregate was the same for all materials, its fineness modulus being 5.58. His results are given in Table X.

TABLE X.

Effect of Type of Aggregate.		
Aggregate.	Percentage change in three months.	
	Contraction in Air	Expansion in Water
Gravel	0.079	0.0074
Sandstone	0.075	0.0055
Limestone	0.039	0.0050
Granite	0.037	0.0131
Quartz	0.036	0.0094

(4) Admixtures.

Davis and Troxell[23] investigated the effects of various admixtures on shrinkage of 1:3 and 1:5 mortars proportioned by volume. The percentage of admixtures replaced corresponding weights of cement, that is, they were not additional to the regular 1:3 or 1:5 mix. All the mortars with or without admixtures were of the same consistency as measured by the flow table. All specimens were continuously stored in dry air for 375 days. The results are given in Table XI.

TABLE XI.

Effect of Admixtures and Surrounding Medium.			
	% Contraction, 375 days in air.		
	Non-absorbent Wood-moulds removed after 48 hours.	Absorbent Burnt-clay moulds, removed after 48 hours.	Absorbent Burnt-clay moulds, left in position.
Plain 3:1 Mix	0.119	0.102	0.072
10% clay in 5:1 Mix	0.092	0.109	0.087
10% hydrated lime in 3:1 Mix	0.106	0.094	0.080
10%clay in 3:1 Mix	0.133	0.122	0.095
5% clay in 3:1 Mix	0.135	0.114	0.085
Plastic cement, 3:1 Mix	0.153	0.134	0.096

The results for the specimens with moulds removed show that the replacement of 10% of the cement by hydrated high magnesian lime reduces the contraction somewhat, whereas the replacement by clay increases the contraction as does also the use of the so-called plastic water-proof cement. The effect of the absorption of the mould is to reduce the shrinkage materially.

A. Hummel[27] also found that clay cements shrink more than Portland cements in the beginning. But later a certain equilibrium sets in. After 90 days, the

shrinkage of clay cements was only 10% more than that of Portland Cements.

R.H.Bogue[20] also came to the conclusion that the shrinkage is increased by the addition of clay.

White[17] also found that the use of integral waterproofing compounds (at least those investigated) does not aid in reducing the volume changes resulting from alternate wetting and drying of cement mortars.

Gypsum.

Mr. John Grant[28] in 1879-80 reported that expansion was increased when cements contained gypsum.

Bates[8] also found that the addition of gypsum increased considerably the expansion in the case of both the normal and reground cements, this being more than doubled in the case of the normal cements.

O.Goffin and Musgnag[19] found that cement containing more than 4% of gypsum shows greater swelling in water and less shrinkage in air. Bogue[20] also came to a similar conclusion. He also mentions that up to 1.7% of sulphuric acid has only very little effect on linear changes.

A.Guttman[29] has stated that a suitable percentage of gypsum could be added to cement to neutralise the shrinkage of cement by swelling.

Hans Kuhl[18] has also come to a similar conclusion that a properly selected amount of gypsum

can reduce the shrinkage; the correct amount of gypsum increases with the alumina modulus according to him.

Calcium Chloride.

The effect of calcium chloride has been found to be swelling.

Goffin and Musgnug[19] found that $CaCl_2$ effects shrinkage in air more than expansion in water.

Steope[30] investigated the effect of the additions of $CaCl_2$ due to different curings of a specimen. He found that those specimens which contained $CaCl_2$ showed more expansion on wetting later on and a higher shrinkage on drying again than those containing none.

Guttman[29] has recommended the addition of gypsum and $CaCl_2$ to decrease shrinkage.

Hans Kuhl[18] found that the addition of calcium chloride increases shrinkage in air as well as expansion in water.

Sodium Chloride.

Steope[30] found that the addition of salt increases shrinkage. Repeated wetting in salt increases expansion. Initial shrinkage becomes less by repeated drying.

$Ca(OH)_2$.

R.E.Davis[23] investigated the effect of the

addition of slaked lime and stated that it has no recognisable effect while O.Graff[31] found that it increases the shrinkage.

Silica additions.

There is a considerable amount of contradictory opinion as far as the effect of silica additions is concerned.

Guttman and Gille[32] found that increase in shrinkage is directly proportional to the percentage of trass added. Addition of trass below 20% decreased shrinkage of normal Portland cement.[32A]

Carlson and Troxell[33], on the other hand, found that an addition of volcanic matter with 75% silicate contents reduced shrinkage.

It must be mentioned here that the method of mixing, whether ground or not, will have a considerable influence and will be one of the important factors in accounting for the discrepancies in the results of the various investigators.

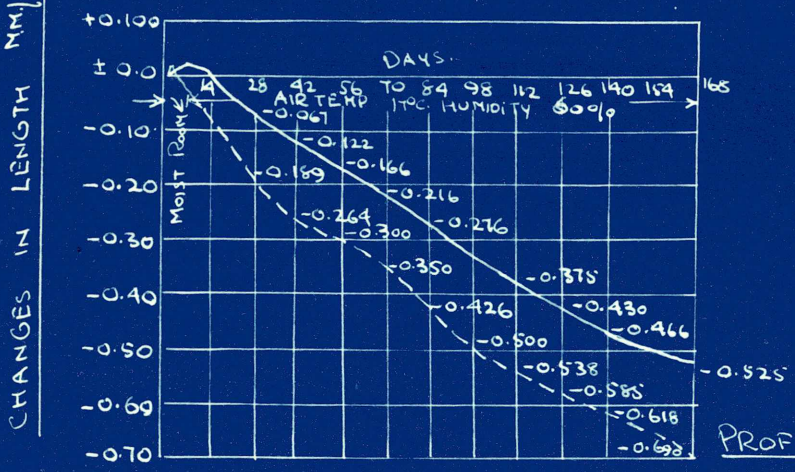
Bitumen.

Dr. Dyckerhoff[34] has investigated the effect of the addition of bitumen to the cement after the appearance in German markets of a material known as "Binding Medium No.10"(Bindemittel 10) which was claimed not to shrink at all. The material was made

in accordance with a secret formulae from a mixture of lime, cement and bitumen. In this mixture, it was claimed, the positive shrinkage of one part was cancelled by the negative shrinkage of the other. Many other fantastic arguments were advanced in its support. Shrinkage cannot be balanced out by an opposite sign and Dr. Dyckerhoff found that the lime portion of this much vaunted product showed no useful purpose, but had a deleterious effect upon the properties of the product.

He mixed bitumen with cement by a "spraying process"(Vernebelungs-verfahren). In this process, hot bitumen is completely rendered into the form of a fine spray by being forced through special nozzles under compressed air. The Portland Cement is subjected to a similar treatment, and the two "mists" are allowed to commingle. He claims that they interpenetrate one another to such an extent that the bitumen is at last deposited in a breath-like layer on the surface of the cement particles without interfering with the granular composition of the cement. In this way it is possible to maintain both substances in the condition of greatest activity, i.e. of greatest surface.

The product, thus formed, requires a greater quantity of water in mixing than the corresponding



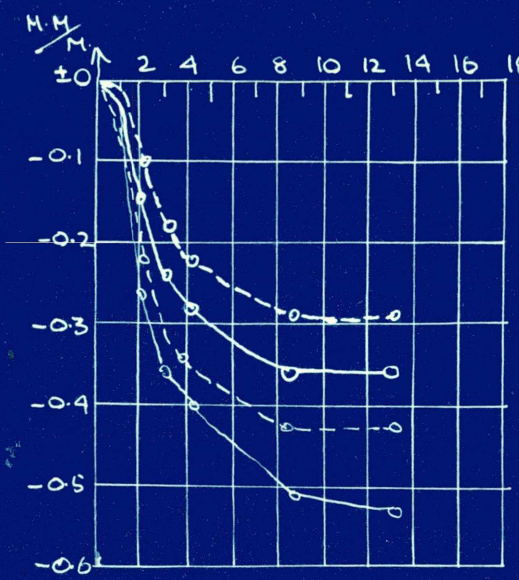
LEGEND

---- PURE PORTLAND CEMENT + 14.2 % WATER.

—— PORTLAND CEMENT + 4 % BITUMEN + 18.7 % WATER.

1 PART BY WEIGHT BINDING MATERIAL — 3 PARTS BY WEIGHT OF SAND 0.5 M.M.

FIG. - 9. CHANGES IN LENGTH OF MORTAR BARS - 15 X 15 X 50 C.M.S



LEGEND.

— PORTLAND CEMENT
— PORTLAND CEMENT + BITUMEN. } 1:3 PARTS BY WT.

--- PORTLAND CEMENT
---- PORTLAND CEMENT + BITUMEN } 1:4 PARTS BY WT.

EXPOSURE TO AIR (UNCOVERED).

TEMPERATURE 20°C - HUMIDITY OF AIR - 48-55 %.

FIG. 10 — CHANGES IN LENGTH OF SLIGHTLY PLASTIC PRISMS 10×10×10 C.MS.

non-bituminous cement. This may be due to the fact that the finely divided bitumen forms a kind of emulsion with the water, the latter being rendered alkaline by the lime present. The excess of water is rejected as soon as the mortar is put into the mould or when it is being worked. Bituminous Portland cement takes longer to set than non-bituminous. They are more elastic and evolve less heat during hydration.

Fig. IX and X show that the behaviour of the bituminous cement thus obtained as regards shrinkage is considerably superior to Portland Cement.

If all these claims could be established definitely by further research, the product seems to have immense possibilities in the future as it combines the properties of cement and bitumen to their advantage, thus producing an ideal material for constructional purposes in which disadvantages of both are got rid of.

(5) Consistency.

All authorities seem to favour the view that wet mixes shrink more than dry ones; dry mixes expand more than wet ones.

Davis and Troxell[23] have investigated the effect of the quantity of mixing water upon volume changes in mortars and concretes. They began their observations when the specimens were about 2 days old.

Their results show that for air storage, the wet, rich mixes contract more than the dry ones, but the effect upon the lean mixes is much less pronounced. For the specimens in water storage, the dry mixes in general expand the most, although the lean mixes show but little variation for the various consistencies.

Hans Kuhl[18] also found that larger amounts of mixing water reduce initial shrinkage and increase final shrinkage.

A. Guttman[35], M. Ross[16] and O. Graff[36] all found that the shrinkage of cement increases in proportion to the quantity of mixing water. Carlson[46] also found that wet mixes shrink more than dry ones. His results are given in Table XV (Page 64).

A. Klienlogel[31] states that the effect of larger additions of water on the shrinkage is small in initial stages. It is much greater finally.

Goldbeck[24], on the other hand, states that the amount of contraction of air dried concrete is influenced very little by the consistency of the mixture. He found that the rate of shrinkage of dry mixtures is very slightly higher at earlier periods than that of the wet mixes. There is, however, very little difference between the shrinkage of the different mixtures except that the contraction of the wet specimens is delayed. The unit contraction

of the oldest specimen of very dry mix is 0.00052 ins. at the age of 3 months, and the rate of contraction after this age is very small. His results are given in Table VII.(Page 45).

(6) Moisture Conditions.

The action of concrete in damp air depends upon the dryness of the specimen at the time of the test; if dry it will expand, and if wet it will contract. The results of various measurements, therefore, are indicative of ranges for a particular condition and so cannot be applied directly to any other specified case.

The data seems to show that the actual contraction of mortar after the period of curing is more or less independent of the magnitude of the previous expansion resulting from curing in water, and indicate that the final contraction (based upon the original length) is inversely related to the expansion developed by the water curing; that is those mortars[9] which expand the most during curing, develop the lesser contraction in air, showing that the immersion test by itself is not a true measure of the volume changes of concrete.

Freysinnet[37] observed the movements of unloaded specimens exposed to atmospheric conditions for two years; and plotted against them the

temperature and humidity of the air. The diagram of the movements was a jagged line and he concluded that the movement was in the same sense as t(1-e), where e is the humidity and t is the temperature.

A.H.White[10] gave the following values of shrinkage in air.

TABLE XII.

Condition of Air.	Shrinkage.
In 1/3 saturated air.	0.15%
,, ½ ,, ,,	0.14%
,, 2/3 ,, ,,	0.10%

He states that for neat cement and rich mortar bars there appeared to be a progressive growth of the specimen due to alternate wet and dry storage conditions. His explanation of this phenomenon is that thorough drying of the specimen opens up certain passages through the mass, due to shrinkage, and that the water may penetrate more deeply into the cement grains upon re-immersion, and therefore a greater length than the original immersed length is obtained. Singleton-Green[38] believes that very fine cracks may develop in the bar due to excessive drying, and that particles of dust which may enter the cracks may cause a wedging action

upon soaking and hence increase the length of the specimens.

White[10] also found that the length of a bar which has passed through a cycle of drying and wetting is not usually the same as before the cycle, but it may be longer or shorter, depending upon the actual treatment received.

Similar observations have been made by R.E. Davis[23] and R. Dutron[39] about decrease in shrinkage with increased humidity.

Jesser[40] also found that the volume of a mortar increases with the moistness of the air and diminishes as it becomes drier. A mortar placed in air saturated with moisture undergoes a further, but relatively small, expansion when placed in water. These changes are reversible, except for a change which takes place in mortars which have only hardened for a short time.

For thoroughly dried concrete bars, Davis and Troxell[23] found that air of high relative humidity was nearly as effective in producing expansion as was immersion in water.

Hatt[41] states that the careful curing of concrete, beginning at an early age, will postpone

the period of surface shrinkage until the concrete has attained sufficient strength to take up this shrinkage without experiencing cracks.

Menzel[42] states that by curing in high pressure steam and by proper selection of aggregates and mixtures, concrete can be obtained 1-2 days after moulding which will have higher strength and lower volume change than concrete moist-cured for 28 days at normal temperatures. He believes that this is due to the supplementing of the primary chemical reactions between the cement and water by secondary reactions between the calcium hydroxide liberated during the hydration of the cement and the siliceous particles of aggregate in the mixture.

Masumoto[21] has shown that after repeated wetting and drying, a specimen may contract to less than its initial size, though it has a net increase of weight. In other words, its density has increased.

Messrs. Louis Schumann and S.A.Pisapia[43] found that concrete cylinders (using high early strength cements) expanded from .001 to .018% in one year in damp storage. Cylinders in air storage contracted from 0.025 to 0.053% in one year. Cylinders subjected to freezing and thawing expanded from .003 to 0.031% in one year. Freezing, thawing,

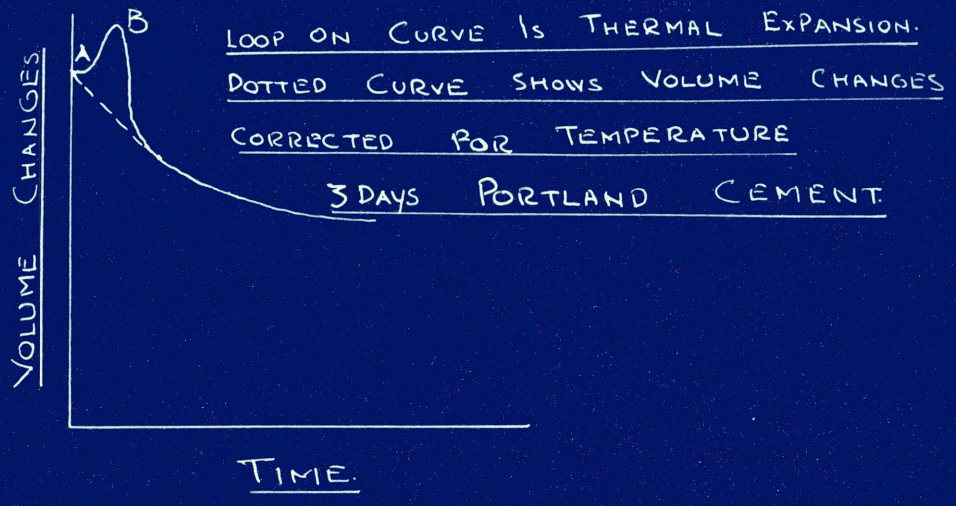


Fig. 11. — Hydration Changes In Portland Cement.

drying and soaking of the 2" by 12" cylinders caused so much spalling that few data were obtained after the 25th cycle.

Hans Kuhl[18] found that the greatest shrinkage takes place in completely dry air. Only very small differences in shrinkage are found as long as the moisture content of the air is between 0 and 40%. Prolonged storage of the specimens in the moist closet retards the beginning of shrinkage but does not decrease the final amount of shrinkage. In air-tight containers the specimens shrink very little.

(7) Age at first observation.

Due to the great difficulty of taking measurements while the cement or concrete is in plastic state, the measurements are usually taken after the specimen has acquired sufficient strength and rigidity so that it may be safely handled, usually at the age of 1 or 2 days. Some investigators have argued that since mortars and concretes expand when stored in water and contract when stored in air, no change in length will occur if the proper amount of moisture is supplied. Curing under damp burlap has been suggested by them as a practical way of doing it to furnish just enough moisture so that this condition will be realised, how closely is problematical.

Fig.XI shows the volume changes of Portland cement

during hydration obtained by Neville and Jones[44] using a dilatometer with a plastic container. It is obvious that the shrinkage in a day in Fig. XI measured from point A would be very different from that measured from point B. There does not seem to be any record of experiments relating to autogeneous shrinkage only due to this difficulty.

Pearson's[45] measurements on specimens while they were plastic are given in Table XIII.

TABLE XIII.

Mix.	Percentage of Shrinkage.
Neat	0.217
1:1	0.123
1:2	0.110
1:3	0.109
1:4	0.094
1:5	0.086
1:6	0.084
Concrete 1:4	0.067
Concrete 1:6	0.050

(8) Duration of Test.

Tests conducted by White[17] and others show that, up to ages of at least 20 years, mortars and concretes still respond quickly to a variation in moisture conditions, although the rate of change in length may not be quite as great as for a

freshly cast specimen. For constant conditions of storage the change in length after a year or two is small in comparison with that developed previously.

White[17] investigated the effect of the duration of the test upon volume changes of 1"x1"x4" neat cement bars and his results are given in Table XIV.

TABLE XIV.

Duration of Test and Volume Changes.

Duration of Test.	Percentage change in length.	
	Under Water.	In Air.
7 days	+0.030	-0.085
2 months	+0.080	-0.225
6 months	+0.090	-0.285
1 year	+0.100	-0.303
5 years	+0.144	-0.381
10 years	+0.162	-0.410
20 years	+0.161	-0.427*

(*Air dried by calcium chloride).

Carlson's[46] results for contraction of small neat cement bars (1½ in. by 1½ in. by 12 ins.), moist cured for 28 days, and then exposed on all sides in an air of 50% relative humidity at 80°F. are given in Table XV.

TABLE XV.

Shrinkage of Neat Cement Bars.

Water-Cement Ratio.	Change in length, Millionths per unit.			
	35 days.	2 months.	3 months.	4 months.
0.30	786	1514	1822	1998
0.40	1037	2205	2530	2847

The above table shows that although the most rapid shrinkage occurred during the early stages of drying, there is every indication that the contraction has not ceased at the age of 4 months. Also bearing in mind that a maximum distance of only $\frac{3}{4}$ in. must be travelled by the moisture to reach the surface and escape, it becomes apparent that in field structures where larger dimensions are the rule, only a small part of the potential shrinkage may be realised during the course of the average drying season.

(9) Size and Shape of Specimen.

The size and shape of the specimen have a marked effect upon the rate of loss of moisture upon exposure to dry air or upon the gain of moisture upon immersion. There is also a greater likelihood of unequal distribution of moisture in large, thick specimens than in thin ones.

The reaction of concrete with water, being an exothermic one, concrete evolves a certain amount of heat while hydrating and setting. In a thin plate,

the heat would be radiated as soon as evolved, and evaporation from the whole body of the concrete would be rapid in dry air. In such a case, external conditions play the predominant part and practically all movement would be induced movement. In a large mass of concrete, such as a gravity dam, the temperature of the interior - unless controlled as in recent American dam work - may remain at a high level for a long period. The effect of external conditions would be confined to a relatively thin skin, and the main movements would be caused by autogenous shrinkage and thermal changes, though considerable internal stress might be created.

Carlson[46] has investigated the effect of the size of specimen on the shrinkage. His specimens were prisms of 6 ins. square cross-section, with lengths of 6 in. and 22 ins. As measurements on larger specimens exposed to drying on all surfaces are complicated by stresses and cracking, because the shrinkage is more rapid near the surface than in the interior, he allowed them to dry from one surface only by sealing the rest of the surfaces with soft copper jackets. All specimens were made of concrete containing silicious gravel, aggregate $\frac{3}{4}$in. maximum size; 5.25 sacks commercial cement per cubic yard; 0.70 water-cement ratio by weight. They

were moist cured for 28 days, then in air of 50% relative humidity at 80° F.

TABLE XVI.

Influence of Size of Specimen, Distance from exposed Surface and direction of moisture travel upon Shrinkage of Concrete.

Age.	Change in length, Millionths per unit. Parallel to Moisture Movement. Inches from drying face. 3.5	8.5	13.5	18.5	Perpendicular to Moisture Movement. Inches from drying face. 1	6	11	16	21	Change in length of small bars ($1\frac{1}{2}$"x$1\frac{1}{2}$"x12 ins.) for comparison.
	6 ins. by 6 ins. by 22 ins. Prism.									
28 days	-26	-4	-2	-6	+46	+20	-22	-4	+2	+30
35 ,,	+28	-10	-18	-28	-106	+2	-24	-36	-26	-323
2 months	+50	0	-34	-24	-156	+2	-32	-8	+2	-454
3 ,,	+22	+18	0	-10	-276	+8	-20	-14	-10	-499
4 ,,	+8	0	-10	-20	-306	-8	-12	-24	-18	-516
	6 in. Cube.									
28 days	+14	-	-	-	+14	+10	-	-	-	+30
35 ,,	+32	-	-	-	-52	0	-	-	-	-323
2 months	-28	-	-	-	-192	-64	-	-	-	-454
3 ,,	-26	-	-	-	-266	-34	-	-	-	-499
4 ,,	-56	-	-	-	-286	-56	-	-	-	-516

It will be seen from the table XVI that the shrinkage measured on the longer prisms are so small as to be negligible on all lines of the prism except that which is near the exposed surface and parallel to it. The gauge line nearest to the exposed surface but perpendicular to it showed no shrinkage but rather a

slight expansion up to the age of three months. Carlson believes that this may be due to an abrupt change in shrinkage from the exposed face inward. This results in shearing stresses which tend to curl the end of the specimen and make it concave, expanding the edges that are perpendicular to the exposed surface, thus influencing the measurements. It seems more likely that this is due to the differential shrinkage of the skin and core as has been mentioned previously.

In the case of the shorter prisms there is some shrinkage in all parts of the specimen, even in the direction of mositure travel. The shrinkage near the surface of both the smaller and the larger prism were about equal, but the larger prism showed no shrinkage elsewhere.

It is also seen that for short periods the shrinkage of small bars is far greater than that of the larger specimens.

(10) Mixing and Placing.

Unfortunately, no data are available regarding the effect of method or time of mixing. This is regrettable as it is possible that any factor affecting the porosity of the mass might exert some influence upon the absorption or loss of moisture taking place with time and thus modify the resulting volume changes.

Pearson[45] states that absorptive forms will

greatly reduce the shrinkage of mortar specimens. The total normal shrinkage for specimens cast on non-absorptive bases may be reduced on the average by 25 to 50% by the use of an absorptive base.

Davis and Troxell[23] have likewise come to the conclusion that contraction of 1:3 mortars cast in absorbent moulds is about 15% less than for similar mortars cast in non-absorbent moulds. The first observations for these tests were made at the age of 2 days, all bars being covered by damp sacks up to that time. The results are given in Table XI.(Page 50).

Grabo[47] also reports that cast iron ends in the moulds decreased the normal contraction of the mortar.

(11) Reinforcement.

All authorities favour the idea that steel reinforcement decreases the expansion and contraction of mortars and concretes. When shrinkage occurs in an unrestrained reinforced structure, compressive stresses are developed in the steel and tensile stresses are set up in the concrete.

Considére[7] in 1899 reported the behaviour of small bars of neat cement and of 1:2:5 mortar. The prisms were 1"x2.4"x24". Half of them were reinforced with a round steel bar of 0.4 in. diameter. The measurements extended over a period of 63 days and at the close of the period showed the changes given in Table XVII.

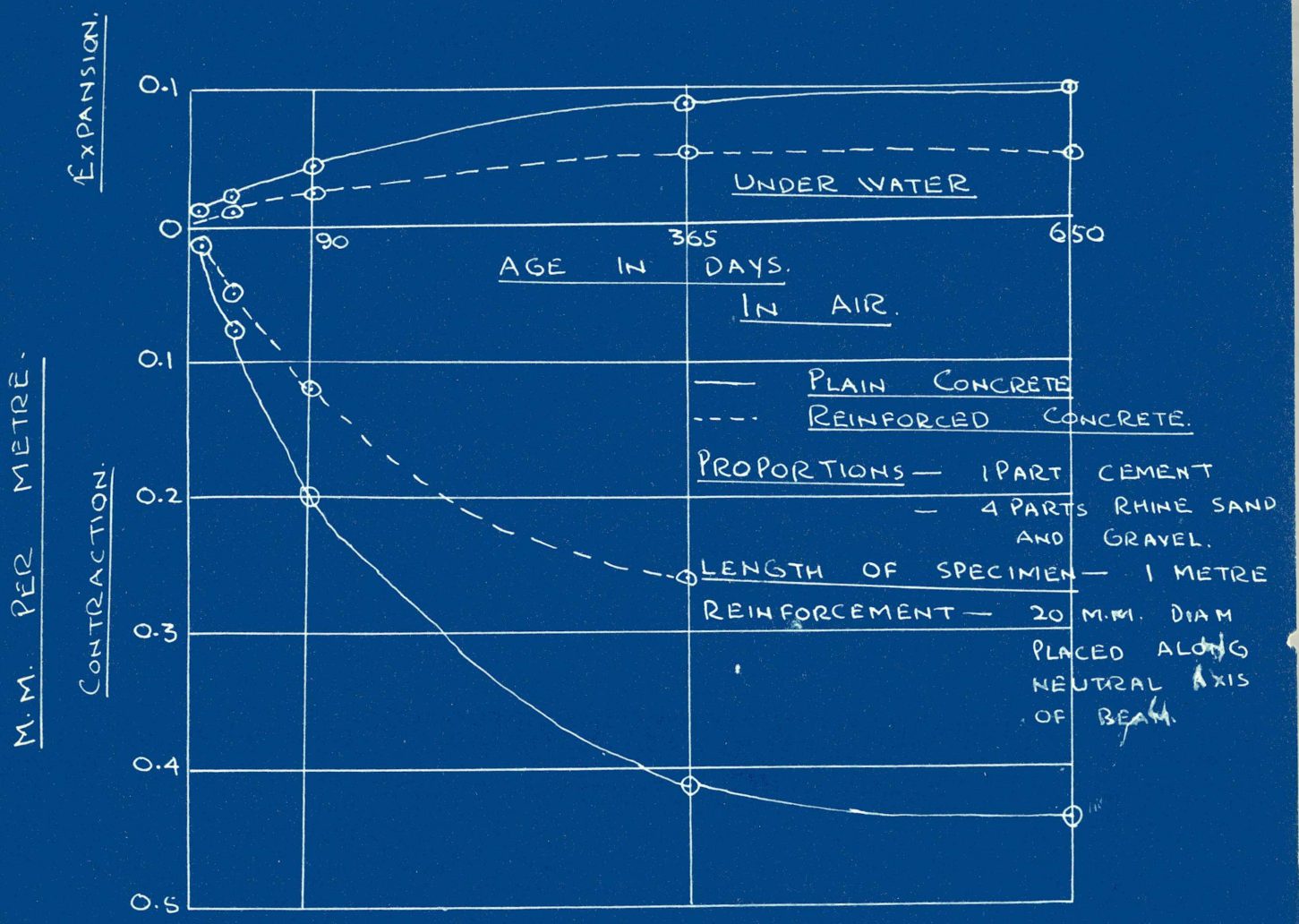


FIG 12— CHANGES IN LENGTH OF PLAIN AND REINFORCED CONCRETE SPECIMEN WITH INCREASE IN AGE AND DIFFERENT METHODS OF STORAGE.

TABLE XVII.

Effect of Reinforcement.

Type of Specimen.	Percentage change in length.	
	In Water.	In Air.
Neat cement, not reinforced.	+0.079	-0.132
Neat cement, reinforced	+0.022	-0.025
Mortar, not reinforced	+0.028	-0.050
Mortar, reinforced	+0.006	-0.010

Dr. Morsch carried out measurements on beams 1 metre long and 20 cm. by 20 cm. in cross-section with a central reinforcement of 2 cm. diameter. His results are given in Fig. XII.

H. Rabozee[48] carried out tests on volume changes in plain and reinforced concrete blocks - 65 cms.(25½") by 1 m.(3'3") by 1.40 m.(4'6"). He found that the shrinkage is less marked in reinforced than in the plain concrete and that the shrinkage ratio decreases with the increase in the percentage of reinforcement.

Matsumoto[21] has shown that, in reinforced concrete, the shrinkage stress in the steel may reach the safe working stress if there is less than 1.5% of steel, and that the shrinkage stress in 1:2:4 concrete may exceed the ultimate tensile strength of the concrete if the reinforcement exceeds 1.5%.

J.T.Pauls[49] has observed that, with a high percentage of continuous steel, relatively fine,

closely spaced cracks may be looked for; with a low percentage, breaks in the steel may be expected to permit wider cracks to form at considerable intervals.

In Sweden, where the annual temperature variation is considerable, N. Royen[50] has carried out extensive research on the effects of temperature on concrete and shrinkage of concrete. He states that the dangers arising from shrinkage and temperature variation are less than to be feared when using thin reinforced concrete sections than with mass concretes.

Professor Adams[51] has also suggested as a remedy against cracking due to shrinkage upon the drying out of moisture, the use of temperature reinforcement which consists of the insertion of light rods, say $\frac{1}{4}$"diameter and not more than 12 ins. apart in the opposite direction to the main reinforcement and near the surface whereby the shrinkage being confined within this limited area is so slight as to be invisible.

(B) Temperature.

Tests indicate that there is a wide range in the value of the coefficient of expansion for concrete, though it is generally assumed not to be greatly different from that of the steel and is regarded as constant for all concretes within the ordinary ranges of temperature. Factors[52] which influence the magnitude of volume changes in mortars and concretes due

to variations in temperature are:-

(1) Richness of mix;
(2) Kind of cement;
(3) Character of Aggregate;
(4) Water-cement ratio;
(5) Age;
(6) Mositure content;
(7) Temperature;
(8) Alterations of high and low temperature.

Hardened neat cement[53] has a coefficient considerably above 0.0000080 and the low figures previously given by the investigators may be due to shrinkage during the test. Mr. S.L. Myers[53] found that if a neat cement or concrete specimen is not protected by an airtight cover while under test, shrinkage will occur due to loss of moisture unless the humidity of the air approaches 100%; even in the latter case, if higher than normal atmospheric temperatures are used, shrinkage will occur. Neat cements are more sensitive to this condition than mortars or concretes.

H. Rabozee[48] found the thermal expansion of plain concrete specimens (prisms 10 cm. square by 40 cm.) to be $.8 \times 10^{-5}$.

Davis and Troxell[23] have conducted a number of tests on the thermal coefficient of expansion of concretes. In their first series of tests, they used a concrete of 1:4 mix, the aggregate consisting

entirely of granite. The temperature range for the test was from 39° to 125° F. The results are given in Table XVIII.

TABLE XVIII.

Thermal Expansion of 1:4 Granite Concrete.

	Coefficient of Thermal Expansion per °F.	
	At age of 7 weeks.	At age of 4 months
Immersed in water	0.0000045	0.0000041
In dry air.	0.0000038	0.0000039

The coefficient does not seem to be markedly affected with age or moisture conditions from the above results. They also found that the variation with temperature is also insignificant. The observed coefficients are rather low - only about two-thirds of the value commonly assumed - which may be due to the fact that the coefficient of thermal expansion of granite itself is low.

In their second series of tests they used both mortars and concretes (1:3 and 1:8 mixes by weight). The aggregate used was a graded sand for the mortar and a graded gravel for the concrete. The temperature range was from 40° to 130° F. during the test. They found in this series that the coefficient for wet storage is slightly greater than that for dry storage, but there is practically no variation between the different consistencies, ages, or mixes. The coefficients were

quite constant throughout the entire temperature range.

Their results of a third series on gravel concretes is given in Table XIX.

TABLE XIX.

Coefficient of Thermal Expansion as influenced by Richness of Mix.

Mix	Thermal Coefficient of Expansion per °F.	
	2" Slump.	6" Slump.
3:1	0.00000644	0.00000639
4½:1	0.00000600	0.00000581
6:1	0.00000580	0.00000556

In this series, it is seen that the coefficient increases with the richness of the mix and is slightly greater for dry mixes than for wet ones. They also found that the coefficient varies quite markedly with the aggregate as is shown in Table XX. For the specimens stored at 70°F., the coefficients at 23 weeks averaged 3.5% greater than the coefficient at 9 weeks. 100 cycles of alternating temperatures decreased the coefficient by 14.1% from that which would have existed had the specimens been stored at 70° F. The coefficient was found to be fairly constant for ordinary ranges of temperature.

TABLE XX.

Effect of Character of Aggregate upon Thermal Expansion.

Kind of Aggregate.	Coefficient of Expansion per °F.
Quartz	0.0000066
Sandstone	0.0000065
Gravel	0 .0000060
Granite	0.0000053
Basalt	0.0000048
Limestone	0.0000038

They investigated a fourth series using high alumina cement and gravel aggregate in the proportions of 1:4.1, 1:5.1 and 1:7.6 by weight. The mixes had a slump of 3 to 4 inches and the specimens were stored in dry air continuously. The results are shown in Table XXI.

TABLE XXI.

Effect of Temperature and Richness of Mix on Thermal Expansion of Aluminous Cement Concrete.

Coefficient of Thermal Expansion per °F.				
Mix	39° to 72° F.	72° to 103° F.	103° to 133° F.	Average.
1:4.1	0.00000513	0.00000548	0.00000552	0.00000538
1:5.1	0.00000489	0.00000528	0.00000502	0.00000506
1:7.6	0.00000510	0.00000519	0.00000520	0.00000516
				0.00000520

In this case, cement ratio as well as temperature range was found to have very little influence over the coefficient of expansion determined at the age of about 4 months.

Mr. S.L. Myers[53] on the other hand found increase in the coefficient of thermal expansion of neat cement bars with time. His results are given in Table XXII.

TABLE XXII.

Effect of Age on Coefficient of Expansion.

Cement.	3 days.	1 week.	1 month.
Standard Cement	0.0000072	0.0000079	0.0000103
High-Silica "	0.0000066	0.0000068	0.0000081
High-Lime "	0.0000101	0.0000103	0.0000106
	6 months.	9 months.	
Standard Cement	0.0000108	0.0000118	
High-Silica "	0.0000099	0.0000099	
High-Lime "	0.0000107	0.0000109	

He associates the increase in coefficient with time with the moisture condition of the neat bars, as he found that the coefficient of bars having a high coefficient at nine months is lowered to values approaching the coefficient in early periods upon soaking the bar in water for a few days. Also if the neat cement bars are stored in a dry atmosphere, the coefficient is increased, as indicated by Table XXIII. In the case of steam treatment, low coefficient cements were only slightly lowered, while cements with high coefficient were lowered into the same coefficient range as low-lime or higher acid cements.

TABLE XXIII.

	Conditions.	Coefficient of Expansion.
Standard Cement.	Average 9 months.	0.0000093
	In $CaCl_2$ dessicator, 1 week.	0.0000080
	In steam, 1 week.	0.0000066

Mr. Myers[53] also investigated the coefficient of expansion of a number of cements with different compositions. His results are given in Table XXIV. The results show that the thermal coefficient of expansion appears to increase in the following order:- dicalcium silicate, tricalcium aluminate, tetracalcium aluminoferrite, tricalcium silicate, the latter having more than twice the value of the first named coefficient. The coefficients also appeared to increase with time.

TABLE XXIV.

Thermal Coefficient of Expansion for neat Cements.

	% Cement Minerals.				Coefficient of Expansion
	C_4AF	C_3A	C_2S	C_3S	
Gamma dicalcium silicate	-	-	98.0	-	0.0000052
Tricalcium aluminate	4.13	32.10	0.0	57.75	0.0000068
Tetracalcium Alumino-ferrite	99.0	-	-	-	0.0000063
Standard cement	8.80	9.20	15.0	58.0	0.0000093
High Silica	5.65	5.58	46.85	34.86	0.0000078
High Early Strength	10.50	12.0	3.60	66.23	0.0000108
White cement	1.40	12.50	41.50	33.0	0.0000104
High iron, high C_3S	18.24	3.83	6.49	68.79	0.0000092
Low tricalcium silicate	5.53	3.49	54.81	28.89	0.0000073
High tricalcium silicate	7.97	8.81	5.75	69.34	0.0000116
High Silica, Low R_2O_3	5.17	3.68	50.75	33.25	0.0000097
Very Low C_3S	7.90	8.89	4.17	70.62	0.0000118
High R_2O_3, low lime	22.71	14.54	56.0	0.0	0.0000054

Norton in 1910 investigated the effect of high temperature on the thermal expansion of concrete. His specimens were 6 ins. and 10 ins. cubes of 1:2:5 crushed stone concrete. The changes were measured when these cubes came to complete equilibrium by heating them in an electric furnace. The results are given in Table XXV.

TABLE XXV.

Thermal Expansion at High Temperatures.

Temperature, ^{o} F.	Mean Coefficient per ^{o} F.
72 to 360	0.0000045 to 0.0000060
72 to 750	0.0000050 to 0.0000060
72 to 1090	0.0000045 to 0.0000050
72 to 1600	0.0000035 to 0.0000042

He found that the coefficient increased slightly up to 575^{o} F., but became smaller at higher temperatures. At about 1500^{o} F., it became zero and above that temperature took on a negative value. Further, the blocks heated to 1500^{o} F. did not return to their original dimensions on cooling, but retained an elongation of about 75% of their maximum elongation. On heating these blocks, a second time, no sensible permanent elongation was evident.

White[20] has investigated the effect of freezing neat cement and 3:1 mortar bars while wet. All the bars contracted while freezing. It was thought

that they might expand as a result of freezing as water expands about 8.5% on freezing. All the bars were from 3 to 6 years old. After four successive freezing and thawings the bars were entirely unaffected in length.

Messrs. Louis Schuman and S.A. Pisapia[43] on the other hand found that concrete cylinders (using high early strength cements) subjected to freezing and thawing expanded from .003 to 0.031% in one year. Freezing, thawing, drying and soaking of the 2" by 12" cylinders caused so much spalling that few data were obtained after the 25th cycle.

Table XXVI gives the data[38] of Keller as well as the results of a review by Shitkewitsch regarding the coefficient of expansion of various cements, mortars, concretes and other building stones. It is seen that the values given by the various authorities differ greatly from one another due to the variables already mentioned.

TABLE XXVI.

Thermal Coefficient of Expansion.		
Material.	Coefficient of Expansion per °F.	Authority.
Neat Cement	0.0000068	Meier
" "	0.0000081	"
" "	0.0000079	Adie
" "	0.0000059	Bouniceau
" "	0.0000076	Hyatt
" "	0.0000078	"
" "	0.0000070	Keller
1:3 Mortar	0.0000066	Bouniceau
1:1 Mortar	0.0000061	Keller
1:2 Mortar	0.0000056	"
1:4 Mortar	0.0000058	"
1:6 Mortar	0.0000051	"
1:8 Mortar	0.0000053	"
1:2:4 Bedford limestone concrete	0.0000055	Pence
1:2:4 Kanakakee limestone concrete	0.0000056	"
Granite (Average)	0.0000045	Bouniceau, Adie, Hurst, Dana.
Limestone(Average)	0.0000051	Bouniceau, Dana, Pence.
Marble (Average)	0.0000042	Bouniceau, Adie, Ganot.
Sandstone(Average)	0.0000069	Haswell, Ganot, Dana, Adie, Thurston.

The above presents in brief the qualitative data regarding shrinkage and how it is affected by the attendant circumstances. From the data presented above, it will be seen that though much qualitative knowledge has been gained about shrinkage, it does not seem that any quantitative knowledge of general application is yet available.

Various values have been given for shrinkage. In a discussion on a paper by Mr. A.C.Janni, on a method of designing a rectangular reinforced concrete flat slab, Mr. F.R. Macmillan[22] gave a series of measurements of shrinkages of various concretes, with percentages of water ranging from 7.75 to 10 and mixtures of 1:1½:3 to 1:3:6. The shrinkage does not depend greatly on these variations and according to him, its average value is about .005 at 60 days and .0006 at 440 days.

Professor M. Rudeloft and Dr.H.Sieglerschmidt[54] gave it as about .00032 of which two-thirds takes place in the first 40 days and the rest in 200-400 days.

Matsumoto[21] gave it as about .0003 after 60 days storage under wet burlap and 40 days in air and as about .005 when exposed to air from the start.

Professor F.E. Furneaux and E. R. Maurer[55] have mentioned tests carried out by Mr. A.T.Goldbeck which gave .00034 in 30 days and .00048 in 60 days for dry

mixed concrete and .00011 and .00041 respectively for wet mixed concrete, while previously Goldbeck[24] had stated that the approximate contraction of concrete of the proportions and consistencies ordinarily used is 0.05% at the age of 3 months and that consistency or proportion of concrete has practically no effect on shrinkage.

Messrs. L.C.Urquahart and C.E. O'Rourke[56] gave the contraction as ranging from .0002 to .0005.

Mr. W.L. Scott[57] gave it approximately as .004.

Gessner[58] has given the following values for percentage volume diminutions calculated on the initial volume of a mixture of 100 parts of cement and 33 parts of water.

TABLE XXVII.

Cement.	Percentage Volume Diminution of System.				
	no.	1 Day.	7 Days.	28 Days	100Days.
Portland Cement	1	2.8	4.8	6.0	6.9
" "	2	1.7	4.4	-	6.3
Portland Cement with Gypsum	3	2.7	8.0	8.6	8.7
" "	4	2.6	6.3	7.5	7.6
High Alumina Cement	5	11.1	13.8	15.2	16.3

The striking point brought out by some of the values of shrinkage given above is the variation,

amounting to several hundreds per cent., in the values given. One experimenter[9] may even show a variation of 400% in his own results. Even qualitative statements do not always agree. These difficulties arise from the fact that all the variables are rarely recognised and so no allowance is made for them.

Many efforts have been made to ascertain the laws governing shrinkage and expansion and the magnitude of the stress caused by its prevention. Most of them have failed as attempts have been made only to correlate shrinkage with some property of cement or concrete without trying to formulate a basic theory which would account not only for shrinkage but for all - creep, shrinkage, plastic flow, setting, etc.

Matsumoto[21] has shown that the volume of the aggregate in concrete is not altered by moisture conditions - all movements must take place in the cement paste. This has led some of the investigators to establish a relationship between the constituents of cement and shrinkage. Woods, Davis, Gonnerman, Bogue, Lerch, and Taylor, and many others, have done considerable work as regards the contribution of cement compounds to the shrinkage. The results of the first three investigators are given in Table XXVIII.

The data of Woods and his co-workers[59] were obtained from 1:3 plastic mortars, ~~and~~ prepared from 16 experimental cements, the test specimens being 12 x 1 x 1 in. bars which were stored for 21 days in moist air and then in air in the laboratory. The data of Davis and his co-workers[60] were obtained from 1:3¼ mortars prepared from 12 experimental cements, the test specimens being 12 x 1½ x 1½ ins. bars which were cured under "mass" conditions for 28 days and then in air at 21° C. and 50% relative humidity. The data of Gonnerman[61] were obtained from 1:3:6 mortars prepared from some 70 experimental cements, the test specimens being 15 x 3 x 3 ins. bars stored either 6 or 89 days in moist air and then in air at 21° C. and 50% relative humidity.

The relative extent to which equal weights of the compounds C_3S, C_2S, C_3A, and C_4AF[70] contribute to the shrinkage was calculated in each case by analysis of the data obtained using the Bogue compound content of the cements. For purposes of comparison, in reproducing these results, the shrinkage contribution of C_3S has been put equal to 100 in Table XXVIII and that of equal weights of the other compounds recalculated to this basis.[62]

TABLE XXVIII.

Comparison of the contributions of equal weights of cement compounds to the shrinkage of mortars.

Authors	Preliminary Curing.	Period of air storage over which shrinkage measured	Relative Contribution to Shrinkage.			
			C_3S	C_2S	C_3A	C_4AF
Woods, Starke & Steiner. (59)	21 days moist curing	276 days	100	230	365	700
Davis, Carlson, Troxell, & Kelly (60)	28 days "Mass"(a) conditions.	1 year	100	156	-29	78
Gonnerman (61)	6 days moist air.	1 year	100	97	295	62
	89 days moist air.	1 year	100	94	260	56

(a) Mass Curing defined as the thermal conditions within a large given mass concrete for the particular cement concerned, i.e., the thermal history corresponds to that in the concrete from the same cement when kept under approximately adiabetic conditions.

Bogue, Lerch and Taylor (63) also found for neat cement bars (13 x 1 x 1 ins.) made from the same cements as those used by Gonnerman that shrinkage increased with the content of C_3A in the cement, but

showed no significant change with alterations in the ratio of C_3S to C_2S. Their results are therefore in general agreement with those obtained by Gonnerman with mortars from the same cements.

The discrepancies between the results of the different series of tests shown in Table XXVIII are so great that no conclusion can be drawn from them. This had led many of the investigators[64] to believe that there is no relation between the constituents of the cement and shrinkage. This is mainly due to two reasons. First, the use of the compound contents calculated by the methods known to-day (Four or five compound methods), for the analysis of data on cement properties involves errors of uncertain magnitude. Second, shrinkage has been assumed as an additive property of the compound constituents of the cement, represented by

$P = aA + bB + cC + dD$, where P represents the numerical value of the shrinkage, A,B,C,D are the percentage contents of C_3S, C_2S, C_3A and C_4AF present in the cement, and a,b,c,d coefficients representing the contribution of 1% of the corresponding compounds. The use of such[62] an equation also assumes that the contribution of a unit weight of any given compound to a given property remains unchanged throughout the series of cements considered.

The extent to which shrinkage can be regarded as additive property is more in doubt. It seems likely that it may depend not only on the relative amount and specific individual properties of the compounds concerned, but also on the structure of the set cement mass as a whole. It is not clear how this structure is related to cement composition, or to the conditions of setting under which it is first established. If shrinkage were determined primarily by the structure established in the set cement during its early hardening, it could not be expected to be an additive property. It would on the other hand be influenced by any factors affecting the early hardening period.

Inge Lyse(65) claims that his tests show that the quality of the paste showed little effect upon the shrinkage, while the quantity of the paste contrubuted approximately in proportion to its percentage of the volume of the concrete. He states that the shrinkage of concrete could be expressed approximately by the equation $S = k.p.$ where S represents the shrinkage of the concrete, k is a constant which depends upon the materials used and the conditions of exposure and p the percentage of cement paste in the concrete. It is very difficult to agree with Lyse that the richness of the mix or the water content

have no effect whatever upon the shrinkage. It is more probable that the quantity as well as quality of the cement paste have influence on the shrinkage of concrete.

The fact[38] that mortar mixes of a given cement ratio are subject to greater volume changes than concrete mixes of the same cement ratio has given rise to the general impression that the changes in length of mortar and concrete specimens vary directly with the fineness of the aggregate. But tests by Davis and Troxell[23] disclosed that the percentage of fines had no marked influence either upon the magnitude of the shrinkage in the oven-dry state or upon the magnitude of the expansion after the prolonged period of immersion. Inge Lyse[65] on the other hand found that fine aggregate showed more effect upon shrinkage than did coarse aggregate. Carlson[46] also found that the shrinkage varies greatly with the size of the aggregate; the larger the aggregate, the lesser the shrinkage.

A study of such data as are available indicates a greatly increased shrinkage of concretes over what would be expected from the dimensions of the paste and aggregate. Numerous test results[46] show that water soaking of well-cured neat specimens causes them to expand very nearly to their original length,

while poorly cured specimens retain much of their shrinkage. In the case of concrete, the expansion upon resaturation may be sufficient to increase the volume beyond the original. The paste attempts to shrink upon drying, but the aggregate particles attempt to remain constant in volume. The shrinking paste attempts to compress the aggregate particles, while the aggregate particles attempt to prevent the paste from shrinking. Thus the bulk of the paste is in a state of tension and the aggregate particles are in a state of compression. Since the tensile strength of a paste is limited, it cracks between large particles of aggregate. But before the internal cracking occurs, the paste has been subjected to large forces which may have deformed it plastically. Upon resaturation, the paste may then expand into a slightly modified shape which will not perfectly fit the spaces between the aggregate particles. Furthermore, after internal cracking occurs, the cracks may tend to heal with gel. When such effects predominate, there may be an expansion beyond the original volume. Table XXIX by Carlson[46] illustrates this expansion.

TABLE XXIX.

Shrinkage of Neat Cement, Mortar and Concrete - Evacuated series (a).

Mix by weight.	Aggregate size.	Voids %	Change in length-Millionths per unit.			
			35 days	2 months	Oven dry	Saturated (b)
Water-Cement Ratio 0.30.						
Neat	(None)	9.6	-705	-1420	-3400	-708
1:2.85	No.48 to No.14 sieve	41.0	-759	-988	-1492	-622
1:2.85	3/8 to ¾"	6.2	-325	-404	-458	+182
1:2	No.48 to No.14 sieve	34.9	-809	-1009	-1527	-722
1:2	⅜ to ¾"	5.7	-293	-404	-459	+123
Water-Cement Ratio 0.40.						
Neat	(None)	13.8	-1037	-2205	-4195	-1212
1:2.85	No.48 to No.14 sieve	28.7	-802	-1115	-1805	-727
1:2.85	⅜ to ¾"	7.3	-374	-460	-555	+72
1:2	No.48 to No.14 sieve	11.3	-548	-903	-1229	-537
1:2	⅜ to ¾"	7.0	-317	-388	-450	+158

(a) Mixtures placed under vacuum for 2 minutes before casting in forms.

(b) Saturated values measured on bars in water after oven drying, age 2 months.

A further effect of the dilution of paste with aggregate will be the entraining of air and the production of additional voids not present in the neat paste. The voids not only permit the more ready escape of moisture from the mortar or concrete, but they may also permit the paste to shrink more fully. Mortars and concretes are therefore expected to shrink more than would be computed from relative volumes and dimensions of paste and aggregate. Carlson's[46] tests demonstrate this. He used a mix of one part of cement to about three parts by weight of gravel aggregate, approximately uniform in size, so that the volume of the paste was only about that necessary to fill the voids in the aggregate and the aggregate particles were almost in contact with one another. Although a random section cut through the specimen did not cut every particle where it was closest to another particle, a line could be found that ran almost straight from end to end along which every particle was only slightly separated by paste from its neighbour. Along such a line, the paste separating the aggregate made up less than 5% of the length of the specimen. Assuming that the paste between the particles along this line shrinks exactly as it did in the neat paste specimens and assuming that the particles along this line shrink exactly as

in the neat paste specimens, and assuming that the aggregate particles remain constant in volume, the mortar or concrete would contract less than 5% as much as the neat paste.

TABLE XXX.

Shrinkage of Neat Cement, Mortar and Concrete.

Mix by Weight	Aggregate Size	Voids (a) %	Change in length(b), Millionths per unit.			
			35 days	2 months	4 months	Oven dry(c)
	Water-Cement Ratio 0.30.					
Neat	(None)	9.5	786	1514	1998	3410
1:2.85	No.48 to No.14 sieve	38.8	730	970	1091	1740
1:2.85	⅜ to ¾"	5.9	345	400	414	535
	Water-Cement Ratio 0.40.					
Neat	(None)	13.2	1076	2107	2847	4647
1:2.85	No.48 to No.14 sieve	26.9	743	1016	1129	1492
1:2.85	⅜ to ¾"	6.0	353	431	443	458

(a) Voids computed as percentage absorption by volume after drying 4 months at 50% Relative Humidity.

(b) Change in length measured on 1½ by 1½ by 12 ins. bars, moist cured for 28 days, then at 50% relative humidity.

(c) Oven-dry values measured on bars oven dried after 4-month readings are taken.

Comparing the shrinkage at all ages up to four months, it may be seen from Table XXX that for both sizes of aggregate and for all ages, the shrinkage of the concrete or mortar is far in excess of 5% of that of the neat paste. It will be seen, however, that the general tendency is for the neat pastes to continue shrinking at a more rapid rate than the mortars or concretes.

While the whole system (cement + water) while hydrating shows a dimunition in volume, the volume of the actual solid matter present increases. This has led to some of the investigators to try to establish a relationship between the volume and weight changes of concretes. The final total change[66] estimated from the differences in the density of Portland cement and dried fully hydrated cement corresponds to a volume increase of the solid of about 50%. Thus Anderegg and Hubbell[67] found a density of 3.19 for a sample of concrete and 2.13 for the completely hydrated material after drying at 110°. The increase in solid volume on hydration of lime (density 3.3) to form calcium hydroxide (2.230) is also nearly 50%. The decrease in volume of the system lime + water is 5.1%.

Matsumoto[21] has shown that after repeated

wetting and drying a specimen may contract to less than its initial size, though it has a net increase in weight. In other words, its density has increased.

Withey[68] claims that his tests show that the expansion or contraction of concrete is proportional to its gain or loss in weight; but his points are much too scattered to justify this claim. Matsumoto's[21] experiment completely disproves it; and it is probable that the linear dimensions of Withey's specimens depended on the humidity just prior to measurement. W.K. Hatt[9] also found that the percentage loss or gain in weight due to moisture for a given cement is indicative of (though not necessarily directly proportional to) the change in length. Among the different cements, one might exhibit larger weight changes yet smaller volume changes than another.

R.E.Mills and Creps[69] found that the specimens showed expansion and gain in weight during the initial 28 days of moist room storage. The net change in all cases was approximately the same for both, speed Portland Cement and Blended Cement. A comparison of the mixes indicates slightly more expansion and gain in weight for richer mixes. Following the moist room storage the specimens were placed in the air of the

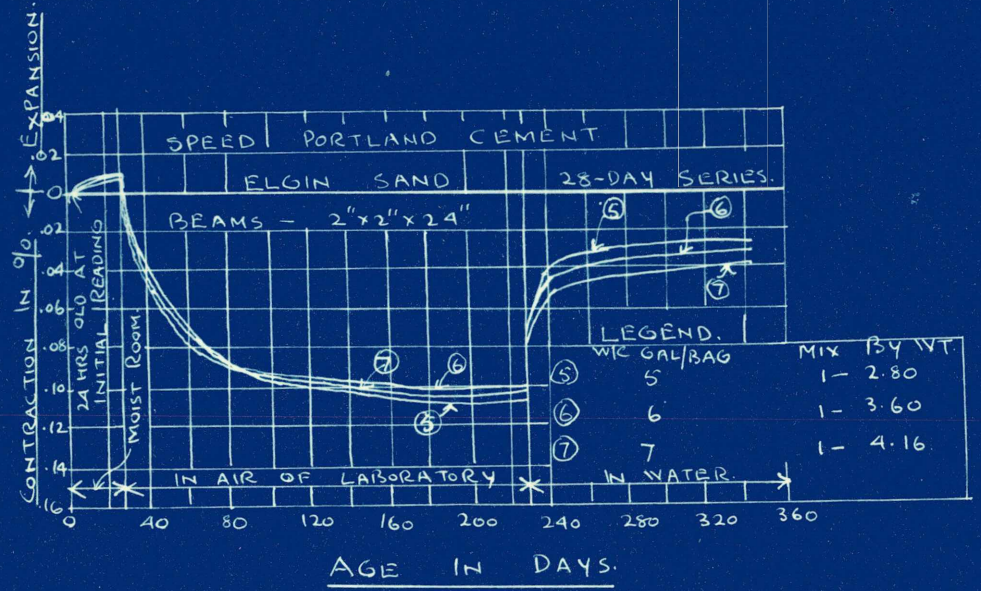


FIG. 13 — EXPANSION AND CONTRACTION OF SPEED PORTLAND CEMENT MORTAR BEAMS. — 28 – DAY SERIES.

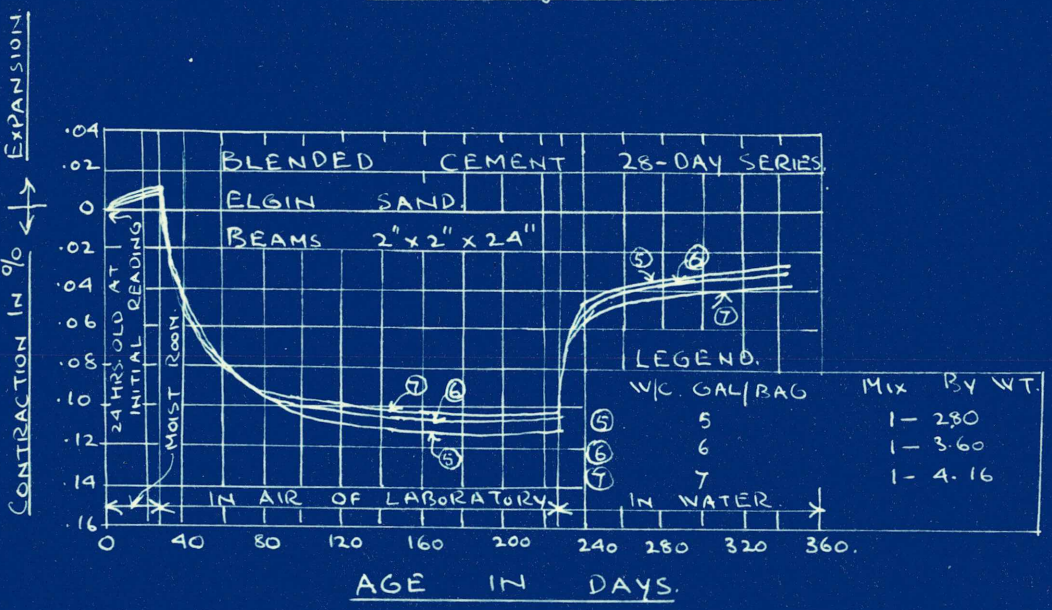


FIG. 14 — EXPANSION AND CONTRACTION OF BLENDED CEMENT MORTAR BEAMS — 28 – DAY SERIES.

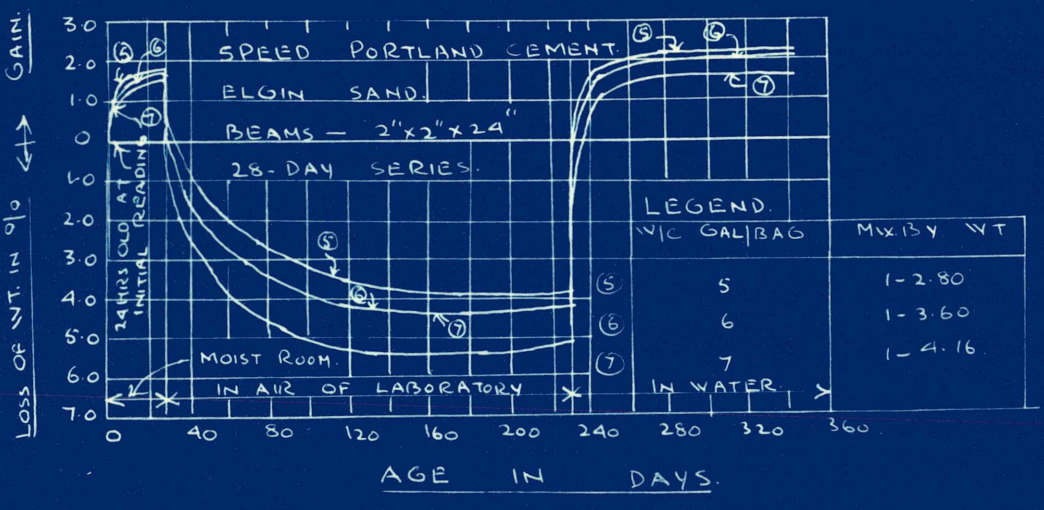


FIG. 15 — CHANGE OF WEIGHT OF SPEED PORTLAND CEMENT MORTAR BEAMS — 28-DAY SERIES.

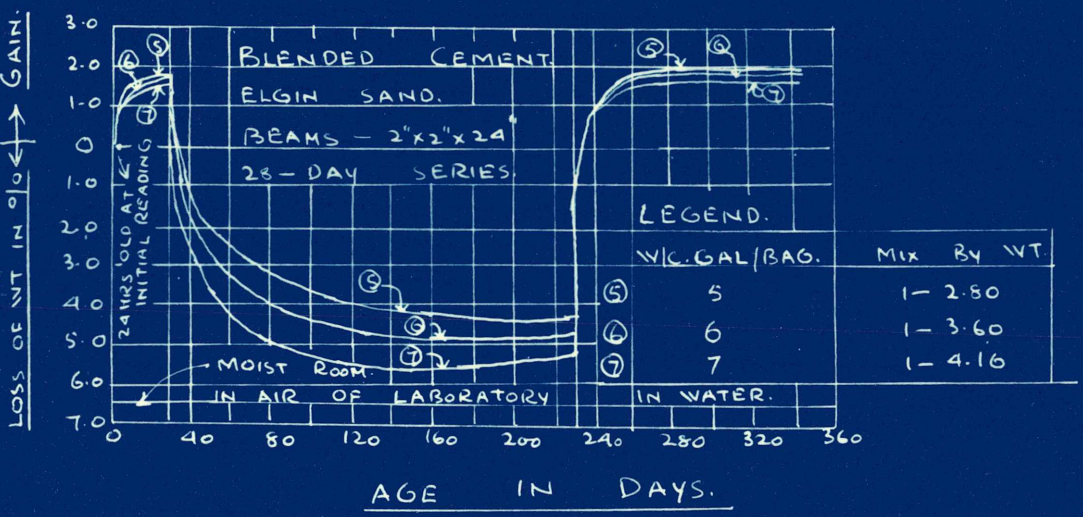


FIG. 16 — CHANGE OF WEIGHT OF BLENDED CEMENT MORTAR BEAMS — 28-DAY SERIES.

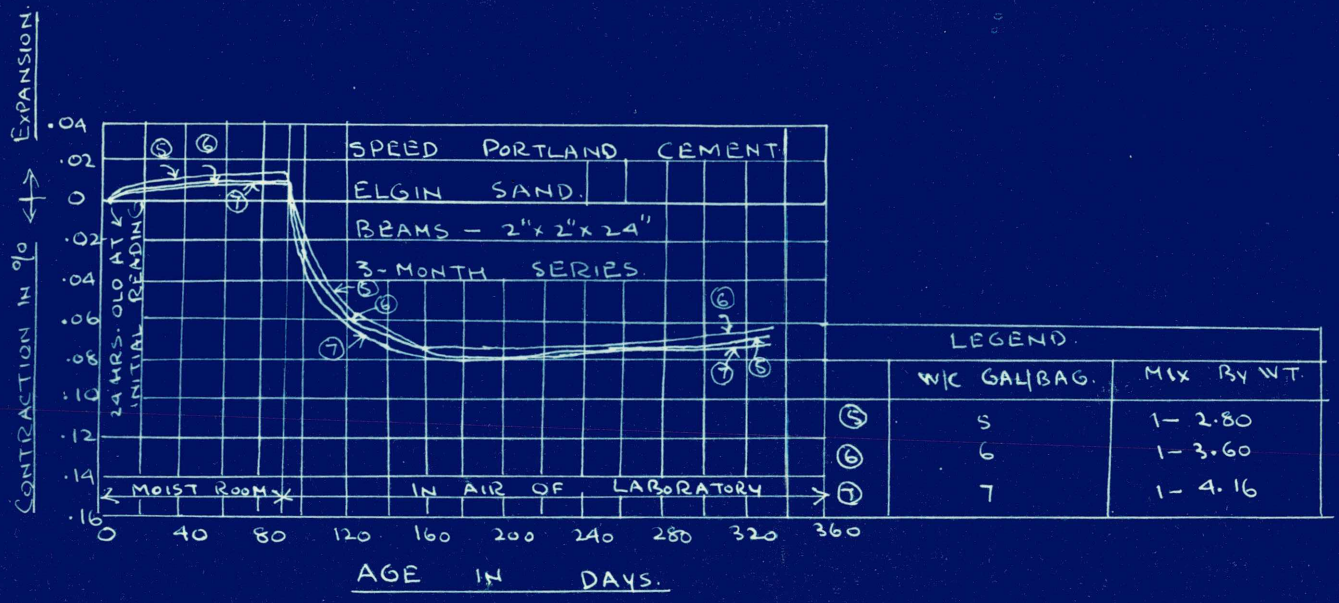


FIG. 17— EXPANSION AND CONTRACTION OF SPEED PORTLAND CEMENT MORTAR BEAMS — 3-MONTH SERIES.

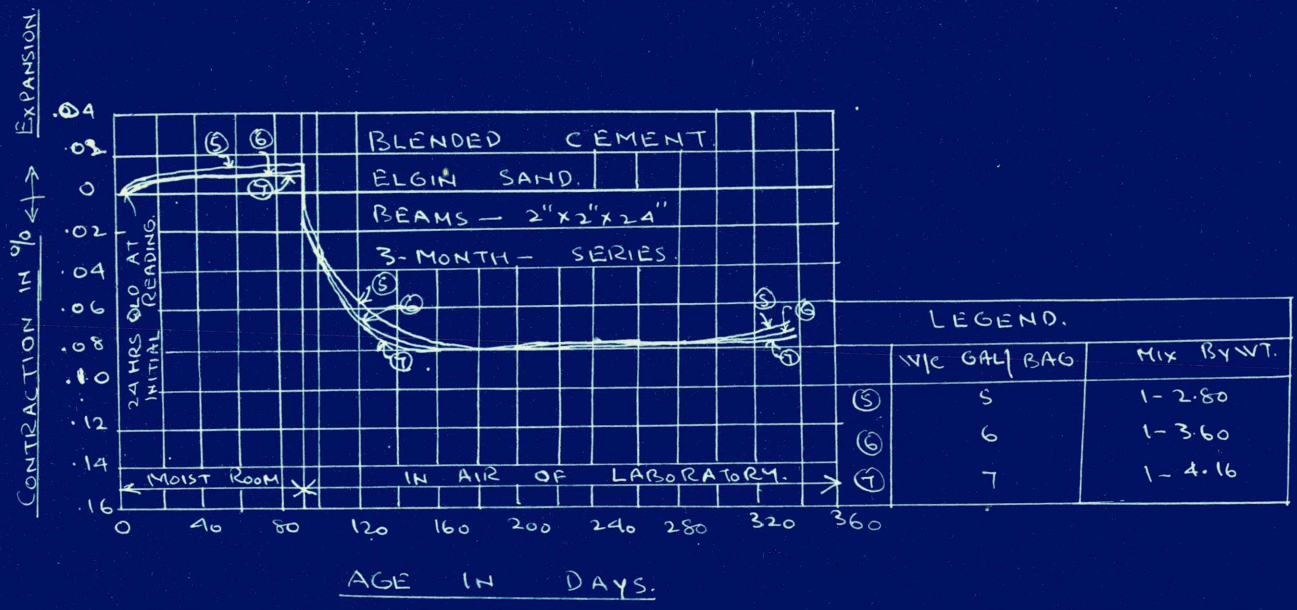


FIG. 18— EXPANSION AND CONTRACTION OF BLENDED CEMENT MORTAR BEAMS — 3 MONTH SERIES.

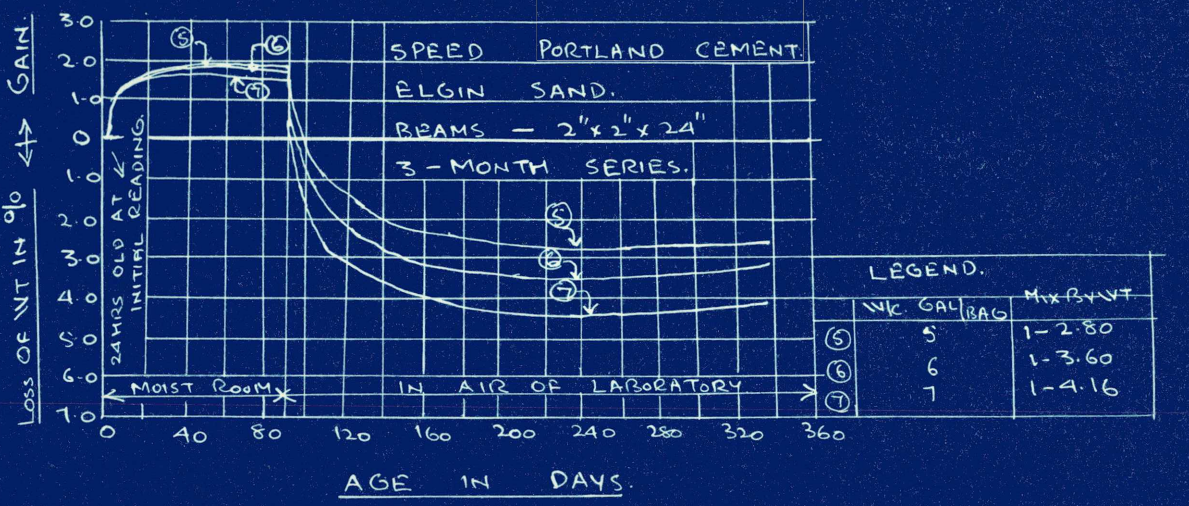


FIG. 19 — CHANGE OF WEIGHT OF SPEED PORTLAND CEMENT MORTAR BEAMS — 3-MONTH SERIES.

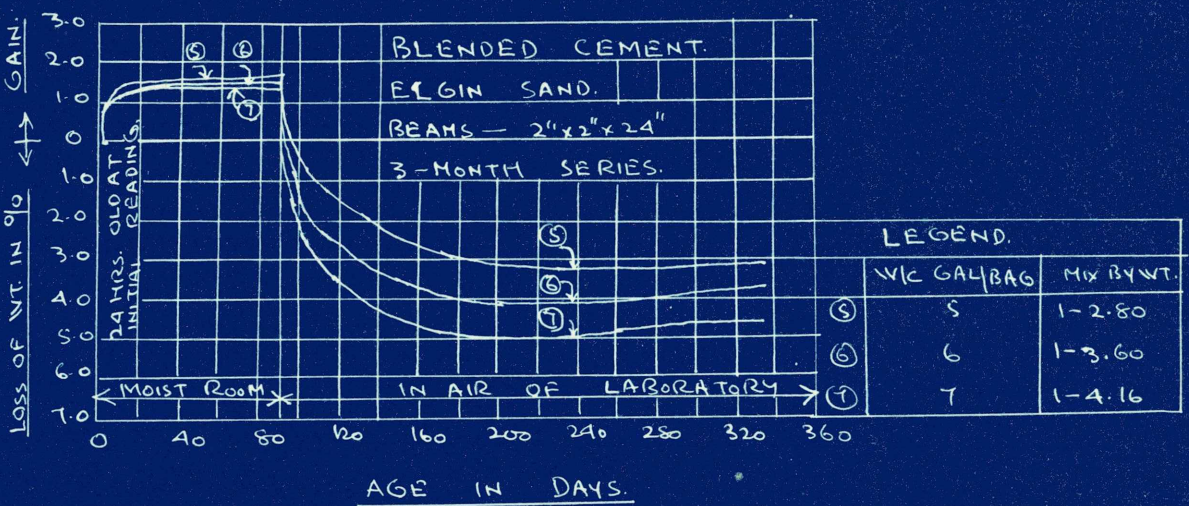


FIG. 20 — CHANGE OF WEIGHT OF BLENDED CEMENT MORTAR BEAMS — 3-MONTH SERIES.

laboratory and allowed to dry to constant weight. The time required for this drying out process was 203 days. The average net contraction of the speed Portland Cement was 0.0995%; of the Blended Cement, 0.1036%. Corresponding values of loss of weight were: Speed Portland Cement, 4.46%; Blended Cement, 4.81%. A comparison of the mixes indicates somewhat more contraction for the richer mixes. However, the leaner mixes with the higher water-cement ratios show the greater loss in weight. (Figs. XIII to XVI).

Immediately after the drying period the specimens were immersed in water for 112 days. At this time their expansion and gain of weight had practically ceased. From an inspection of the curves, it is evident that all of the mortar beams exhibit considerably more change of length for the drying period than they do for the saturation period which followed. This would indicate that for long periods of drying followed by saturation in water, the total expansion is less than the total contraction, leaving a residual shrinkage. However, no residual loss of weight is indicated.

They also investigated a 3 months series. (Figs.XVII to Fig. XX).

A comparison of the 28-day series with the 3-month series indicates consistently larger values of

contraction and loss in weight for the 28-day series. No doubt, the prevailing humidity conditions during the drying periods were somewhat responsible for this difference. The specimens were 2 ins. by 2 ins. by 24 ins. beams in both the series. Water-cement ratio was 5,6,7 gal. per bag and aggregate used was sand 0 - $\frac{1}{4}$".

This summarises in short our present knowledge about shrinkage. It will be seen from the above that shrinkage is dependent on a number of factors and unless we first know the effect of all these qualitatively as well as quantitatively it would not be possible to formulate a general law regarding shrinkage.

Further, also it is seen that practically no unequivocal data is available for the volume change of the cement during the early stages of hydration and particularly during the early plastic period before setting occurs due to the great difficulty of taking measurements while the cement is in plastic state. Unless some data can be obtained about this, the whole chain of information about shrinkage would not be complete. So now an attempt would be made first to explain in detail how the volume change takes place in cement during the early stages of hydration and later description of a suitable apparatus designed to measure these changes while the cement is in plastic state

would be described and certain measurements obtained therefrom would be given.

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(70) For convenience, the following abbreviated formulae will be used henceforth:-

C_3S = $3CaO.SiO_2$;

C_5A_3 = $5CaO.3Al_2O_3$;

C_2S = $2CaO.SiO_2$;

C_4AF = $4CaO.Al_2O_3;Fe_2O_3$;

C_3A = $3CaO.Al_2O_3$.

CHAPTER VI.

THE CONSTITUTION OF PORTLAND CEMENT.

Chapter VI.

The Constitution of Portland Cement.

The properties of any material are a function of the compounds present and not of the hypothetical oxides. The properties of cement are not a function of the properties of its oxide constituents, but of the compounds which they form. Some of these compounds might be hydrating rapidly, others slowly; some to give high strength, others low strength or no strength at all; some to evolve much heat during hydration, others but little or no heat; some to produce large volume changes, others small or no volume changes; some to be attacked by the various salts and chemicals, others to be resistant to them. So to know the definite property of a material, in this particular case, shrinkage, it would be essential to know about the individual compounds of it and their actions, to form a comprehensive view of the problem.

It might be repeated here once more that though this is true regarding shrinkage, it does not necessarily mean that shrinkage is an additive property of the compound constituents. It depends not only on the relative amount and specific individual property of the compounds concerned, but also on the structure of the set cement mass as a whole.(See p.86)

Although Le Chatelier(1) was perhaps the first

to learn something of the chemical combinations of Portland cement by an application of microscopic technic (methods of photography as employed in the study of rocks), it remained for high-temperature research on the cement components to produce an adequate picture of the compound constitution of Portland cement. More than 90% of this material is made up of lime, silica, and alumina in some form of chemical combination, but what form that chemical combination took was not known.

Törnebohm[2] independently confirmed Le Chatelier's observations and gave names, alite, belite, celite, and felite to the four minerals observed in thin sections of cement clinker.

Alite[3], the most abundant constituent, consisted of colourless biaxial crystals of weak birefringence, rectangular or hexagonal in outline. Belite consisted of small rounded grains of no definite crystal form, having a darker colour and a higher birefringence, showing interference colours. The grains were biaxial and often striated. Celite was recognised by its dark orange-yellow colour and its high birefringence. In well-burnt clinker, it formed the filling material and magma form which the alite had separated. Felite was described as a colourless biaxial compound with strong

birefringence occurring in a rounded, or elongated, striated form. It was found in variable quantity in different clinkers and was often entirely absent. It seemed to replace belite. In addition to these four minerals, Törnebohm observed an isotropic colourless glass of high refractive index which also occurred as a filling material between the alite grains.

The nature of the minerals classified by Törnebohm and particularly that of alite, attracted much attention. Le Chatelier's view that tricalcium silicate was the main cementing constituent of Portland cement did not meet with general acceptance, and alite was regarded by many investigators as a solid solution of calcium aluminates and silicates, though no adequate experimental evidence was advanced for this hypothesis.

Rankin & Wright[4] were perhaps the first to realise that it was not possible to understand the nature of the chemical combination in cement until an intensive physico-chemical research on the phase relationships of the compounds formed and their regions of stability is carried out. They were the first to establish the equilibrium composition within the system $CaO - Al_2O_3 - SiO_2$, with all possible mixtures of these three oxides.

So, in 1915, it was established that the three principal compounds formed of lime, alumina, and silica

within the region of Portland cement are tricalcium silicate, dicalcium silicate and tricalcium aluminate. The criterion for identification was based on petrographic microscopical examination making use of the phase rule of Gibbs.(5)

There has, however, been a strong school of thought, which, at any rate up to quite recent times, has denied the validity of the conclusion drawn from the phase equilibrium studies and asserted that Portland cement is not an equilibrium porduct, and that present in it there are compounds and solid solutions which are not met with in equilibrium studies on phase rule lines. Some of them maintained the view that a solid solution was formed by the dicalcium silicate and lime; many believed that other solid solutions were formed in which the alumina had a part. Almost all of them regarded alite as containing alumina. Dyckerhoff(6) however suggested that it consisted of a solid solution of lime in B C_2S which slowly but only partially became converted to C_3S during burning. Jänecke believed that the three compounds united to form a ternary compound of the composition $8CaO.Al_2O_3.2SiO_2$ though he(7) has now accepted the existence of C_3S while still maintaining the existence of the compound C_8AS_2 and considering that the nature of alite is not yet fully solved.

This school of thought, which held the allegiance of many of the German cement chemists, therefore regarded alite as a solid solution of tricalcium silicate with an alumina-containing compound, despite the non-existence of any such solid solution in the $CaO-Al_2O_3-SiO_2$ system at equilibrium. The cumulative increase in the evidence indicating the essential correctness of the conclusions based on the phase equilibrium studies has in recent years won over most of its former opponents. Most of these objections were withdrawn after X-ray diffraction technique[8] was adopted to Portland Cement. Commenting upon this, Guttman[9], the famous German investigator, remarked that "at last the fifty year old problem 'what is Alite' is solved", as more agreement had been found among the investigators about the nature of other compounds than alite.

Recent X-ray analysis and optical examination have now definitely shown that no appreciable amount of solid solution (the formation of which the German school had so much favoured) of aluminates in tricalcium silicate occurs and the view that this compound occurs in a substantially pure form in Portland cement is correct. It must be mentioned here that neither X-ray nor optical examination [3] is adequate to show that a very small amount of solid solution may not occur, for it is

practically impossible to detect optically small amounts of C_3A in the presence of C_3S. Solid solutions generally show up in the X-ray patterns as a progressive shift in the lines, but if the amount of solid solution is rather small, no such shift is observed. Anderson and Lee[10] obtained recently a compound of tricalcium silicate containing 2.01% FeO, 0.76% Fe_2O_3, 1.20% MnO, 1.29% MgO, 0.18% TiO_2, and 0.20% Al_2O_3 of which the greater part was in solid solution, the remainder being present as discrete particles of impurities. There is also a possibility that small amounts of alkalies might be similarly dissolved. Such small amounts of solid solution do not appreciably affect the optical properties of it and hence may not be noticed in optical examination. But they might affect the reactivity of the material with water. More study will have to be carried out before any definite information can be obtained.

Belite and Felite have been known to be dicalcium silicate. They used to be considered as β and γ forms of dicalcium silicate. Recently, Sundius[11] has concluded after a re-examination of Törnebohm's slides and of modern clinkers that it is the α and not the β form of C_2S which is commonly present in the cement. So Belite is now considered

to be α C_2S and Felite to be β C_2S.

Celite occurs as one of the interstitial materials between the alite and belite crystals and hence its identification is not so easy. It is clearly a compound containing iron, and since C_4AF is shown by X-ray examination to be present in cements, it is probably that compound.

An examination of modern Portland cement[3] clinkers usually shows quite clearly three or four constituents: tricalcium silicate occurring as prismatic shaped crystals and showing only a greyish-white interference colour under crossed nicols if the section is of the normal thickness, about 0.025 m.m., dicalcium silicate occurring usually as more irregular and rounded grains and showing yellow to red interference colours; brown crystal grains and interstitial matter which are anistropic and pleochroic (yellow brown to a deep, and sometimes opaque, brown); an opaque brown interstitial material.

Brownmiller and Bogue[8] carried out X-ray analysis on twenty-eight clinkers and they identified C_3S and β C_2S in all of them. Their patterns were always the most prominent indicating that they were the most abundant constituents. They also identified one or more of the other compounds C_3A, C_4AF and MgO, but could not identify all of these in all the clinkers

examined.

So qualitatively the nature of the minerals in a cement as now settled is as follows:-

Alite	C_3S
Belite	α (β?) C_2S
Felite	βC_2S
Celite	C_4AF
Isotropic Matter	C_3A, C_5A_3, and glass.

Quantitative Examination of the Components.

Quantitative examination of the components of Portland cement has proved much more difficult. The components of Portland cement besides the principal oxides of lime, alumina, silica and ferric oxide are magnesia, alkalis, titania and a small amount of uncombined lime owing to the deficiencies in the burning of the cement. A very small amount of sulphur trioxide is also present, but it is usually assumed to be combined as calcium sulphate.

Recent researches of Brownmiller, Bogue[8] and others have shown that magnesia is present in the free condition at least in part but very little is known about the combination of the other oxides. It is usual to ignore them when considering the contents of the various compounds in Portland cement as their amount is rather very small. Neglecting these other oxides and assuming that magnesia is all uncombined and

that CaO, Al_2O_3, SiO_2 and Fe_2O_3 are combined to form the compounds $3CaO,SiO_2$; $2CaO.SiO_2$; $3CaO.Al_2O_3$ and $4CaO.Al_2O_3.Fe_2O_3$. Bogue[12] has worked out an arithmetical as well as a diagrammatical method to claculate the compound content of a cement from its analysis, after correcting the total lime content for that present as gypsum and that found to be uncombined by a free lime estimation.

Qualitative analysis of free lime present in cement clinker can be made by adding a few drops of White's reagent, (A solution of 5 gm. of phenol in 5 c.c. of nitrobenzene to which two drops of water are added) to a few milligrams of the cement placed on a microscopic slide and then examining the slide under crossed nicols with a microscope fitted with polarising and analysing nicols. If appreciable amounts of free lime[3] are present, long needles of high birefringence are observed within a few minutes of preparing the slide, at first radiating from the small particles in which free lime is present and gradually spreading over the slide. The test is quite sensitive and will detect less than 0.1% free lime in a cement.

The quantitative estimation of the free lime present in a Portland cement can be carried out by the alcohol-glycerol method of Lerch and Bogue.[13]

As lime is soluble in a mixture of alcohol-glycerol, cement is put in a flask containing the mixture. Free lime is dissolved in the mixture forming calcium glycerolate. A solution of 0.2 gm. phenolphathalein in 100 c.c. of alcohol is used as indicator. Calcium glycerolate while hot is titrated with a standard solution of ammonium acetate in absolute alcohol until the pink colour disappears. Then the amount of free lime is calculated by the usual method of calculating the strength of the solution in terms of grams of CaO per cubic centimetre. P. Schläpfer and Bukowski[14] and several others[15] have suggested other alternative methods of determining the quantity of the total free lime present in cement.

Having determined the quantity of free lime in the cement, the compound composition of a Portland cement can be calculated as follows by Bogue method. The SO_3 content is first considered and the equivalent amount of CaO required to form $CaSO_4$ calculated. This, and the free lime content are subtracted from the total lime content. The remaining lime and the compounds SiO_2, Al_2O_3 and Fe_2O_3 are now assumed to form the compounds C_4AF, C_3A, C_3S and C_2S. The amounts of CaO and Al_2O_3 required to combine with the Fe_2O_3 to form C_4AF are derived and the content of

this compound obtained. The remaining alumina is now calculated to C_3A. The CaO remaining after subtraction of the amounts used in forming the above two compounds is finally allotted to the silica and the contents of C_3S and C_2S calculated.

Bogue's calculation is based on the assumption that there is complete equilibrium in cement clinker. Recent evidence has definitely proved that cement is an equilibrium product[3] if by an equilibrium product we mean to infer that cement contains the compounds whose presence is predicted from phase equilibrium studies. It will be clear, however, that although the equilibrium compounds are present, the proportions of these may not represent precisely the equilibrium state. Thus, if burning is not sufficiently prolonged, a small amount of free lime may remain in the clinker, the proportion of C_3S is thereby lowered, and that of C_2S raised. Some 20% to 30% of the mix becomes liquid at the clinkering temperature. Lea and Parker[16] have shown that some reaction must take place between this liquid and the existing solid during cooling of the clinker if complete equilibrium is to be maintained in the clinker. As time available during cooling is short over the temperature range involved, no such reaction takes place. Hence the

conception[17] that Portland cement clinker is to be regarded as a material which closely approaches equilibrium at the clinkering temperature, but in which the equilibrium is "frozen" on cooling has gained much support. On this conception, the compound content of cements may differ somewhat from the values given by the Bogue calculation. This difference arises in the appearance of $5CaO.3Al_2O_3$ as one of the products of crystallization and a resultant change in the proportions of $3CaO.SiO_2$, $2CaO.SiO_2$, and $3CaO.Al_2O_3$. Lea has worked out formulae to calculate the compound content of cement on this basis. He has pointed out, however, another difficulty that still exists about the calculation of compound content. In the calculation of compound content, it is assumed that all the liquid formed in the cement clinker at the clinkering temperature crystallizes on cooling. Microscopic examination of cements suggests, however, that part of this liquid may sometimes fail to crystallize and form a glass. There is at present no means by which the extent of glass formation may be estimated quantitatively, and there is little knowledge of the relative properties of glass and crystal phases of the same mean composition. Unless their properties are the same and such evidence as is available suggests the contrary, the use of the compound contents,

calculated by either the four or the five compound methods for the analysis of data on cement properties must involve errors of uncertain magnitude.

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CHAPTER VII.

REACTION OF THE INDIVIDUAL COMPOUNDS OF PORTLAND CEMENT WITH WATER.

Chapter VII.

The compounds in Portland cement as known now are C_3S, αC_2S, βC_2S, C_3A, C_4AF, C_5A_3 and glass. Their individual reaction with water will now be considered.

Tricalcium silicate (C_3S).

Messrs. S. Kondo and T. Yamachi[1] studied the hydration of pure calcium silicates mixed with 1,3, 6, and 9 parts of water for periods up to 3 months under the microscope. They found that $3CaO.SiO_2$ begins to hydrate after about four hours and prism and hexagonal plates of $Ca(OH)_2$ form in four or five hours. Silicic acid gel begins to form in drops after 40 hours. They found no difference between the action of water and limewater. As the amount of water was reduced the crystal and gel formation was increased.

The hydration of this compound may therefore be represented as

$$3CaO.SiO_2 + Water \longrightarrow Ca(OH)_2 + xCaO.ySiO_2.aq.$$

This action does not stop when the solution is saturated with calcium hydroxide, but hydration continues and the further lime liberated by the reaction is deposited as crystals of calcium hydroxide. The hydrated silicate is quite stable in the presence of the saturated lime solution. If it is placed in water, it undergoes hydrolysis and liberates lime till the concentration of the lime solution

reaches saturation point to stabilise it. Continued extraction with water of the hydrated calcium silicate eventually leaves a solid composed only of hydrated silica, all the lime having been dissolved and removed whilst very little of the silica is dissolved.(2)

Tricalcium silicate must be very finely divided and the mix reground at intervals to expose fresh surfaces to the water, for obtaining complete hydration. If this is not done, a product is obtained showing unattached cores of tricalcium silicate surrounded by a layer of the hydrated silicate, which being very impervious to water, renders further attack slow. Complete hydration can be obtained by allowing $3CaO.SiO_2$ to harden 24 hours in water and then heating in an autoclave under steam pressure. The products obtained under steam pressure are not the same as formed by hydration at ordinary temperatures.(3)

Dicalcium Silicate (α or β) C_2S.

Messrs. Kondo and Yamachi(1) found that C_2S hydrates after about 40 hours with separation of silica acid gel. C_2S hydrates very slowly and even after some weeks, only a surface coating of an amorphous hydrated silicate may be found on the original crystals. The thickness of the coating is very small and goes on increasing slowly as the hydration proceeds with time. The process of hydration can be accelerated a little by extremely fine

grinding. The quantity of lime liberated during hydration is also much smaller than from C_3S.

γ C_2S hydrates still more slowly, but eventually a hydrated silicate and calcium hydroxide crystals are formed. The latter may not be observed if the solid is mixed with relatively large proportions of water.

Tricalcium Aluminate (C_3A).

C_3A[3] reacts very rapidly with water. It does not form any calcium hydroxide or hydrated alumina on hydration but forms hexagonal plate crystals within a few minutes which increase rapidly in size and amount. After a period of some weeks, or a lesser period at higher temperatures, formation of isometric form, $3CaO.\ Al_2O_3\ 6H_2O$, begins at the expense of the hexagonal plates. This isometric compound may crystallise in a number of different forms all belonging to the same crystal system.

The heat evolution, when tricalcium aluminate is mixed with water is so great that the plastic mass becomes almost dry. On regauging with water and subsequently storing in moist air or under water, the hydration products initially appear amorphous, but subsequently the hexagonal plate and needle crystals become visible. Complete hydration in such a mass is only reached slowly owing to the protection afforded

to the unhydrated cores by the hydrated material surrounding them. Hydration is found to be hastened by grinding the mix occasionally.

When hydration of tricalcium aluminate takes place under steam pressure or in water at high temperatures, a granular mass is formed, made up of very small crystals of the isometric or cubic form.

The hydration of C_3A is affected by the presence of gypsum. If C_3A is placed in a calcium sulphate solution on a microscopic slide, formation of the hexagonal plates and needles commences, but very soon other extremely fine needles of calcium sulphoaluminate begin to grow and steadily increase in length and thickness. Their chief characteristic is a negative elongation in contrast to the positive elongation of the hydrated aluminate needles.

Tetracalcium Aluminoferrite (C_4AF).

$4\ CaO.Al_2O_3.Fe_2O_3$ reacts rapidly with water like tricalcium aluminate and forms hexagonal plate crystals of hydrated tricalcium aluminate. These crystals change to isometric crystals of $3\ CaO.\ Al_2O_3.\ 6H_2O$ in course of time. No free lime is formed during hydration and it is probable therefore that hydrated monocalcium ferrite must be formed. This cannot be identified in crystal form and it is deposited as a light red product around the grains of C_4AF. A mass of C_4AF mixed with just

sufficient water to give a plastic mass shows excellent crystal formation within one day.

PentaCalcium trialuminate (C_5A_3).

$5CaO.3Al_2O_3$ reacts rapidly with excess water to form fine needles and plates of hydrated calcium aluminate together with amorphous material which probably contains hydrated alumina.

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CHAPTER VIII.

AUTOGENEOUS SHRINKAGE OF CEMENTS AND CONCRETES.

Chapter VIII.

Autogeneous Shrinkage.

By the term 'autogeneous shrinkage' is meant the change in volume that takes place in concrete due to the hydration of cement and which is quite distinct from the others, which are due to thermal causes or to loss of moisture to the air. The hydration of cement goes on for a considerable time. In fact,[1] so intense is the activity, so varied the movement, and so continuous the growth within a mass of concrete for many years after it is cast, that it may almost be compared to some lower form of organism. This type of shrinkage goes on until all the cement is hydrated. Over a long period of years it is the most important of all; but its accurate measurement is not easy on account of the difficulty of finding a point from which to measure it. (see page 61).

Neville and Jones[2] plotted time-volume change curve (Fig.XI) for Portland cement and found that Portland cement, on hydration, contracts continuously, but this is masked by incidental exothermal chemical reactions. These are surface reactions occurring in adsorption films. The free lime in this particular cement was measured and its heat of hydration accounted for only a small proportion of the total heat evolved. The investigators attribute the rise in temperature and the initial expansion to the heat of wetting

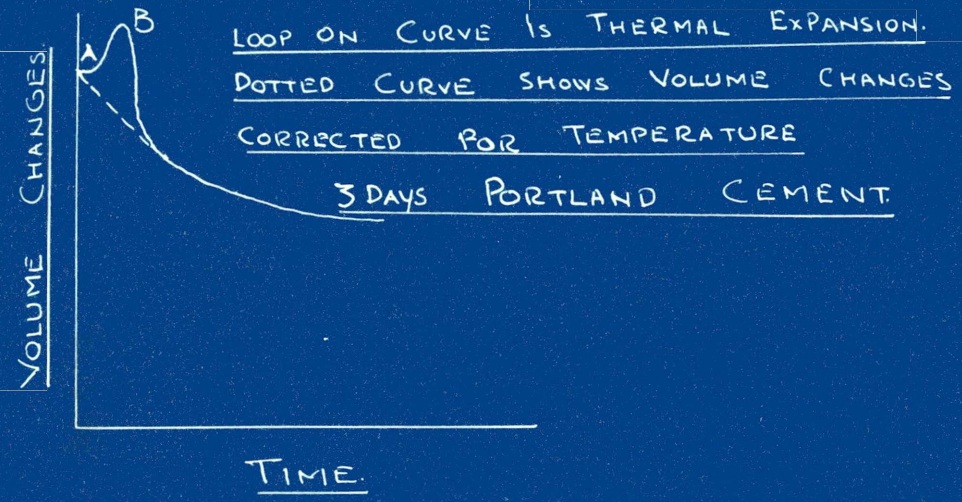


Fig. 11 — Hydration Changes In Portland Cement.

(Pouillet effect); heat of hydration and solution of free lime and gypsum; and the heat of hydrolysis of the otner constituents.

It is obvious that the shrinkage in a day in Fig. XI measured from point A would be very different from that measured from point B. There does not seem to be any record of experiments relating to autogeneous shrinkage only and its effect over a period of years, in un-controlled specimens is generally masked by induced shrinkage and expansion.- Fig. XI shows how the expansion effect of the heat of hydration of cement masks the continuous shrinkage of the gel. Neville and Jones[2] found that with gelatine there was no measurable rise of temperature, and the mixture contracted from the beginning. Correction for temperature is difficult, for as Freysinnet[3] has pointed out, it is impossible to measure the coefficient of thermal expansion of concrete owing to the movements induced by the changes entailed in moisture content.

Some knowledge of the phenomenon associated with the hardening of, and the products of, hydration of Portland cement would be essential to understand how this type of shrinkage takes place in cements.

Even the earliest authors[4] dealt with the theory

of setting, but their explanations were naturally of an extremely hypothetical character.

The scientific explanations put forward fall mainly into two classes, the crystal theory and the gel theory. Two authors who have materially contributed to the solution of the problem involved are W. Michaëlis and H. Le Chatelier.

The crystal theory was first propounded by Le Chatelier[5]. He explained the hardening of cement by the crystallisation of its constituents, just as $CaSO_4$, on hydration was supposed to become a 'brush heap' of crystal needles which interlace and hold each other together, so, according to the crystal theory the particles of aggregate and concrete in sand are held together in position by the surrounding mass of interwoven crystals. Microscopic examination under crossed nicols of cement grains when dissolved in an excess of water reveals the presence of crystals of calcium hydroxide, calcium aluminate, calcium hydrosilicate, and calcium sulphoaluminate, and some amorphous calcium hydrosilicate which has not yet crystallised out, by the addition of dyes which are selectively absorbed by lime, silica and alumina. Keiserman[6] has described a series of suitable stains. This test was held as sufficient proof to demonstrate the validity of the

"crystal" theory by the early authors. But later it was realised that the conditions of test were quite different from those found in the actual use of cement. The amount of water usually used is much smaller and the reaction of cement with the proportion usually added in making concrete would be quite different from that found with an excess of water of a hundred fold. There was no justification whatsoever for assuming it to be otherwise. For one thing there would not be enough water for the solution and crystallisation of large quantities of calcium hydroxide. Also cement pats, up to thirty years old, when examined microscopically, showed very little trace of crystallisation and the "crystal" theory began to lose most of its supporters.

The second theory, which was first propounded by W. Michaëlis (7) Snr., in 1893 and developed in later years, is the "colloidal" theory. According to this theory, concrete hardens by the formation of a colloidal gel, which like glue, grips the aggregate and the unhydrated particles of cement and a set cement is a colloidal gelatinous mass which hardens as it dries and shrinks.

The hardening of Portland cement (4) according to Michaëlis proceeds as follows:- The reaction of water with the cement produces hydrated compounds in

solution which, owing to their insoluble nature, become highly supersaturated. To quote Michaelis' own words: "After the decomposing and dissolving influence of the water upon the freshly gauged cement has lasted for some time, a point is very soon reached at which, suddenly, the supersaturated solution surrounding the cement grains coagulates. This is the point of time when the water disappears on cement pats and when the setting cement attains a dull surface, briefly the time when the setting proper has taken place". The gel layer forms around the cement grains, causing the swelling which can be observed in a cement grain placed in water. The gelatinous mass was supposed to consist mainly of a hydrated calcium silicate with some aluminate, and to contain distributed in it crystals of calcium hydroxide and hydrated calcium aluminate and sulphoaluminate. Hardening was due to the gradual elimination of the water from the gel; this process was considered to be assisted by the formation of the crystalline calcium hydroxide and aluminate compounds and by the withdrawal of water from the gel layers to hydrate the inner unhydrated core of the grains. This "inner suction" as Michaelis termed it, was used to explain the hardening of cements under water. While the

general view was expressed by Michaelis that a large part of the hydration products of cement forms a colloidal or amorphous mass seems unquestionable and has received much support by the recent researches of Kuhl, Bates and others, some of the details with which the theory was adorned cannot now be sustained.

The question whether the products of hydration of cement are to be regarded as crystalline or colloidal may appear at first sight to be purely academic, but upon a proper understanding of such questions depends the solution of such complex problems as shrinkage.

The majority of modern opinion seems to favour some variation of the gel theory. So before actually considering the hydration and setting of Portland cement in detail, it would be necessary to understand the meaning of the various terms, colloidal solutions, gels, adsorption, etc., as frequent use would be made of them later. Lynam[1] has grouped together in his book most of the properties of gels, etc. and they are reproduced from it.

A colloidal solution has been defined as a suspension in a liquid medium, of fine particles ranging in size from microscopic to molecular. These suspended particles may either be homogeneous -

liquid or solid - or solutions of a small percentage of the liquid medium in an otherwise homogeneous complex; and it has been suggested that they may be groupings of smaller crystallised particles.(8) These particles are held by the equilibrium of a number of forces such as crystal forming tendencies, surface tension, and electrical attraction and repulsion. A colloidal solution is quite different from a true chemical solution. It is not possible to make chemical solutions of certain materials, but colloidal solutions are possible. As for example, it is quite impossible to make a true solution of gold in water; but it is quite possible to make a colloidal solution of gold in water by breaking down gold into infinitely small particles by means of an electric arc. To make a colloidal solution - generally spoken of as a sol - of any solid, it is necessary to reduce it to such a small size, and thereby so greatly increase the ratio of its surface area to its mass that the surface activities of the particles can overcome the effects of gravity which generally mask the existence of these surface activities. A recent example of this process is the manufacture of colloidal- coal-oil fuel. The oil does not dissolve the coal in the chemical sense; but the particles of coal are so reduced in size that they do not settle

out under the influence of gravity.

Weimann has shown that when insoluble substances are precipitated from excessively supersaturated solutions the product tends, at least initially to take a colloidal form. Thus when dilute solutions of barium chloride and sulphuric acid are mixed slowly, the resultant precipitate is finely crystalline barium sulphate. But if the strong solutions are rapidly mixed, a gelatinous precipitate is obtained. We may imagine that momentarily an enormously supersaturated solution of barium sulphate is formed and that this precipitates immediately as a gelatinous mass before any orientation of the molecules, such as typifies the crystal state, can occur.(4)

In certain conditions - the more common being concerned with temperature, evaporation, or the addition of an electrolyte - colloidal sols will stiffen and turn into gels such as glue or the ordinary dinner-table jelly. It seems probable that they(9) then tend to assume a definite structure - fibrous, cobweb, or honeycomb - this skeleton being caused by the formation of chains of oriented polar molecules. The gel(10) is a network of the solid phase, permeated by the liquid phase.

Its most striking characteristic is the great

amount of the liquid medium the gel can hold while in this comparatively rigid state. Much of this may be lost by evaporation, and 99% may be expelled by heavy pressure. In some cases, some of this liquid may be held as water of hydration or crystallisation, or may be dissolved in the solid phase; and it has been suggested(11) that the gel particles may in effect by sacks of semi-permeable membrane enclosing liquid under osmotic pressure. A great deal of liquid may be held by adsorption on the surfaces of the gel particles. This forms a solid or semi- solid layer round the particles of gel; but free liquid may condense in the "micropores" or relatively large spaces between the adsorption layers on neighbouring particles.

Adsorption(1) is a species of attraction between a gas or a liquid and the surface of a solid, which is illustrated for instance by the wetting of a stone by water. Its exact mechanism is a very obscure question; and the various theories which have been put forward to explain it involve highly technical consideration of the fundamental ~~construction~~ constitution of matter. The wetting of a stone by water is explained in this way. Air is attracted to the surface of the stone and in dry weather will be adsorbed on it. Water, if present, will also be attracted by the surface of the

stone; and the wetting of the stone by water is the result of a competition[10] for the surface of the stone between air and water, in which the water wins owing to its greater affinity for the surface of the stone. What exactly happens at the surface of the contact is not known. The mutual attraction might be caused by molecular forces which might be due to chemical valencies and electrical forces. These chemical and physical forces between atoms and molecules in contact cause the formation of chains of oriented molecules extending into the liquid.[12] As a result of this powerful attraction, the liquid is highly compressed at the contact surface; and surface films are really solid, not liquid.[13] As a result of this compression, there is always a loss of volume when a liquid is adsorbed. Mechanically, this results in the evolution of heat frequently spoken of as the "heat of wetting". There is evidence[14] that chemical reactions sometimes take place at the contact surface, and that loose compounds are formed there, though these break down when adsorption breaks down. Hence, when a liquid is in contact with a solid which adsorbs it, the contact surface of the liquid phase may have a different composition from the main body,[10] and that again may differ from the composition of the liquid

when adsorption was not active. Adsorption is not permanent if conditions change. It increases rapidly with falling temperature[10][15] and with a rise in temperature it decreases rapidly and probably finally breaks down altogether. An adsorbed liquid can be driven off by heavy pressure, and may be displaced by one which has a greater affinity for the solid surface, and changes in the structure of the solid, such as crystallisation, appear to lessen adsorption.[16]

It is therefore possible for a gel to hold water in three different ways. Firstly, water may be chemically held as water of hydration or crystallisation. Secondly, it may be held by adsorption as "colloidal water" and finally it may be free water in the micropores or in macropores and larger cracks.

There is a continuous diffusion of liquid through a gel; and by this means liquid is added to or removed from the gel as external conditions dictate, causing the gel to swell or shrink. A body of gel does not remain similar to itself during swelling and shrinkage, but suffers considerable deformations.[10] As has already been mentioned on page 15 in the case of a cylinder, diffusion is easier from the sharp edges than from the surfaces; and when the cylinder

shrinks, it first assumes the form of a barrel with convex ends. As drying progresses, the edges become less permeable, and the cylinder finally assumes the form of a single shell hyperboloid with concave ends. When wetted, it swells again but never recovers its first shape. The reason for this is not definitely known; but it is possible that some of the particles have changed from colloidal gel to a crystalline or semi- crystalline state; that in some cases definite chemical reactions may have taken place; or that further particles may have passed from colloidal suspension and formed a fresh network or skeleton of gel which restrains the first structure from returning to its former position.

Gels differ in their capacity for changing in volume with changes of moisture.

A gel shrinks in drying and swells on wetting; and, while so doing, it exerts very considerable pressure. Starch[15] will swell against a pressure of 2500 atmospheres, and gelatine will bend glass in drying - but the volume of gel is always less than the total of the free volumes of its constituents. Water of adsorption is always highly compressed, and White[17] concludes that the water in cement gel may be compressed to half its initial free volume.

As a gel loses water and shrinks, it hardens and increases in strength, its modulus of elasticity being approximately proportional to the square of the concentration of the colloid.[10][15] Elastic gels have stability of shape notwithstanding a high content of liquid, and perfect elasticity within narrow limits.[10] A ball of silica gel dropped 40 ft. on to a stone floor will rebound without permanent deformation[16]. On the other hand, this ball can be crumbled to pieces in the hand; and if kept under stress for a period it will flow. When a bar of gelatine was bent by Hatschek[10], the lines of stress were clearly apparent by polarised light. The load was kept on for five days; and when it was removed the bar still remained bent and the lines of stress were still visible with no apparent change in location or intensity. Lynam[1] thinks that the above two cases do not show plastic flow - sliding on crystallographic planes -, but that some of the liquid phase was expelled by pressure from the highly compressed fibres, and possibly transferred to those stressed in tension. Then some of the irreversible changes already mentioned took place and held the fibres in their strained position. In a similar manner, if the branch of a living tree is released after bending, it will return to its original position. If, however, it is kept bent for a long period and then freed from ~~strain~~ restraint, it will retain its bent

position, partly owing to a change in the fibres first existing, partly owing to the deposit of more and unstressed material confirming to the bent shape.

A gel[18] is impervious to other gels; but it allows electrolytic solutions to pass through. Two of these meeting, or a fall in the temperature of a saturated solution, may form a crystal in the micropores; and, as the crystal grows, it compresses the gel, expels some of its water, and hardens it. Gels, through adsorption, take up other gels in varying and irregular proportions; and the final product may be a mixture of several gels, minute crystals, and hardened gel. The effect of time[1] and temperature on a hardened gel is to induce a crystalline structure. This is generally fibrous or radial, and is called colloform, the name of metacolloid being applied to the pseudo-crystals. Those occurring naturally as minerals are often described as mammillary, botroydol or reniform. In contradistinction to a crystal, a metacolloid will not necessarily have a definite chemical composition, though its composition may be approximately constant. Quartz and Opal are good examples of the two types. All hardened mineral gels contain more or less water held colloidally.

Gels can be divided into two types - elastic or

non rigid, and rigid gels. The non rigid gels such as gelatine swell on the addition of water and finally pass into a solution, while on drying the gel is reformed. The rigid gels, such as silica gels on the other hand do not show this reversible behaviour and once formed will not again disperse to a solution on the addition of water.

In gelatine dehydration and swelling seem to be reversible over a large range, though there may be a change of shape. In silica gel, on the other hand, the volume change is not all reversible. If it is dried far enough, pores[15] are developed which fill with air, and can be filled with a liquid other than water, but with no appreciable swelling. The reason for this is not clear; Lynam believes that possibly incipient crystallisation of the silica has lowered its adsorptive power, and thus broken some of the chains of attraction. The result is to make the substance more like a porous solid than a pure gel.

The gel formed on the hydration of cement is a rigid gel like silica gel according to the colloid theory and hence set cement is somewhat analogous to silica gel.

Silica gel can be precipitated by the addition of hydrochloric acid to sodium silicate solution. Silica gel after making is unstable and begins to

shrink to about an eighth of its size, expelling water from the mass, undergoing a process of synerisis and after which it expands or contracts depending on the surrounding humidity conditions but will never expand to anything approaching the dimensions when freshly made.(19) During synerisis(20) no volume change occurs in the whole system (gel + water) and the process consists simply in the expulsion of the free liquid enmeshed in the gel, the shrinkage of the gel reducing the available pore space. Silica gel(9) may hold up to 300 mols of water to one of silica. We may regard this spontaneous shrinkage(4) as a further stage in the coagulation which caused the formation of the gel. Synerisis comes to an apparent end when the water content of the gel is still very high, about 90%. This is much above the point where the reduction in vapour pressure characteristic of gels commences, and far above the true equilibrium water content. On drying the gel further, it shrinks until a point, known as opacity point, at which the previously clear gel begins to become opaque, is reached. The path to this opacity point is entirely irreversible and represents yet a further stage in the coagulation process. Beyond the opacity point the gel ceases to shrink appreciably with further removal of water and the

capillary pores empty while the vapour pressure falls. This further dehydration path beyond the opacity point is, except for a certain hysteresis effect, a reversible one and the water content - vapour pressure curve can be successively passed over in either direction. The gel which started as a soft pliable jelly is now a hard glass-like mass and retains this condition in water. Though it does not appear to have been shown experimentally, there seems little doubt that this hard mass must expand very slightly on wetting and contract again on drying. The final products of the hardening of silica gel over geological ages are flint and agate.

Another familiar example (4) of the shrinkage in a colloid is the drying of plastic clay. Once the clay has dried, it is practically impervious to water and takes up water again with very considerable difficulty.

The hydration of Portland cement with water is essentially the sum total of the reactions of the individual constituents mentioned in Chapter VII, modified perhaps by the formation of some hydrated tricalcium aluminate. It is possible, though there is no evidence of it, that a hydrated calcium aluminosilicate may be formed.(4)

When a cement is shaken with water, the alumina

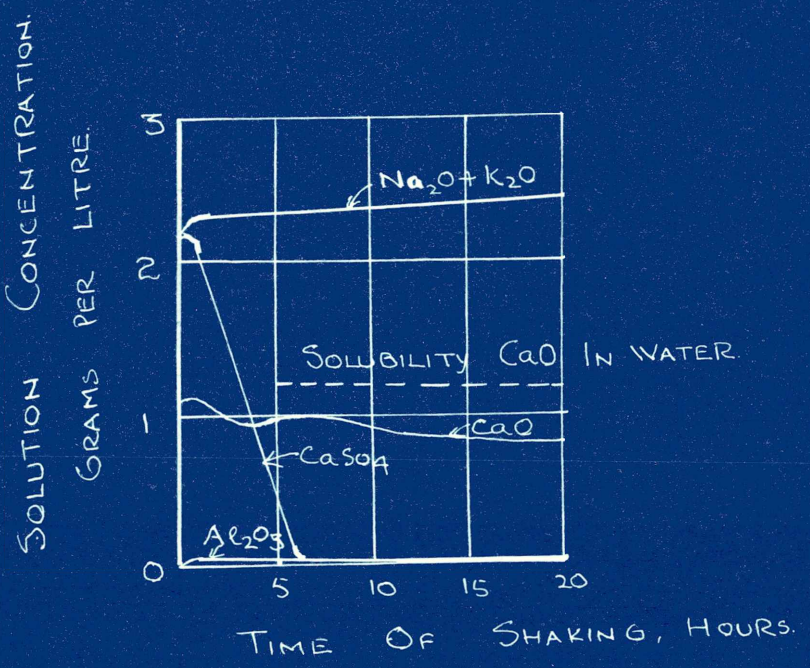


FIG-21

Concentration Of Solution Obtained By Shaking A Portland Cement With An Equal Weight Of Water.

compounds (the tricalcium aluminate and probably tetra-calciumaluminoferrite) are the first to hydrate as they react very rapidly with water. The gypsum which is added to cement to regulate the setting time, passes rapidly into solution and the alumina compounds crystallise out both as calcium aluminate and sulphoaluminate. The gypsum is thereby removed from the solution (See Fig.21). The presence of gypsum does not affect the hydration of calcium silicates at all but only affects the hydration of alumina compounds as mentioned on page (12.) The formation of the compounds, calcium aluminate and sulphoaluminate, cannot be observed from all cements. The alkalis[4] in Portland cement may perhaps have some influence on the hydration, though it is not exactly known how they affect it. Part of the alkalis (soda and potash) is present in alumina compounds which react very rapidly with water, liberating the alkalis into the gauging water as hydroxides. When large quantities of water are used in gauging, the concentration of the alkalis does not become appreciable to affect the solubility of lime. But when small quantities are used, as in the actual use of cement in concretes, the concentration of the alkalis becomes appreciable and reduces considerably the solubility of lime. Assarson[21] investigated

the change with time of the constituents of the solution obtained by shaking a Portland cement with its own weight of water and his results are shown in Fig.21. Lea[4] found that the diminution in the solubility of lime may be considerably more than that shown by Assarson and his figures are given in Table XXXI. He obtained them by shaking ground clinkers with their own weight of water.

TABLE XXXI.

Clinker	Concentration in Solution (Gram per litre)		
	CaO	Na_2O	K_2O
A	0.60	0.82	0.69
B	0.50	0.89	1.14
C	0.35	1.39	5.41

In less than a day, the formation of well developed calcium hydroxide crystals can be observed, together with the usual structureless hydrated silicate products.

Jesser[22] has shown the existence of the gelatinous material in quite an ingenious way. He found that when two elements made of the same metal are immersed in Portland cement or sorel cement mortar, a difference of potential is established between them, which rises to a maximum a few hours after gauging the mortar and then falls later. The metal must be capable of reacting with the liquid phase in the mortar.

He states that this phenomenon indicates that the setting and hardening of cement are of an electro-technical character. He carried out a number of experiments to elucidate this phenomenon, and came to the conclusion that it is caused by the difference of potential due to the existence of a colloid, the actual difference of potential occurring between the solid and the liquid phases.

Kühl[23] has studied the question of the composition of the structureless hydrated calcium silicates produced. He succeeded in separating by decantation the gelatinous products from the unreacted cement and, in some degree, from crystalline reaction products by shaking coarsely ground cement (88-120 μ) with ten times its weight of saturated calcium hydroxide solution. He then separated the gel from the solution by filtration. At first the crystalline hydration products remain in the gel layer, but as the crystals grow in size, they pass out of this layer into a residual fraction. This is true of the calcium hydroxide and calcium sulphoaluminate crystals, but the hydrated calcium aluminate mostly remains in the gel layer, which eventually consists of hydrated calcium aluminates and silicates and the hydrated monocalcium ferrite.

Microscopic methods have certain disadvantages in

the investigation of the setting and hardening of cement. The material cannot be examined at an early date and that thin sections are spoilt by atmospheric carbon dioxide before they can be mounted. Koyanagi[24] has developed a method by which a fraction from a cement, smaller than 10 μ. in diameter is separated by sedimentation in absolute alcohol and mixed with 40% water. The mixture is placed on a microscopic slide and a cover glass pressed on. In this way, sections 10 μ. and less in thickness can be obtained and protected from atmospheric action. He examined the sections thus prepared between crossed nicols. He found that after five to six hours, a few points of light are observed which in about twelve hours may be recognised as crystals; later they grow bigger to form hexagonal plates and prisms. After about three days, the whole field of view is filled with crystals. With high early strength cements, the formation of crystals is much quicker than with ordinary cements and they are much smaller and more numerous. Effect of the addition of calcium chloride was similar. Addition of a minute amount of sugar had the effect of stopping crystal formation and even after fourteen days they are small and poorly developed.

Staining tests have been found very useful in the microscopic identification of the reaction products of

cement. A good deal of care is necessary in using them. A series of stains have been described by Keisermann[6] of which the best are methylene blue in water or acetic acid solution, safranine in acid and alkaline solutions, anthrapurpurine and patent blue.

Anderegg and Hubbel[25] have measured the rate at which the hydration of Portland Cement and its pure components proceeds into the grains as shown in Table XXXII.

TABLE XXXII.

Depth of Hydration in Microns (0.001 m.m.) at 20°- 25°

	3 hours.	1 day.	3 days.	7 days.	28 days.	5 mnths.
$3CaO.Al_2O_3$	4.35	-	5.68	-	5.66	-
$3CaO.SiO_2$	1.68	2.25	-	4.32	4.44	-
$2CaO.SiO_2(\beta)$	-	0.28	-	0.62	0.83	3.5
Portland cement A	-	0.43	-	2.60	5.37	8.9
Portland cement B	-	0.47	-	1.71	3.54	6.1

From the above table, it will be seen that the tricalcium aluminate hydrates the most rapidly, the tricalcium silicate comes next, and the dicalcium silicate is much the slowest. The Portland cements show intermediate values.

Bogue and Lerch[26] measured the percentage of water retained after heating the hydrated components

of cement to 100° C. and their results are given in Table XXXIII.

TABLE XXXIII.

Per Cent Water retained after heating to 100° C.

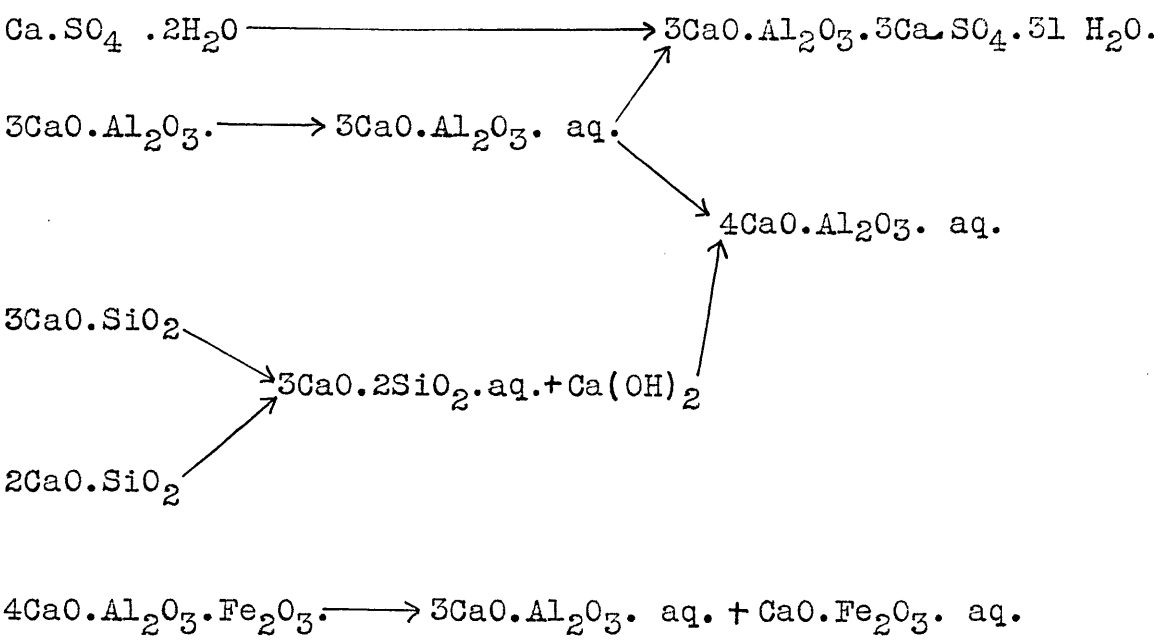
Compound	% of Gypsum added	1 day.	7 days	28 days	6 months	2 years
$3CaO.SiO_2$	0	8.6	12.0	14.6	15.0	18.6
"	5	11.7	12.9	15.0	15.1	18.9
$\beta 2CaO.SiO_2$	0.	0.8	1.7	3.4	10.8	12.1
"	5	1.2	1.8	3.8	8.7	11.6
$3CaO.Al_2O_3$	0	30.2	32.4	34.9	36.2	38.5
"	15	25.8	29.3	29.6	32.3	39.0
$4CaO.Al_2O_3.Fe_2O_3$	0	25.7	27.1	27.9	28.8	30.1
"	15	22.0	24.0	25.6	30.0	31.9

It will be seen from the above table that the hydration of tricalcium aluminate is almost complete within 24 hours, that of tricalcium silicate far advanced in seven days, while that of dicalcium silicate only becomes appreciable at longer ages. This is quite in agreement with what has been mentioned before.

Also it is seen that the presence of gypsum seems to accelerate somewhat the rate of hydration of tricalcium silicate. Bates and Klein[27] also found similarly. Anderegg[25] found that the hydration rate of Portland cement was slightly decreased by the presence of gypsum although the effect at long ages was negligible.

The reaction of Portland cement[4] with water may

according to our present knowledge, be therefore shown schematically as follows:-



It is doubtful to what extent any hydrated tetracalcium aluminate is formed. A calcium sulpho-ferrite may perhaps be formed. Alumina compounds yield crystalline hydrated aluminates on reaction with water. These crystalline aluminates are not usually observed in a cement gauged with sufficient water to form a plastic mass. Perhaps the presence of excess lime in the liquid medium reduces the solubility of the alumina compounds to a low value with the resultant effect of producing very small crystals. This, when combined with the obscuring effect of the hydrated calcium silicates present, seems sufficient to account for the failure to identify the hydrated aluminates in set cement. So of the various products of hydration, the calcium hydroxide becomes coarsely crystalline, the calcium sulphoaluminate finely crystalline, the hydrated calcium aluminate very finely crystalline or initially, amorphous; and the hydrated calcium silicate and ferrite amorphous or gelatinous. In short, hydrated cement contains both crystalline as well as gelatinous products.

Both the schools of thought, crystal as well as gel, have utilised this fact to demonstrate the truths of their theories. Exponents of crystal theory advocate that the setting of cement and its strength is entirely due to the formation of $Ca(OH)_2$ crystals and that set cement is essentially crystalline $Ca(OH)_2$, containing

some ralatively useless hardened silica gel.

Blount[28], so far as he commits himself, seems to favour the opinion that the strength of Portland cement after setting is due entirely to the crystallisation of $Ca(OH)_2$ and not at all to the hydration of the silicates or aluminates present.

Tippman[29] agrees with him that the initial strength of hydrated cement is due to $Ca(OH)_2$ crystals and the final products of hydration are $Ca(OH)_2$ crystals and the silica gel in which the former preponderate and are very important being the basis of the cementitious properties.of cement, and the cause of its hardening. He states that when $Ca(OH)_2$ is formed by hydrolysis it passes directly from the molecular solution to the crystalline form with a decrease of volume of 5.06%, whereas whem free lime is slaked, the hydroxide comes down in the amorphous form with an increase of volume of 1.56%. Cement has been known to contract on setting and so he deduces that the hydroxide can only be present in the crystalline form. He states that the presence of gypsum and silica gel tend to convert amorphous hydroxide to the crystalline form; and as these two substances are always present in cement, it would seem that even if amorphous hydroxide were formed, it would soon be converted to the crystalline form. He visualises the setting taking

place in some sort of way as follows. The water when mixed with cement dissolves the surface of a cement grain and forms an increasingly rich solution of lime and silica. When lime solution reaches a certain concentration, the silica is precipitated as gel and when it becomes fully saturated finally, hydroxide crystals are deposited. These crystals grow and expel water from the silica gel; and this water and the dilute solution of lime attack some more of the unhydrated cement and the hydration goes on in this fashion. He does not agree with the view that setting and hardening are two distinct phenomena but believes them to be consecutive stages in the hydration of cement, during which crystals are formed outside the gel and crypto-crystals in its micropores, giving - together with the shrinkage and hardening of the gel - the semblance of a change from the colloid to the crystalline condition. He specifically denies the existence of calcium hydro-silicate and states that in the examination of a set cement paste by oblique light under the microscope, he recognised a high proportion of calcium hydroxide crystals. So according to him, set cement is essentially crystalline $Ca(OH)_2$, containing some relatively useless hardened silica gel.

Koyanagi (24) states that the hardening of cement

is due to the crystallisation of calcium hydroxide as he found formation of crystals of calcium hydroxide during the hardening period only. He found no sign of any crystal formation during the setting period.

To quote a representative of the other school, Kuhl[30] states that set cement is essentially a hardened gel of calcium silicate and that to this the cementitious properties and strength of cement are due. He asserts that the crystals to be seen in set cement are tricalcium silicate and not $Ca(OH)_2$ as Tippman and others suggest. He could not find any $Ca(OH)_2$ crystals in set pastes two years old; some were visible in pastes twenty years old. Those which had been gauged with most water showed most hydroxide crystals, and he infers that excess water had decomposed some of the cement into free hydroxides, but that in practice, this could only occur to a minute and unimportant extent. He points out that the proportion of water usually added in making concrete would dissolve very little lime, and hence very little hydroxide could crystallise out. The colloid form of hydroxide is quite common, a great deal being initially present in lime paste. Crystals can be seen in lime paste after a lapse of time, but these are crystals of calcium carbonate, not of calcium hydroxide. He also found that the addition of gypsum and limewater to alumina gel forms calcium sulphoaluminate, which may be

crystalline; and that when silica gel is treated with lime-water it takes on a cobweb structure without the deposition of hydroxide crystals. He asserts that the most important constituent of set cement is calcium hydrosilicate; and points out that many calcium hydrosilicates occur in nature. He rejects absolutely the theory of a coarsely mechanical interweaving of crystals; and points out that though a colloidal material in the solid phase may have a finely crystalline structure its dimensions are colloidal.

Cement grains swell when water is first added to them. This swelling[31] can only be produced by crystal formation. Swelling is not necessarily a sign of gel formation. But a set Portland cement exhibits certain physical properties such as its volume change on wetting and drying and the relation between its vapour pressure and water content which are definitely characteristic of a rigid gel. So though hydrated cement contains certain crystalline products, its behaviour in setting seems best explained by the theory that its physical structure is based on an amorphous, or gel silicate mass. Majority of modern opinion seems to favour some variation of the gel theory. We may therefore assume that gel formation is the main factor in determining the physical properties of set Portland cement and that

both the "gel" theory and "crystal" theory may be true if allowance is made for the time factor. Only gel is present in the first few hours; only crystals and pseudo-crystals after a great lapse of time; and in the intervening period both are present, the gel continuously passing to metacolloid, and being replaced by fresh gel.

The gel mass which is formed probably remains unchanged in volume over a long period if kept wet, but on drying it undergoes a contraction and reduction in water content which are both irreversible. The cement gel may therefore be regarded as being initially formed in an unstable condition, occupying a greater volume and containing more water than in its stable state. There is a maximum amount of water which can be held by silica gel, and it is probable that there is a similar ratio for Portland cement gel and water. Abrams[32] by applying pressure to concrete while it was taking its set, expelled large quantities of water. Unfortunately he did not test the water for cement content or cementitious qualities, but as its loss resulted in an increase of 100% in the strength of the concrete, it is probable that it was free water. Specimens of concrete of all cements hermetically sealed and stored adiabetically for 87 days were all found by Schuman and Pisapia[33] to contain free water varying in amount from one-quarter to one-half of the original mixing water.

Thus free water may exist in a mass of concrete after gel formation has commenced either because there is more water than the gel can carry, or because it has been squeezed out of the gel. The gel[1] has an inherent tendency to shrink and give off some of the water it contains; this may be attributed to the mutual attraction of the gel miscelles (ionisable colloidal particles). In water no measurable contraction occurs, owing perhaps to the mechanical resistance of the mass to deformation, though it would in any case be offset by the effects of continued hydration of previously unattacked cement grains.

All authorities[30][29][17][34] agree that there is a continuous movement of the contained water in cement paste or concrete, though its velocity gradually decreases. It is adsorbed on the cement grain, dissolves the surface, and moves away bearing increments for the gel or saturated solutions which will readily deposit crystals; and is replaced by fresh supplies from the water-charged gel or the free water. The new colloid is adsorbed by the gel already formed. From the saturated solutions, the calcium sulphoaluminate crystallises out at once, and the calcium hydroxide then or later. The growth of these crystals in the micropores compresses the gel and expels some of its water, which serves to hydrate some more cement. This

process of hydration of cement and formation of gel slows down as the size of the cement particles decreases and the gel envelope gets denser, but it continues for an extremely long time. Grün[35] gauged a neat cement with water, allowed it to harden for three days, and then reground the set material. This was repeated a second time. The compressive strength (lbs.per sq.in.) developed by this cement in 1:3 sand mortar cubes was as follows:-

TABLE XXXIV.

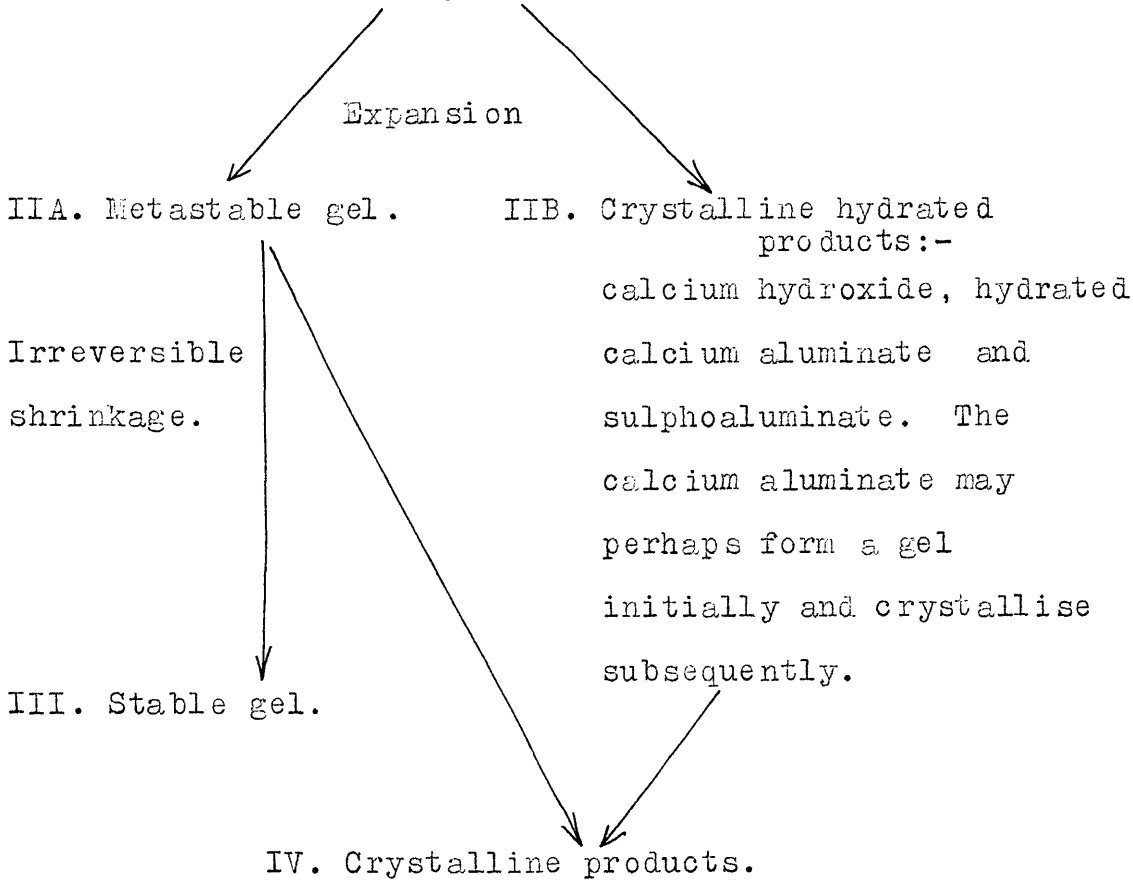
Days.	Fresh Cement.	After first hardening.	After second hardening.
3	3170	940	256
7	3940	1310	355
28	6000	1850	655

It is evident from the above table that even after a second gauging of cement with water some cores of unhydrated cement still remain. This is hardly surprising since it has been found that the hydration of cement grains proceeds to a depth of 6-9 M in five months (see Table XXXII, Anderegg & Hubbel, Page 144) and the subsequent increase must be very slow. Cement pats, 30 years old, have been ground and found to possess marked cementitious properties, proving the existence of much unhydrated cement.[30] In practice, with coarse grains (50% or more by weight of cement consists of particles of

diameter greater than 10 m and ranging up to 100 m.) frequently stuck together, and a sluggish change of water, the curve of hydration tends to become asymptotic. Lynam states that in fact, so intense is the activity, so varied the movement and so continuous the growth within a mass of concrete for many years after it is cast, that it may almost be compared to some lower form of organism.

On drying the set cement, the gel is changed into an apparently stable condition, for the expansion on subsequent wetting, and the quantity of water taken up, become reversible and are reproduced on successive wettings and dryings. A slow change may well occur with prolonged ageing and the individual silicate gel particles grow in size and an approach towards true crystal formation occurs.

The setting, hardening and ageing process can be set out diagrammatically, as follows:-(4)



The changes I - IIA and IIB are part of the setting process. It is probable that the gel initially formed undergoes a spontaneous shrinkage accompanied by syneresis (see page 138) as occurs with silica gel, but there is no definite evidence to show this. In any event, any such change is likely to be over within a few hours of the formation of the gel mass. It may alternatively be considered that the cement gel is formed directly in a condition comparable to that reached by silica gel after syneresis is complete. The change from stage IIA to III occurs when the set cement is

allowed to dry in air, but under water storage the stage II persists. A slow change in ageing in water from stage IIA to III or a direct change to stage IV, may perhaps occur, but we have no definite evidence of it. The final change from stage III to IV seems to be exceedingly slow, and never occurs in mortars or concretes under normal conditions.

As has already been mentioned, a set cement[4] on first drying undergoes an irreversible volume dimunition. This irreversible shrinkage takes place in two ways. The cement gel undergoes an inward shrinkage during which existing voids are increased in size and new ones formed, and contemporaneously, the whole structure suffers a small contraction in its outward dimensions. This contraction of the outward form of the mass is rather less than the inner shrinkage, thus accounting for the small increase in pore space which occurs. At the same time as a cement undergoes this irreversible shrinkage, a change occurs in the relation between its water content and vapour pressure. The vapour pressure over a set cement remains at the saturation value as long as free water is present, but when this is removed and the water surface recedes into the capillaries the water pressure drops.

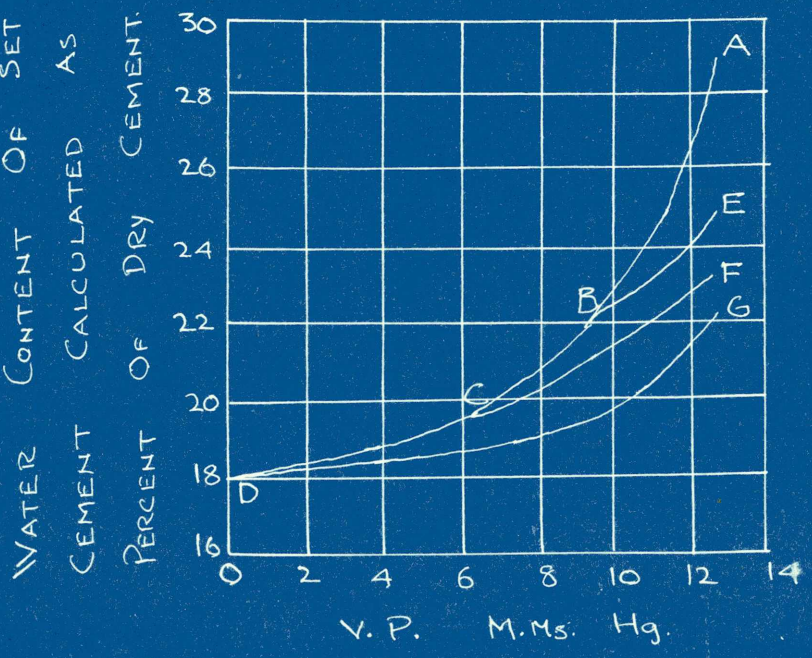


FIG-22

VAPOUR PRESSURE-WATER CONTENT CURVES FOR SET PORTLAND CEMENT.

Plotting the total water content of a set cement against the vapour pressure as the material is dried, Jesser[36] found that on drying for the first time a curve A B C D is obtained (Fig. 22). If after drying down to the point D, which corresponded to the condition when the material is stored over sulphuric acid, and only the water contained in the gel miscelles and in certain crystalline compounds remains, the set cement is allowed to absorb water again, the curve D G is obtained. On further successive wetting and drying the curve is retraced and it thus represents a reversible condition. Recent work by Brady[37] has suggested that this reversible curve actually contains a hysteris loop and that even after the first drying the successive paths are thus not entirely identical. The initial curve A D is irreversible and can never be retraced. If drying is stopped at B and the set cement allowed to absorb water, the curve B E is obtained. This curve is approximately reversible as long as the water content is kept between B and E. Once, however, the material has been dried further, say to C, it can never be regained, and a new curve, C F, is followed on rewetting. This curve is similarly only reversible as long as the material is never dried beyond the point C. Both B E and C F belong, therefore as the curve A B C D, to unstable states which, once passed, cannot be regained. This behaviour of set cement

is similar to that shown by silica gel, and it affords, therefore, evidence in favour of the theory that set cement is essentially a rigid gel.

If instead of plotting the water content as ordinate, the length of a specimen is plotted, a similar series of curves is obtained. The final curve D G then represents the reversible length change on wetting and drying, while A B C D represents the length change on the first drying. The irreversible shrinkage on first drying is given by an ordinate similar to A G. By drying only to intermediate points, such as B and C, and then re-wetting, portions only of the irreversible and reversible movements are obtained. This is illustrated by the data in Table XXXV., due to Jesser.[36]

TABLE XXXV.

Range of Vapour pressure at 15° over which cement is dried. Mm. in mercury.	12.7-9.5	12.7-6.4	12.7-0
Irreversible shrinkage (%)	0.137	0.162	0.186
Reversible shrinkage (%)	0.060	0.090	0.135

The irreversible shrinkages correspond to A E, A F and A G, and the reversible changes to the difference in the ordinate values of B and E, C and F, D and G. The total length change on the first complete drying is the sum of the reversible and

irreversible movements and, in the case cited, amounted to 0.321% compared with subsequent reversible change of 0.135%. Whilst numerical values such as these apply only to the particular specimen of neat cement on which they are measured, the general behaviour is typical of all mortars and concretes. The actual values are of course considerably lower for mortars and concretes than for neat cements.

The reversible volume changes in a set cement on wetting and drying may be explained in several ways. It may be attributed to the filling of the capillaries with water. White[17] found that a cement bar immersed in benzene increased 3.5% in weight, but did not alter in length. This has led some of the investigators to believe that the explanation of the reversible volume change lies somewhere else. They attribute it to a limited reversible hydration of the gel miscelles or submicroscopic particles. But it must be mentioned that benzene[1] cannot hydrate lime, nor be held in place of water of crystallisation; nor is it likely that it can be adsorbed on or dissolved in gel. Hence it may be inferred that it only entered the capillary channels and macropores. These considerations lead to the conclusion that water in the free state has no effect on the movement of concrete.

Movement is caused mainly by change of moisture content in the gel, with subsequent swelling or contraction, and secondarily by water being taken up in hydration and crystallisation. No exact division[38] of the water in a set cement into free water, capillary and gel water, and water combined in hydrated cement compounds seems possible. Giertz-Hedström [39] has attempted to divide the water in set cements into different groups according to the ease with which it can be removed by freezing or drying. He classified the contained water under three heads: (a) firmly held, chemically combined as in $Ca(OH)_2$; (b) loosely held, as in $CaSO_4, 2H_2O$, and colloidal water; (c) free or mechanically held. Specimens were stored for 28 days in air of 99% humidity; and typical results gave the following distribution of water.

As cast, 26.8%, After 28 days: (a) 14.5%; (b) 15.3%. Total 29.8%.

As cast 49.2%. After 28 days (a) 17.2%; (b) 25.7%; (c) 9.8%. Total 52%.

He found that water was held more firmly with age; especially if the water/cement ratio was low; that chemically combined water was low in young concrete, but increased with age; and that all concretes

took up water from damp air.

This shows how in a conservative system, in which water neither entered, nor left a mass of concrete, and neglecting thermal effects, the concrete would shrink continuously until all the cement was hydrated, all the water used up, or all movements of water rendered impossible.

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CHAPTER IX.

HEAT EVOLUTION IN THE SETTING OF CEMENT AND CONCRETE.

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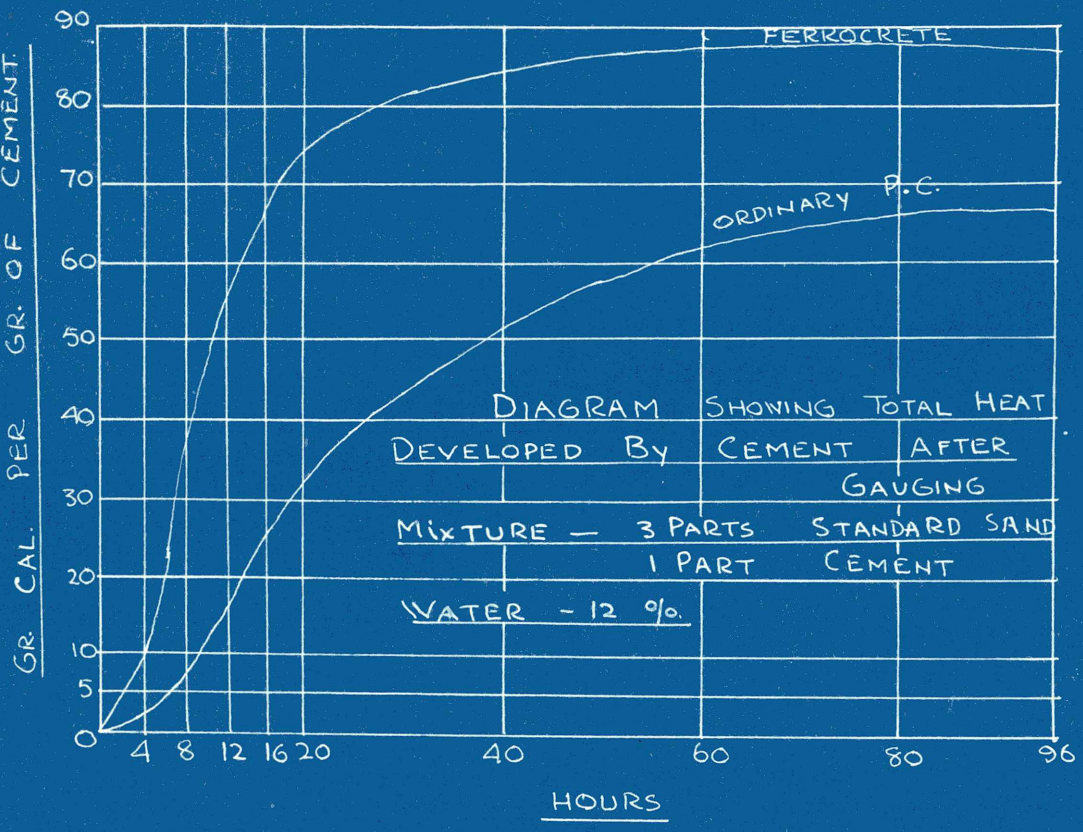

GR. CAL. PER GR. OF CEMENT.
90
80
70
60
50
40
30
20
10
5
0
4 8 12 16 20 40 60 80 96
HOURS
FERROCRETE
ORDINARY P.C.
DIAGRAM SHOWING TOTAL HEAT
DEVELOPED BY CEMENT AFTER
GAUGING
MIXTURE — 3 PARTS STANDARD SAND
1 PART CEMENT
WATER - 12 %.

FIG- 23

Chapter IX.

Heat Evolution in the setting of Cement.

The reaction of cement with water is exothermic and liberates a considerable amount of heat. Neville and Jones[1], using a dilatometer with a plastic container, observed the results of hydrating Portland cement. A mixture of 40 grams of Portland cement and 20 c.c. of water expanded and the temperature rose - the maximum rise of 2°C. being reached in 12 minutes. Then the temperature fell, and the mixture contracted, at first rapidly and then more slowly. The investigators attribute the rise in temperature and the initial expansion to the heat of wetting (Pouillet effect); heat of hydration and solution of free lime and gypsum; and the heat of hydrolysis of the other constituents.

Fig. 23 shows the heat generated[2] during setting by Rapid-hardening Portland cement and ordinary Portland cement. Mortars were gauged and put in thermoflasks of 1 pint capacity. The flasks were embedded in sawdust. Corrections were made to allow for the loss of heat by radiation from the flasks and for the heat absorbed by the rest of the apparatus. It is seen from the above figure that, after 12 hours, more than three times as much heat has been evolved by the rapid-hardening Portland cement and after 24 hours, the

NOTE :— THE INITIAL PORTION OF THE CURVE IS PLOTTED ON AN EXTENDED TIME SCALE.

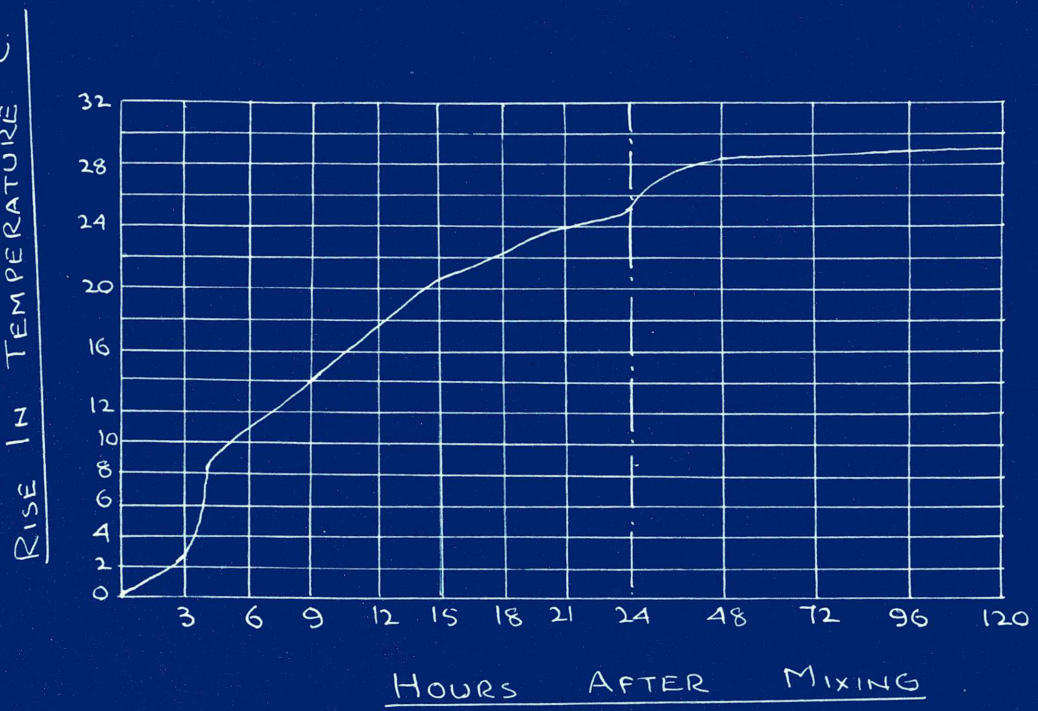


FIG.— 24

TEMPERATURE RISE IN 1:5 PORTLAND CEMENT CONCRETE MIX WITH 60 % MIXING WATER (BY WEIGHT).

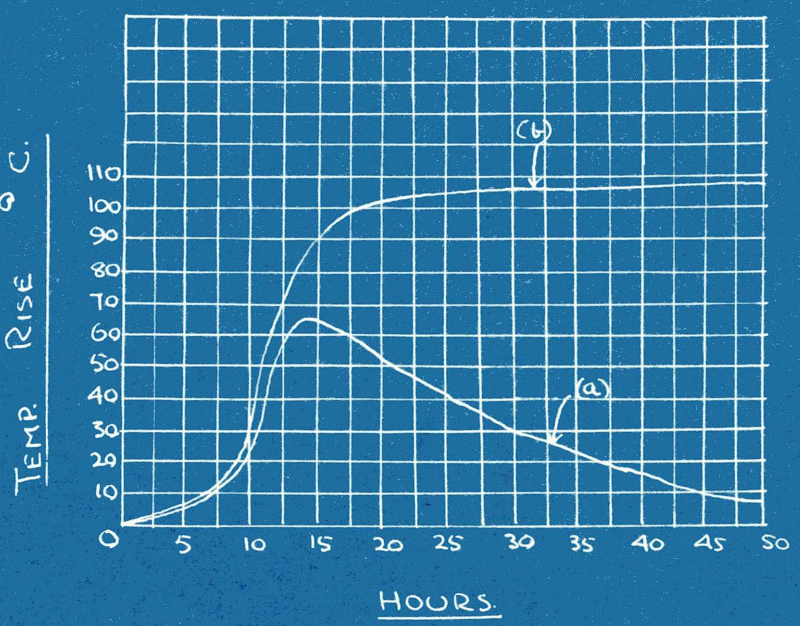


FIG. – 25

TEMPERATURE RISE CURVES

a) UNCORRECTED

b) CORRECTED.

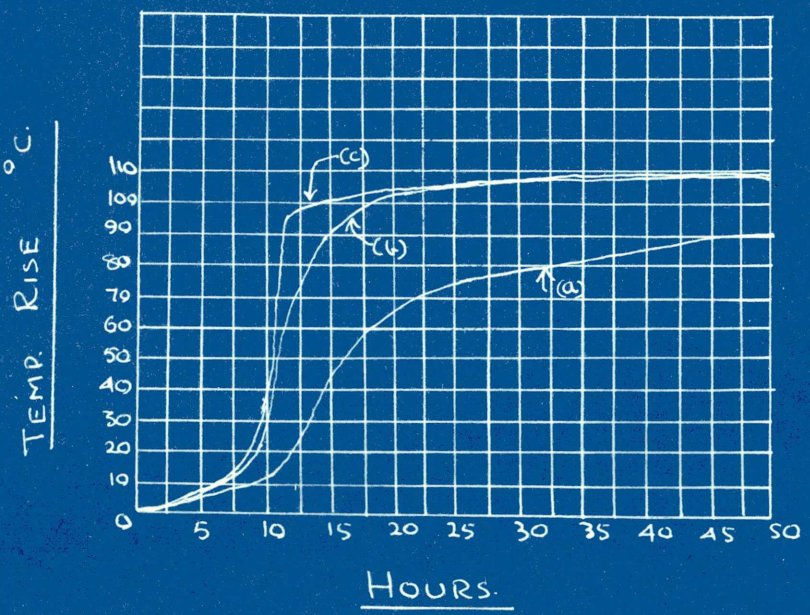


FIG. — 26

TEMPERATURE RISE CURVES.

a) ORDINARY PORTLAND CEMENT.

b) RAPID HARDENING PORTLAND CEMENT.

C) ALUMINOUS CEMENT.

rapid-hardening Portland cement is still 100% above the other. At the end of four days, rapid-hardening/Portland cement generated 30% more heat than ordinary Portland cement.

Fig. 24[3] shows the rise in temperature plotted against time of a sample of 1;5 (by weight) Portland cement gauged with 60% water for a period of 5 days. Davey found that in very large masses, the maximum temperature rise may not occur for many days after placing.

Dr. Faber[4] has given a curve (Fig.25) showing a rise of temperature in cement of about 100° C. 20 hours after hydration. Fig.25(a) gives the temperature rise during setting uncorrected for radiation losses. This falling off after the maximum occurs when the radiation loss exceeds the heat generated by setting. Fig.25(b) represents what the temperature rise would be with no radiation. This curve becomes horizontal when the setting is complete. Fig. 26 gives curves for ordinary Portland cement, rapid-hardening, and aluminous cements.

With concretes lower values would of course be obtained, depending on the mixture; but with a 1:2:4 mixture, temperature rise of about 40° C. is obtainable. In an eight feet thick retaining wall,

in the Bank of England rebuilding, Dr. Faber[4] measured a rise of 50°F. (from 50°F. to 100°F.) which occurred three days after placing. In this case the concrete was about 1:1.6:3.2, one face of the wall being against earth and the other inside centering.

Measurements made by Davey[5] on a large block of concrete, measuring 30 ft. by 15 ft. by 6 ft., placed in one operation showed that the temperature at the centre rose to 49° C.(120° F.) during a period of four and a half days, the air temperature during the same period averaging about 6°C. (43°F.), although at times dropping to zero.

In large works like dams, bridges, retaining walls, etc., the rise in temperature may be considerable and this rise may not only affect the properties of the material itself, but may also influence the distribution and intensity of the stresses throughout the mass. Temperatures in the interior of such large masses up to 50°C., above the original temperature of the concrete mass at the time of placing have been recorded, and found to persist for a prolonged period; a time as long as 2 years has been found to elapse before the temperature in the centre of the mass sinks to its ultimate value. It has been realised that the principal cause of the

serious cracking which has occurred in large concrete masses is the shrinkage which takes place as the mass cools from the high temperatures attained during setting and hardening. Davey and Fox[6] have collected data on many large structures and have found that there is a tendency to attain higher temperatures with modern than older ~~concretes~~ cements. Some examples taken from this compilation of the temperatures recorded in the interior of masses of concrete are shown in Table XXXVI.

TABLE XXXVI.

Temperature Rise in Concrete Masses.

Structure	Date of Construction	Proportions Cement: Aggregate.	Maximum Temperature Rise, °C.	Maximum Temperature reached, °C.
Boonton Dam, U.S.A.	1903-5	1:14	8	32
Lake Spaulding Dam Extension, U.S.A.	1916	1:9	24	33
Stevenson Creek Dam, U.S.A.	1926	1:5	19	47
Shute-a-caron Dam, Canada.	-	1:7	37	70
Ariel Dam, U.S.A.	1930-1	1:10	42	57
Canal Wall, Panama	-	1:9	13	54
Graving Dock, Rosyth, Scotland.	-	1:5	31	38
Foundation Wall, London, England.	1926	1:4.8	28	38
Retaining Wall, Dagenham, England.	1931	1:4	40	48
Caisson, Detroit, U.S.A.	1931	1:3.2	39	69

The maximum observed temperature rise is

0.083°C. per lb. of cement per cubic yard of concrete, a value equivalent to about 83 calories per grain of cement.

The minimum rise observed for points at a depth of not less than 2 ft.6 ins. from the surface of the concrete is 0.028°C. per lb. of cement per cubic yard of concrete.

The heat of hydration of cement can be determined either by the differential heat of solution method or calculated from the heat evolved from the compound content of the cement. The heat of solution method can be applied to any cement without any assumption but the values calculated from the composition of cements differ so widely in some cases from the observed values that the validity of the calculated value for cements seems very doubtful. The effect of differing fineness of grinding, burning conditions, and other factors, seems to be so considerable that the values calculated for one standard condition from the data at present available are inapplicable. A more complete knowledge of the corrections which need to be applied would perhaps render the calculated values more reliable.

A differential heat of solution method for the determination of the heat of hydration has been described by Woods and his co-workers(7) and has been

adopted in some recent American specifications for large dams[8]. The principle upon which this determination is based is Hess's law of constant heat summation - namely the change in heat content of a system in passing from one state to another is independent of the path whereby the passage is made. As applied to cement, this method requires a determination of (1) the heat of solution of the cement in its initial state (that is, unreacted); (2) the heats of solution of the cement after reaction with water for various lengths of time, and (3) the difference between the two quantities to obtain the value of the heat evolved in hardening.

The contribution of each percent of each compound to the total heat evolution has been calculated on the assumption that there exists a linear relationship between the compound composition and its heat evolution. The heat evolved[9] can be expressed as:-

Heat (calories per gram of cement) =

$$aw + b\,x + c\,y + d\,z$$

where a,b,c,d, represent the percentage content of CaO, SiO_2, Fe_2O_3, and AL_2O_3 respectively in the cement; the CaO content is corrected for the lime present as gypsum. w,x,y and z are the coefficients for 1% of each oxide in the cement and their values are as follows:-

TABLE XXXVII.

Oxide	Coeff-icient	3 days	7 days	28 days	90 days	180 days
CaO	w	+3.40	+3.92	+3.31	+3.28	+3.29
SiO_2	x	-5.79	-6.8	-4.93	-4.55	-4.65
Fe_2O_3	y	-3.2	-3.2	-3.1	-2.90	-2.6
Al_2O_3	z	-1.1	-1.5	-0.1	-0.40	+0.4

Schuman[18] and Pisapia could not derive any satisfactory equations showing the relation between composition and heat evolution of high-early strength cements.

Klein[10] found that there is little relation between the percentage of iron oxide in the cement and the heat evolved. There is a slight trend showing that with less iron oxide, the heat is also less. Until the heat developed by the cement is greater than 90 calories per gram., the alumina-silica ratio is constant, but for heats greater than this, the ratio increases rapidly with the heat developed. As the ratio of silica plus alumina plus iron oxide to lime plus magnesia decreases there is a constant increase in the amount of heat developed.

TABLE XXXVIII.

Authors.	Temp. of curing	Age days.	Heat evolution from cement pounds com-/ Calories per gram of compounds present in the cement.			
			C_3S	C_2S	C_3A	C_4AF
Woods, Steiner and Starke[11]	35°C.	3	98	20	170	29
		7	110	18	188	43
		28	114	44	202	48
		90	122	55	188	47
		180	121	53	218	73
Davis, Carlson, Troxell, & Kelly[12]	"Mass"(a) curing to 28 days, then 21° C.	7	110	20	240	0
		28	120	40	230	10
		90	130	60	210	10
		365	130	80	210	0
Lerch & Bogue[13]	-		Heat of Complete Hydration.			
			120	62	207	100

(a) "Mass curing defined as the thermal conditions within a large given mass concrete for the particular cement concerned, i.e. the thermal history corresponds to that in the concrete from the same cement when kept under approximately adiabatic conditions.

Table[14] XXXVIII presents condensed data by the investigators Woods and his co-workers, Davis and his co-workers and Lerch and his co-workers. The above table shows that the tricalcium aluminate has the largest heat evolution, tricalcium silicate comes next

in order, whilst for short ages the dicalcium silicate and the tetracalcium alumino-ferrite evolve relatively little heat. Due to the fact that the latter two compounds evolve very little heat, Woods, Steinour and Starke[15] have suggested the use of the function (% $3CaO.SiO_2$) + 2.1(% $3CaO.Al_2O_3$) for estimating the heat evolution of experimental cements on the basis of these two compounds only.

This has led to the manufacture of special cements with a low heat evolution in several countries, especially in America. Specifications[8] issued in America for cement for use in the Boulder dam limit the heat evolution to 65 and 75 calories per gram at seven and twenty-eight days. The physical properties[16] of the low heat cement used for Boulder dam are practically identical to the corresponding properties of standard Portland cement as will be seen from Table XXXIX.

TABLE XXXIX.

Physical Properties.

Type of Cement	% passing 200 mesh	Specific surface Sq. cm. per gm.	Specific gravity.	Initial set	Final set	Normal Consistency	Water content by wt.	1:2:9 Plastic mortar	1:5:2 max. aggregate ¼"	1:5:75 max. aggregate ½"	1:9:5 max. aggregate 6 in.
				h m	h m						
Standard Cement	93.9	1795	3.16	3-15	5-40	23.3	.54	1½	3	4⅞	2½
Low-heat cement	94.6	1950	3.16	2-35	5-05	22.6	.54	2	3	4¾	2¾

Chemical Composition.

Type of Cement.	Chemical Analysis.						Ignition Loss.	Compounds.			
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3		C_3S.	C_2S.	C_3A.	C_4AF.
Standard	21.8	6.2	2.9	63.8	2.6	1.7	1.1	40	32	12	8
Low-heat	23.8	5.2	4.6	60.5	2.8	1.9	1.2	18	54	6	14

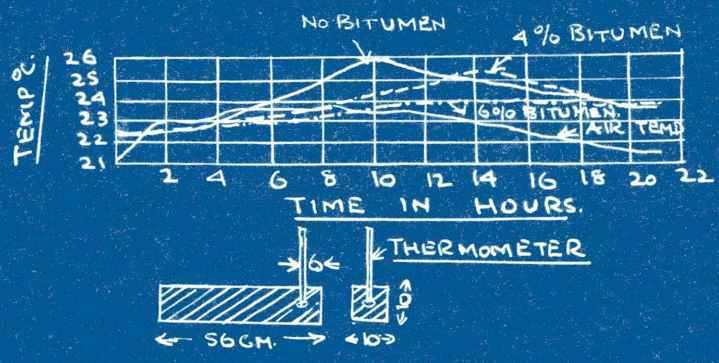
The low-heat cements are characterised by high percentage of dicalcium silicate (C_2S) and tetra-calcium alumino-ferrite (C_4AF), with relatively low percentage of tricalcium silicate (C_3S) and tricalcium aluminate (C_3A) as compared with relatively high C_3S and C_3A contents of standard cements.

It is claimed that low-heat cements result in considerably lower temperature rise and less heat of hydration than normal cements, yet the compressive

strength at 90 days are very nearly equal for both standard and mass curing.(16)

Although numerous studies have been made on methods of producing cements with low heats of hydration, very little data are available on the suitability of preparing low-heat cements by hydrating standard Portland cements with small proportions of water prior to the use of the cements. Experiments(17) carried out by the Bureau of Standards in the United States have shown that prehydration with 3 per cent. of water reduced the average heat of hydration of the standard Portland cements cured at 70° F. by 14, 12, and 6 percent. for the respective ages of 7 and 28 days and 1 year. Prehydration with 5 per cent. of water reduced the average heat of hydration of similar cements cured at the same temperature by 28, 27, and 16 per cent. respectively for the ages of 7 and 28 days and 1 year. Under the conditions of simulated adiabatic storage (150°F. after the first 24 hours) the same order of decrease in the heat of hydration was effected by the two prehydrations as was found at the 70° F. storage.

The prehydrations of the cements with high strength at an early age caused only about two-thirds the decrease in the average heat of hydration as was found for the same prehydration of standard Portland cements.



CEMENT + BITUMEN.

LEGEND.

—— PORTLAND CEMENT WITHOUT BITUMEN.

– – – PORTLAND CEMENT + 4% BITUMEN.

–·–·– PORTLAND CEMENT + 6% BITUMEN.

FIG. 27 — TEMPERATURES ON SETTING.

It appears, therefore, that considering only the heat of hydration values, a low-heat cement can be prepared by prehydrating a standard Portland cement with approximately 5% of water. The prehydration also very materially improved the resistance of the cement to sodium-sulphate solution as measured by the Merrian test.

Dr. Dyckerhoff[18] claims that the addition of bitumen to Portland Cement (by his special spraying process - see page 53) lowers the initial hardening energy. Consequently the setting process is not attended by so rapid or so excessive a development of heat as that which occurs with non-bituminous cement. Fig. 27 shows the temperature changes as the cement sets, the curves being due to the Test Dept. of the Stuttgart Engineering School.

Except for the compound (C_4AF), the data in Table XXXVIII are in rough agreement and the heat evolved at long ages approximates to that found for complete hydration. A close agreement cannot be expected since the rate of hydration and heat evolution of cements are markedly affected by changes in the curing temperature; the fineness of cements was also not identical in the two series. Davis[19] found that for average American Portland cements for each 100 sq.cm. increase in surface area per gram, the heat evolution increases by 4.5 calories per gram at

one day, 1.8 at 28 days, 1.3 at 90 days, and 0.7 at 1 year. An increased loss on ignition, due to aeration or other causes, decreases the heat evolution by 6 calories per gram of cement for each 1% increase in ignition loss.

Schuman and Pisapia[20] found that the total heat evolved at the end of 8 hours of adiabatic storage of concrete made with high-early strength cement, a c/w ratio of 1.5 and hermetically sealed ranged from 10 to 60 cal./gm. of cement; at the end of 24 hours from 60 to 100 cal./gm., and at the end of 87 days from 104 to 130 cal./gm. In general the higher the tricalcium silicate and tricalcium-aluminate content, the greater the amount of the heat developed.

After knowing the heat produced by the cement paste, it is possible to work out the temperature rise that could be expected in a concrete. Dr.Faber[4] has given the following formula:-

$$t = \frac{h\,c}{S_1 c + S_2 a + S_3 b + S_4 w + S_5 n}$$

where t = Rise of temperature;

h = Heat produced by the setting of unit weight of cement;

c = weight of cement;

S_1, S_2, S_3, S_4 = Specific heat of cement, sand, stone,

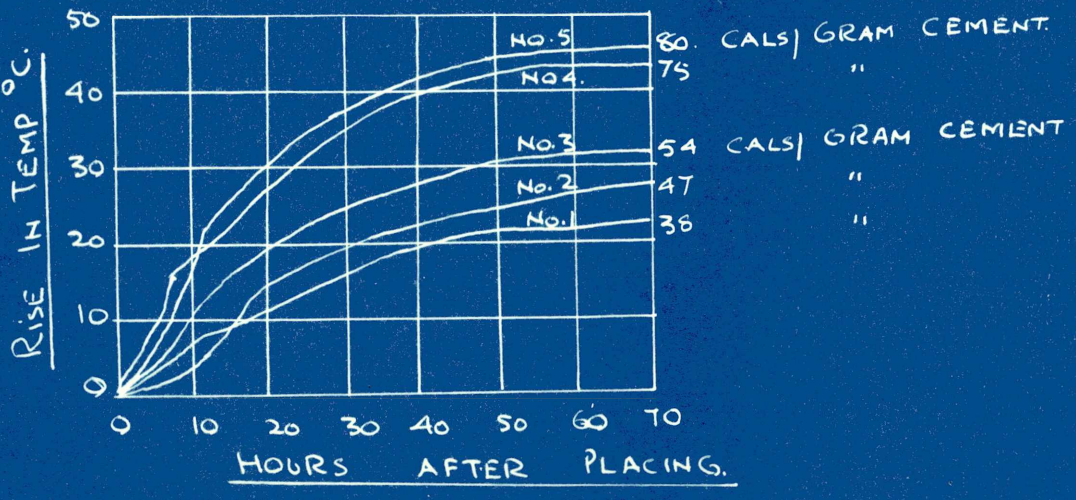


FIG 28— TEMP. RISE IN 1:2:4 CONCRETE (W/C = .60) CURED ADIABATICALLY. (DAVEY & FOX.).

water respectively.

a,b,w = weight of sand, stone, and water in the mixture respectively.

$S_s n$ = Specific heat and weight of enclosing vessel.

As the specific heat of cement is not quite definitely known yet, though for all practical purposes, it is taken as 0.20 calories per gram, the above formula gives a good idea of the rise in temperature to be expected.

Davey[5] has developed a very useful method for determining the maximum temperature which can be reached in the centre of a large mass of concrete. A small sample of concrete is made up and stored in an adiabatic calorimeter, i.e. a calorimeter from which no heat loss can occur. This condition is realised by surrounding the calorimeter by an outer bath, the temperature of which is caused to rise at exactly the same rate as that of the concrete. The heat generated in the concrete serves therefore only to raise the internal temperature and no outward heat loss occurs. The temperature-time curve thus obtained simulates closely the actual thermal history of the interior of a large concrete mass. Fig.28 shows the temperature rise under adiabetic conditions of 1:2:4 concretes. Nos. 1 and 2 are normal and Nos. 3,4,5 rapid-hardening Portland cements. It is seen that

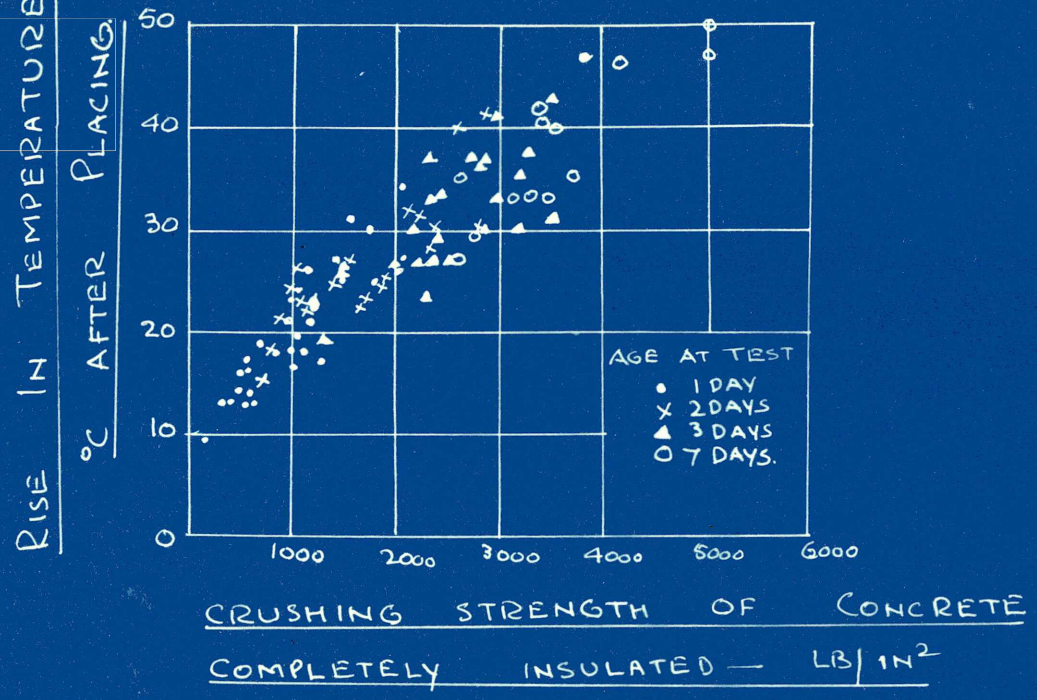


FIG. 29 — RELATION BETWEEN RISE IN TEMP. AND CRUSHING STRENGTH OF CONCRETE UNDER CONDITIONS OF COMPLETE INSULATION.

(1:2:4 MIX), 0.6 WATER-CEMENT RATIO, PROPORTIONS BY WT.

after three days, the curves are only rising slowly, indicating that the period of major heat evolution is over. Davey and Fox found that with leaner or richer mixes the temperature rise is lesser or greater corresponding to the change in proportions of the mix, the heat evolved in calories per gram of cement remaining the same.

In Fig.29[21] the rise in temperature of the concrete after placing is plotted against the crushing strength, when cured under completely insulated conditions to see if any relation between the two exists. The very big difference in the behaviour of the different batches of cement is apparent. Two samples of concrete, although both having a temperature rise of, say, 30°C. after placing, may have strengths as widely divergent as 1500 and 3500 lbs./sq.in. The graph also shows that a rise in temperature of about 10°C. occurs after placing with this particular mix of concrete (1:2:4:0.6 by weight) without any appreciable development of strength. Schuman and Pisapia[20] also came to the conclusion that no satisfactory equation could be derived showing the relation between heat evolution and strength of the cements.

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PART II.

CHAPTER X.

APPARATUS AND DETAILS OF TEST.

Chapter X.

Apparatus.

In the previous Chapters, it has been shown how in a conservative system, in which water neither entered nor left a mass of concrete, and neglecting thermal effects, the concrete would shrink continuously until all the cement was hydrated, all the water used up, or all movements of water rendered impossible. It has also been shown that practically no unequivocal data is available for the volume changes of cements during the early stages of hydration and particularly during the early plastic period before setting occurs due to the great difficulty of handling specimens and taking measurements while the cement is still in a plastic state.

Measurements of volume changes are complicated (1) by the relatively large early movements occurring while the concrete is in a plastic or semi-plastic condition, and (2) by the difficulty of recognising the point in the hardening period at which volume changes become of practical moment in order to make our initial measurements for reference.

R.E.Davis[1] has carried out a survey of testing apparatus and testing methods employed by 19 investigators to determine volume changes. The survey revealed a wide variety of concrete and mortar mixtures, sizes and shapes of specimens, kinds of moulds, periods and conditions of

curing, ages at first or base reading and methods of observing length changes. Further study of recent work on volume changes indicates an even greater variety of methods toθday.

Of fourteen research projects described by Gonnerman, initial readings were taken within the first hour in five projects, at 20 hour in three projects, at 24 hour in five projects, and at 48 hour in one project. Eleven investigators removed the moulds at the age of 1 day, one at 2 days, one at 3 days, and one at 7 days.

With few exceptions, (Dilatometers have been used by Neville and Jones, Larmour, Davey, Heameon, and others), investigators have determined volume changes in terms of length changes and this practice is followed herein. Length changes are of direct use to engineers.

Most of the investigators (except those who have used dilatometers) have suggested coating the interior surfaces of the moulds with oil, or paraffin to reduce the frictional restraint during the early period of hydration of the cement. Some have used moulds lined with waxed paper, greased paper, or soft rubber. It is not definitely known how far they serve the purpose they are used for.

In the first stages of this investigation a highly polished machine made brass mould was used and various linings as suggested above were tried to reduce the frictional restraint during the early hours of hydration.

None of them were, however, found to be satisfactory.

The best way to avoid this frictional restraint would be to enclose the specimen within the envelope of an elastic membrane (which has no strength of its own) which would allow the specimen to maintain its shape but not restrain its movements in any way; and then to float the specimen in a liquid with a greater specific gravity than concrete, so that it may be completely free to move in all directions while setting. If the measurements of length changes could be obtained under such conditions (provided the temperature and humidity of the room could be controlled) they would represent to some scale true volume changes of the specimen.

It was decided to float the specimen in mercury as being the only easily obtainable liquid heavier than cement which does not react with it. Another reason for selecting mercury was that the heat evolved by the cement while hydrating might be lost quickly, mercury being a good conductor, so that the measurements of autogeneous shrinkage may not be vitiated by the thermal effects to any great extent.

As regards the protective envelope various materials were tried. Rubber tubes from 2" in diameter to cycle tyres were tried, but they were all found to be thick and not perfectly straight. To avoid this, thin rubber sheets were obtained and made into cylindrical shapes by

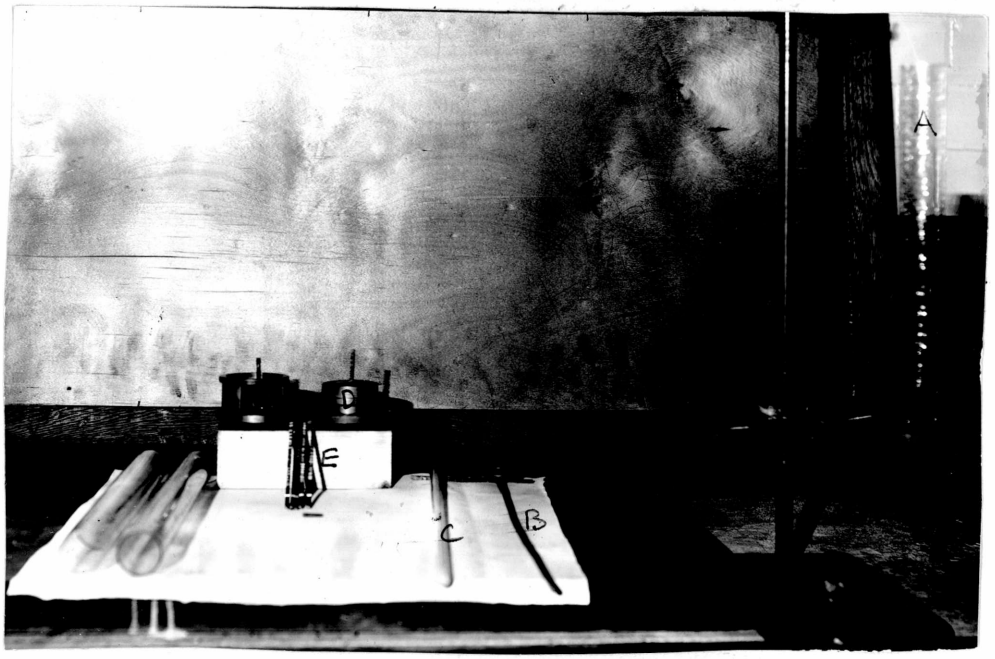


Plate 1



Plate 2.

Plates 1 & 2 — A — Cellophane Envelope ready for filling

B — Steel bar 1/8" for rodding

C — Glass rod with point rounded

D — Moulds for plugs

E — Invar bars.

rolling them on a roller and making the joint with a rubber emulsion. It was found very difficult to obtain a really straight length of uniform diameter in this way. Then accidentally two rubber tubes were obtained, one 1.2" in diameter seamless and another 1.7" in diameter with a seam. The 1.2" diameter one was preferred to the other, being thinner and seamless, due to the possible effect that the seam may have on the shape of the specimen.

It was decided to fill this tube with cement and fit it with plugs at the two ends which had bars of invar steel ⅛" square with notches in them to serve as gauge points.

The plugs were made with invar bars one day in advance in moulds shown in Plates 1 & 2. The invar bars were nicked to give sufficient grip in the cement. One of the projecting ends of the bar was inserted in the specimen. The plugs were made of the same mix with the same water-cement ratio as the specimen to prevent the bending of the specimen due to the difference in the densities of the two. It was realised that the densities would not be absolutely the same as the density of the hydrated and unhydrated cement are different, but it was thought that the difference would be too small to affect the specimen as a whole.

The next stage was filling the tube with cement. One of the plugs was inserted at one end of the tube and

the tube filled in with cement mixture from the other end. Rodding was done to prevent air holes. With considerable difficulty the process of filling the tube and rodding was carried out, keeping the previously inserted plug in position. Having succeeded in doing that, the other plug was inserted at the other end. It was found very difficult to achieve this every time, due to the rubber extending while filling and the plug at the other end slipping out.

Having made the specimen, it was floated in a trough containing mercury. The invar bars had 90° notches in which were inserted ¼" knife edges. Mirror extensometers were mounted on these knife edges which were read on scales by means of telescopes. The magnification obtained was 393.6 times. Knife edges were mounted at both the ends. It was hoped that by such an arrangement the specimen would be free to move longitudinally in either or both directions. But curiously enough, it was observed that one of the ends came to a standstill and while no movement was registered at that end, all the movement took place at the other end.

It is not known what caused this phenomenon, but perhaps a slight excess frictional resistance of one knife edge over the other was just enough to prevent movement from taking place. It was also found very difficult to mount both the knife edges at the same time.

Also it was found that in some cases, the rubber tube used to get stretched a little while filling. The specimen so made would be little bigger and the gauge points would be shifted apart a little more. This displacement of the gauge points was found sufficient to pull the plug out from one of the ends. Due to these difficulties, it was decided to fix one of the ends to simplify the process as well as to make it workable.

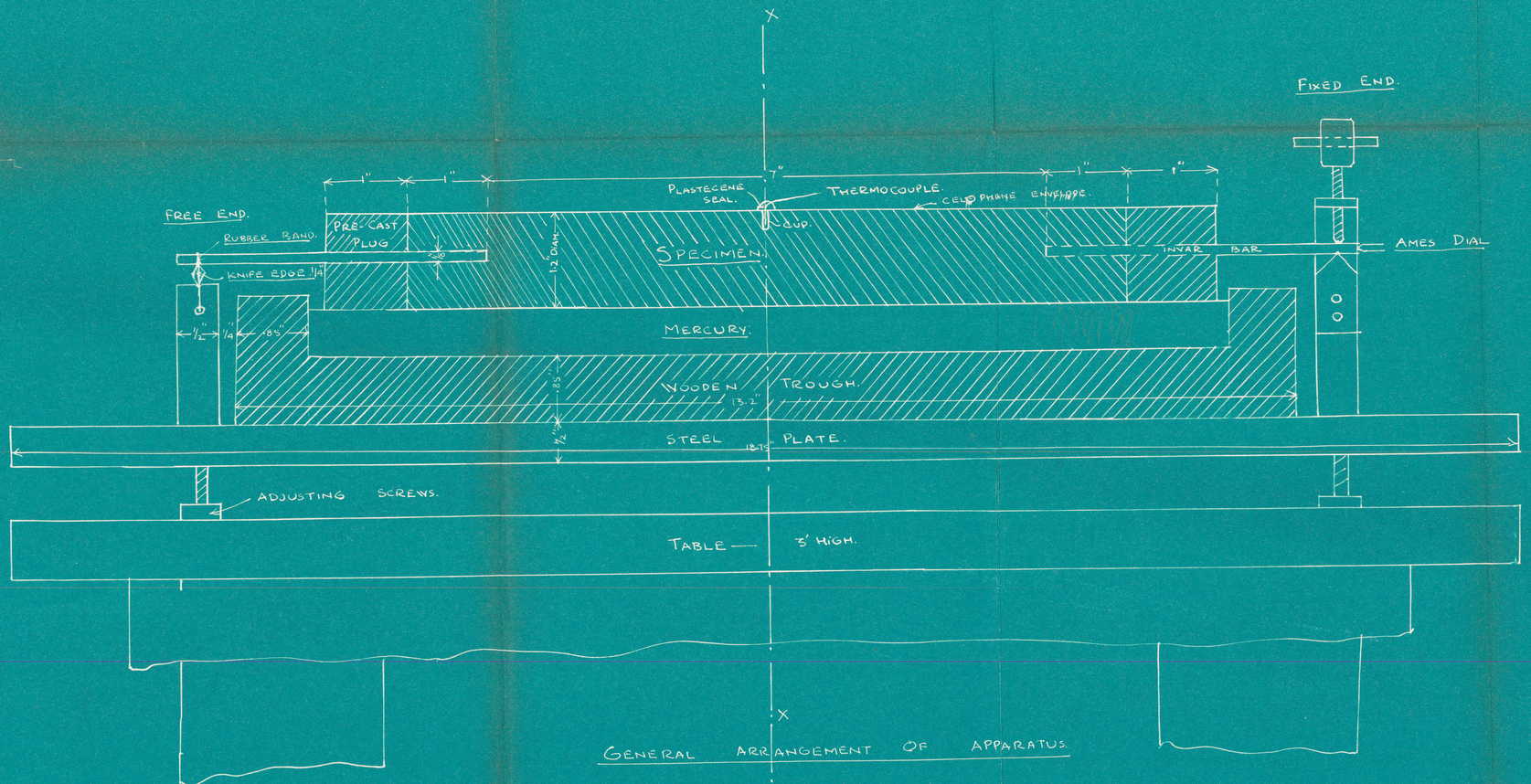
It was realised at that stage that the rubber tube might exert a certain hoop stress on the specimen while still plastic as it was bound to be extended a little while filling and rodding. The values of length changes, thus obtained, would be masked by this. So rubber tubing was given up and experiments were carried out as to the suitability of various other materials such as sausage skins, etc. The effect of the moisture was found to be considerable on the skins themselves and so they were given up. Next a cellophane was tried as a substitute. A standard variety of commercial cellophane, as well as one or two American varieties of it, were tried, but they had also to be abandoned due to the same reason. After that a moisture proof variety of cellophane 300 was obtained. This variety was found to satisfy all the requirements and

has been used throughout all the experiments carried out.

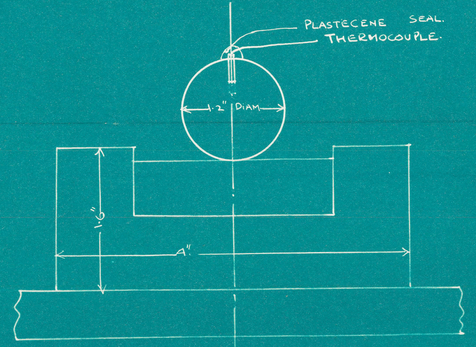
The moulds of the plugs, mercury trough, etc., having already been made, it was decided to keep the size of the specimen the same. A glass tube 1.2" external diameter was obtained and a sheet of cellophane wrapped round it, using a special moisture proof adhesive for the joint. This tube was extracted and was found to keep its cylindrical shape (Plates 1 & 2).

Various methods were tried of filling this tube with cement, such as inserting a glass tube inside and filling it with cement and then extracting the glass tube hoping that the cement would slide down the glass tube and fill the cellophane tube. Due to the diameter being small, it was found that the cement did not slide from the glass tube. In the end a method was devised of filling it and was used throughout the whole series of experiments.

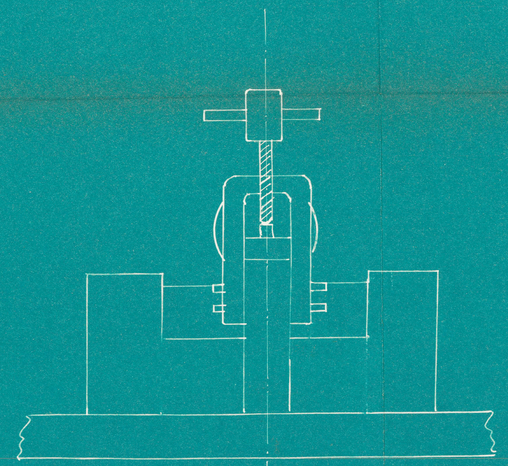
The method consisted in putting the pre-cast plug in one end and then clamping this end in a stand (Plates 1 & 2). The tube was filled slowly from the top with cement, holding the top with one hand to keep the tube vertical. Rodding was done first by a pointed steel bar ⅛" in diameter and then by a glass tube with a rounded end to prevent its breaking the sides of the cellophane tube. This method gave very good specimens,



GENERAL ARRANGEMENT OF APPARATUS.



X-SECTION AT XX



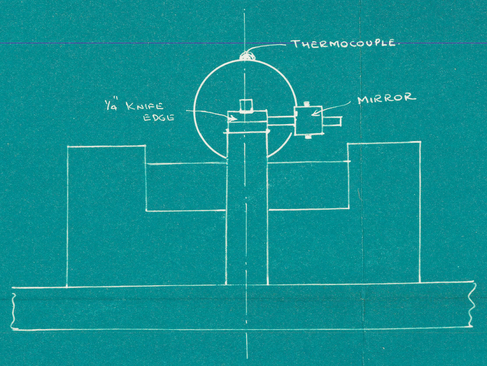


FIG.-30

SHOWING FULL SCALE GENERAL ARRANGEMENT OF APPARATUS.

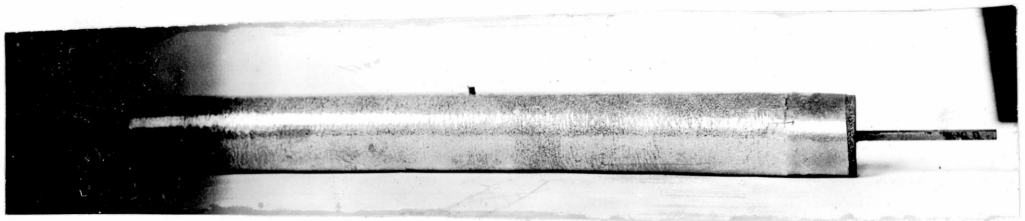


Plate 3 – Showing a Mortar Specimen with Cellophane Envelope



Plate 4 – Showing a Mortar Specimen without Cellophane envelope



Plate 7 – Some of the Specimens made

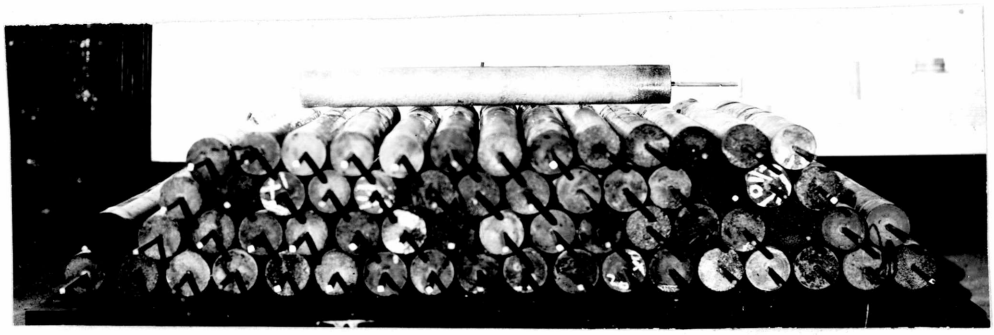


Plate 8 – Some of the Specimens made



Plate 5

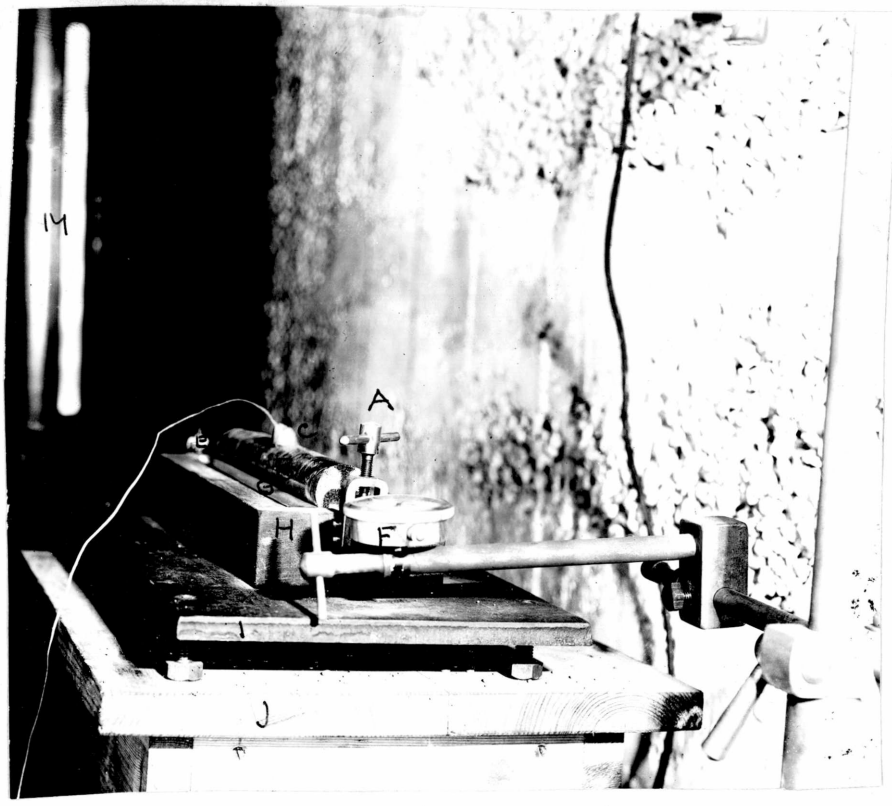


Plate 6

Plates 5 & 6 — Showing the general arrangement of the Apparatus

A — FIXED END
B — SPECIMEN WITH CELLOPHANE ENVELOPE
C — PLASTECENE SEAL.
D — THERMOCOUPLE
E — FREE END-MIRROR EXTENSO-METER
F — AMES DIAL.
G — MERCURY.
H = " TROUGH.
I = STEEL PLATE
J — TABLE.
K — WET & DRY BULB THERMOMETER.
L — THERMO FLASK.
M — SCALE IN DISTANCE

free from air holes and the percentage of tubes damaged while making was quite small. Plate 3 shows a mortar specimen after the test period and plate 4 shows the same specimen with the cellophane removed.

The tube was filled to about an inch from the top and then the top plug put in. The specimen was now dismounted from the stand and placed flat on a slate and the plugs were slightly pressed in to make them adhere to the plastic cement better.

After this, the specimen was mounted on the mercury trough, one of the ends being fixed as shown in Fig. 30. This is shown in Plates 5 & 6 as well. The end was fixed in such a way that no movement took place at that end. But as an extra precaution, an Ames dial recording up to 1/10,000 inch was fixed to record any movement that might take place. The free end carried a ¼" knife edge on which was mounted a mirror extensometer (Fig. 30, Plates 5 & 6).

The magnification obtained by this arrangement was 393.6 times. The length changes of the specimen rotated the knife edge which in turn moved the mirror. The movement of the knife edge was read on a scale by means of the reflection of the mirror. By this arrangement, readings up to 1/100,000 inch were obtained. Plates 7 & 8 show some of the specimens made and tested for length changes as described above.

It has already been mentioned that the reaction of cement with water is exothermic and a certain amount of heat is evolved with it. Dr. Faber's[2] curves have shown a rise of temperature in cement of 85° C., fifty hours after hydration. Assuming a coefficient of expansion of 0.000014 per °C. for cement, this would cause a linear expansion of 1200×10^{-6} in the cement, measured from the start of hydration, or an equal contraction, measured from the start of cooling. This is a deformation of very considerable magnitude, comparable to any recorded shrinkage; and equivalent to a stress of 2400 lbs./sq.in. in cement with $E = 2 \times 10^6$ or of 36000 lbs./sq.in. in steel with $E = 30 \times 10^6$. Jackson's[3] curves show a very brisk evolution of heat over a short space, dropping rapidly to a negligible rate. In practice, since Anderegg and Hubbel[4] have shown that the ordinary cement is not completely hydrated for a long time, the heat evolution must go on for years. Even if it only lasted for a short time, as a mass of cement radiates heat from its surface and as its coefficient of conductivity is only 0.904[5], it would take a long time for the centre in a big mass to sink to the temperature of the surface. Theoretically, it would take an infinite time. The rate of flow of heat is directly proportional to the difference in temperature - the temperature gradient, and as this decreases so does the flow. In concrete[6]

there are other variables to consider. The water and aggregate absorb heat and diminish the temperature rise, the ratio of surface to mass influences the rates of heat loss; the rate of hydration depends on the size and shape[4] of the cement particles, and may be greatly influenced by mixing and placing according as these approach more or less closely to the ideal of spacing the particles separately and symmetrically in the mixing water; the specific heat[7] of concrete is only 0.220 and the evaporation of warm water from the concrete and its replacement by cold may exercise a dominating influence over the rate of loss of heat. There are very little experimental data on these questions. So it was decided to keep a record of the temperature rise within the specimen though most of the heat evolved was expected to be lost very quickly for the reasons already mentioned.

A record of the temperature changes was kept by introducing a thermocouple inside the specimen as being the most convenient and accurate method for the purpose. The metals used were Eureka and Copper (S.W.G. 30) and the hot and cold junctions were formed by silver soldering the ends of the wires together. The cold junction was kept in ice in a thermoflask. The thermocouple was connected to a Cambridge Instrument Co's galvanometer. The deflections of the galvanometer were read on a direct reading scale.

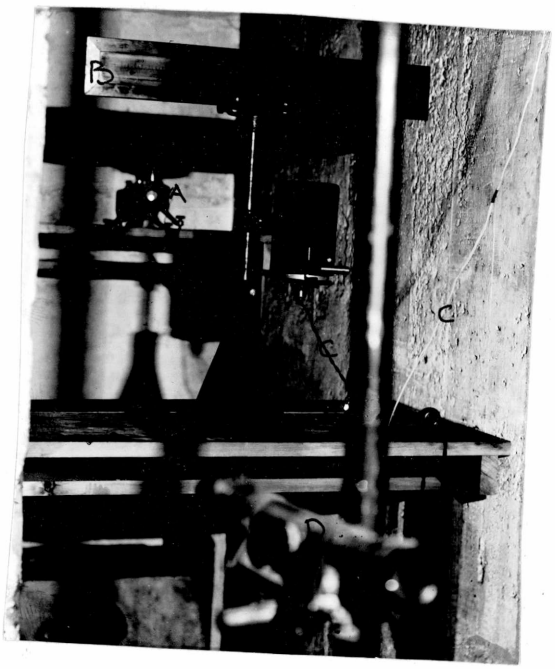


Plate. 9

Plates 9 & 10. — Showing the arrangement for Temp reading by a direct scale Galvanometer.



Plate 10

A — GALVANOMETER
B — SCALE
C - WIRING
D — TELESCOPE
E - REFLECTOR

The calibration of the scale is given in Appendix C, page and gave 4.3625 divisions = 1°C. The whole arrangement is shown in Plates 9 and 10.

The same hot junction had to be used for all the specimens as otherwise different lengths of wire would have changed the constants and meant a new calibration for each specimen. This gave considerable trouble as the hot junction could not be inserted straight in the specimen whilst the cement was plastic and then taken out when the cement has set without damaging it. Various methods were tried and all of them gave very erratic results. Plates 7 & 8 show one of the attempts of putting the thermocouple wire in the pre-cast plug and putting the wire with the plug in the specimen. This did not work as probably the insulation was damaged either due to moisture or to temping while filling the plug and thus establishing a contact with the invar bar. In the end, the following method was found successful and was used throughout.
A small piece of copper tube was soldered at one end and formed into a cup. This cup was inserted in the specimen by piercing a small hole on the top of the specimen by a pin. The hot junction of the thermocouple was slightly bent and introduced in this cup thus establishing a good contact with the cup. The top of the cup was covered up by plasticene to prevent any loss due to radiation, etc. (Fig.30).,(Plate 6).

There was no means of controlling the temperature and humidity in the laboratory where the work was carried out, So the work was done in a small tunnel 3' wide and 15' long which was screened off at one end, so that the variations in temperature and humidity were small. Also the specimen being protected by the cellophane cover, it was thought that it would be free from the effect of changes in temperature and humidity of the surrounding air. A record of these changes was kept by a wet and dry bulb thermometer (Plate 5).

The reproducibility of the points obtained for the various curves (Figs. 31 to 91) justifies the above assumption. Tables 40, 41, 42, & 43 show the variations in the temperature and humidity for the various specimens and it is seen that they show a fairly constant level for the duration of a full test period.

Details of Test.

Throughout the whole series of the experiments, the temperature of mixing water was kept at 15° C.

Four series were made in all. The first series consisted of 21 specimens, all made of Blue Circle Neat Cement. The first eleven of these specimens were made with 21.5% water-cement ratio by weight. This percentage of water was obtained according to the Vicat-needle test laid down by the British Standards Specification No.12 (1931) for the

normal consistency of cement. Specimens Nos. 12 to 17 were made with 23.5% water-cement ratio, 2% more than the normal consistency of cement; and Specimens Nos. 18 to 21 were made with 20.5% of water-cement ratio, 1% less than the normal consistency of cement. It was decided to try specimens with 2% more as well as 2% less than the normal consistency of cement. Accordingly, specimens were tried with 19.5% of water. The mixture was found to be too dry. There was considerable difficulty in making the specimens and the results obtained from them were not found to be consistent, mainly due to the difficulty of obtaining a workable mix to make good specimens from that percentage of water. Hence this percentage was abandoned and 20.5% was used instead.

Series No. 2 consisted of 1:3 mortar. The mortars were made of Blue Circle Cement with Standard sand and B.S. Specifications were followed for the water-cement ratio. Specimens Nos. 1 to 5 were made with 7.9% of water; specimens Nos. 6 to 11 were made with 9.9% water, 2% more than that laid down in B.S. Specifications, and specimens Nos. 12 to 15 were made with 5.9% water, 2% less.

Series No. 3 consisted of Ferrocrete Neat Cement specimens. Specimens Nos. 1 to 4 were made with 23.9% of water. This percentage was obtained according to the Vicat-needle test laid down for the normal consistency of cement (B.S.S. No.12, 1931). Specimens Nos. 5 to 8 were made

with 25.9% of water, 2% more than the normal consistency; and specimens Nos. 9 to 12 were made with 21.9% of water, 2% less than the normal consistency of cement.

Series No. 4 consisted of Ferrocrete-Cement - Standard sand 1:3 mortars. Specimens Nos. 1 to 5 were made with 8.5% water-cement ratio by weight according to B.S.S. No. 12 (1931). Specimens Nos. 6 to 10 were made with 10.5 % water-cement ratio, 2% more; and specimens Nos. 11 to 14 were made with 6.5% water-cement ratio, 2% less.

For all neat cement specimens, 600 grams of cement were used and for all mortar specimens 200 grams of cement and 600 grams of Standard sand were used.

The time was noted from wetting the cement. Six minutes were spent in mixing the cement or mortar with water and 15 minutes in making the specimen, i.e. filling the cellophane tube, ramming, etc. About 4 to 5 minutes were spent in mounting the specimen, fixing the thermo-couple and putting the plasticene seal over it, mounting the knife edge and mirror extensometer, adjusting the telescope, focussing it, and removing parallex, etc. So in all about 25 to 26 minutes were spent in making all these preliminary arrangements preparatory to taking readings. So it was decided to take readings after 30 minutes after putting water in the cement or mortar to standardize the process. So all the readings are taken

with 30 minutes reading as a datum. After reading the telescope for the mirror deflection due to the length change of the specimen, the thermocouple readings were taken immediately to note the temperature changes;wet and dry bulb thermometer readings were recorded every hour to note the temperature and humidity changes in the surrounding air. No movement was expected at the fixed end. Still readings of the Ames Dial were taken every hour as an extra precaution to make sure that no movement whatsoever due to any causes such as slipping, etc.,was taking place at that end. The telescope and thermocouple readings were taken every ten minutes. In most of the specimens, readings were taken every five minutes for the first hour when movement was rather brisk. Readings were taken up to about 400 minutes. The specimen was left in the same position overnight and a reading taken next morning of the movement overnight.

References.

(1) R.E. Davis - Methods of Test for determining volume changes in concrete. - Proc.Am. Soc. of Test. Mat., Part 1 (1935).

(2) Dr. Faber - Temperature and cement - 1st International Congress for Concrete and Reinforced Concrete, Liege.

(3) Jackson - Modern Research on the Nature of Materials of Construction - The Structural Engineer - Oct. (1931).

(4) Anderegg and Hubbel - The Rate of hydration of Cement Clinker. - Proc.Am.Soc. of Test.Mat. (1929).

(5) J.R. Bayliss - The corrosion of concrete - Proc. of Am.Soc. of Civil Engineers, April (1926).

(6) Lynam - Growth and Movement in Portland Cement Concrete. - London, (1934).

(7) Carman and Nelson - Thermal Conductivity and Diffusivity of Concrete. - University of Illinois, Eng. Exp. Station Bull. 122.

CHAPTER XI.

DISCUSSION OF THE RESULTS.

FIG-31

BLUE CIRCLE NEAT CEMENT

WATER – CEMENT RATIO 21.5 % BY WT.

△ SERIES No. 1 SPECIMEN No 1

⊙ " " " " 2

• " " " " 3

◇ " " " " 4.

RATE OF LENGTH CHANGES 1" = 1/1000 IN = 1/90 0/0

CONTRACTION.

EXPANSION.

TIME IN MINUTES

100

200

300

FIG - 32

BLUE CIRCLE NEAT CEMENT

WATER - CEMENT RATIO 21.5 % BY WT.

○ SERIES No 1. SPECIMEN No. 5

• " " " " " 6

△ " " " " " 7

RATE OF LENGTH CHANGES. 1" = 1/1000 IN = 1/90 %.

CONTRACTION.

EXPANSION

INITIAL SETTING TIME.

FINAL SETTING TIME.

7
6
5
4
3
2
1
0
1

30
100
200
300
400

TIME IN MINUTES

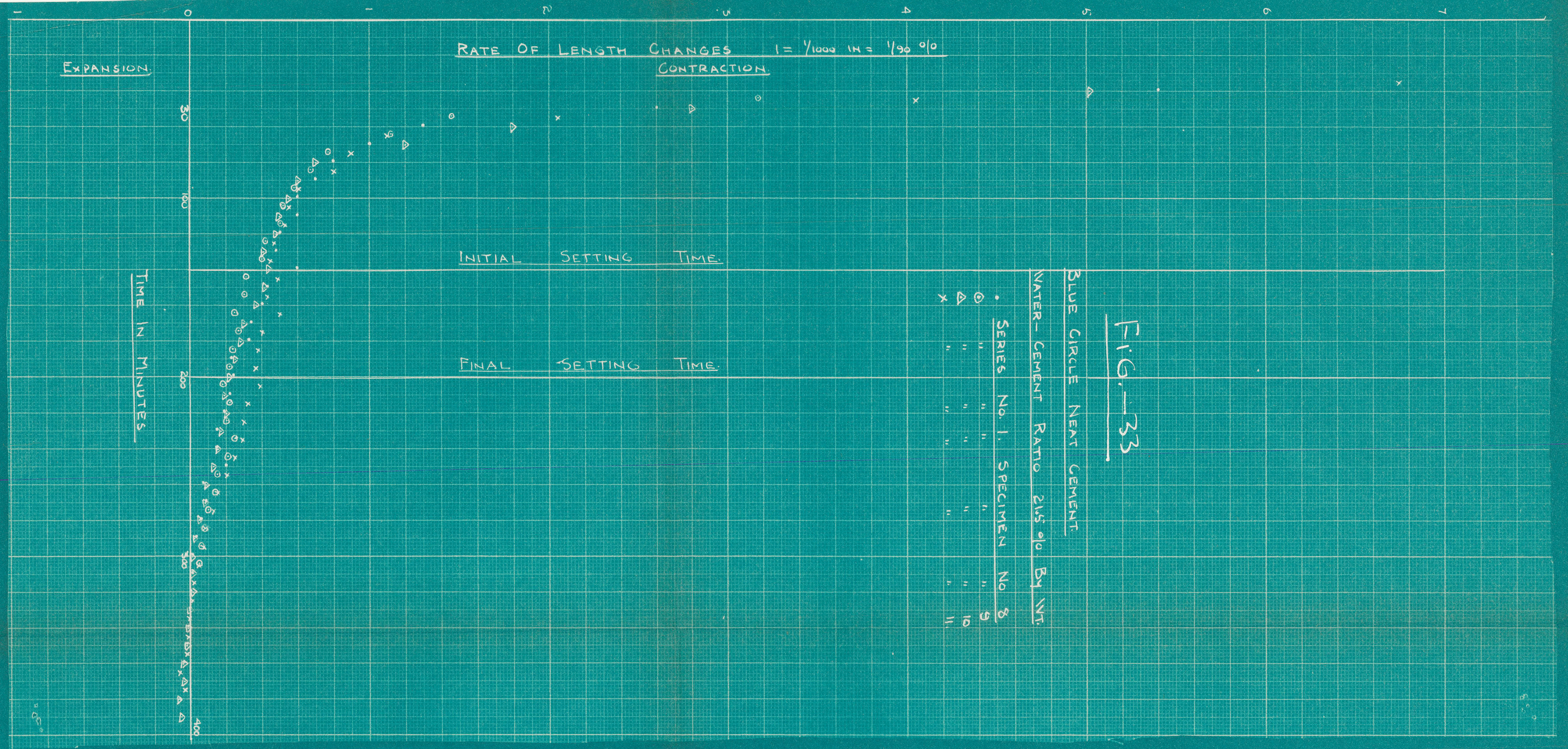

RATE OF LENGTH CHANGES 1 = 1/1000 IN = 1/90 %
EXPANSION
CONTRACTION
INITIAL SETTING TIME
FINAL SETTING TIME
TIME IN MINUTES
100
200
300
400
SERIES No. 1. SPECIMEN No. 8
" " " " 9
" " " " 10
" " " " 11
WATER-CEMENT RATIO 24.5 % BY WT.
BLUE CIRCLE NEAT CEMENT

FIG. 33

FIG.—34

BLUE CIRCLE NEAT CEMENT.

WATER–CEMENT RATIO 23.5 %. BY WT.

⊙ SERIES No. 1. SPECIMEN No. 12

• " " " " " 13

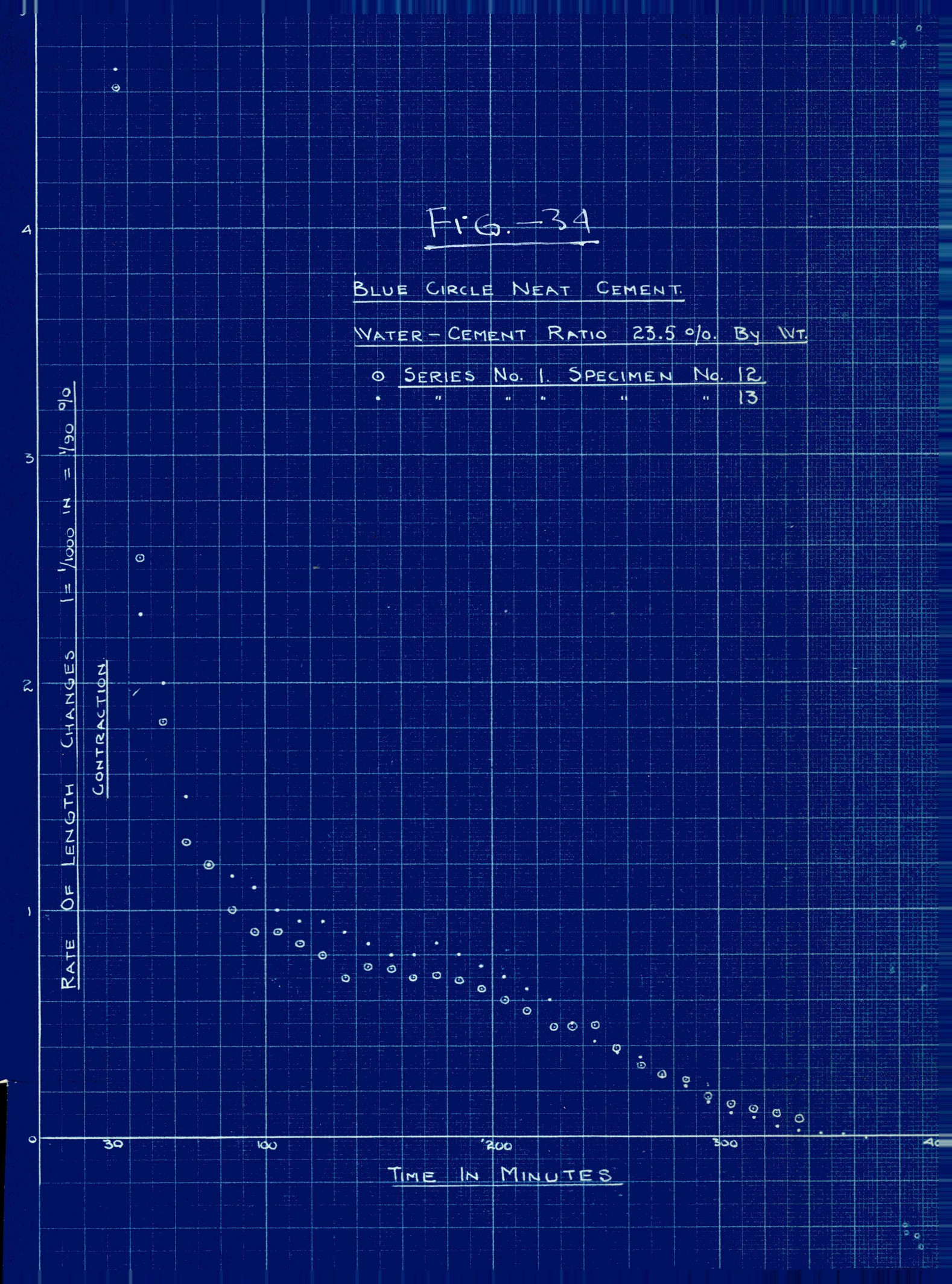


FIG — 35

BLUE CIRCLE NEAT CEMENT.

WATER-CEMENT RATIO 23.5 % BY WT.

- • SERIES No. 1, SPECIMEN No. 14
- △ " " " " 15
- ⊙ " " " " 16
- × " " " " 17

RATE OF LENGTH CHANGES 1" = 1/1000 IN = 1/90 %.

CONTRACTION

EXPANSION

2
1
0
1

5
4
3

30
100
200
300
400

TIME IN MINUTES

23.5 dil

FIG.—36

BLUE CIRCLE NEAT CEMENT.

WATER–CEMENT RATIO 20.5 o/o BY WT.

o	SERIES	No 1.	SPECIMEN	No.	18
•	"	"	"	"	"	19
△	"	"	"	"	"	20
⊙	"	"	"	"	"	21

RATE OF LENGTH CHANGES. 1 = 1/1000 IN = 1/90 o/o.

CONTRACTION.

EXPANSION

100 200 300

TIME IN MINUTES

TOTAL LENGTH CHANGE 1 = 1/1000 IN = 1/90 %.

CONTRACTION

0 5 10 15 20 25

30

100

INITIAL SETTING TIME.

200

FINAL SETTING TIME.

TIME IN MINUTES

300

400

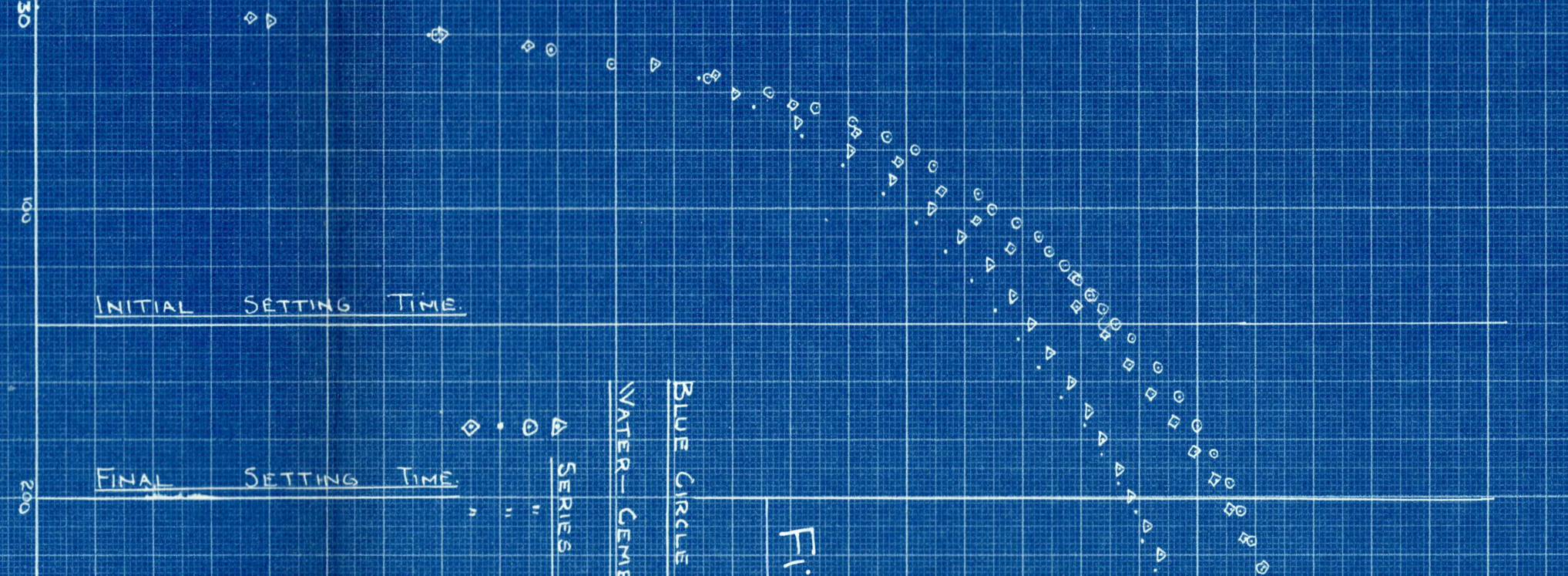


FIG. -31

BLUE CIRCLE NEAT CEMENT.

WATER—CEMENT RATIO 21.5 % BY WT.

SERIES No. 1. SPECIMEN No. 1

" " " " 2

" " " " 3

" " " " 4

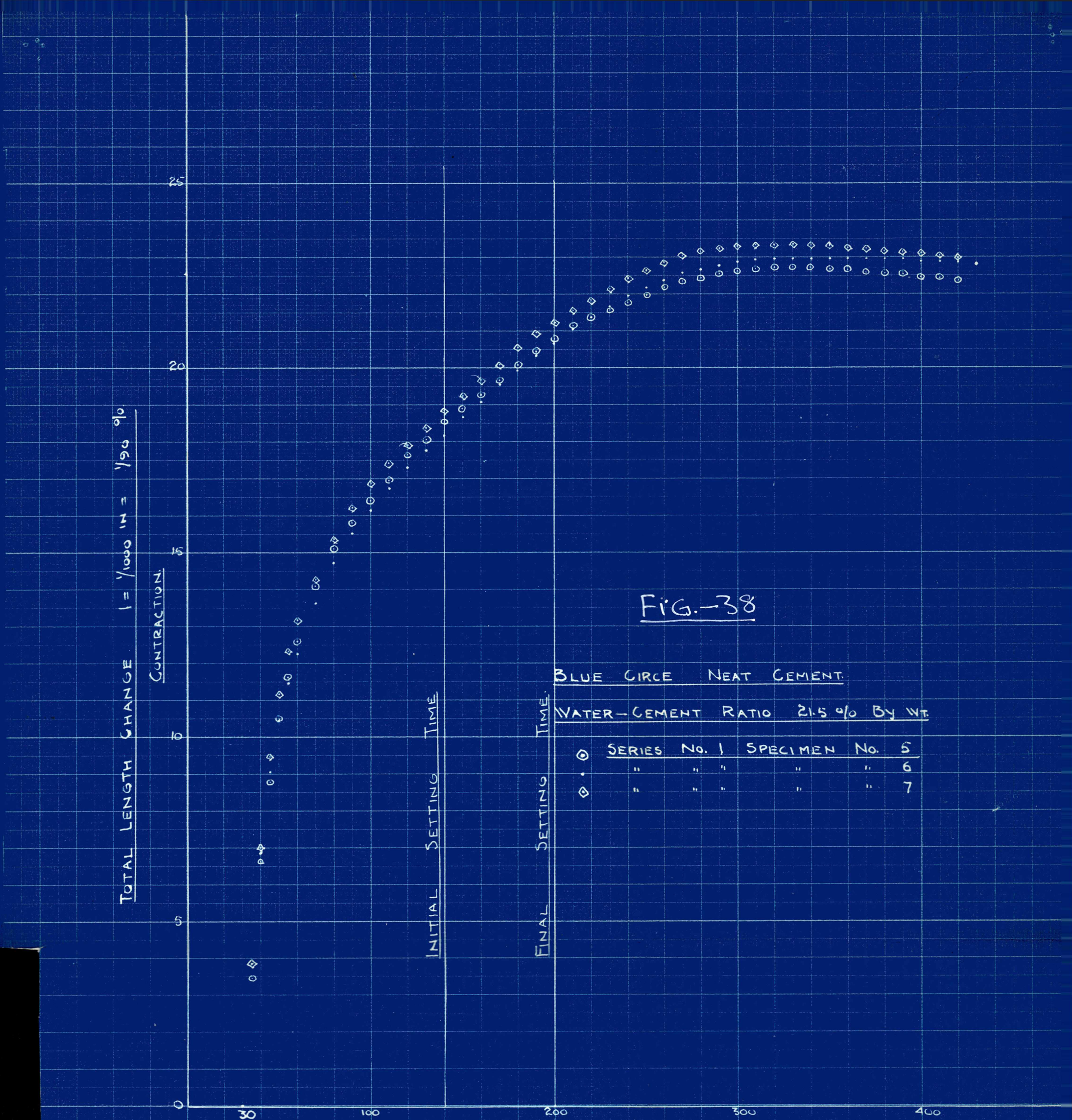


FIG.-38

BLUE CIRCE NEAT CEMENT.

WATER-CEMENT RATIO 21.5 % BY WT.

SERIES No. 1 SPECIMEN No. 5

" " " " " 6

" " " " " 7

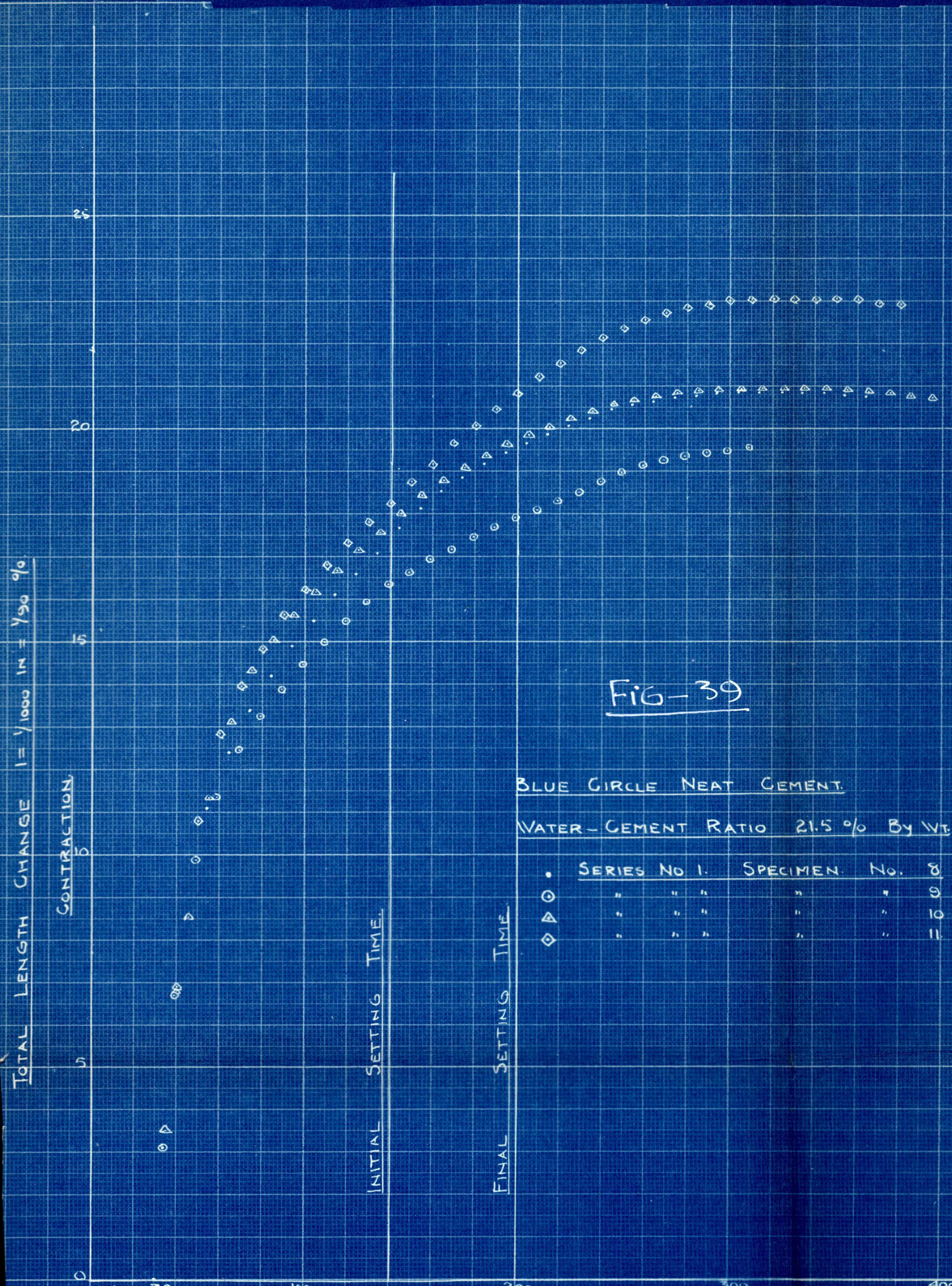

Total Length Change 1= 1/1000 In = 1/50 o/o.
Contraction.
25
20
15
5
0
Initial Setting Time.
Final Setting Time
30
100
200
300
400
Time In Minutes
Blue Circle Neat Cement.
Water-Cement Ratio 21.5 o/o By Wt.
Series No 1. Specimen No. 8
" " " " 9
" " " " 10
" " " " 11

Fig-39

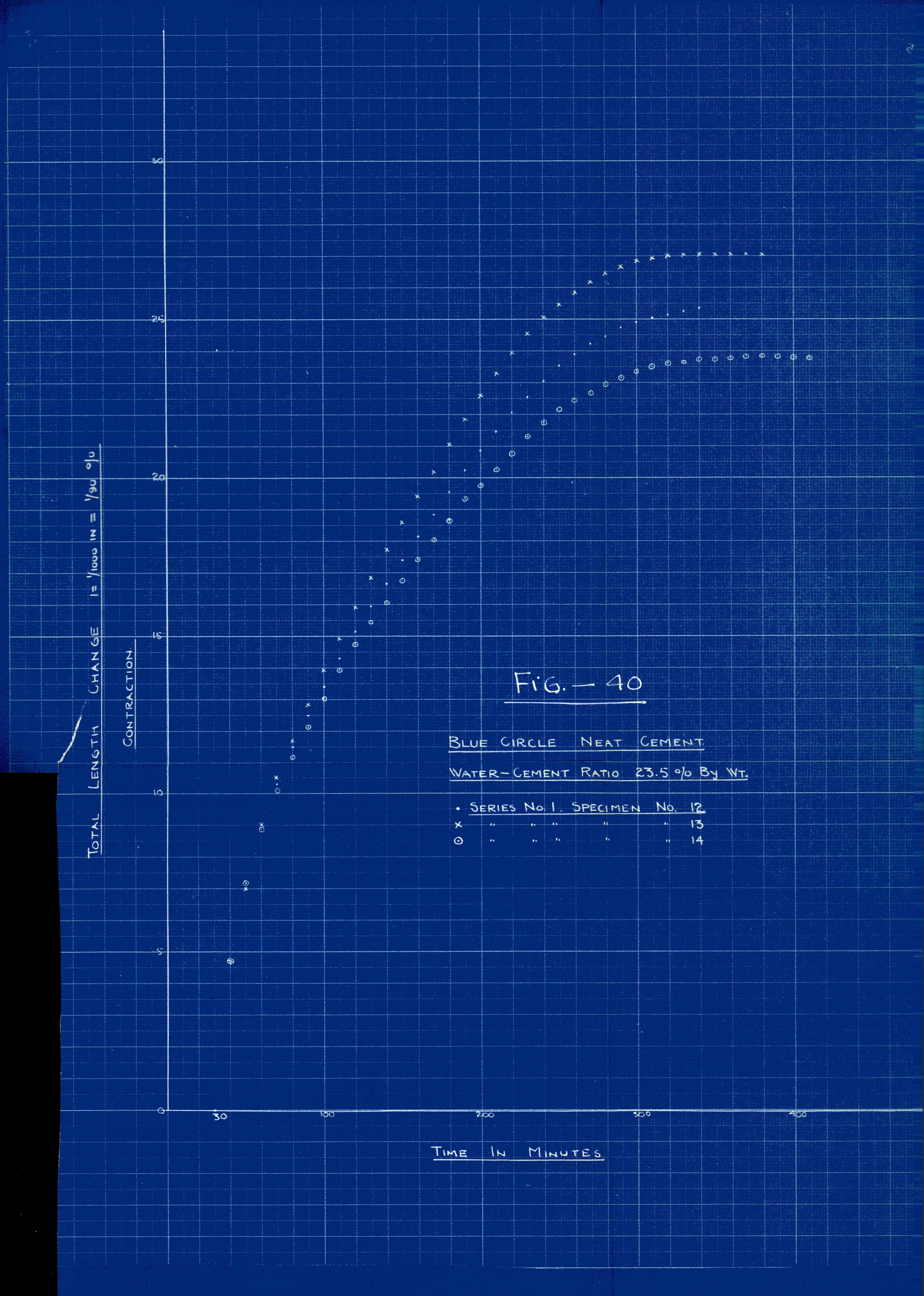


FIG.— 40

BLUE CIRCLE NEAT CEMENT.

WATER–CEMENT RATIO 23.5 % BY WT.

• SERIES No. 1. SPECIMEN No. 12.
× " " " " " 13
⊙ " " " " " 14

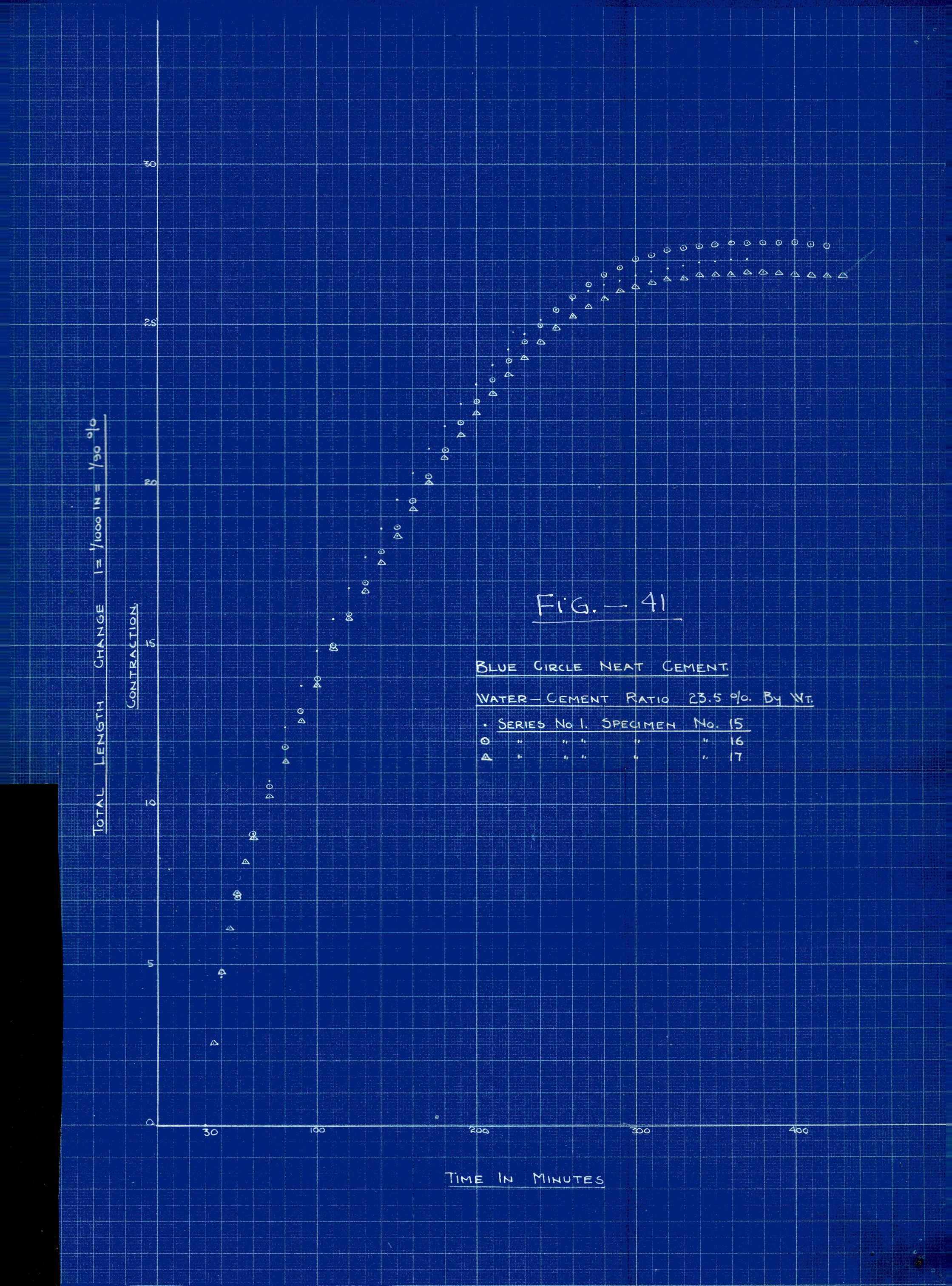


FIG. — 41

BLUE CIRCLE NEAT CEMENT.

WATER — CEMENT RATIO 23.5 %. BY WT.

· SERIES No 1. SPECIMEN No. 15
⊙ " " " " " 16
△ " " " " " 17

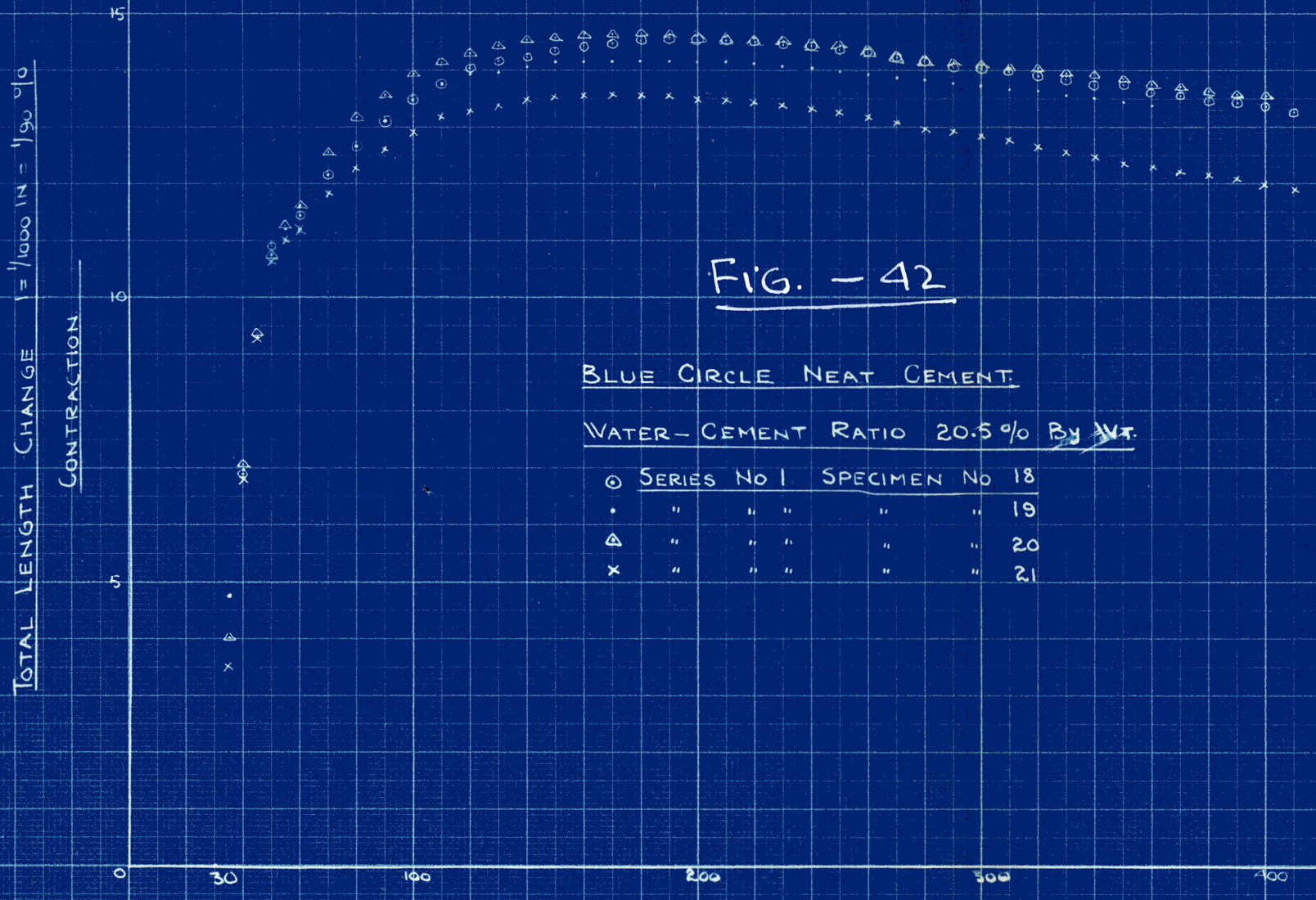


FIG. – 42

BLUE CIRCLE NEAT CEMENT

WATER – CEMENT RATIO 20.5 % By Wt.

⊙	SERIES No 1	SPECIMEN	No	18
•	"	"	"	"	19
△	"	"	"	"	20
×	"	"	"	"	21

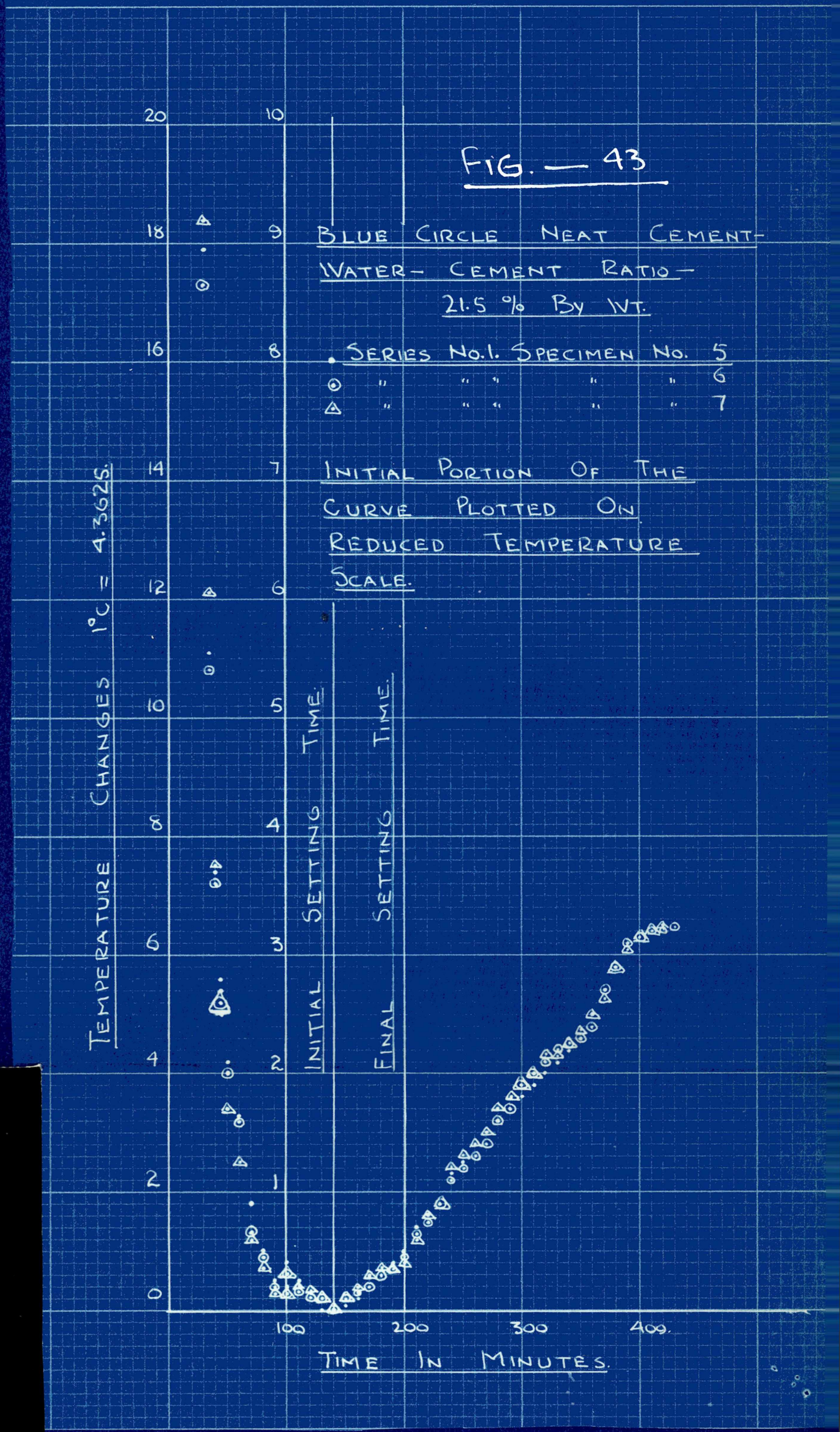
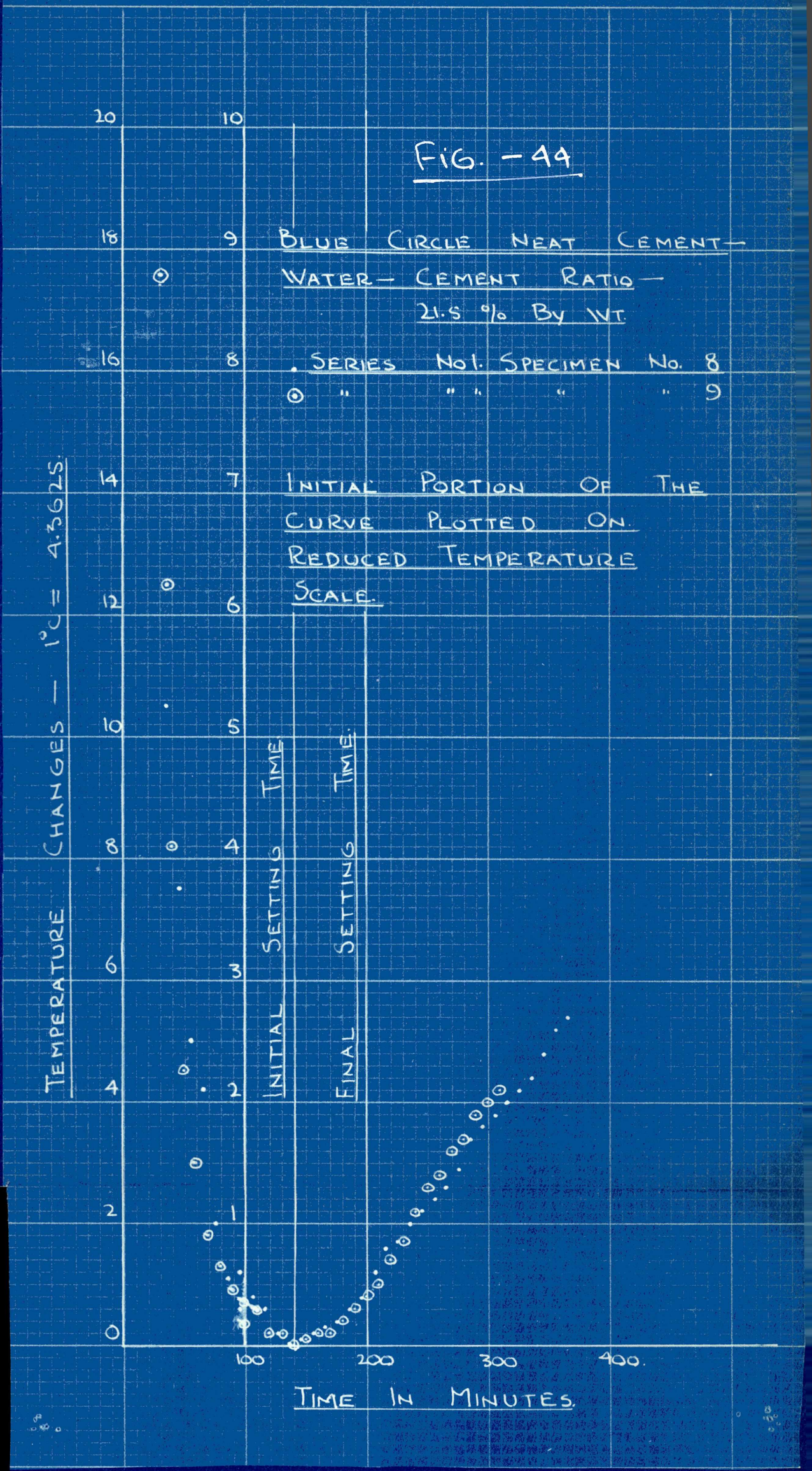

FIG. — 43
BLUE CIRCLE NEAT CEMENT-
WATER- CEMENT RATIO —
21.5 % BY WT.
SERIES No.1. SPECIMEN No. 5
" " " " 6
" " " " 7
INITIAL PORTION OF THE CURVE PLOTTED ON REDUCED TEMPERATURE SCALE.
TEMPERATURE CHANGES 1°C = 4.3625.
INITIAL SETTING TIME.
FINAL SETTING TIME.
20
18
16
14
12
10
8
6
4
2
0
10
9
8
7
6
5
4
3
2
1
100
200
300
400
TIME IN MINUTES.

FIG. - 49

BLUE CIRCLE NEAT CEMENT—
WATER - CEMENT RATIO —
21.5 % BY WT.

● SERIES No 1. SPECIMEN No. 8
⊙ " " " " " 9

INITIAL PORTION OF THE CURVE PLOTTED ON REDUCED TEMPERATURE SCALE.



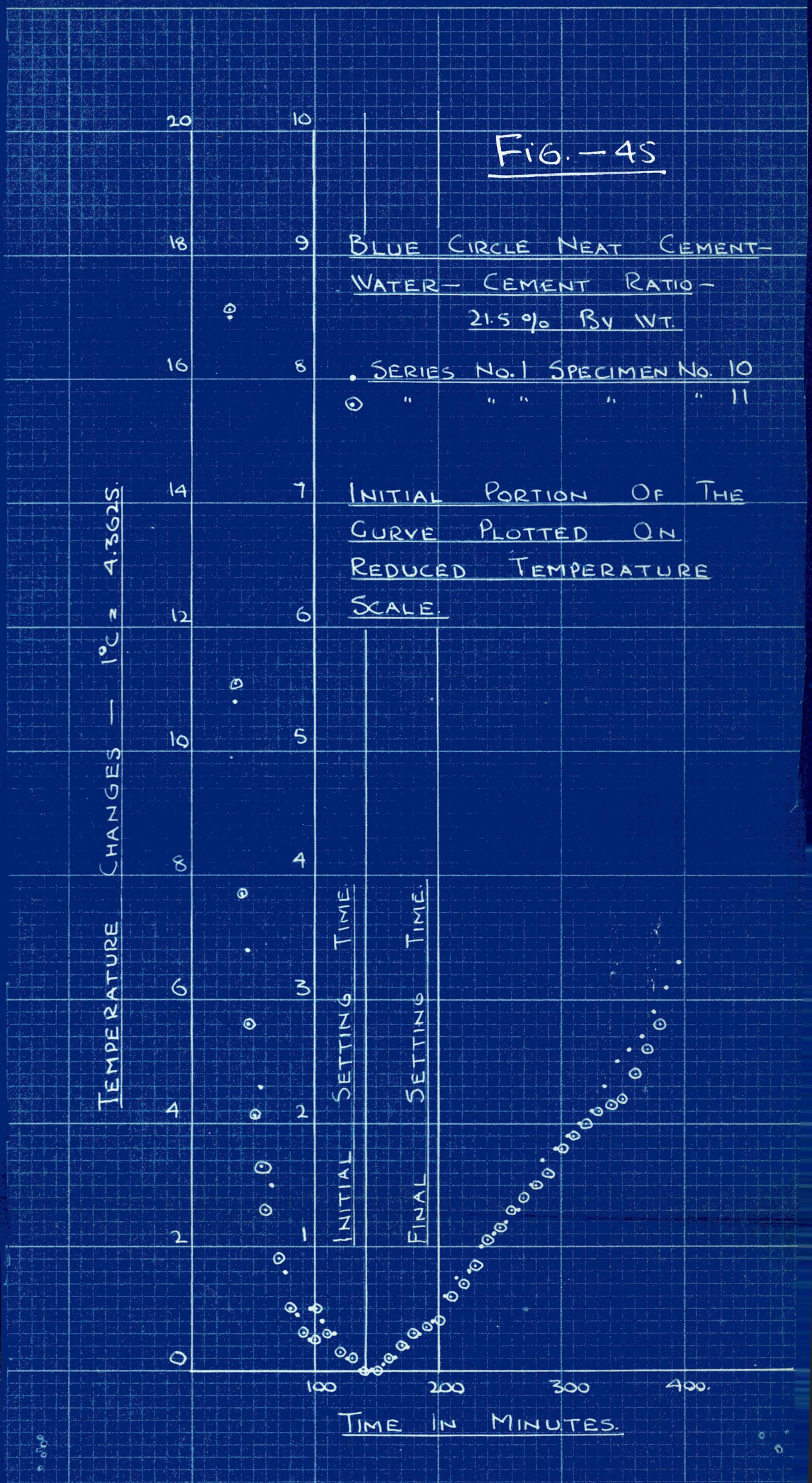

FIG.—45
BLUE CIRCLE NEAT CEMENT—
WATER—CEMENT RATIO—
21.5 % BY WT.
SERIES No. 1 SPECIMEN No. 10
" " " " " 11
INITIAL PORTION OF THE
CURVE PLOTTED ON
REDUCED TEMPERATURE
SCALE.
TEMPERATURE CHANGES — 1°C = 4.3625.
INITIAL SETTING TIME.
FINAL SETTING TIME.
TIME IN MINUTES.
0
100
200
300
400.
1
2
3
4
5
6
7
8
9
10
12
14
16
18
20

FIG. — 46

BLUE CIRCLE NEAT CEMENT.
WATER – CEMENT RATIO —
23.5 % BY WT.

• SERIES No. 1 SPECIMEN No. 12
⊙ " " " " " 13
△ " " " " " 14

INITIAL PORTION OF THE CURVE PLOTTED ON REDUCED TEMPERATURE SCALE.

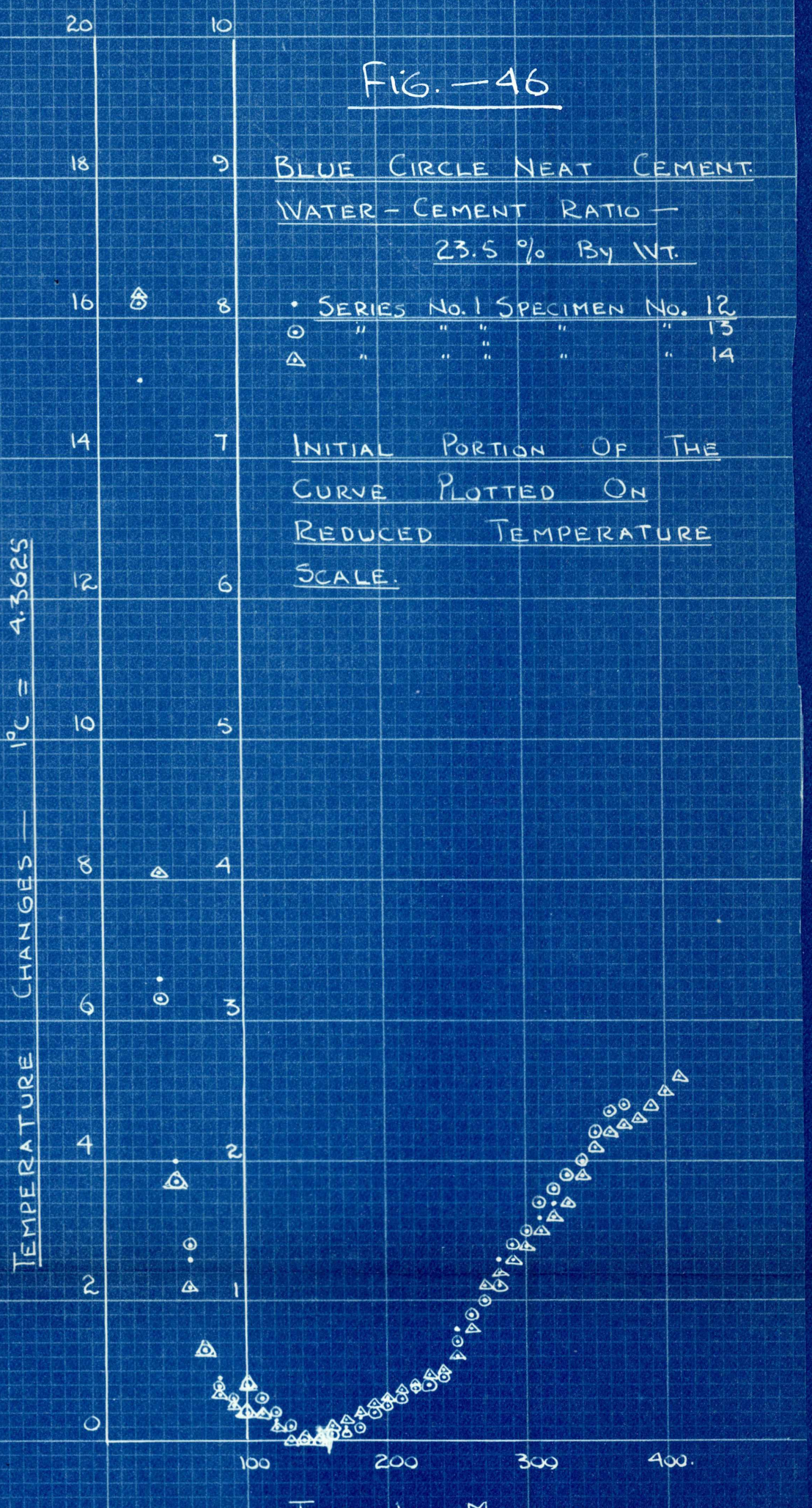


FIG.—47

BLUE CIRCLE NEAT CEMENT—
WATER—CEMENT RATIO—
23.5 % BY WT.

• SERIES No. 1. SPECIMEN No. 15
⊙ " " " " " 16
△ " " " " " 17.

INITIAL PORTION OF THE CURVE PLOTTED ON REDUCED TEMPERATURE SCALE.

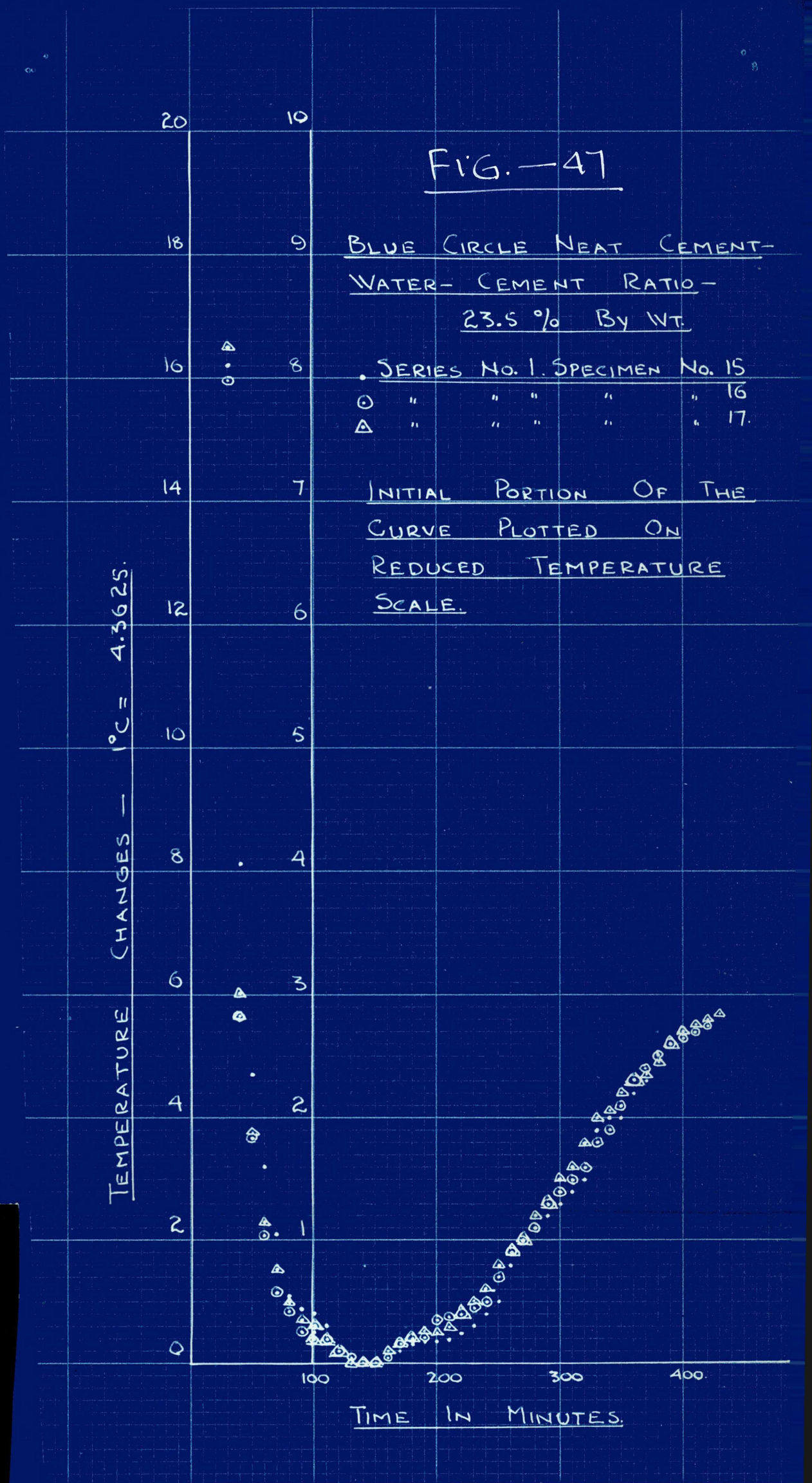


FIG.—48

BLUE CIRCLE NEAT CEMENT.
WATER-CEMENT RATIO—
20.5 % BY WT.
• SERIES No. 1 SPECIMEN No. 18
⊙ " " " " " 19.

INITIAL PORTION OF THE CURVE PLOTTED ON REDUCED TEMPERATURE SCALE.

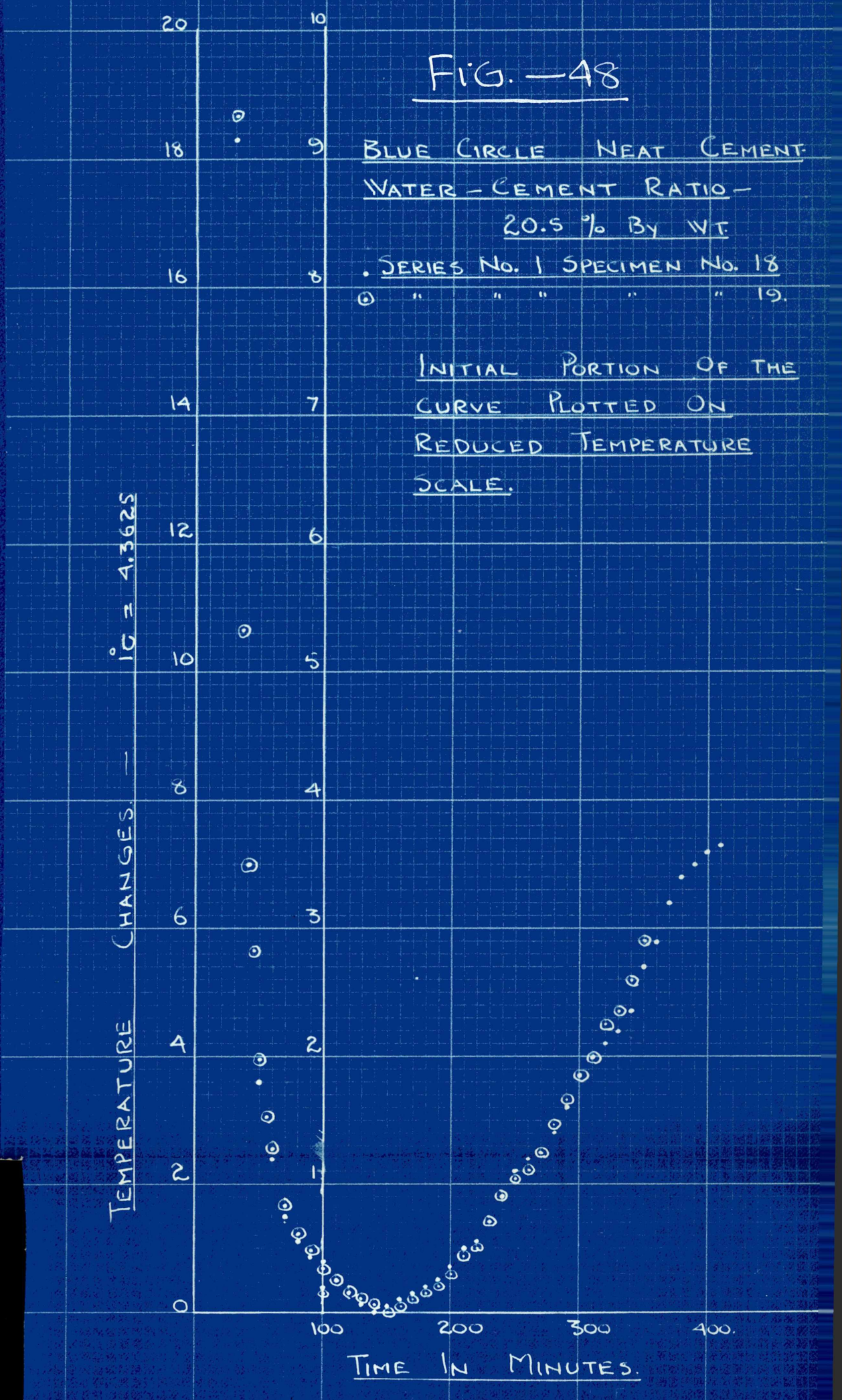
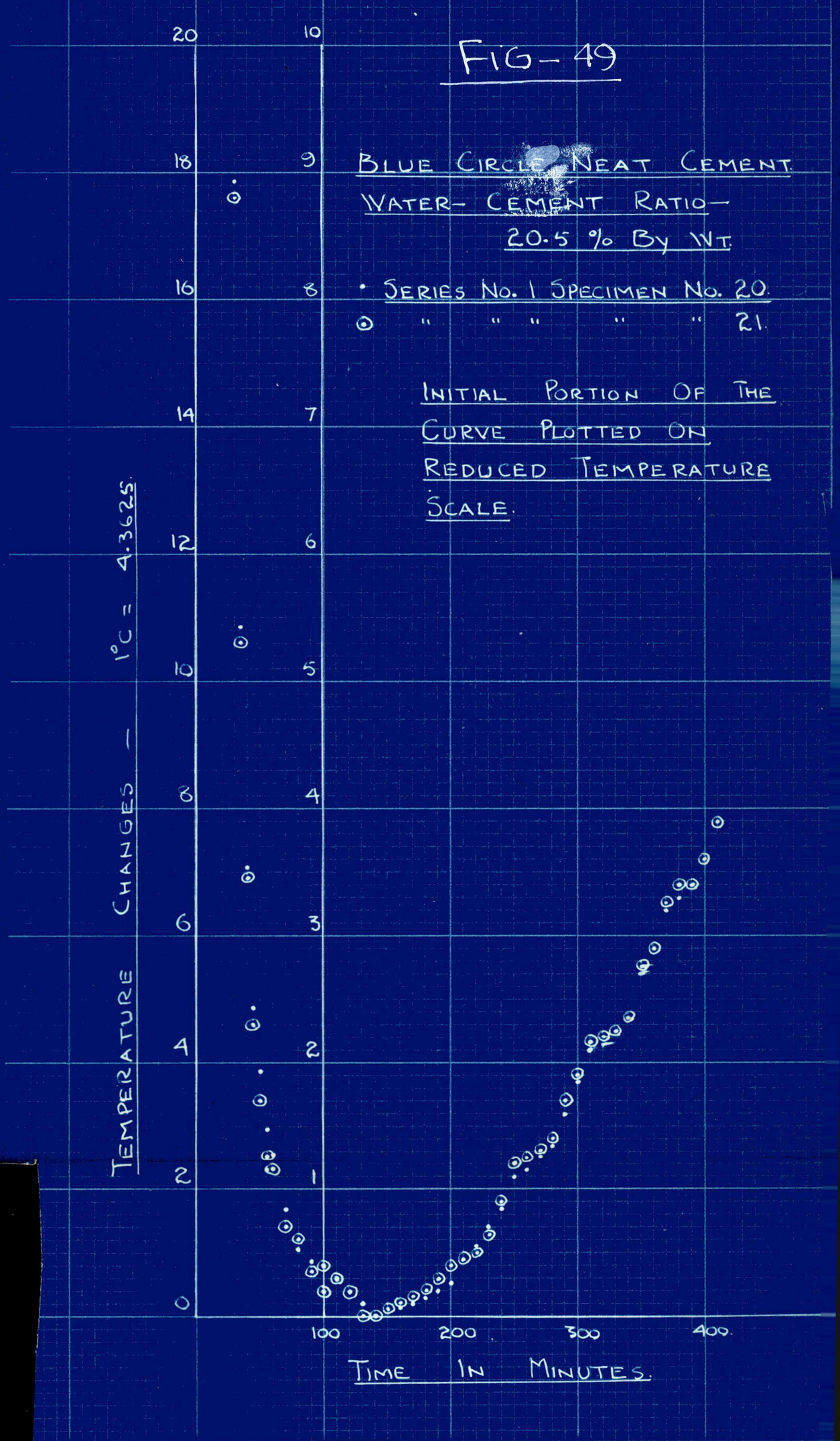


FIG-49


BLUE CIRCLE NEAT CEMENT.
WATER-CEMENT RATIO—
20.5 % BY WT.
• SERIES No. 1 SPECIMEN No. 20.
⊙ " " " " " 21.
INITIAL PORTION OF THE CURVE PLOTTED ON REDUCED TEMPERATURE SCALE.
TEMPERATURE CHANGES — 1°C = 4.3625.
TIME IN MINUTES.
20
18
16
14
12
10
8
6
4
2
0
10
9
8
7
6
5
4
3
2
1
100
200
300
400.

Chapter XI.

Discussion of the Results.

Series No. 1. Specimens Nos. 1 to 21.

Figs. 31 to 36 show the rate of length changes in ten minutes of Blue Circle Neat Cement specimens.

Figs. 31 to 33 show the rate of length changes in ten minutes of specimens Nos. 1 to 11 with water-cement ratio 21.5% by weight. The results of these eleven specimens show that the points obtained for the various curves are fairly reproducible. This gave an indication of the suitability of this simple apparatus for volume-change observations and after that only 4 or 5 specimens were made for each percentage of water in the different series. The rate of length changes in ten minutes is about 7/90% at 30 minutes, which falls to 0 at about 330 minutes after which expansion starts slowly.

According to the Vicat-needle test, the initial setting time of this cement was 140 minutes and the final setting time 240 minutes. The term initial set as given by the Vicat-needle test, is an empirical point of use for practical purposes, but not existing in fact. The normal setting of cement is probably a continuous process without any fixed points, or if such points exist they are not such as are determined by the present setting-time tests. What the test does convey is that a concrete made with a cement giving an initial set of, say, two hours will remain plastic and workable for at least that period.

Hence, if there is a stiffening of the paste after two minutes, it does not imply that the setting of the cement will be disturbed by ignoring it. The lines drawn in the Fig. 31 and 32 and 33 as showing the initial and final setting time show that practically no such change takes place in this curve near the initial setting time line where the curve is continuous. There is a marked change in the curve at 180 minutes or, say, near the final setting time. The readings obtained next day have merely been recorded in the tables, but not plotted as nothing is known about the nature of the curve between 400 minutes and 1400 minutes and it was not possible to generalise about the nature of the curve beyond 400 minutes from these two points only.

In Fig. 31 a curious feature is observed at about 120 minutes for Specimen No.4. The rate increases suddenly from .6 to 1.08 and then straight away drops to .03 at 130 minutes, rising again to .48. The points obtained after that follow the general nature of the curve. No possible explanation can be offered for this phenomenon as it was observed in this specimen only in this series. (A similar case has been observed with neat Cement ferrocrete specimen No. 7 series, No. 3 too).

Fig. 34 and 35 show the rate of length changes in ten minutes of specimens Nos. 12 to 17 with 23.5% water-cement ratio by weight. It is seen that the same type

of the break mentioned above is observed in the curve at about 180 minutes as in Figs. 31 to 33. The rate of length change is about 4.7/90% in 10 minutes at 30 minutes, dropping to 0 at about 400 minutes when the expansion starts.

Fig. 36 shows the rate of length changes in ten minutes of specimens Nos. 18 to 21 with 20.5% water-cement ratio by weight. No break is observed in this case as has been observed with the other two water-cement ratios. The initial rate of length change is about 7/90% in ten minutes at 30 minutes dropping to 0 at about 190 minutes, after which the expansion starts and continues steadily reaching .05/90% in ten minutes at 400 minutes.

Figs. 37 to 39 show the total length change of specimens Nos. 1 to 11 with 21.5% water-cement ratio by weight. The contraction increases rather rapidly in the about 50 minutes, initial stages, after which it increases steadily reaching 22.5/90% contraction in 400 minutes, taking 30 minute reading as the datum.

Figs. 40 and 41 show the total length change of specimens Nos. 12 to 17 with 23.5% water-cement ratio by weight.

The cement contracts rather rapidly in the initial stages, contracting steadily after that reaching 26.5/90% at 300 minutes. After this the curve becomes very flat and at the end of 400 minutes the total

contraction is 27/90% with 30 minute reading as the datum.

Fig. 42 shows the total length change of specimens Nos. 18 to 21 with 20.5% water-cement ratio by weight. The contraction is rapid in the initial stages reaching about 10.5/90% at 50 minutes. After that, the contraction goes on at a steadily declining rate reaching 14/90% at 180 minutes. The specimens then expand steadily, the total contraction at 400 minutes being 13/90% with 30 minute reading as the datum.

Figs. 43 to 49 show the temperature changes in the specimens Nos. 1 to 21. To show clearly the rise and fall in the temperature, the lowest temperature reading obtained has been considered as 0 and the rise and fall connected to that reading and plotted.

No temperature change readings have been given for specimens Nos. 1 to 4 due to the vitiation of thermo-couple readings due to various causes as has already been mentioned. (See page 195).

Figs. 43 to 45 show the temperature variations plotted on the above basis in specimens Nos. 5 to 11 with water-cement ratio 21.5% by weight. Figs. 46 and 47 show the same for the specimens Nos. 12 to 17 with water-cement ratio 23.5% by weight. Figs. 48 and 49 show the same for the specimens Nos. 18 to 21 with water-cement ratio 20.5% by weight.

The reaction of cement with water is exothermic and evolves a considerable amount of heat. The heat evolved is spent (a) in raising the temperature of the cement, water and (in the case of mortars and concretes) of the sand and stone mixed with them; (b) in radiating heat from the exposed surfaces and otherwise dissipating heat by conduction and convection. These again depend one on the other because no radiation can occur until there is a rise in temperature above that of the surrounding objects, and on the other hand, of the radiating surfaces are great in relation to the mass of cement, no important rise of temperature will occur. It is therefore clear that the less water, sand and stone mixed with the cement (always provided there is enough water to satisfy the requirements for setting), the greater will be rise of temperature. In other words, rich concretes and dry mixes tend to higher temperatures. So it is seen that from the point of heat evolution, there will be an optimum percentage of water which will give the maximum.- A wetter or a drier mix will not evolve the same percentage of heat. In this particular series 20.5% water-cement ratio seems the optimum percentage from the heat evolution as the other two percentages (21.5% and 23.5%) evolve much less heat initially as well as finally. From the assumptions that the cellophane is

not a heat-proof material and mercury being a very good conductor, and the specimen being small in size, most of the heat evolved is quickly lost by conduction mainly, as well as partly, due to radiation,&c. The final rise in temperature obtained in the whole series is less than a degree. As the coefficient of thermal expansion for various cement mixes is not correctly known and as the rise in temperature is so small, no temperature correction has been applied to the shrinkage values obtained, as this investigation is more in the nature of a qualitative one than a quantitative one.

The Table XL shows the temperature and humidity variations of series No. 1, Specimens Nos. 1 to 21.

TABLE XL.

Temperature and Humidity Variations - Series No. 1.

Specimen no.	Temperature °F.	Degree of Humidity. Saturation =100.
1	56 - 56.5	64.2 - 67.3
2	55.3- 56.0	66.0 - 67.8
3	59.7 - 60.0	77.2 - 78.5
4	59.8 - 60.3	74.5 - 78.0
5	60.8 - 61.2	73.8 - 78.5
6	61.1 - 62.2	73.0 - 77.0
7	61.2 - 62.0	78.0 - 80.5
8	56.5 - 57.8	65.3 - 67.8
9	55.9 - 57.3	62.4 - 64.2
10	57.8 - 58.7	72.5 - 74.0
11	58.8 - 59.2	73.0 - 76.5
12	58.5 - 59.8	71.0 - 72.5
13	57.0 - 59.0	59.0 - 63.0
14	60.7 - 61.5	69.5 - 72.5
15	61.0 - 61.5	71.5 - 74.0
16	61.0 - 62.0	74.5 - 77.0
17	60.9 - 61.5	72.0 - 76.0
18	59.6 - 60.6	67.0 - 73.0
19	57.5 - 59.0	65.0 - 66.8
20	58.9 - 59.1	62.8 - 66.5
21	58.0 - 60.0	62.0 - 65.6

The above table shows that the maximum temperature variations for a specimen were 1.5° F. and humidity variations were 3 degrees. For the whole series, the temperature variations were from 55° F to 62° F. and humidity variations from 62 degrees to 80 degrees. The

FIG. — 50

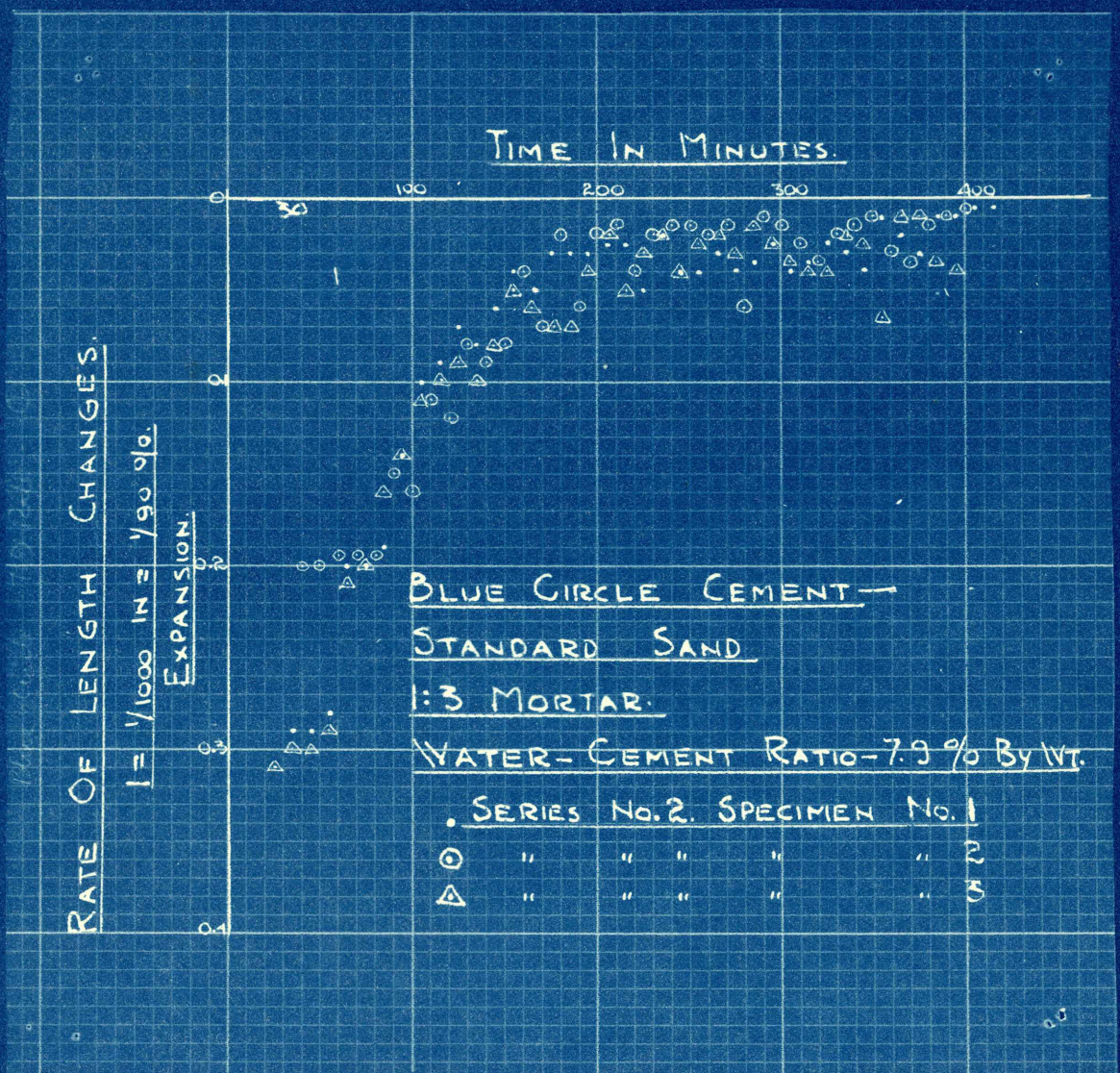

TIME IN MINUTES.
0
100
200
300
400
50
RATE OF LENGTH CHANGES.
1 = 1/1000 IN = 1/90 %.
EXPANSION.
0.2
0.3
0.4
BLUE CIRCLE CEMENT —
STANDARD SAND
1:3 MORTAR.
WATER-CEMENT RATIO - 7.9 % BY WT.
. SERIES No. 2. SPECIMEN No. 1
⊙ " " " " " 2
△ " " " " " 3

FIG.-51

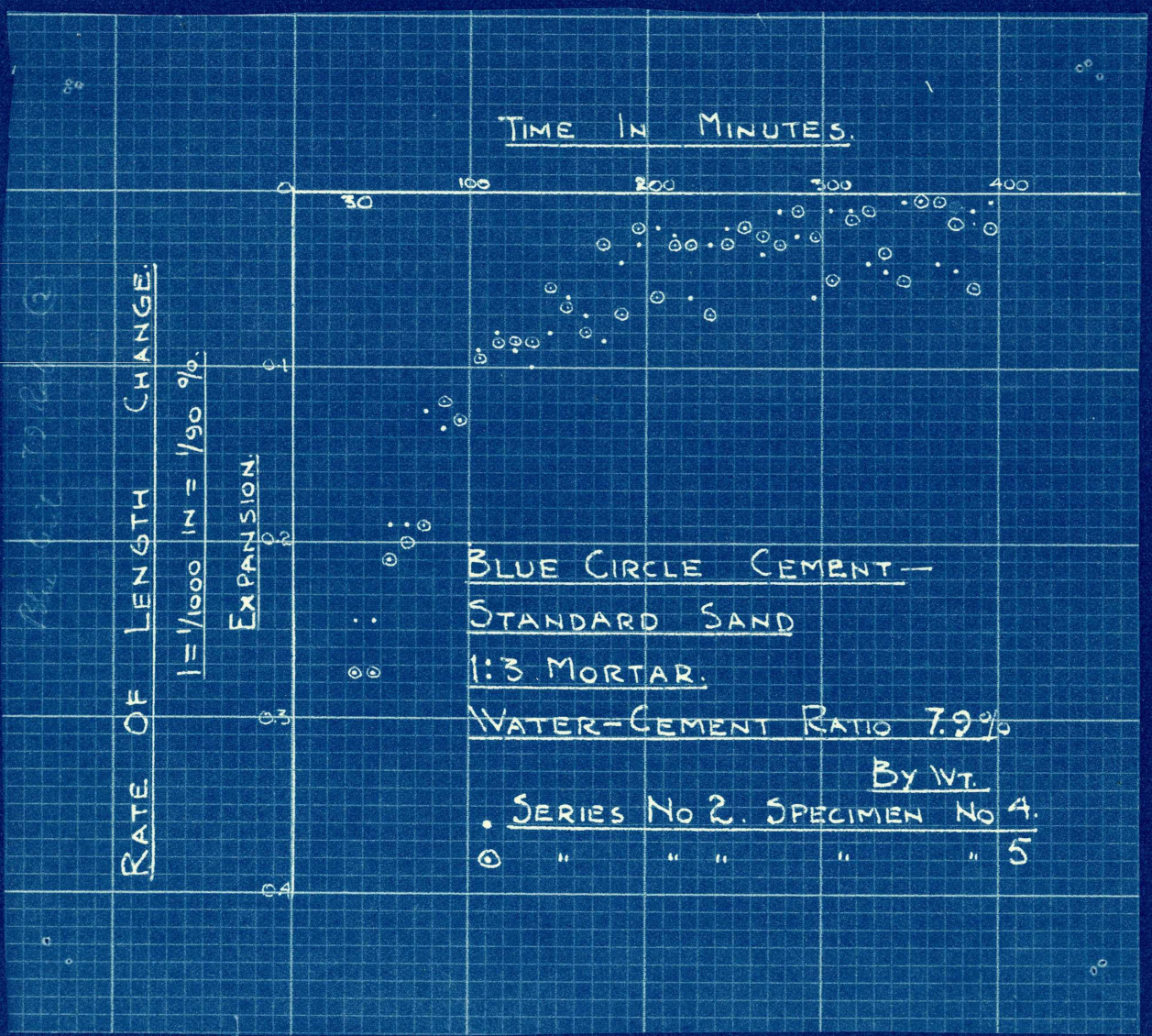

TIME IN MINUTES.
0
30
100
200
300
400
RATE OF LENGTH CHANGE.
1 = 1/1000 IN = 1/90 %.
EXPANSION.
0.1
0.2
0.3
0.4
BLUE CIRCLE CEMENT —
STANDARD SAND
1:3 MORTAR.
WATER-CEMENT RATIO 7.9%
BY WT.
SERIES NO 2. SPECIMEN NO 4.
" " " " 5

FIG. — 52

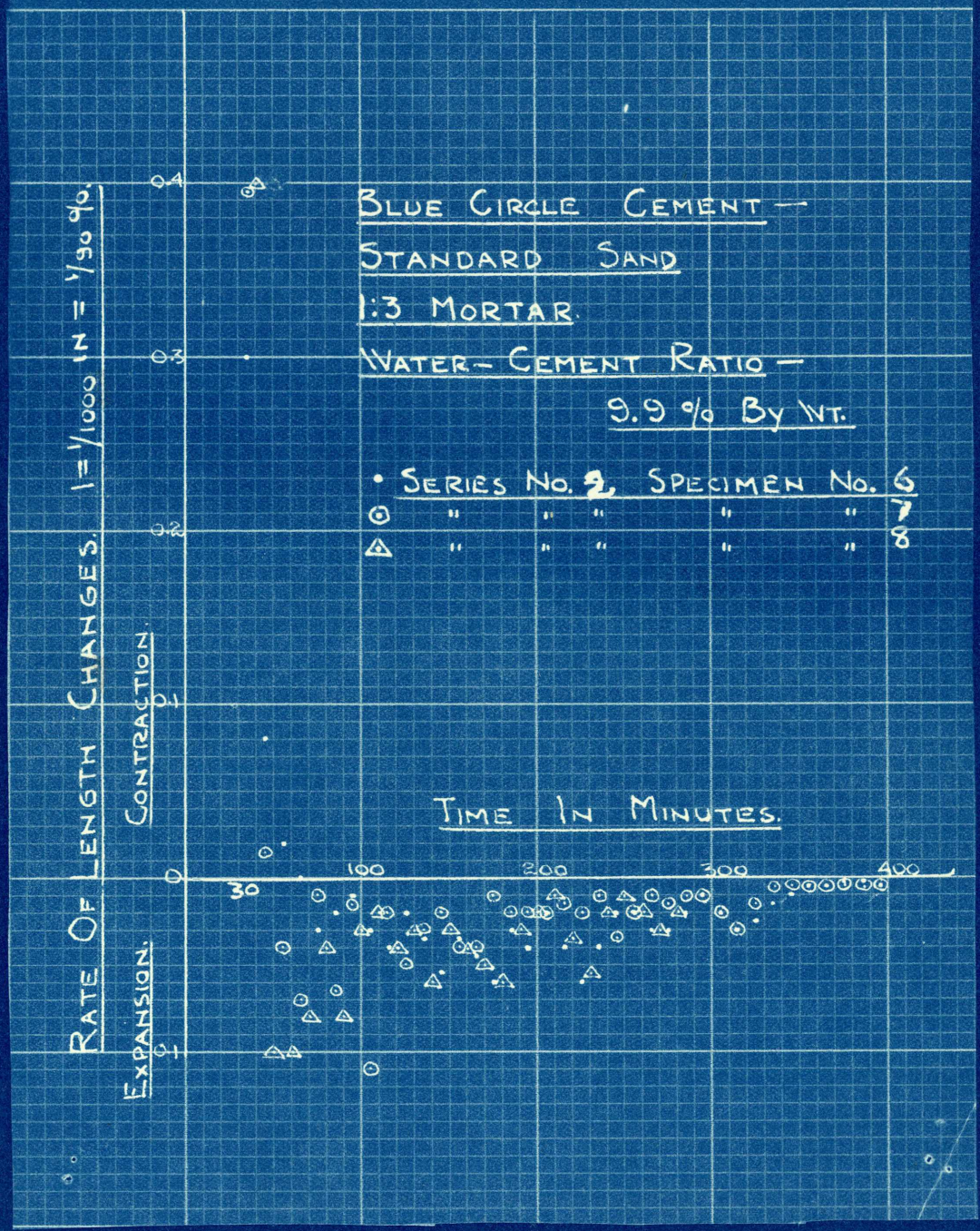

BLUE CIRCLE CEMENT —
STANDARD SAND
1:3 MORTAR
WATER-CEMENT RATIO —
9.9 % BY WT.
• SERIES NO. 2 SPECIMEN NO. 6
⊙ " " " " " 7
△ " " " " " 8
RATE OF LENGTH CHANGES. 1 = 1/1000 IN = 1/30 %.
CONTRACTION.
EXPANSION.
0.4
0.3
0.2
0.1
0
0.1
TIME IN MINUTES.
30
100
200
300
400

Fig. – 53

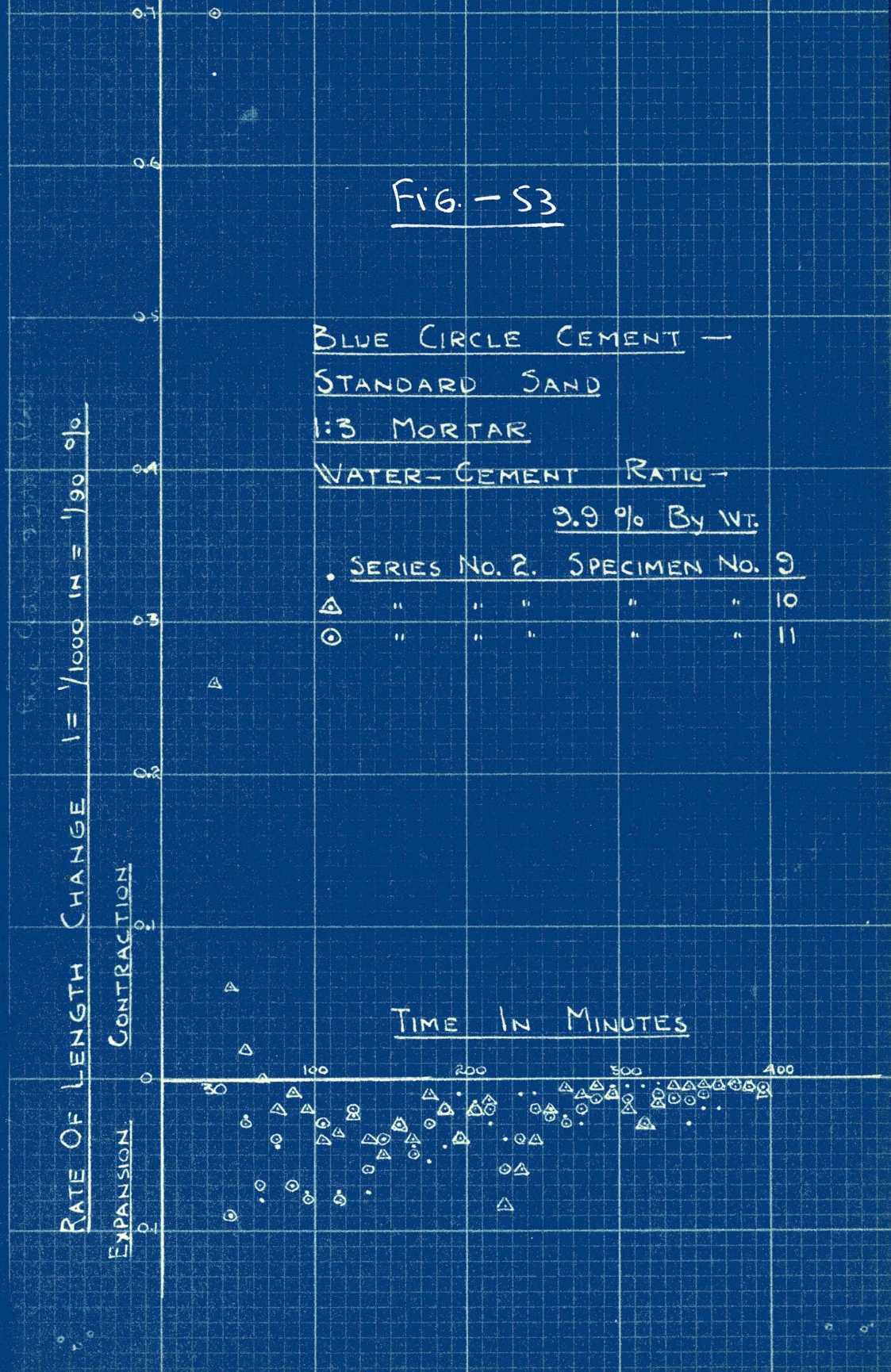

Blue Circle Cement –
Standard Sand
1:3 Mortar
Water-Cement Ratio –
9.9 % By Wt.
Series No. 2. Specimen No. 9
" " " " " 10
" " " " " 11
Rate Of Length Change 1 = 1/1000 in = 1/90 %
Contraction
Expansion
Time In Minutes
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
30
100
200
300
400

FIG.—59

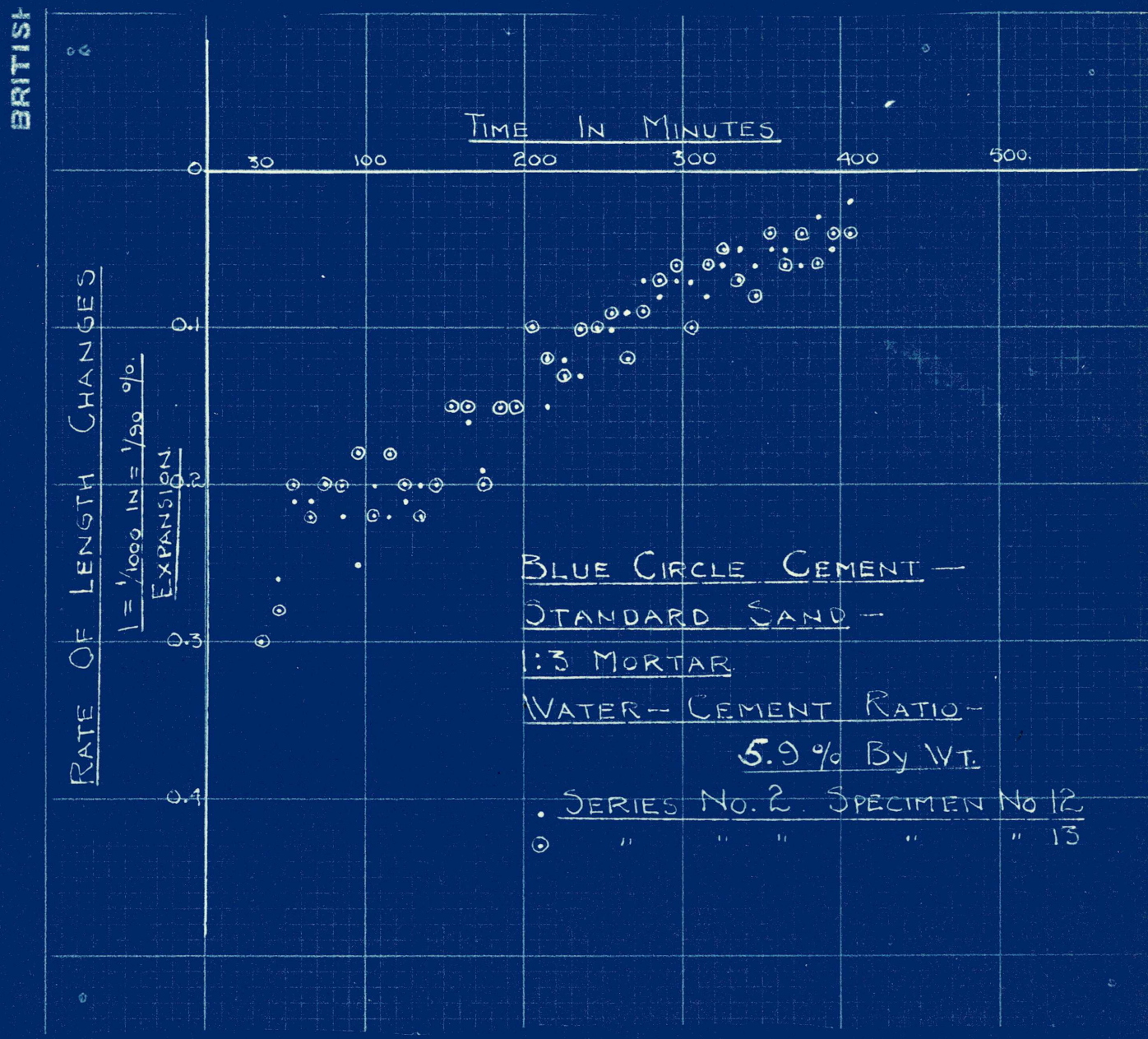
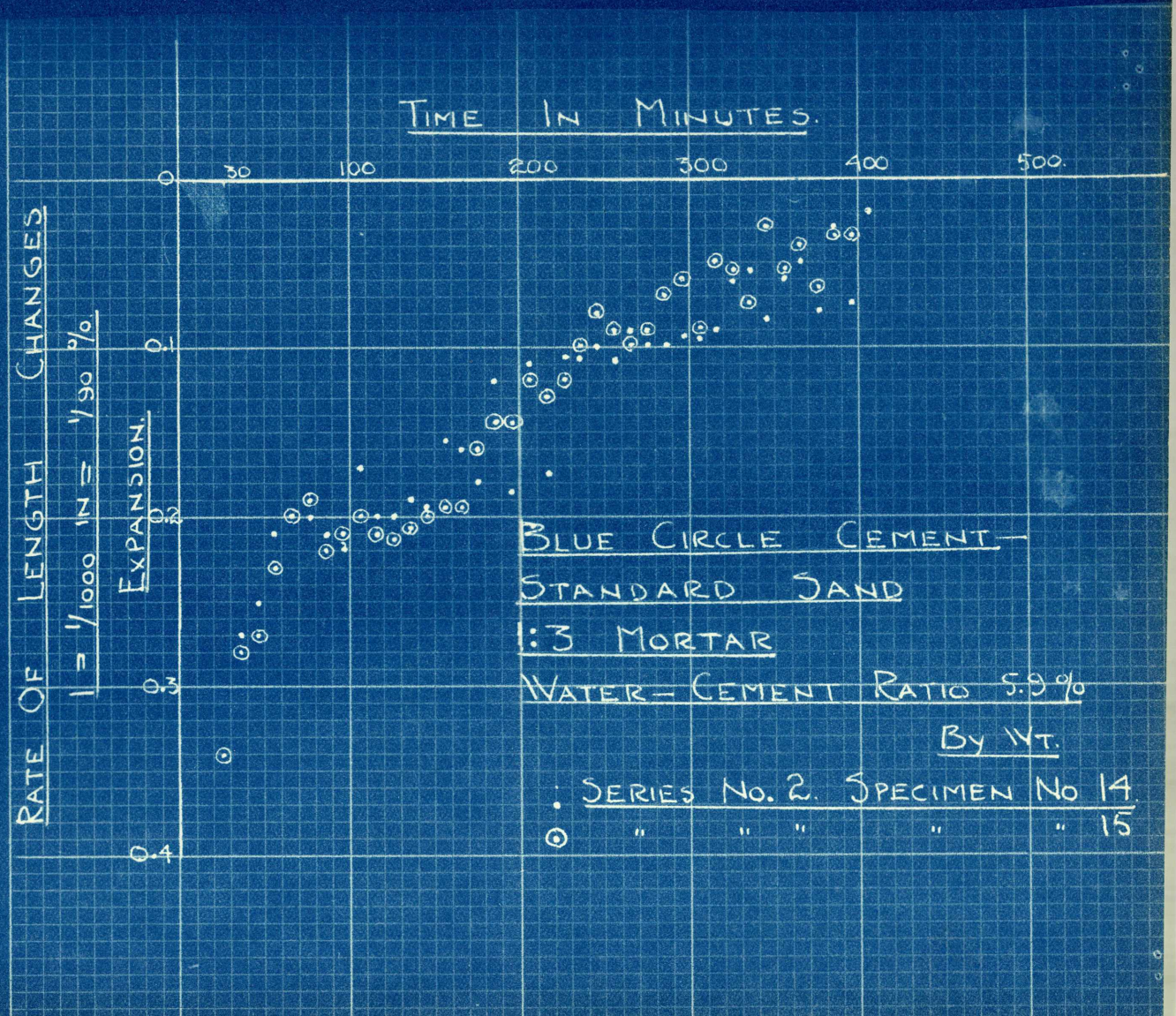

BRITISH
TIME IN MINUTES
0
30
100
200
300
400
500.
RATE OF LENGTH CHANGES
1 = 1/1000 IN = 1/10 %.
EXPANSION.
0.1
0.2
0.3
0.4
BLUE CIRCLE CEMENT —
STANDARD SAND —
1:3 MORTAR
WATER — CEMENT RATIO —
5.9 % BY WT.
SERIES No. 2. SPECIMEN No 12
" " " " " 13

FIG. – 55


TIME IN MINUTES.
0
30
100
200
300
400
500.
RATE OF LENGTH CHANGES
1 = 1/1000 "IN = 1/90 %
EXPANSION.
0.1
0.2
0.3
0.4
BLUE CIRCLE CEMENT –
STANDARD SAND
1:3 MORTAR
WATER – CEMENT RATIO 5.9 %
BY WT.
SERIES No. 2. SPECIMEN No 14
" " " " " 15

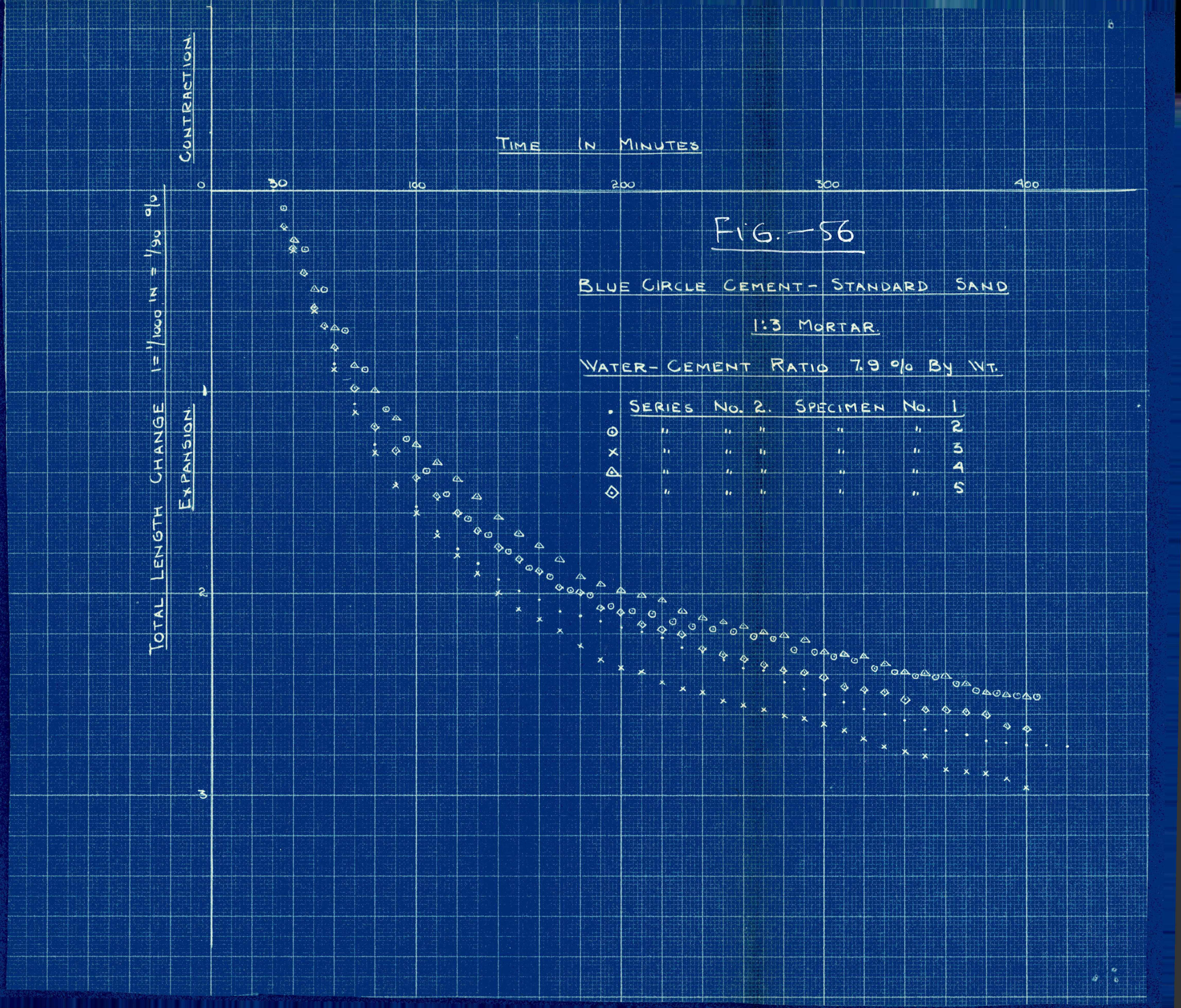

TIME IN MINUTES
0
30
100
200
300
400
TOTAL LENGTH CHANGE 1" = 1/1000 IN = 1/90 %
EXPANSION
CONTRACTION
1
2
3
FIG. - 56
BLUE CIRCLE CEMENT - STANDARD SAND
1:3 MORTAR.
WATER-CEMENT RATIO 7.9 % BY WT.
SERIES No. 2. SPECIMEN No. 1
" " " " 2
" " " " 3
" " " " 4
" " " " 5

FIG-57

STANDARD SAND —

BLUE CIRCLE CEMENT 1:3 MORTAR

WATER-CEMENT RATIO 9.9 % BY WT.

• SERIES No 2. SPECIMEN No 6

○ " " " " " 7

△ " " " " " 8

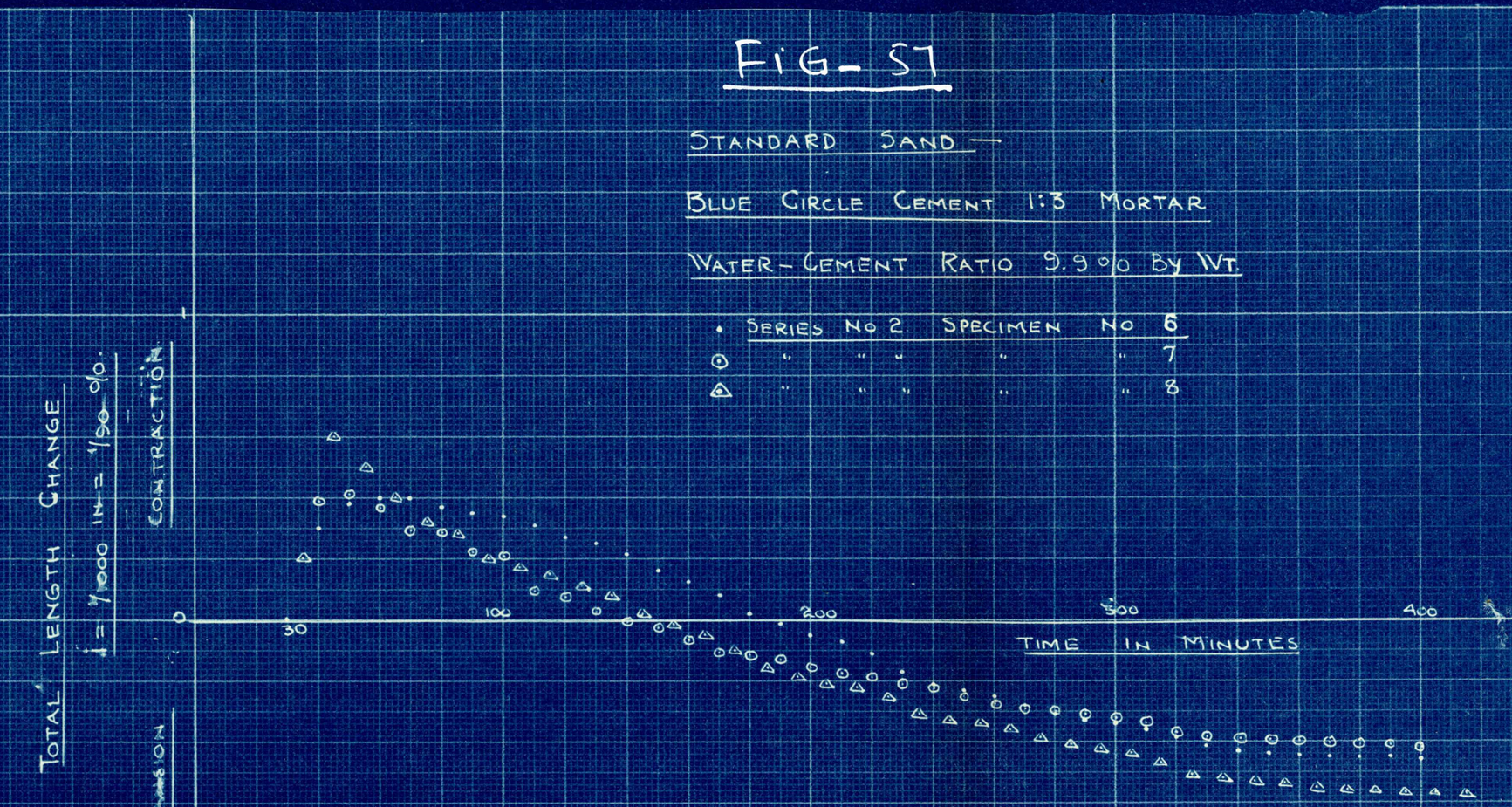
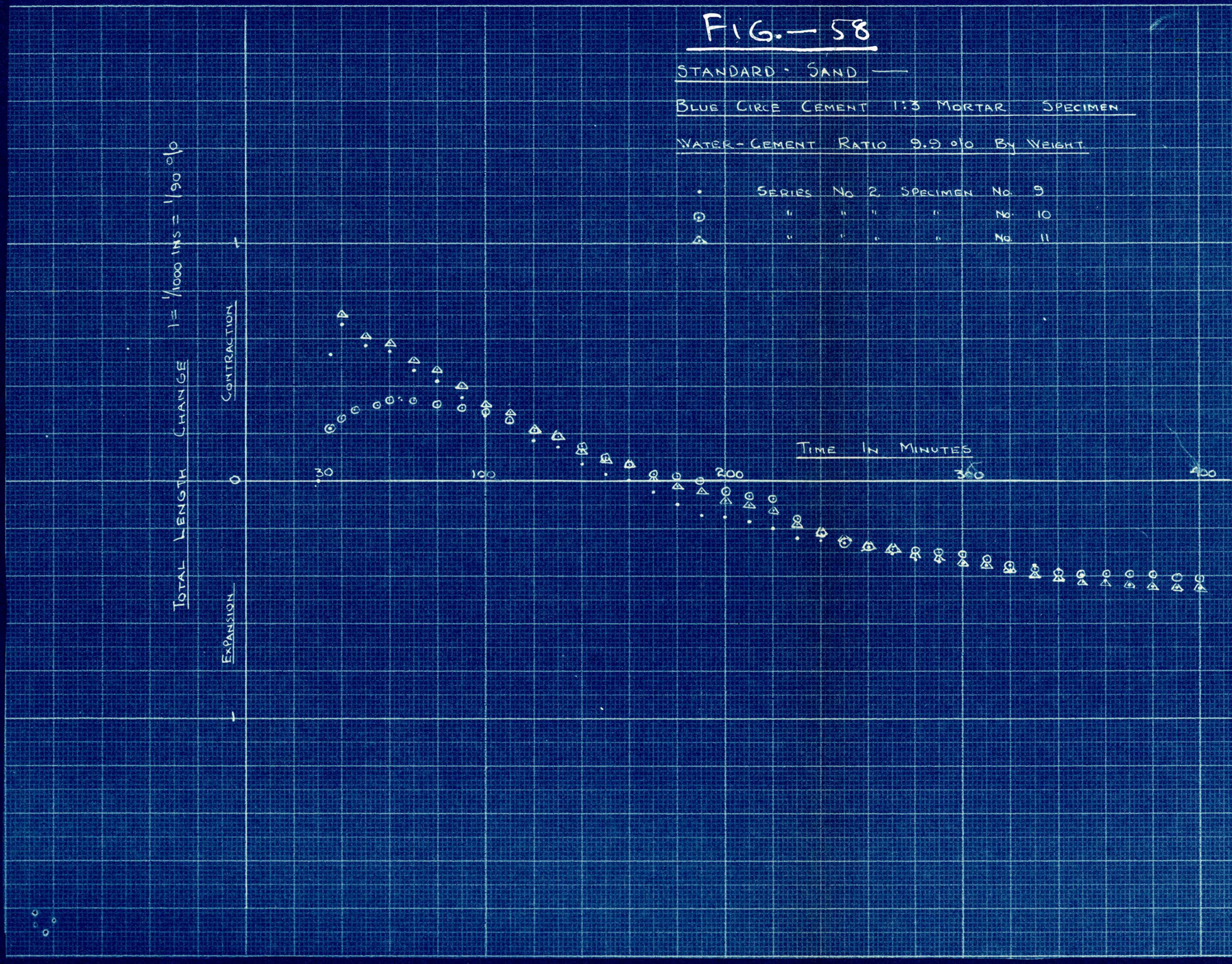


FIG.— 58

STANDARD · SAND —

BLUE CIRCE CEMENT 1:3 MORTAR SPECIMEN

WATER-CEMENT RATIO 9.9 o/o BY WEIGHT.



TIME IN MINUTES

0 30 100 200 300 400

1 2 3 4 5

TOTAL LENGTH CHANGE. 1 = 1/1000 IN = 1/90 %.

EXPANSION.

FIG. – 59

BLUE CIRCLE CEMENT — STANDARD SAND

1:3 MORTAR.

WATER – CEMENT RATIO 5.9 % BY WT.

- SERIES No. 2 SPECIMEN No. 12
- ⊙ " " " " " 13
- △ " " " " " 14
- × " " " " " 15

FIG. — 60

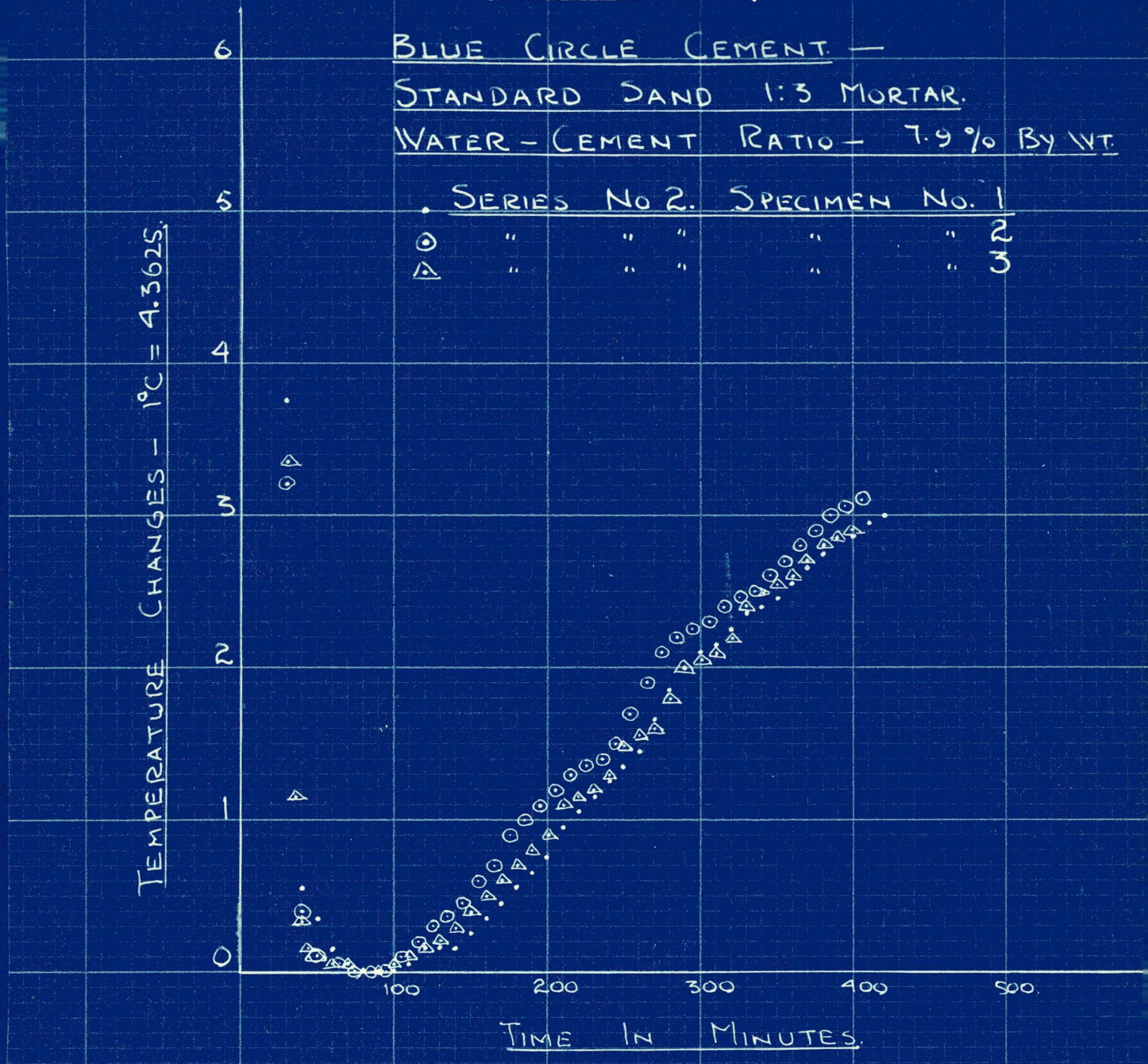

BLUE CIRCLE CEMENT —
STANDARD SAND 1:3 MORTAR.
WATER-CEMENT RATIO — 7.9 % BY WT.
SERIES NO 2. SPECIMEN NO. 1
" " " " " 2
" " " " " 3
TEMPERATURE CHANGES — 1°C = 4.3625.
0
1
2
3
4
5
6
100
200
300
400
500
TIME IN MINUTES.

Fig. – 61

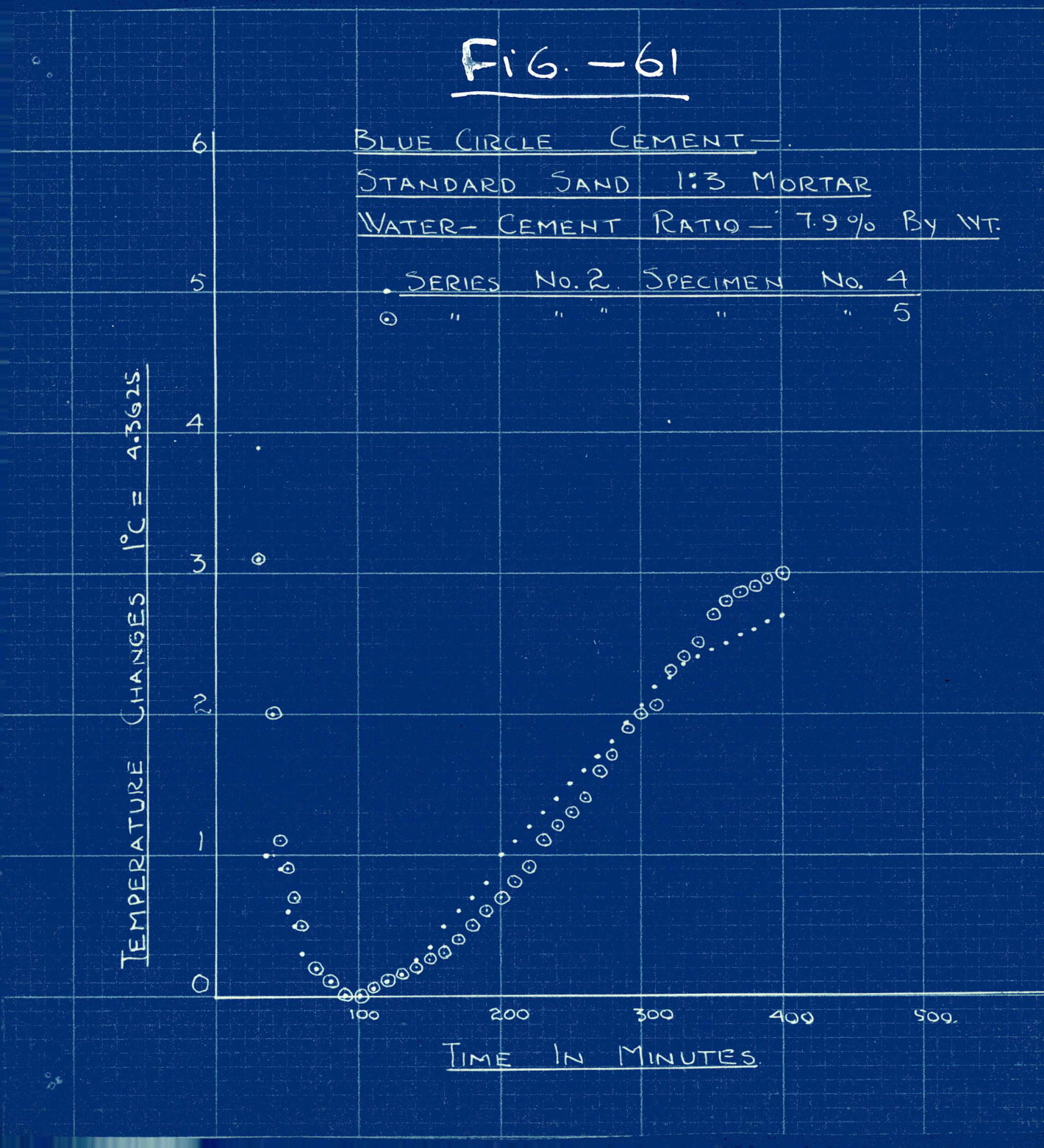

Blue Circle Cement –
Standard Sand 1:3 Mortar
Water – Cement Ratio – 7.9% By Wt.
Series No. 2. Specimen No. 4
" " " " 5
Temperature Changes 1°C = 4.3625
0
1
2
3
4
5
6
100
200
300
400
500
Time In Minutes

FIG. — 62

BLUE CIRCLE CEMENT —
STANDARD SAND 1:3 MORTAR.
WATER — CEMENT RATIO — 9.9% BY WT.
○ SERIES No. 2 SPECIMEN No. 6
· " " " " " 7
△ " " " " " 8

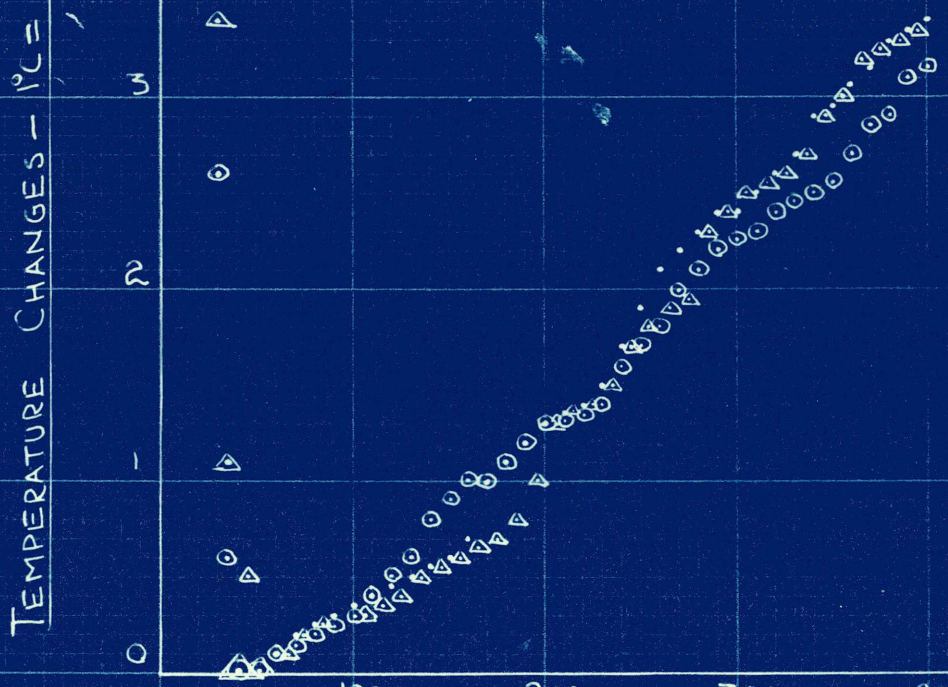
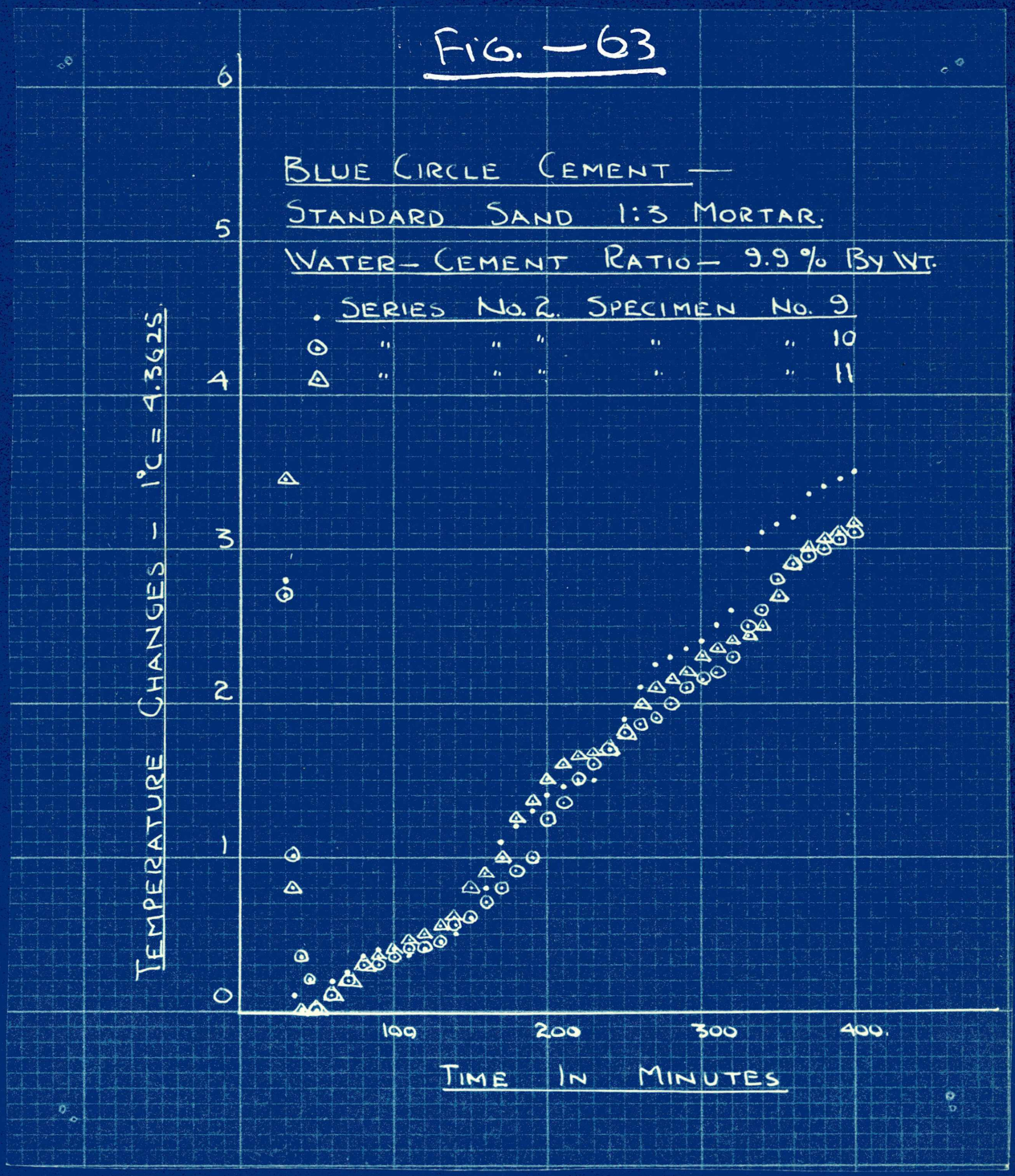
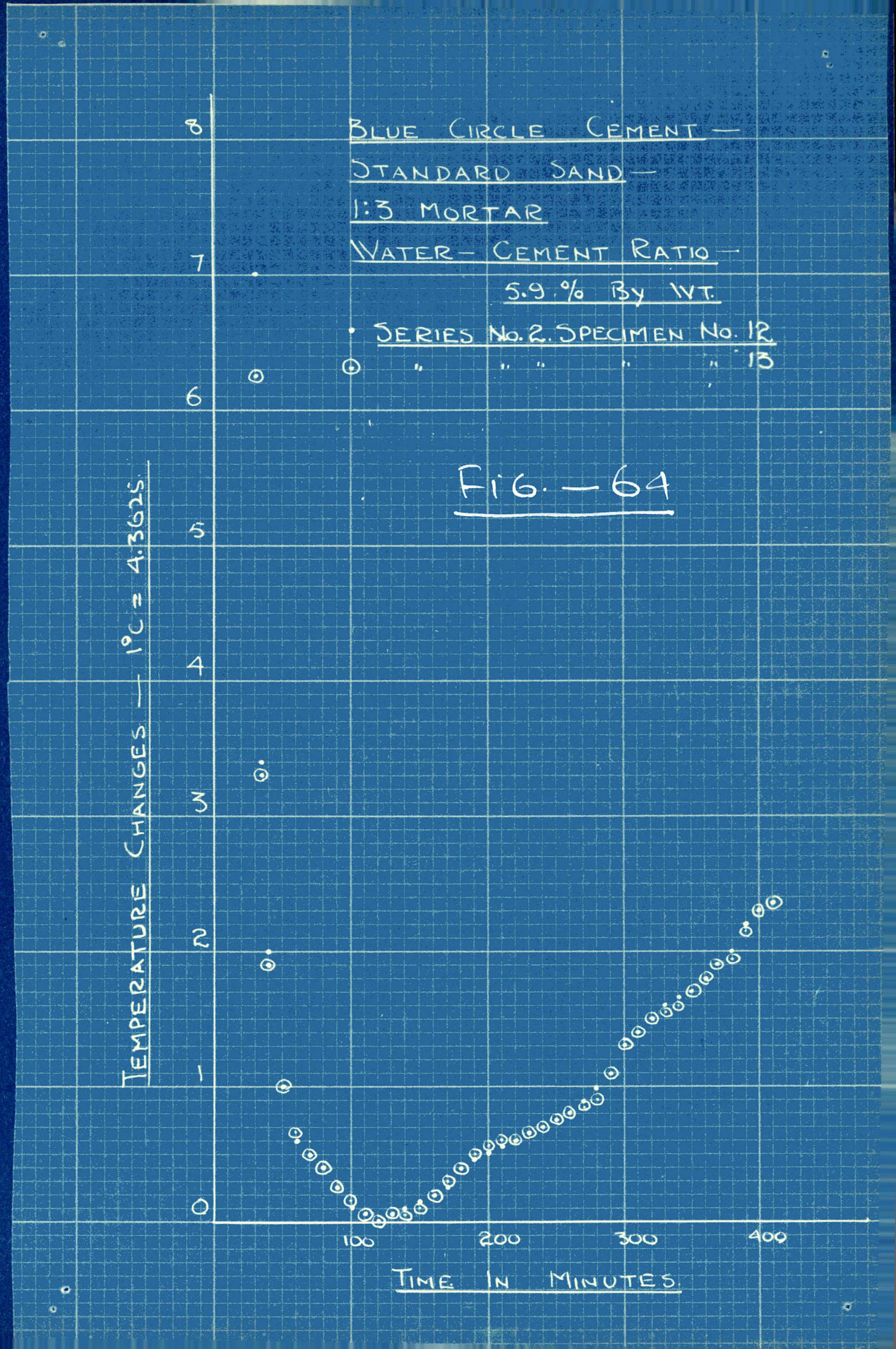


FIG. – 63


BLUE CIRCLE CEMENT —
STANDARD SAND 1:3 MORTAR.
WATER – CEMENT RATIO – 9.9 % BY WT.
SERIES No. 2. SPECIMEN No. 9
" " " " " 10
" " " " " 11
TEMPERATURE CHANGES – 1°C = 4.3625.
0
1
2
3
4
5
6
100
200
300
400.
TIME IN MINUTES


BLUE CIRCLE CEMENT —
STANDARD SAND —
1:3 MORTAR
WATER – CEMENT RATIO —
5.9 % BY WT.
SERIES No. 2. SPECIMEN No. 12
" " " " " 13
FIG. — 64
TEMPERATURE CHANGES — 1°C = 4.362S.
0
1
2
3
4
5
6
7
8
100
200
300
400
TIME IN MINUTES

BLUE CIRCLE CEMENT.—
STANDARD SAND.—
1:3 MORTAR.
WATER— CEMENT RATIO—
5.9% By Wt.
SERIES No. 2. SPECIMEN No. 14
" " " " " 15

FIG. — 65

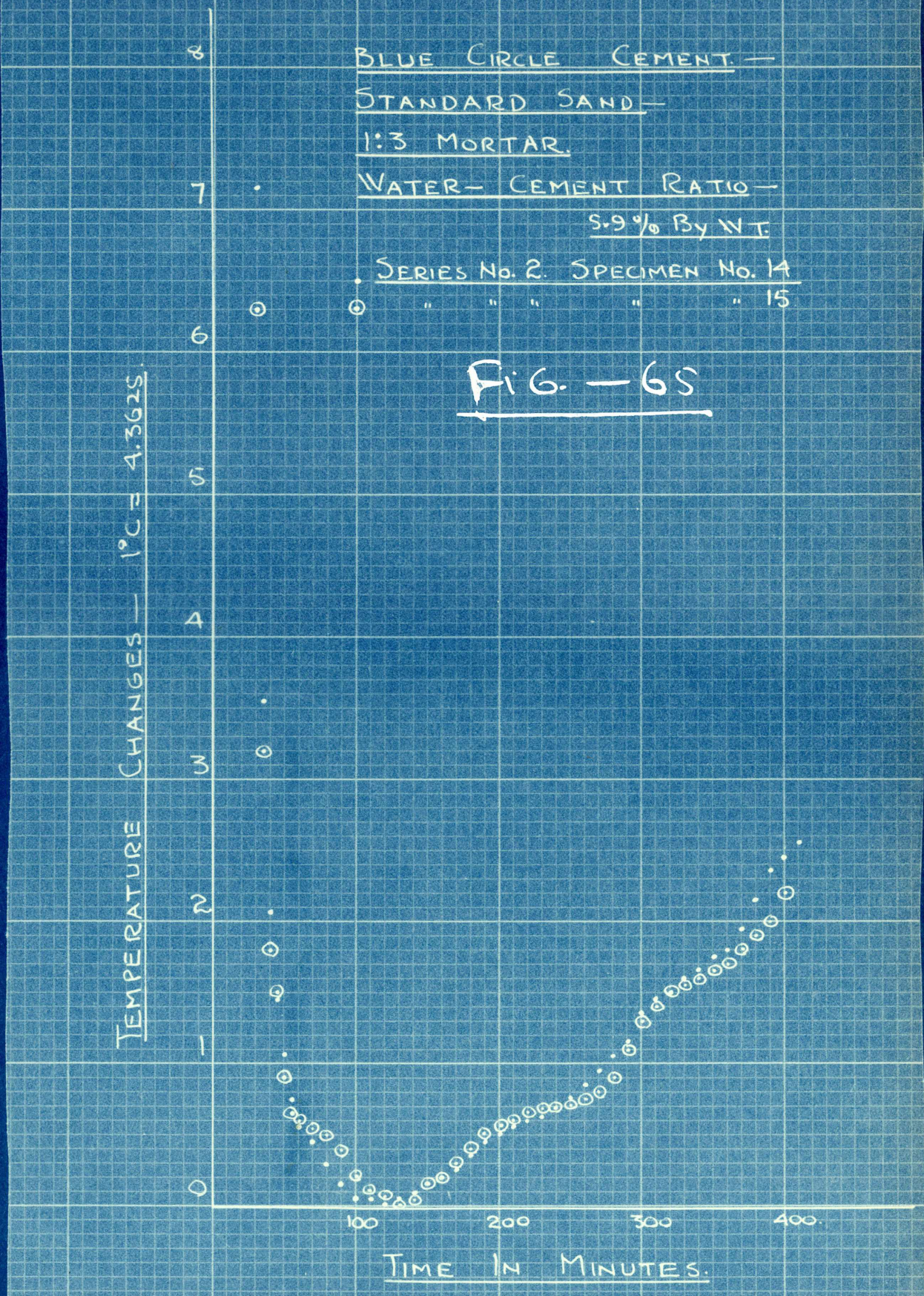


Fig.-66

FERROCRETE NEAT CEMENT.

WATER- CEMENT RATIO 23.9 % By Wt.

△ SERIES No. 3 SPECIMEN No. 1

○ " " " " " 2

• " " " " " 3

◎ " " " " " 4

RATE OF LENGTH CHANGES 1= 1/1000 IN = 1/90 %

EXPANSION

CONTRACTION

INITIAL SETTING TIME

FINAL SETTING TIME

8 7 6 5 4 3 2 1 0 1 2

30 100 200 300 400

TIME IN MINUTES

Fig.—67

FERROCRETE NEAT CEMENT.

WATER—CEMENT RATIO— 25.9 % BY WT.

- □ SERIES No. 3 SPECIMEN No. 5
- △ " " " " " 6
- ⊙ " " " " " 7
- • " " " " " 8

RATE OF LENGTH CHANGES 1 = 1/1000 IN = 1/90 %

CONTRACTION

EXPANSION.

7 6 5 4 3 2 1 0 1

30 100 200 300 400

TIME IN MINUTES.

FIG.—68

FERROCRETE NEAT CEMENT.

WATER-CEMENT RATIO 21.9% BY WT.

⊙ SERIES No. 3. SPECIMEN No 9.
• " " " " " 10
◇ " " " " " 11
△ " " " " " 12

RATE OF LENGTH CHANGES

CONTRACTION.

1" = 1/1000 IN = 1/90 %

EXPANSION

TIME IN MINUTES

0 1 2 3 4 5 6 7 8 9

30 100 200 300

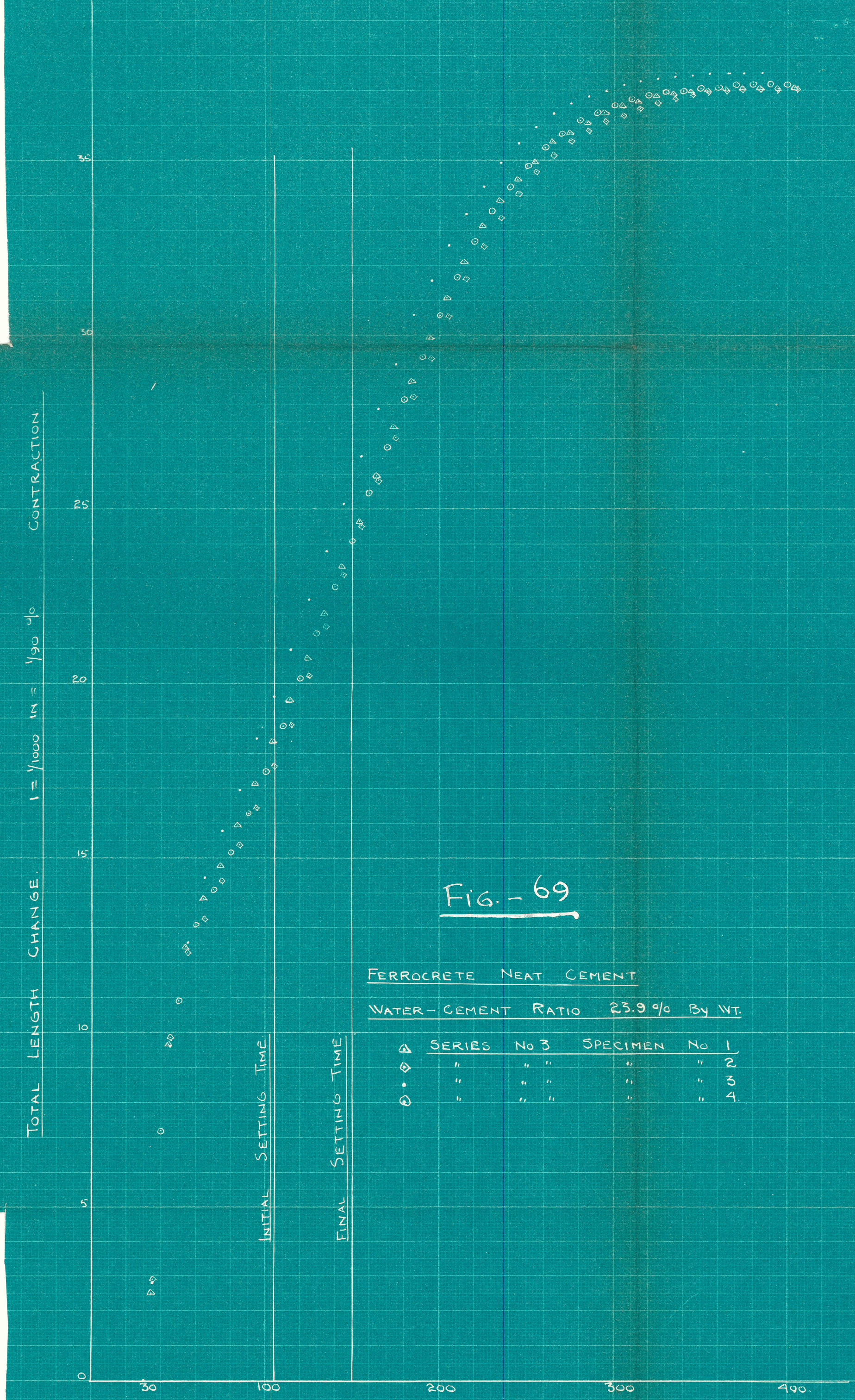


FIG. - 69

FERROCRETE NEAT CEMENT

WATER - CEMENT RATIO 23.9 % BY WT.

△ SERIES No 3 SPECIMEN No 1
◇ " " " " 2
• " " " " 3
○ " " " " 4.

BRITISH MADE

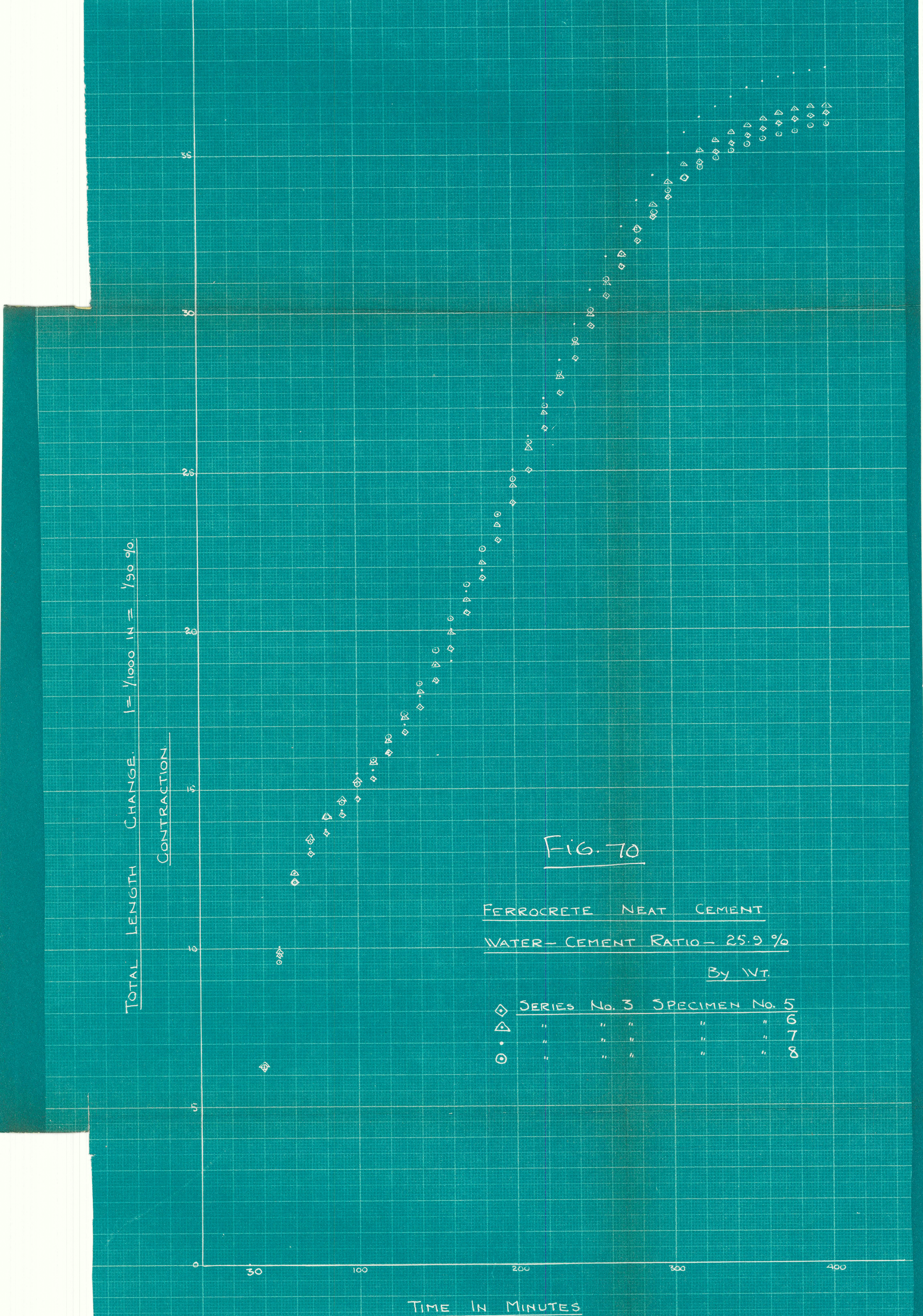


Fig. 70

FERROCRETE NEAT CEMENT

WATER – CEMENT RATIO – 25.9 %

By Wt.

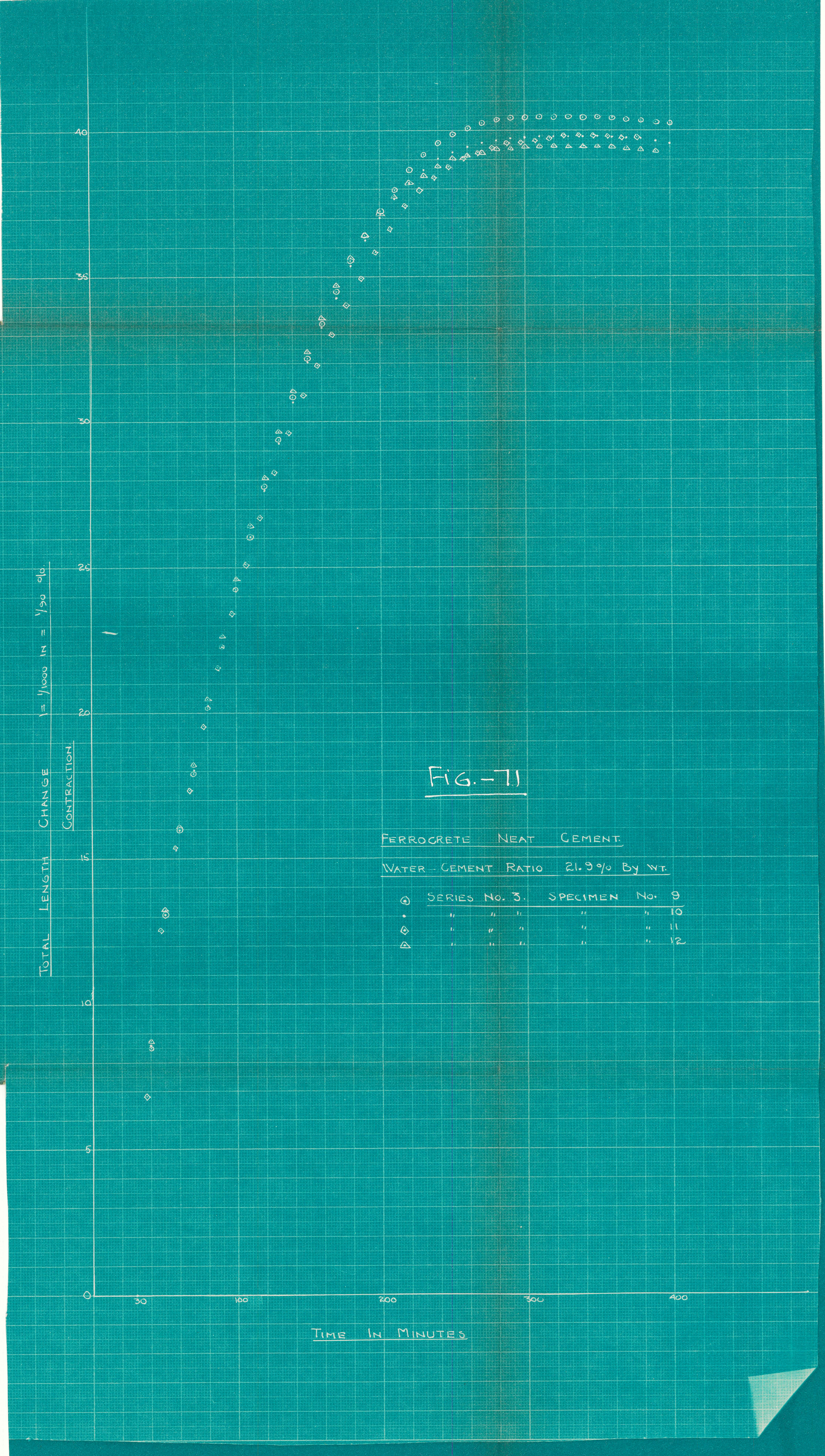


FIG.-71

FERROCRETE NEAT CEMENT.

WATER - CEMENT RATIO 21.9% BY WT.

- ◎ SERIES NO. 3. SPECIMEN NO. 9
- • " " " " " 10
- ◈ " " " " " 11
- △ " " " " " 12

reproducibility of the points in the curves justifies the assumption that the specimens were effectively protected by the cellophane envelope from the temperature and humidity changes of the surrounding air.

Series No. 2. Specimens Nos. 1 to 15.

Series No. 2 consisted of Blue Circle- Standard sand - 1:3 mortars with 7.9%, 9.9% and 5.9% water-cement ratios by weight.

Figs. 50 & 51 show the rate of length changes in ten minutes of specimens Nos. 1 to 5 with 7.9% water-cement ratio by weight. The movements in the case of the mortar being small, they are plotted on a bigger scale. No break is observable in this curve. The mortar expands from the beginning and the rate of expansion decreases steadily. The rate of expansion is about 3/900% in ten minutes at 35 minutes and 3/9000% in ten minutes at 400 minutes.

Figs. 52 & 53 show the rate of length changes of the specimens Nos. 6 to 11 with 9.9% water-cement ratio by weight. In this case, it is observed that the mortar contracts in the initial stages. Expansion starts at about 60 minutes. The initial contraction in one case was 3/900%, 4/900% in two cases, and 7/900% in two cases. The maximum rate of expansion was about 1/900% in ten minutes.

Figs. 54 & 55 show the rate of length changes of specimens Nos. 12 to 15 with 5.9% water-cement ratio by weight. For these specimens the nature of the curve is similar to that of the specimens with 7.9% water-cement ratio, though much flatter. The specimens show expansion throughout. The initial rate of expansion is about 3/900% in ten minutes.

Fig. 56 shows the total length change in specimens Nos. 1 to 5 with 7.9% water-cement ratio by weight. The total expansion, taking 30 minutes reading as the datum is 27/900%.

Figs. 57 & 58 show the total length change in specimens 6 to 11 with 9.9% water-cement ratio by weight. These specimens were found to contract initially and expand later. Out of the six specimens, it is found that in the case of the specimens 6,7, and 10 the change from contraction to expansion is brought about gradually. In the case of specimens 8,9, and 11, the change is rather sharp. The contraction in all cases goes on till about 50 minutes after which the specimen starts expanding. The maximum contraction observed was 7/900%. The net effect at the end of 400 minutes with 30 minutes reading as the datum is an expansion of 1/200%.

Fig. 59 shows the total length change of specimens

Nos. 12 to 15 with 5.9% water-cement ratio by weight. The specimens expand from the beginning and the expansion at the end of 400 minutes with 30 minutes reading as a datum is 5/90%.

Figs. 60 & 61 show the temperature changes in specimens Nos. 1 to 5 with 7.9% water-cement ratio by weight. The curve has been plotted with the lowest reading obtained as 0 to show the rise and fall in temperature more clearly.

Figs. 62 & 63 show the temperature changes in Specimens Nos. 6 to 11 with 9.9% water-cement ratio by weight.

Figs. 64 & 65 show the temperature changes in Specimens Nos. 12 to 15 with 5.9% water-cement ratio by weight.

It is seen from the above figures 60 to 65 that the heat evolved in the case of the specimens with 9.9% water- cement ratio is the maximum and hence that must be the optimum percentage of water for this series. The heat evolved at 30 minutes is a little less than 1° C. which is lost very rapidly by conduction, radiation, etc. and after 45 minutes the temperature of the specimen steadily increases to about $.8^{\circ}$ C. at the end of 400 minutes. In the specimens 1 to 5, the percentage of water available for hydration is less than in the specimens 6 to 11, but the amount of water to be heated up is also

small. So in the cooling curve, the temperatures are about the same in both the cases initially, but the fall takes place a little more gradually in 7.9% specimens than in the 9.9% specimens, showing that the heat evolution in 7.9% specimens is less than in 9.9% specimens as the nature of the cooling curve depends upon the heat evolved. The rise at the end of 400 minutes is also less, being about .7° C. in the case of 7.9% specimens. In the case of the specimens 12 to 15, the temperature ~~rise~~ at 30 minutes is higher than in the other two cases as the heat evolved being much smaller, the cooling curve is more gradual. The rise in temperature at the end of 400 minutes in 5.9% specimens is only .5° C. No radiation correction being possible, and the temperature rise being so small, and the value of the coefficient of thermal expansion of mortars with different percentages of water not being correctly known, no temperature correction has been applied to the length change readings.

The temperature and humidity changes in the surrounding air are shown in Table XLI.

TABLE XLI.

Temperature and Humidity Variations - Series No. 2.

Specimen no.	Temperature °F.	Degree of Humidity-Saturation = 100
1	57.5 - 59.0	55.8 - 57.8
2	57.5 - 59.4	57.8 - 62.6
3	60.9 - 61.6	67.1 - 72.0
4	60.4 - 62.0	67.0 - 70.3
5	60.0 - 61.0	71.5 - 73.0
6	53.0 - 54.0	59.0
7	55.0 - 56.3	57.2 - 61.0
8	55.6 - 57.0	59.0 - 62.6
9	56.9 - 58.2	66.4 - 70.0
10	58.4 - 60.1	66.1 - 74.0
11	59.95- 61.1	66.6 - 71.5
12	51.0 - 58.9	75.0 - 80.0
13	55.0 - 56.8	72.0 - 78.6
14	61.4 - 62.4	76.5 - 79.0
15	62.6 - 63.5	75.5 - 79.0

The maximum temperature variation was about 2°F. and humidity variation has been about 6 degrees during the whole test period for a specimen. For the whole series, the temperature ranged from 53.0° F. to 63°F. and the humidity variation has been from 55.8% to 80%. The reproducibility of the points in the curves justifies the assumption that the specimens were effectively protected by the cellophane envelope from the temperature and humidity changes of the surrounding air.

FIG. 72

FERROCRETE NEAT CEMENT.
WATER-CEMENT RATIO – 23.9 %.
SERIES No. 3 SPECIMEN No. 1.
" " " " " " 2
" " " " " " 3
" " " " " " 4.

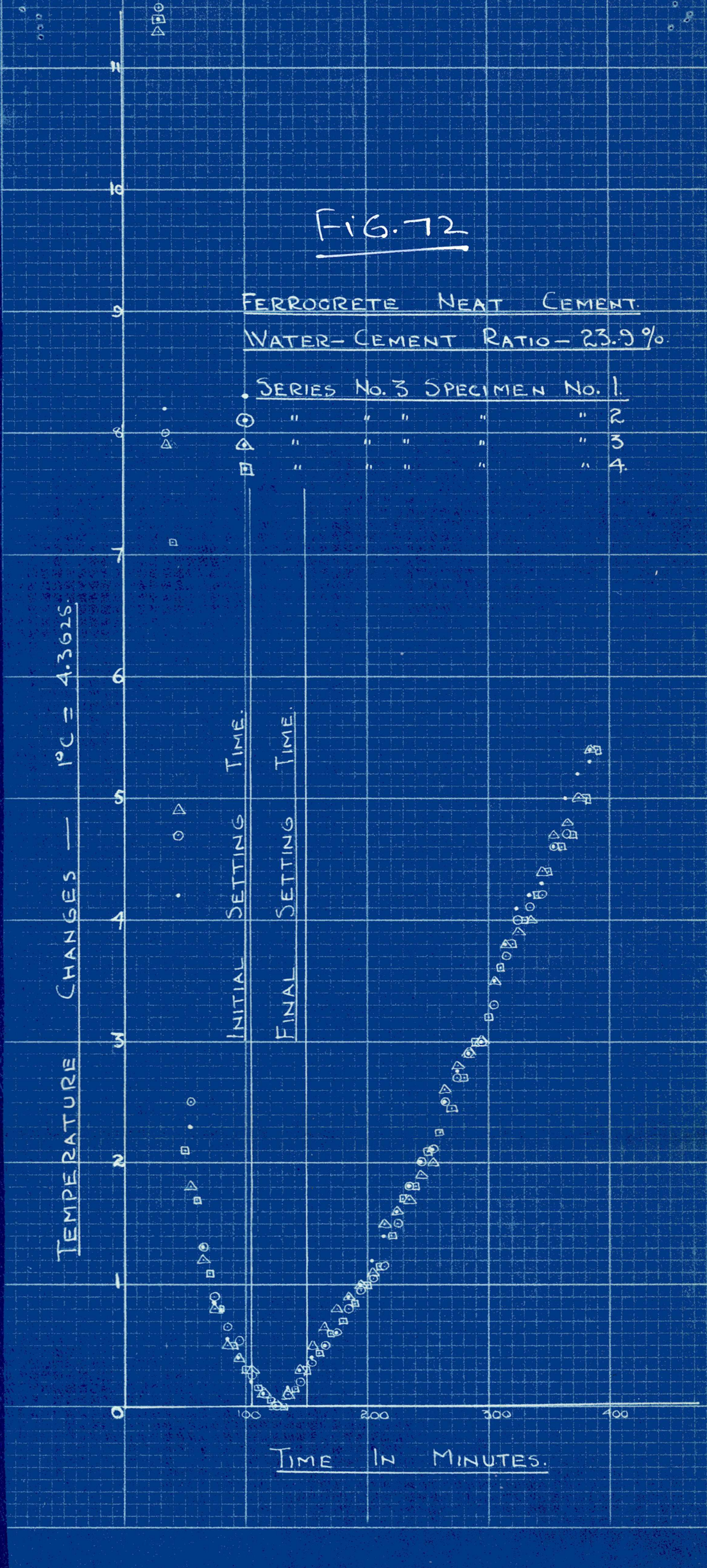


FIG-73

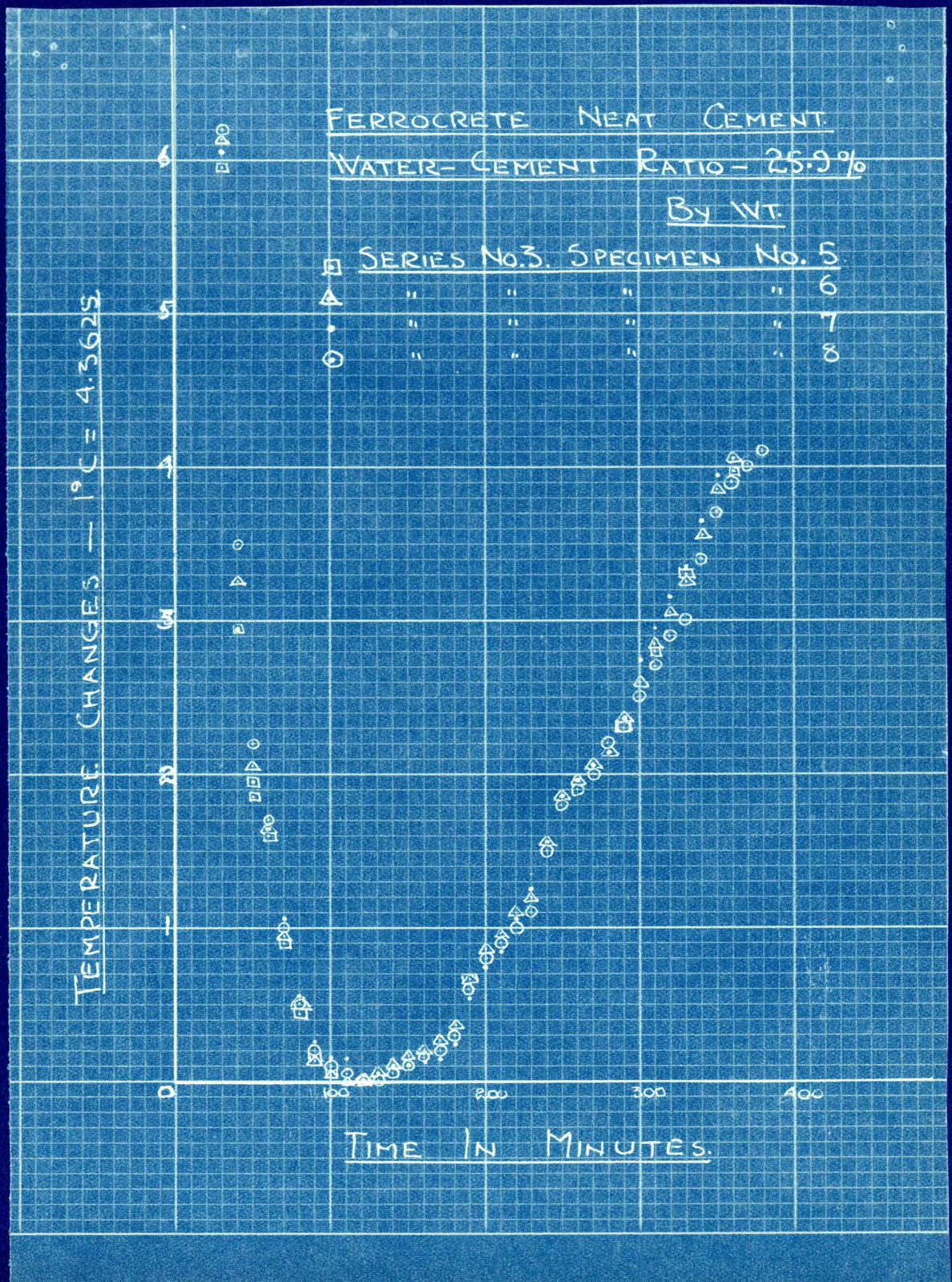
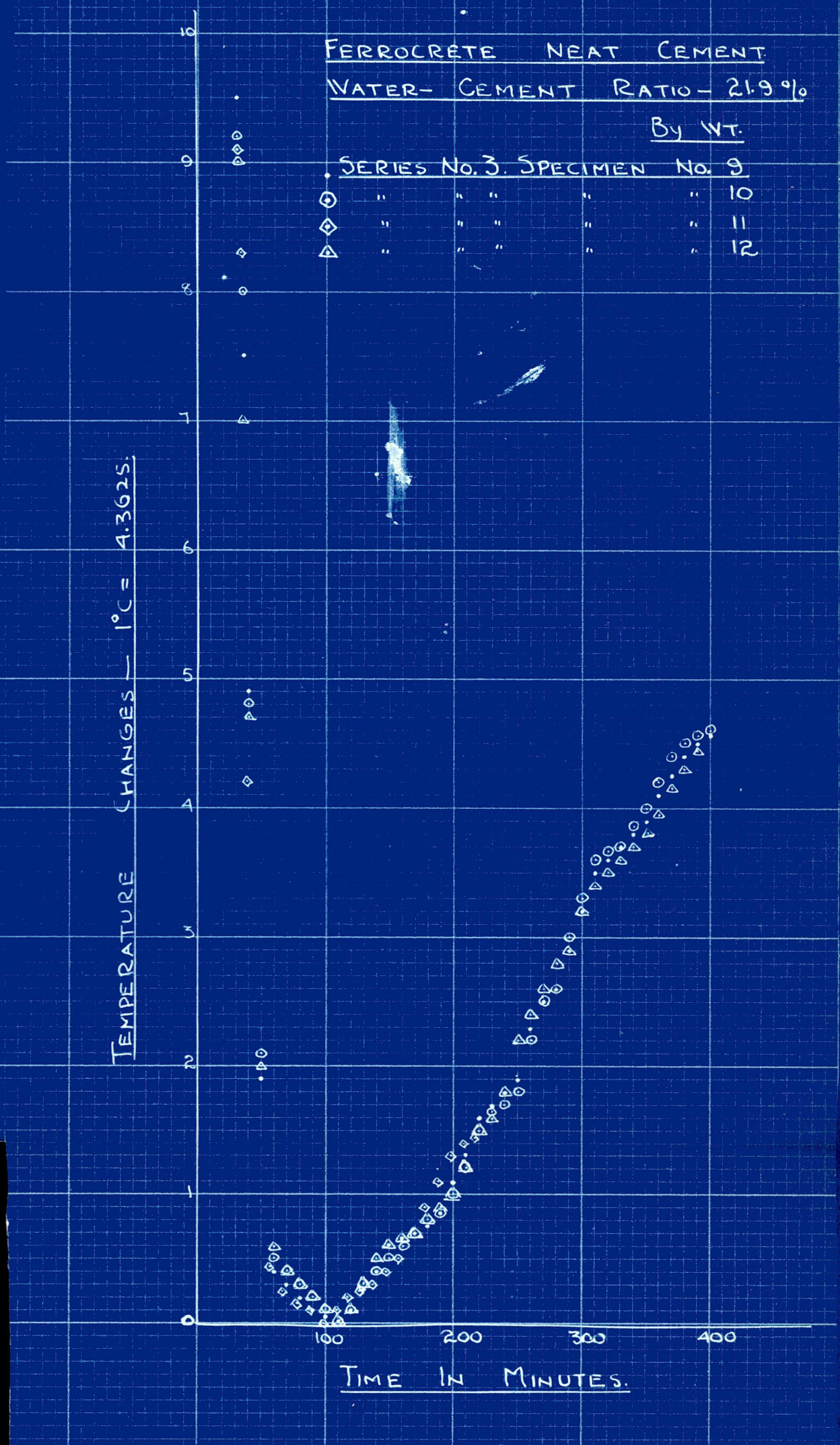

FERROCRETE NEAT CEMENT.
WATER-CEMENT RATIO - 25.9%
BY WT.
SERIES No.3. SPECIMEN No. 5.
" " " " 6
" " " " 7
" " " " 8
TEMPERATURE CHANGES — 1°C = 4.3625
0
1
2
3
4
5
100
200
300
400
TIME IN MINUTES.

FIG-74



BRITISH MADE

Series No.3. Specimens Nos. 1 to 12.

Fig. 66 shows the rate of length changes in ten minutes of specimens Nos. 1 to 4 with water-cement ratio 23.9% by weight. This percentage of water was obtained by the Vicat-needle test as specified by B.S.Specification No.12 (1931), for the normal consistency of cement. The initial setting time of this cement was 105 minutes and the final setting time was 150 minutes according to the Vicat-needle test. A break in the above curve is observed at 60 minutes, but there is no break in the curve near the initial setting time according to the Vicat-needle. The rate of shrinkage decreases till about 50 minutes after which it steadily increases till 140 minutes which is near the final setting time line according to the Vicat-needle test. After reaching this peak, the rate of contraction steadily decreases reaching 0 at 400 minutes. The maximum rate of contraction observed has been 7/90% in ten minutes at 40 minutes, which falls to 1/90% in ten minutes at 60 minutes, rising again to 1.4/90% in ten minutes at 140 minutes after which it steadily falls.

Fig.67 shows the rate of length changes in ten minutes of specimens 5 to 8 with 25.9% water-cement ratio by weight. The rate of shrinkage at 35 minutes is 6.3/90% in ten minutes which falls to about .5/90% in

ten minutes at 100 minutes. After this it steadily rises to 1.2/90% in ten minutes at 200 minutes. It decreases steadily after this reaching about 5/9000% in ten minutes at 400 minutes. A similar phenomenon to that observed in specimen No.4, Series No.1, was observed with specimen No.7. The rate of shrinkage suddenly increased from 5/900% in ten minutes to 12/900% in ten minutes at 95 minutes, falling suddenly to 1/900% in ten minutes at 105 minutes, after which the rest of the points follow the general nature of the curve. A repetition of this phenomenon was observed again at 180 minutes in the same specimen. No possible explanation can be suggested as it has only been observed in one or two cases.

Fig. 68 shows the rate of length changes in ten minutes of specimens Nos. 9 to 12 with 21.9% water-cement ratio. The initial rate of shrinkage is 8.7/90% in ten minutes at 35 minutes which falls to about 2/90% in ten minutes at 60 minutes. After this it rises a little for a very short time reaching 2.3/90. in ten minutes at 75 minutes after wh ich it steadily falls, reaching 0 at 300 minutes. Expansion starts at this stage and the rate of expansion in ten minutes is 5/900% at 400 minutes.

Fig. 69 shows the total length change of specimens 1 to 4 with 23.9% water-cement ratio with 30 minute reading as a datum. The contraction increases rapidly

in the initial stage reaching 12.5/90% at 55 minutes. After this the rate of increase becomes a little slower reaching 36.5/90% at 300 minutes. The curve then becomes much flatter reaching the value 37.4/900% at 400 minutes with 30 minute reading as the datum.

Fig. 70 shows the total length change of specimens 5 to 8 with 25.9% water-cement ratio with 30 minutes reading as a datum. The contraction increases rapidly in the initial stages reaching 12/90% at 60 minutes, after which the curve becomes a little flatter than in the initial stages;the total contraction reached at 140 minutes is 17.5/90% . After this the rate of contraction increases (though not reaching the value in the initial stages) and the total contraction at 320 minutes is 35/90%. After this, the increase is very small, the total contraction being 36.5/90% at 400 minutes, with 30 minute reading as the datum.

Fig. 71 shows the total length change of specimens Nos.9 to 12 to be with 21.9% water-cement ratio with 30 minutes reading as the datum. The contraction increases quite rapidly reaching 39.5/90% at 260 minutes after which the curve becomes very flat, the increase is very small, the value reached at 300 minutes being 39.7/90%. Expansion starts at this stage and the final value of contraction obtained at 410 minutes is 39.5/90% with 30 minutes reading as the datum.

Fig.72 shows the temperature change curve plotted as has already been mentioned with the lowest reading obtained as the datum of specimens Nos. 1 to 4 with 23.9% of water-cement ratio by weight. Fig. 73 shows the temperature changes of specimens Nos. 5 to 8 with 25.9% water-cement ratio, and Fig. 74 shows the temperature changes of specimens Nos. 9 to 12 with 21.9% water-cement ratio.

It is seen from the above Figures 72 to 74, that 23.9% ratio of water seems to be the optimum percentage of water for this series as the heat evolved in this case is the maximum in the initial as well as the final stages. For the reasons already mentioned, with a wetter cement mix (i.e. 25.9% specimens) the heat evolved is much less initially as well as finally. Similarly with a drier cement mix (i.e. 21.9%) the heat evolved is less than that of the specimens Nos. 1 to 4 though more than that of the specimens 5 to 8 with 25.9% water-cement ratio. This is quite in agreement with what could have been expected from what has already been mentioned.

Most of the heat is lost in the initial stages and very little heat is evolved after that, the temperature rise at 410 minutes being a little more than $1^{o}C$. So, for the reasons already mentioned, no temperature correction has been applied to the shrinkage values obtained.

Table XLII shows the temperature and humidity variations during this series.

TABLE XLII.

Temperature and Humidity Variations.: Series No. 3.

Specimen No.	Temperature °F.	Degree of Humidity - Saturation = 100.
1	57 - 58.9	75 - 79.8
2	58 - 59.7	74.3 - 77
3	57.9 - 60.3	64.3 - 69.5
4	55.0 - 57.4	72.0 - 78.6
5	57.9 - 60.3	64.3 - 69.5
6	56.5 - 58.2	66 - 68.7
7	56.2 - 58.1	66.1 - 69.2
8	57.05- 58.5	67.20- 70.5
9	57.05- 58.5	67.20- 70.5
10	56.2 - 58.1	66.1 - 69.2
11	57.9 - 58.1	60.2 - 63.4
12	55.9 - 57.9	64.6 - 70.0

The temperature variation has been about 2° F. and the humidity variation about 4% for the duration of a full test period for a specimen.

For the whole series, the temperature variation has been from 55° F. to 60° F. and humidity variation from 60 degrees to 80 degrees. The reproducibility of the points in the various curves is such as to justify the assumption that the cellophane envelope provides sufficient protection to the specimen from the atmospheric temperature and humidity changes.

FIG. -75

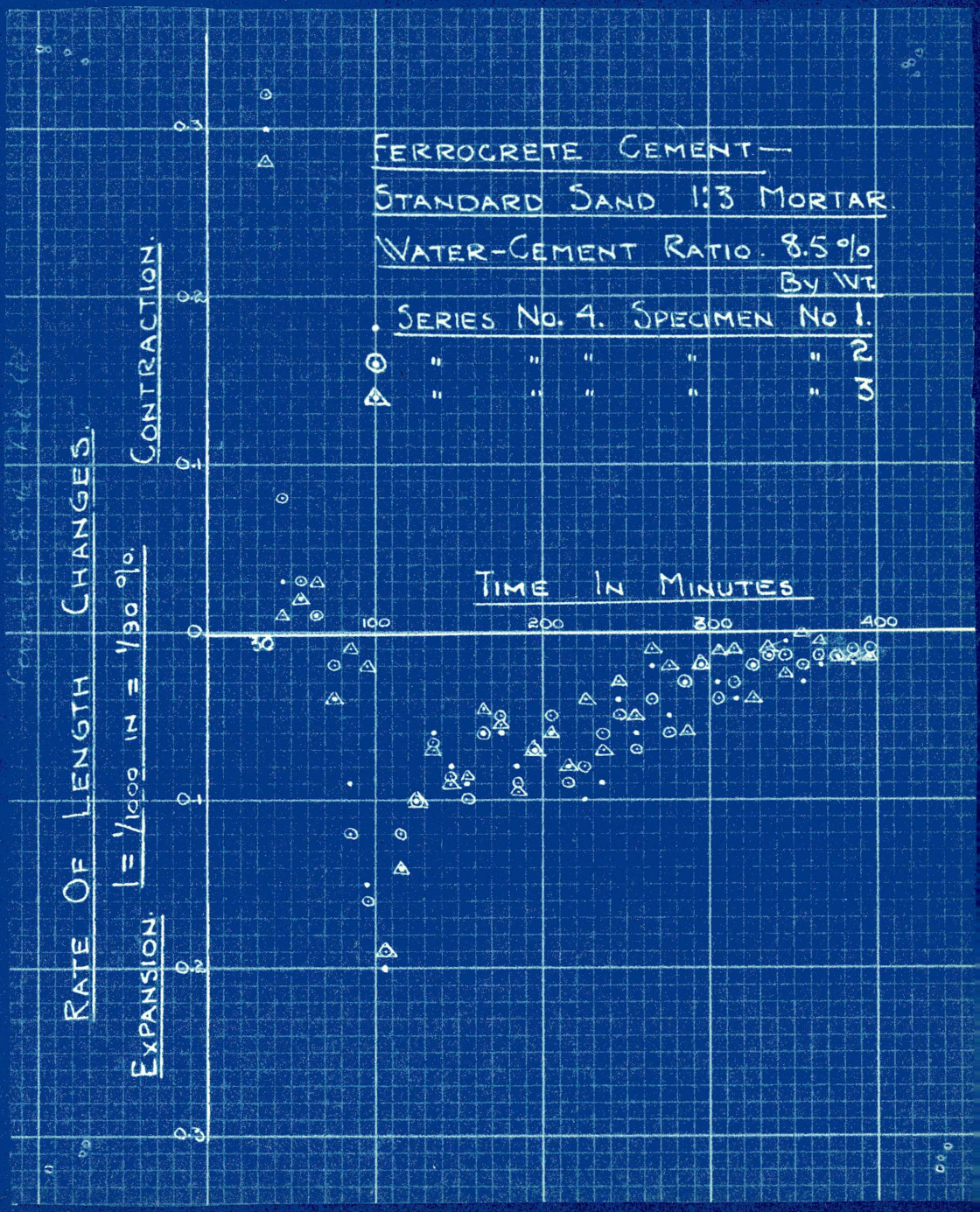
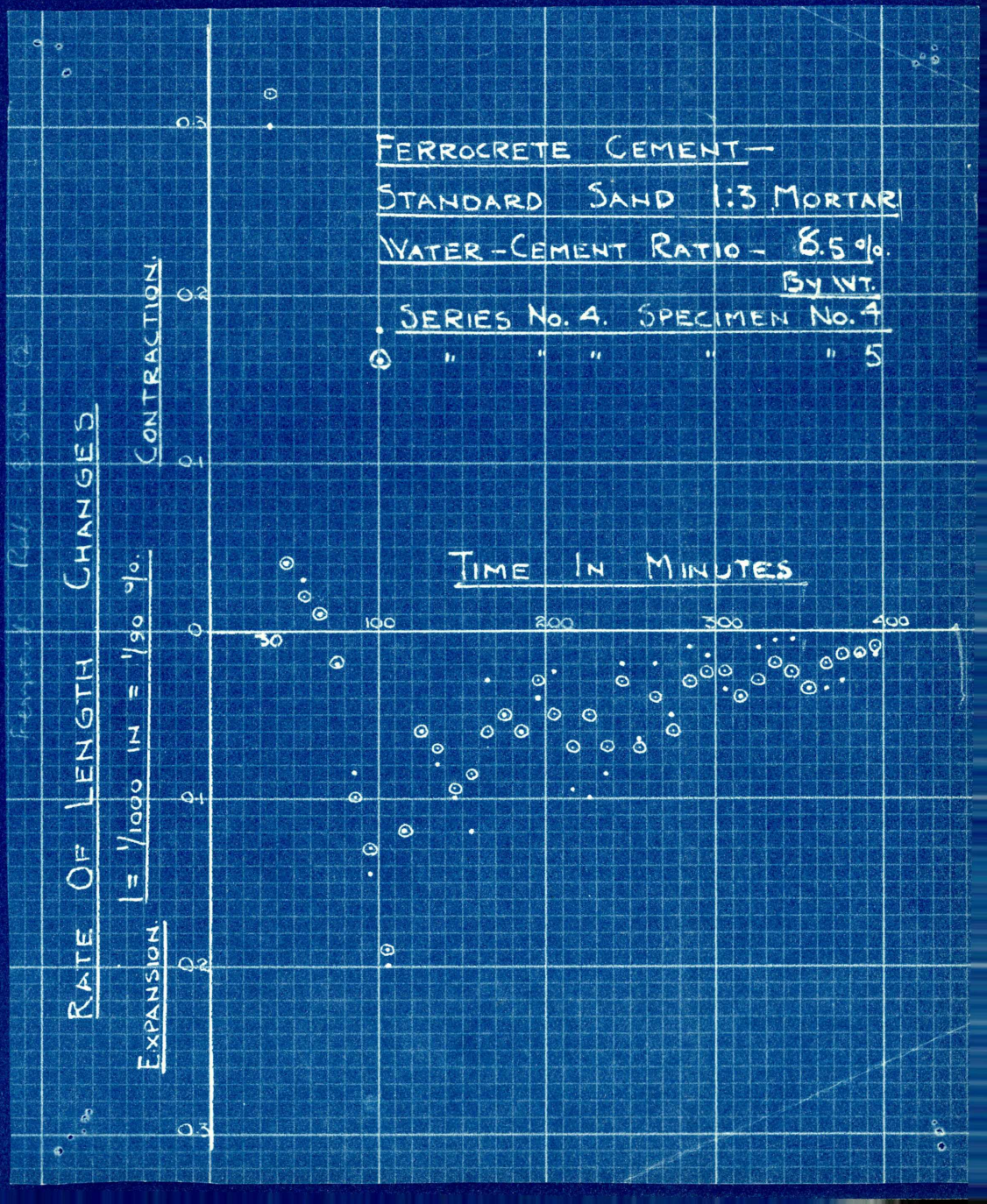

FERROCRETE CEMENT—
STANDARD SAND 1:3 MORTAR
WATER-CEMENT RATIO. 8.5 % By Wt.
SERIES No. 4. SPECIMEN No 1.
" " " " " 2
" " " " " 3
TIME IN MINUTES
30
100
200
300
400
RATE OF LENGTH CHANGES.
EXPANSION. 1 = 1/1000 IN = 1/90 %.
CONTRACTION.
0.3
0.2
0.1
0
0.1
0.2
0.3

Fig.—76


Rate Of Length Changes
Expansion. 1 = 1/1000 in = 1/90 %. Contraction.
Ferrocrete Cement—
Standard Sand 1:3 Mortar
Water-Cement Ratio - 8.5 % By Wt.
Series No. 4. Specimen No. 4
" " " " " 5
Time In Minutes
0
100
200
300
400
0.1
0.2
0.3

FERROCRETE CEMENT—
STANDARD SAND.
1:3 MORTAR.
WATER-CEMENT RATIO—
10.5 % BY WT.

• SERIES No. 4. SPECIMEN No. 9
⊙ " " " " " 10.

FIG.—78

RATE OF LENGTH CHANGES 1" = 1/1000 IN "

CONTRACTION.

EXPANSION.

1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
0.3
0.4

30
100
200
300
400

TIME IN MINUTES.

FIG. -79

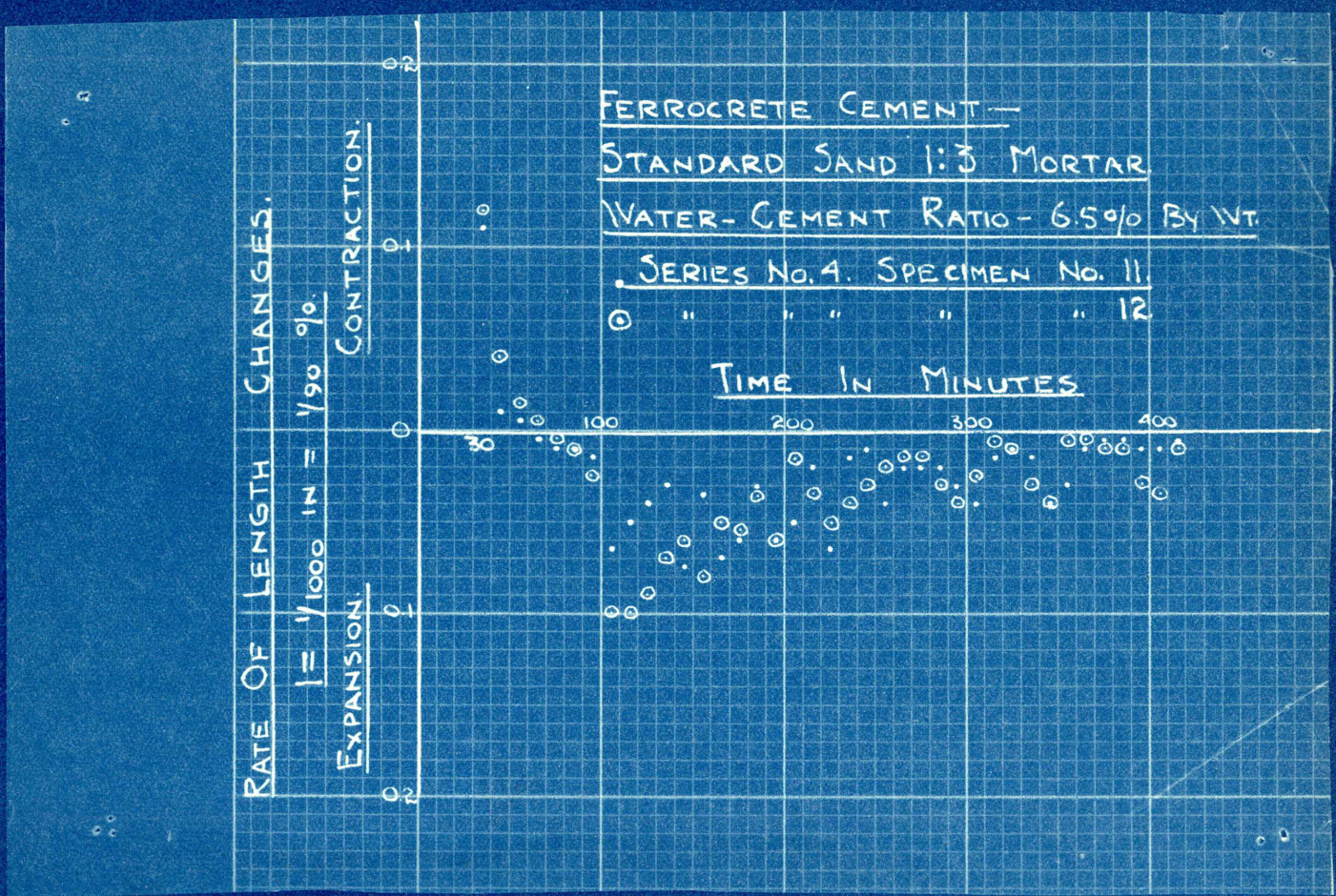
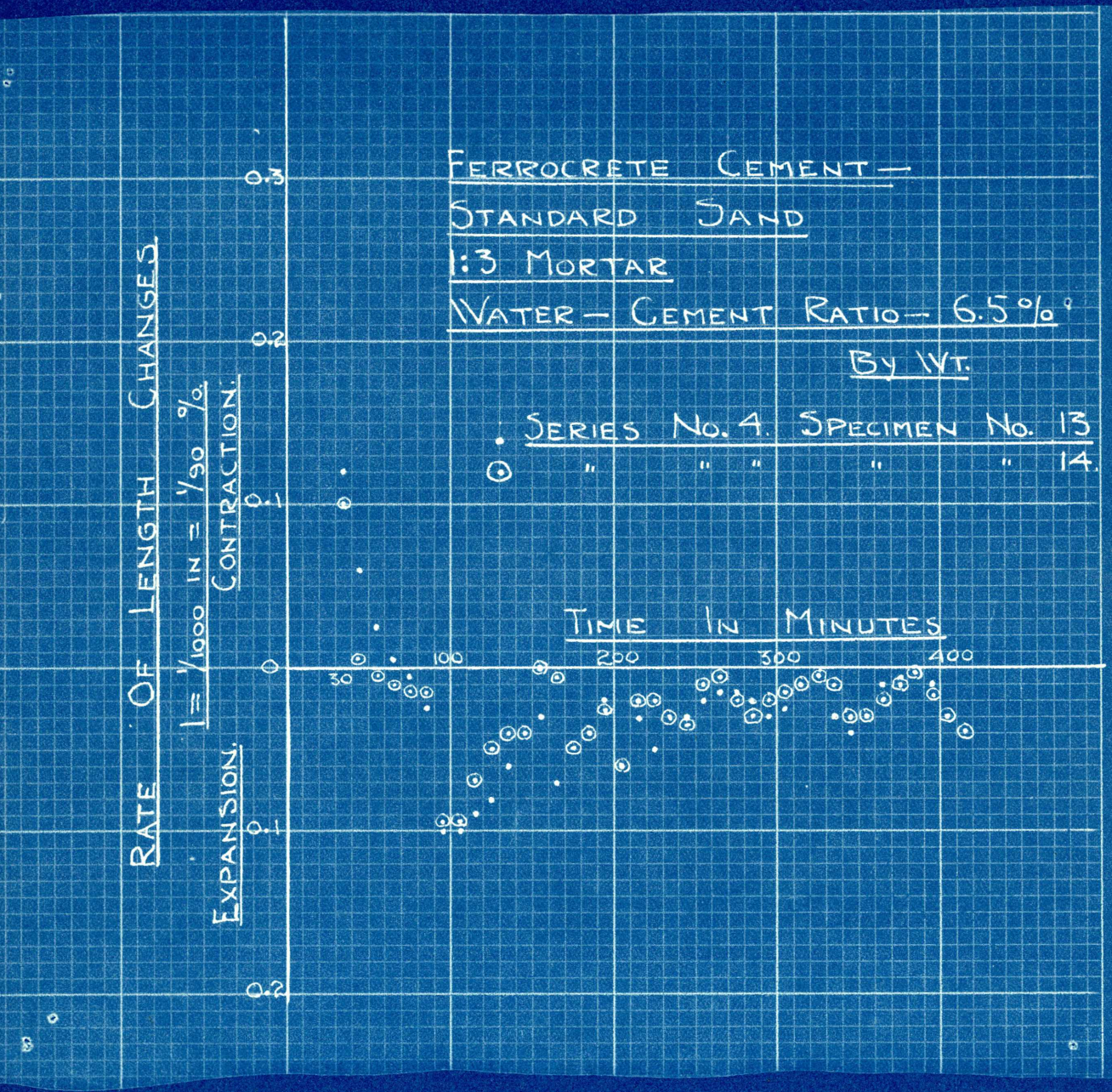

RATE OF LENGTH CHANGES.
1 = 1/1000 IN = 1/90 %.
EXPANSION.
CONTRACTION.
0.2
0.1
0
0.1
0.2
FERROCRETE CEMENT —
STANDARD SAND 1:3 MORTAR
WATER-CEMENT RATIO - 6.5% BY WT.
SERIES NO. 4. SPECIMEN NO. 11.
" " " " " 12
TIME IN MINUTES
30
100
200
300
400

FIG. — 80


FERROCRETE CEMENT —
STANDARD SAND
1:3 MORTAR
WATER — CEMENT RATIO — 6.5 %
BY WT.
SERIES No. 4. SPECIMEN No. 13
" " " " 14.
RATE OF LENGTH CHANGES
1 = 1/1000 IN = 1/90 %
EXPANSION.
CONTRACTION.
0.3
0.2
0.1
0
0.1
0.2
TIME IN MINUTES
30
100
200
300
400

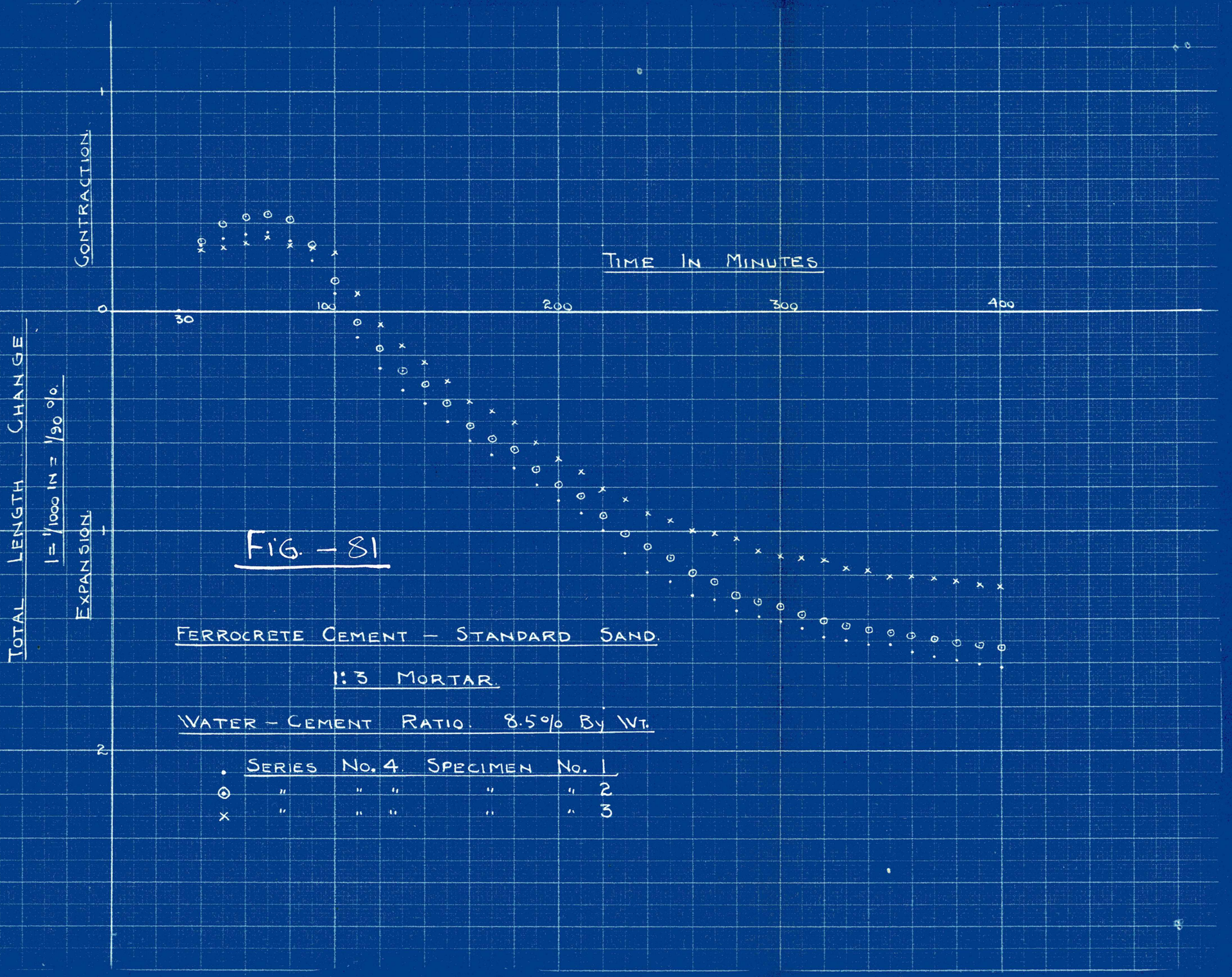


FIG. - 81

FERROCRETE CEMENT — STANDARD SAND.

1:3 MORTAR.

WATER - CEMENT RATIO. 8.5% BY WT.

. SERIES No. 4. SPECIMEN No. 1

⊙ " " " " " 2

× " " " " " 3

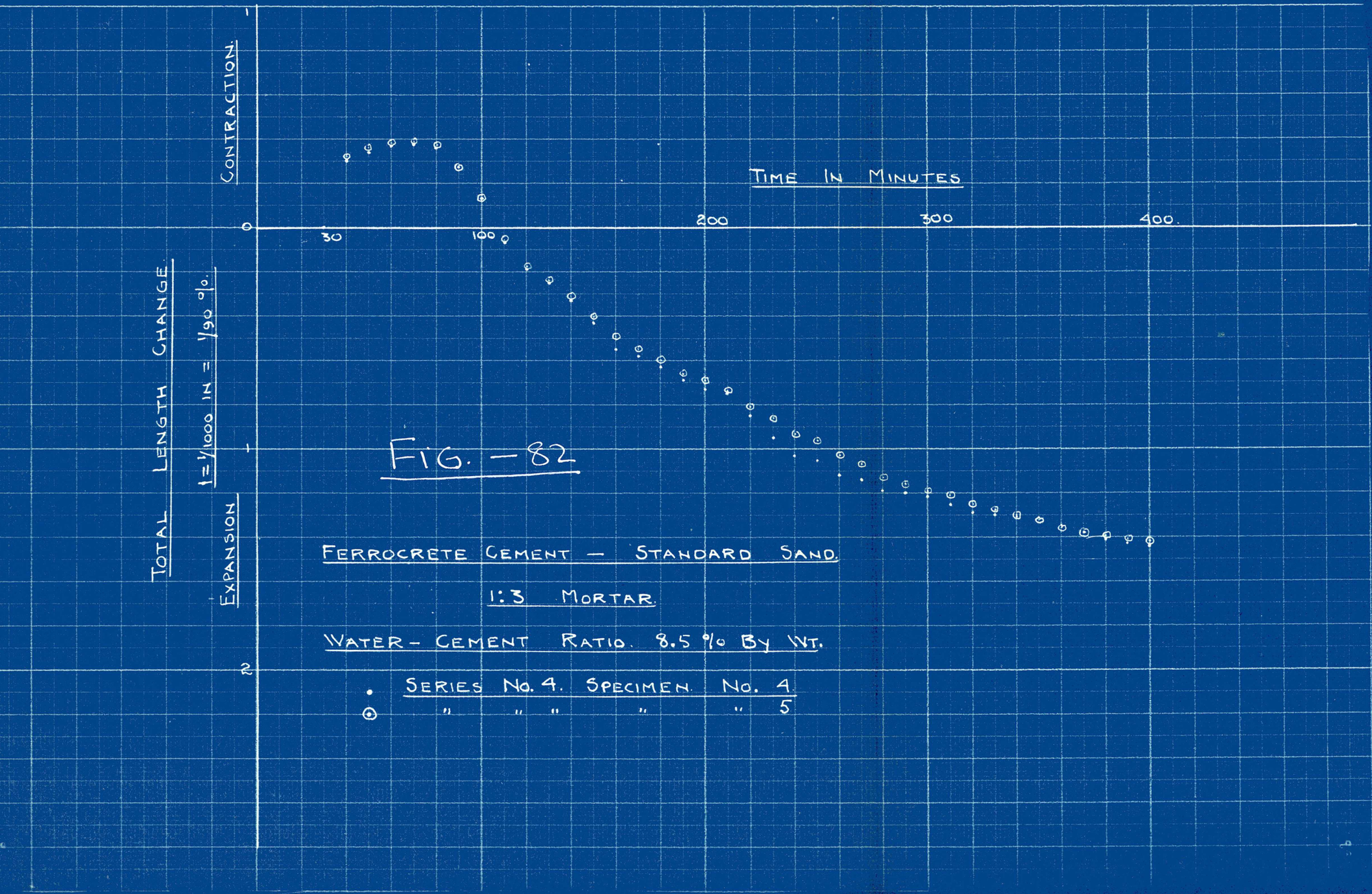


FIG. - 82

FERROCRETE CEMENT — STANDARD SAND.

1:3 MORTAR.

WATER - CEMENT RATIO. 8.5 % BY WT.

• SERIES No. 4. SPECIMEN No. 4

⊙ " " " " " 5

FIG. – 83

FERROCRETE CEMENT — STANDARD SAND.

1:3 MORTAR.

WATER – CEMENT RATIO 10.5 % BY WT.

• SERIES No. 4. SPECIMEN No. 6

⊙ " " " " " 7

△ " " " " " 8

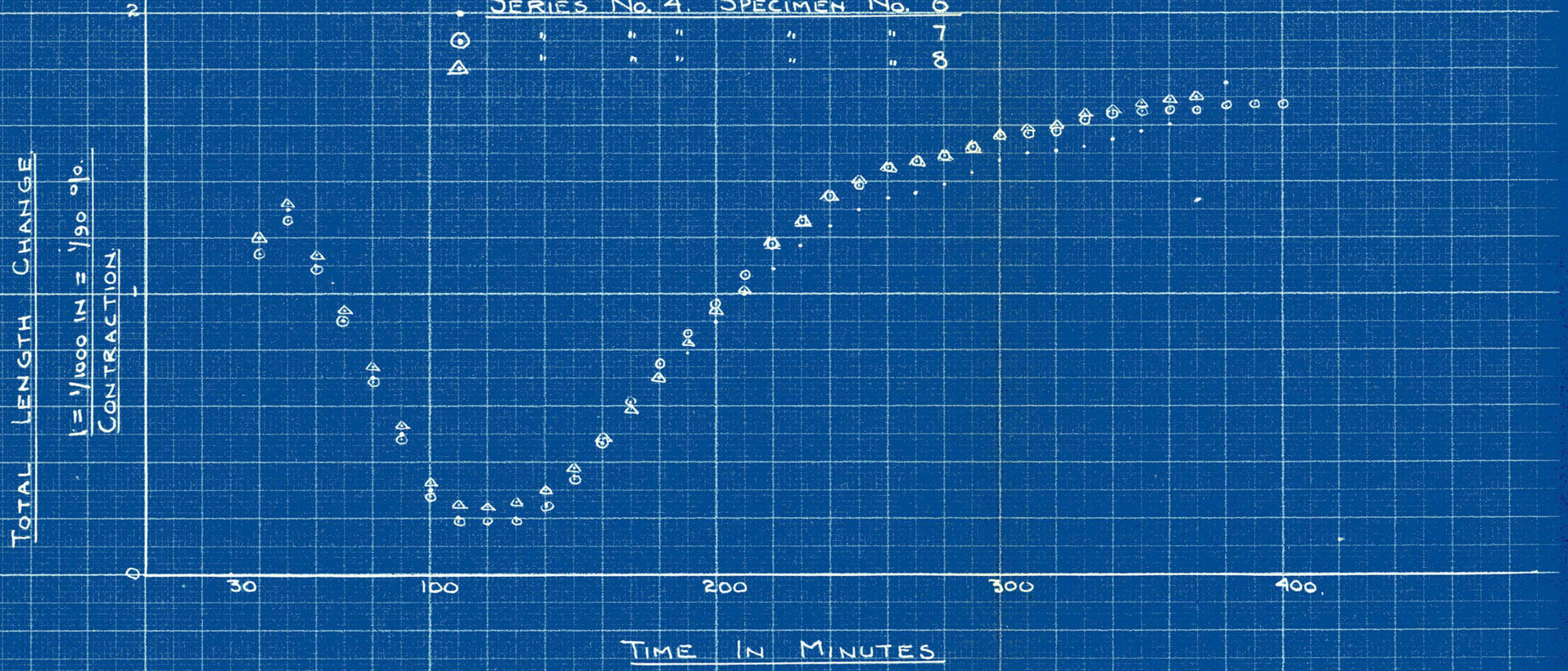


FIG. – 84

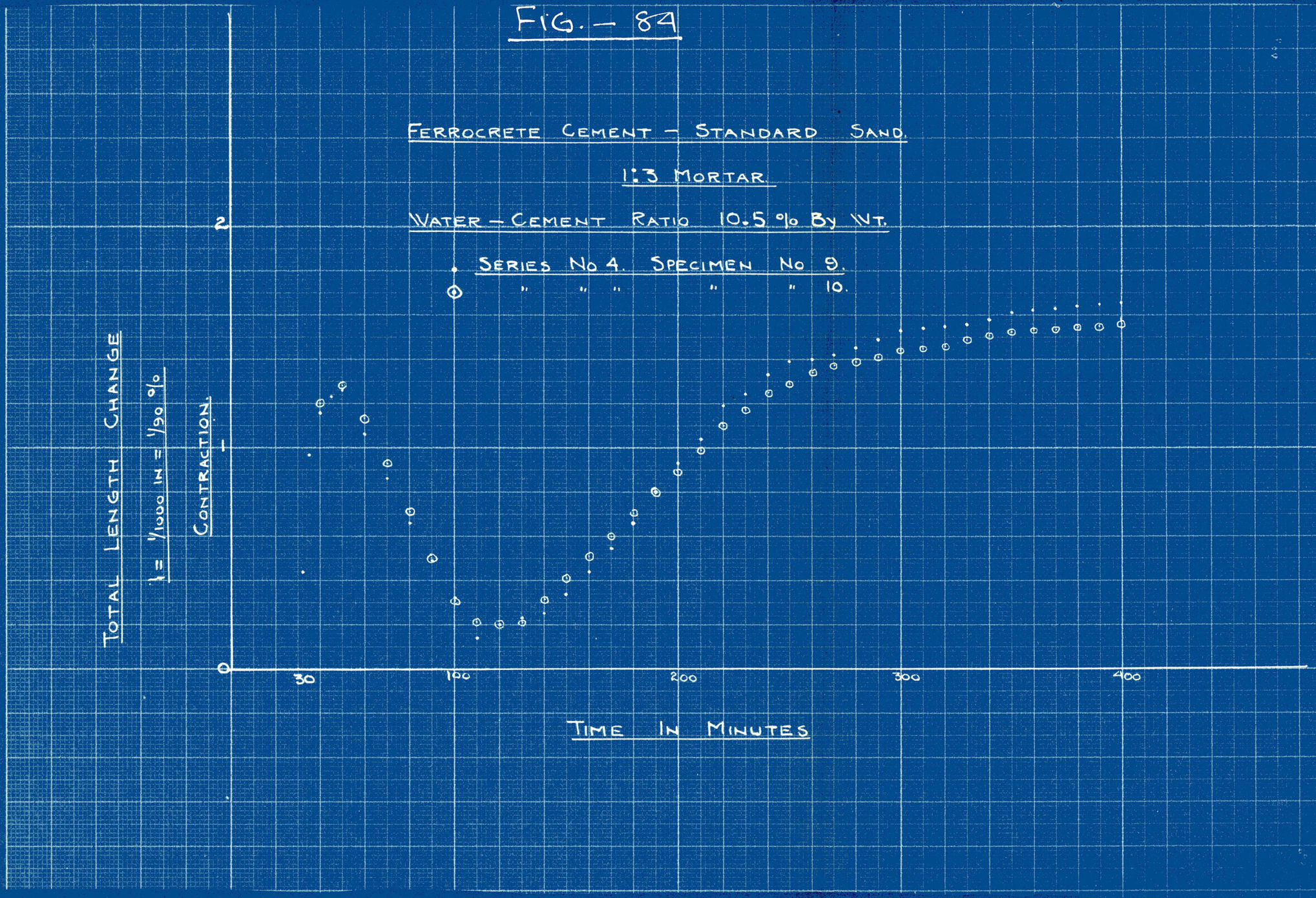

FERROCRETE CEMENT – STANDARD SAND.
1:3 MORTAR
WATER – CEMENT RATIO 10.5 % BY WT.
SERIES No 4. SPECIMEN No 9.
" " " " " 10.
TOTAL LENGTH CHANGE
1 = 1/1000 IN = 1/90 %
CONTRACTION.
2
1
0
30
100
200
300
400
TIME IN MINUTES

FIG.—85

FERROCRETE — CEMENT — STANDARD SAND

1:3 MORTAR.

WATER — CEMENT RATIO 6.5 % BY WT.

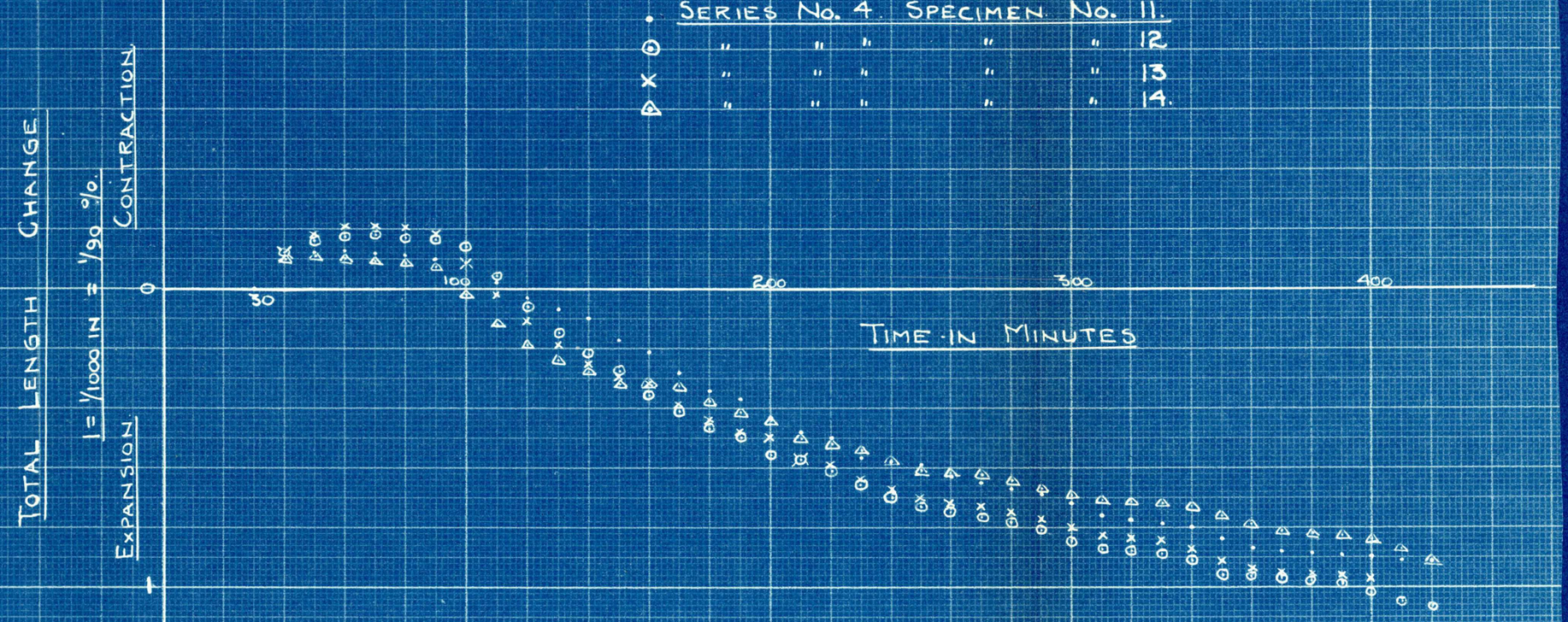


FIG. — 86

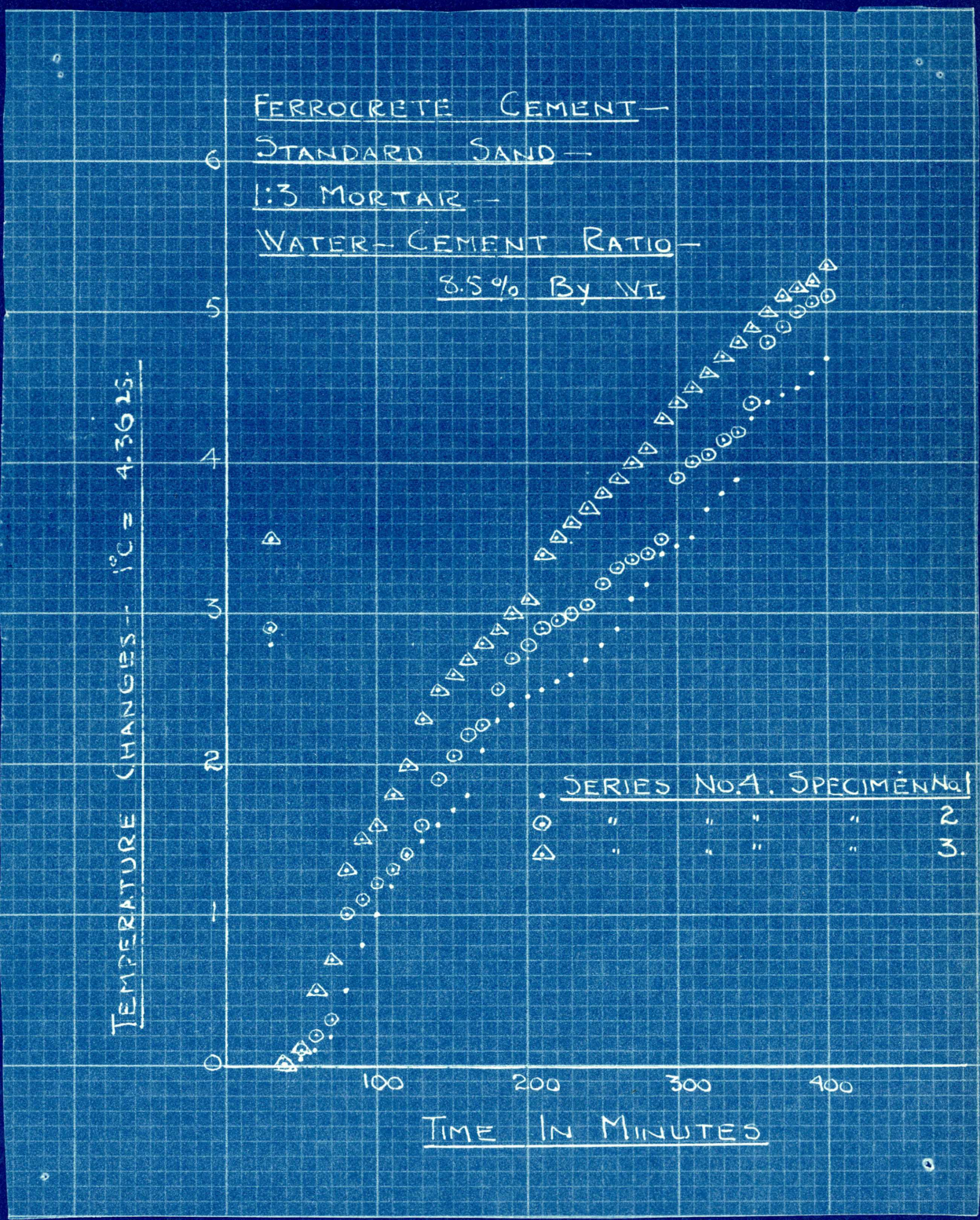
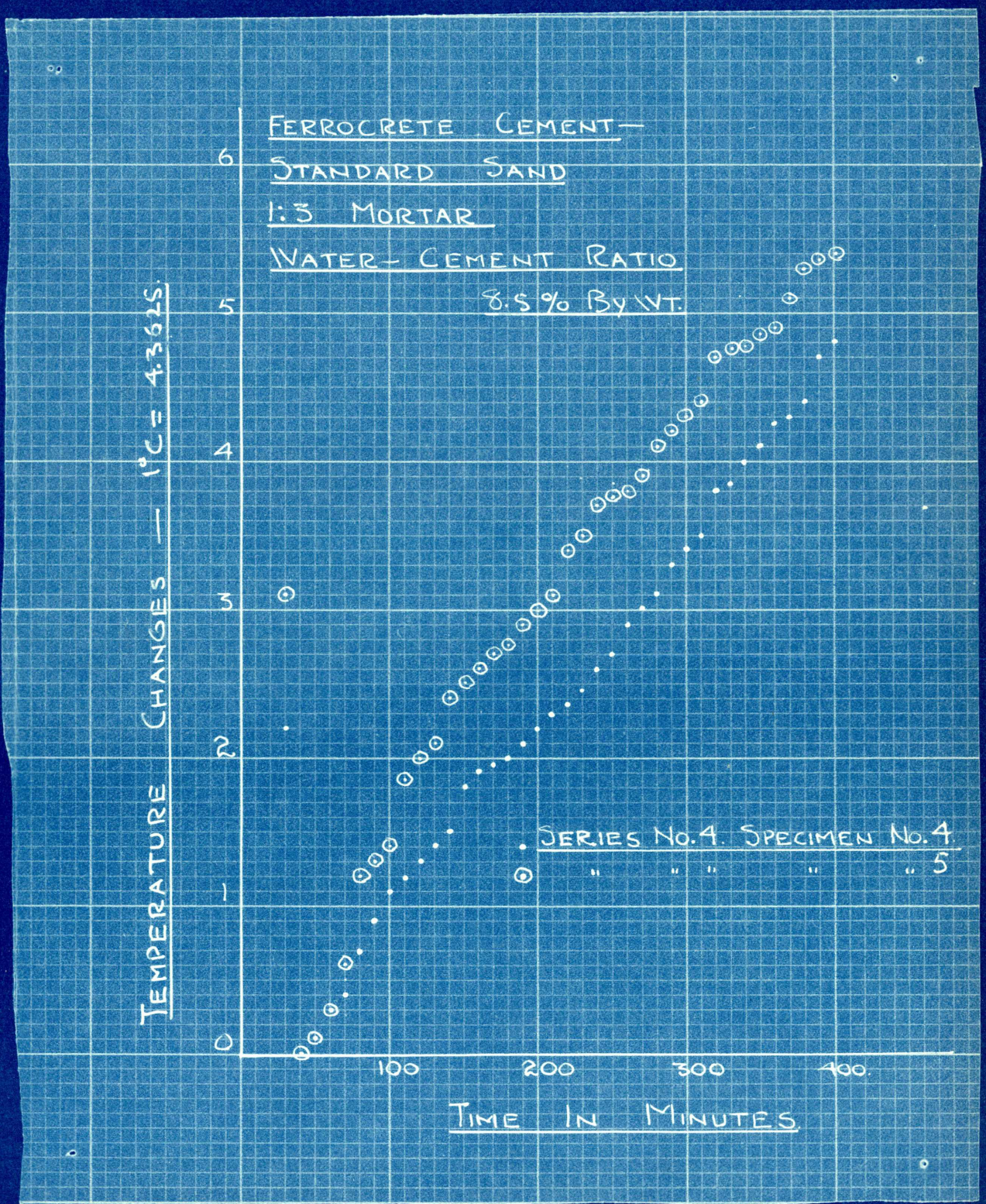

FERROCRETE CEMENT —
STANDARD SAND —
1:3 MORTAIR —
WATER — CEMENT RATIO —
8.5% BY WT.
TEMPERATURE CHANGES — 1°C = 4.3625.
0
1
2
3
4
5
6
100
200
300
400
TIME IN MINUTES
SERIES NO.A. SPECIMEN No.1
" " " " 2
" " " " 3.

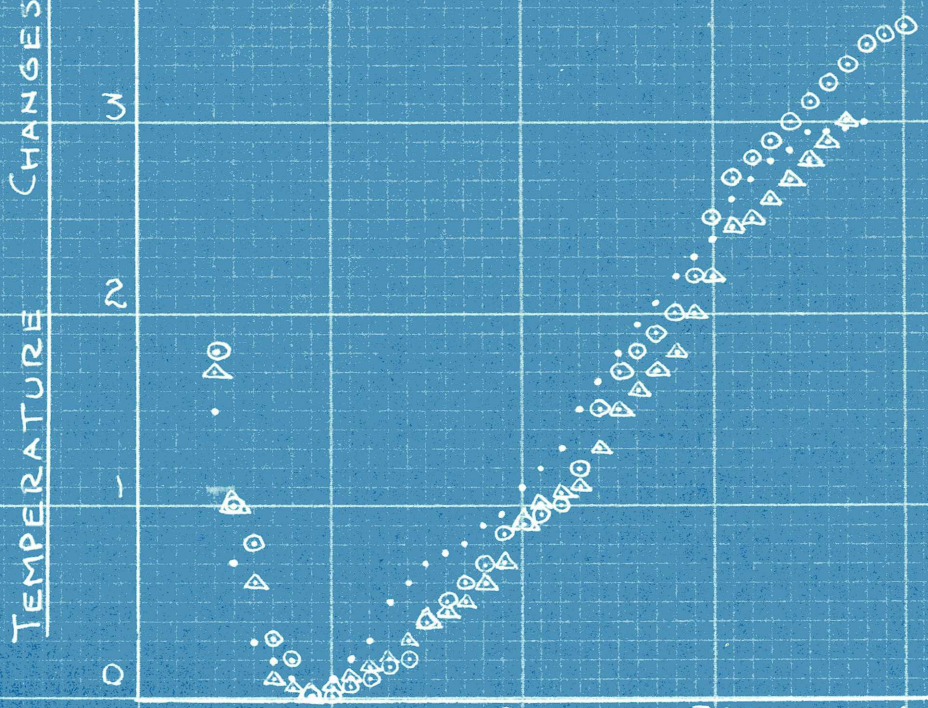
FIG.-87


FERROCRETE CEMENT—
STANDARD SAND
1:3 MORTAR
WATER-CEMENT RATIO
8.5% BY WT.
SERIES No.4. SPECIMEN No.4
" " " " " 5
TEMPERATURE CHANGES — 1°C = 4.362S.
0
1
2
3
4
5
6
100
200
300
400
TIME IN MINUTES

FERROCRETE CEMENT—
STANDARD SAND—
1:3 MORTAR
WATER—CEMENT RATIO—
10.5 % BY WT.

• SERIES No. 4. SPECIMEN No. 6.
⊙ " " " " " 7
△ " " " " " 8

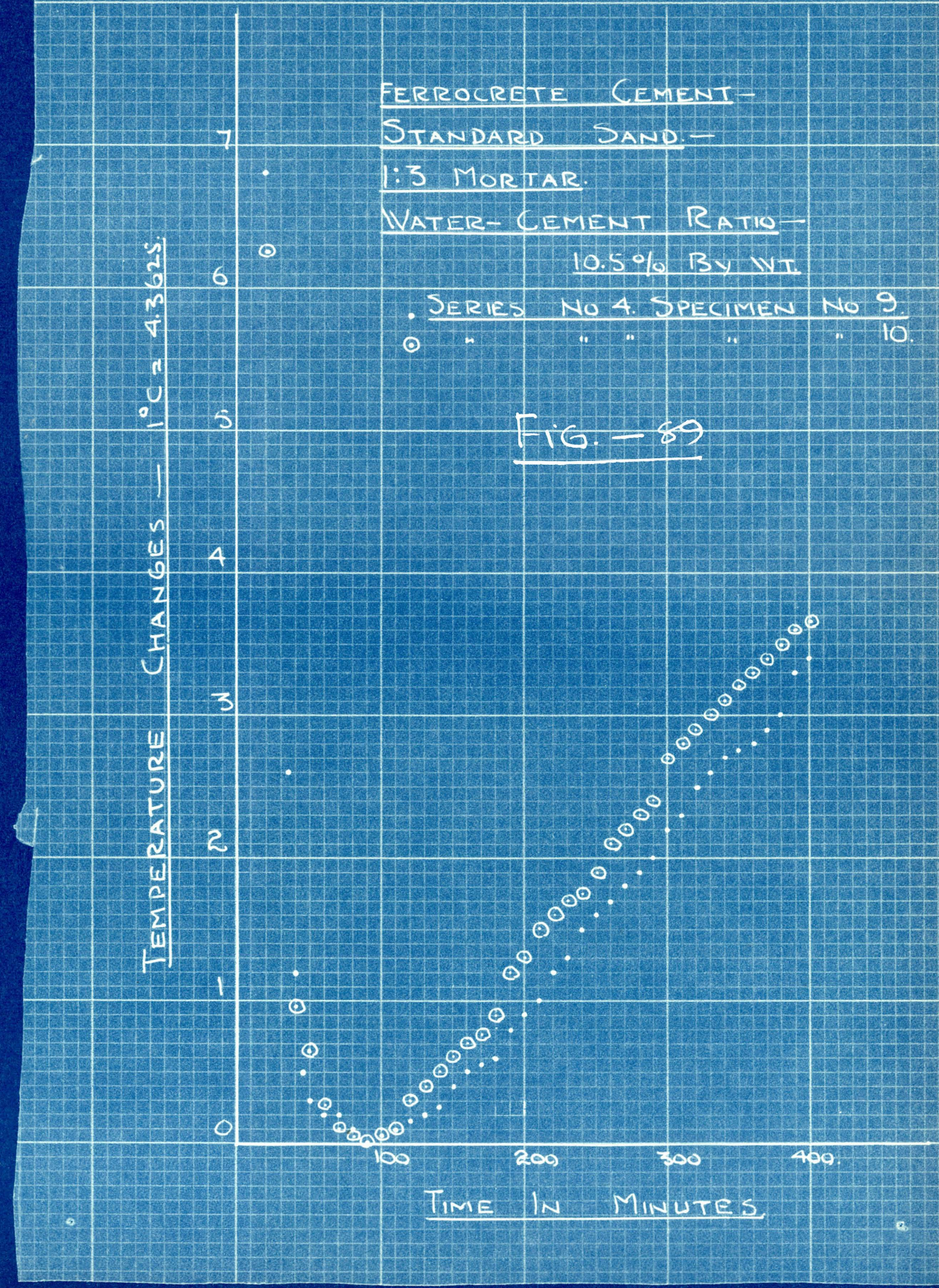
FIG.—88



FERROCRETE CEMENT –
STANDARD SAND –
1:3 MORTAR.
WATER-CEMENT RATIO –
10.5% BY WT.

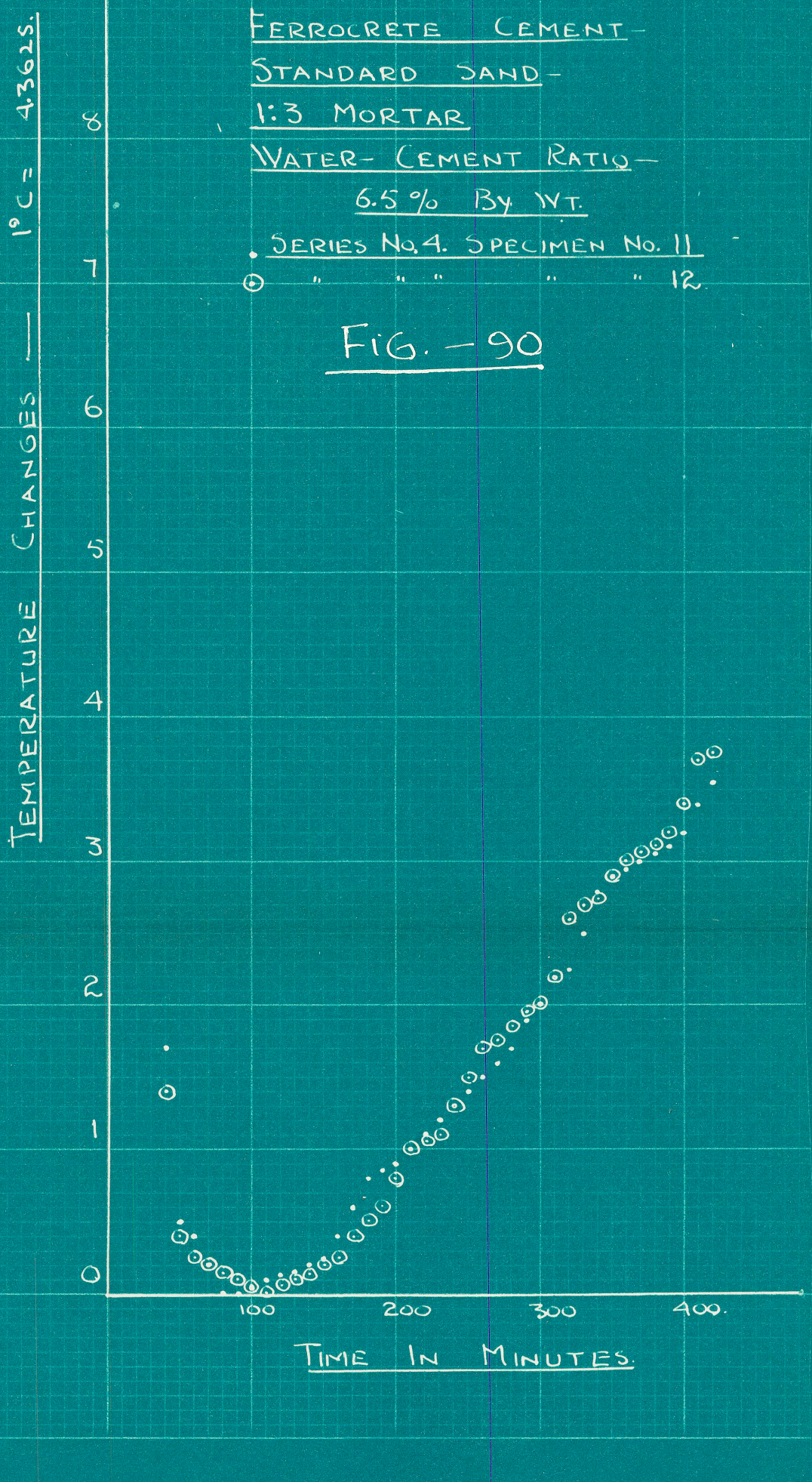
. SERIES No 4. SPECIMEN No 9.
o " " " " " 10.

FIG. – 89



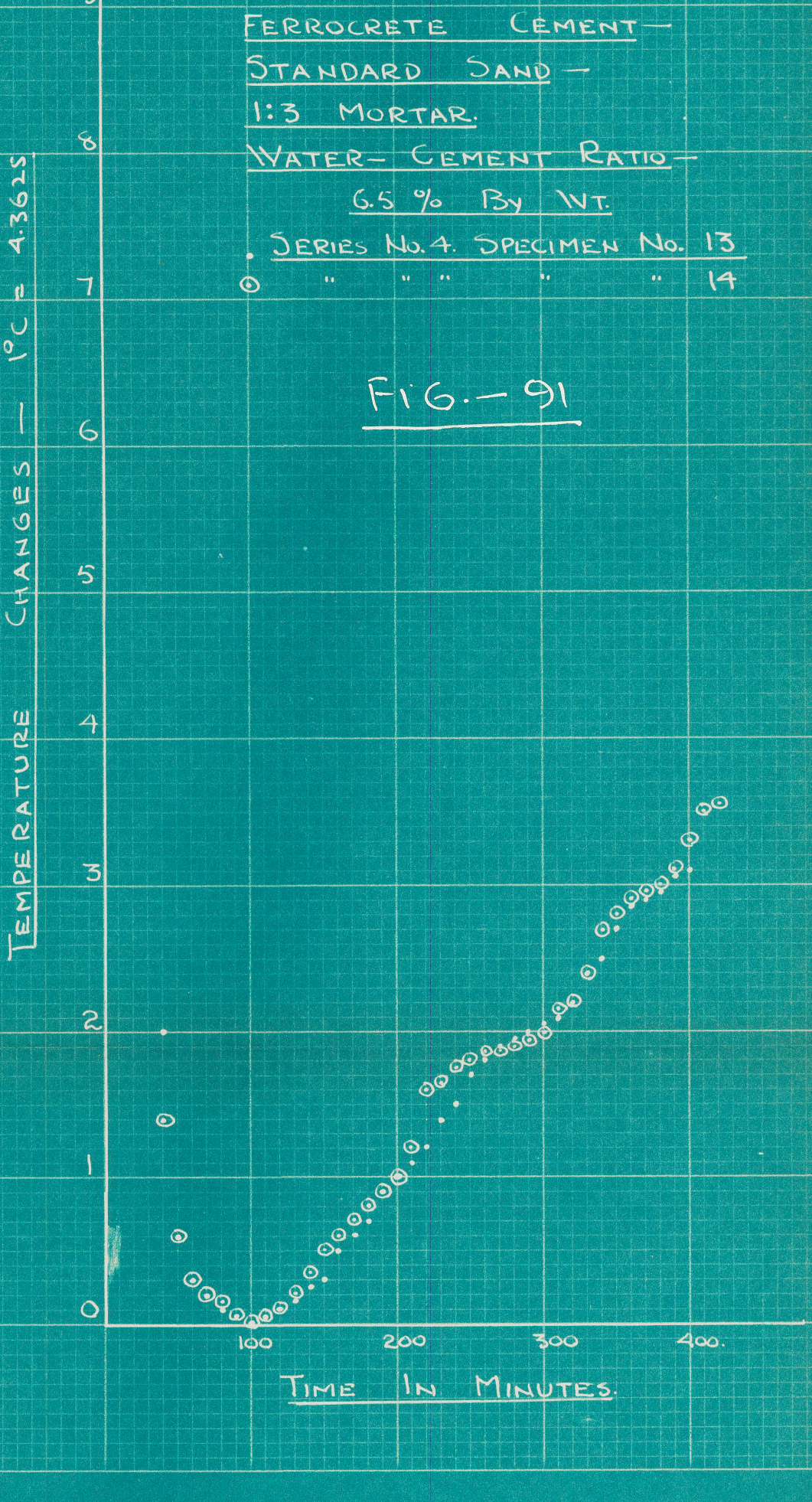
FERROCRETE CEMENT –
STANDARD SAND –
1:3 MORTAR
WATER – CEMENT RATIO –
6.5 % BY WT.
SERIES No. 4. SPECIMEN No. 11
" " " " " 12

FIG. – 90



FERROCRETE CEMENT—
STANDARD SAND—
1:3 MORTAR.
WATER—CEMENT RATIO—
6.5 % BY WT.
SERIES No. 4. SPECIMEN No. 13
" " " " " 14

FIG.—91



Series No. 4. Specimens Nos. 1 to 14.

Figs. 75 and 76 show the rate of length in ten minutes of specimens Nos. 1 to 5 of Ferrocrete cement - standard sand 1:3 mortar with 8.5% water-cement ratio by weight. The initial rate of contraction is about 31/9,000% in ten minutes at 35 minutes, which decreases till reaching 0 at 70 minutes. Expansion starts at this stage reaching the value 2/900% in ten minutes at 105 minutes. After this the rate of expansion decreases rapidly initially and gradually finally reaching about 1/900% in ten minutes at 400 minutes.

Figs. 77 and 78 show the rate of length changes of specimens Nos. 6 to 10 with 10.5% water-cement ratio by weight. The initial rate of contraction is (greater than the 8.5% specimens) 12/900% in ten minutes at 35 minutes. This rate falls very rapidly reaching 0 at about 45 minutes after which expansion starts. The expansion is very rapid for a few minutes reaching 2/900% in ten minutes at 75 minutes, after which it goes on decreasing, reaching 0 once again at about 120 minutes after which the specimen starts contracting once again. The rate of contraction reaches 15/9000% in ten minutes at 170 minutes after which it decreases at a rapid rate at first reaching 3/9000% in ten minutes at 280 minutes after which the curve becomes very flat, the decrease is very gradual, the rate falling to 5/90000% in ten minites

at 400 minutes.

Figs. 79 & 80 show the rate of length changes in ten minutes in specimens Nos. 11 to 14 with 6.5% water-cement ratio by weight. The rate of initial contraction is very small, being only 12/9000% in ten minutes at 35 minutes, falling to 0 at about 70 minutes. After this the specimen expands, the rate being 1/900% in ten minutes at 110 minutes. The final rate of expansion reached was 1/9000% in ten minutes at 400 minutes.

Figs.81 & 82 show the total length changes of specimens Nos. 1 to 5 with 8.5% water with 30 minutes reading as a datum. The mortar contracts initially reaching 4/900% at 70 minutes, after which it expands, the final value of expansion reached at 410 minutes being ~~15%~~ 15/9000% with 30 minute reading as the datum.

Figs. 83 & 84 show the total length changes of specimens Nos. 6 to 10 with 10.5% water-cement ratio by weight. The mortar contracts initially reaching the value 13/900% at 50 minutes. After this, the specimen expands till the value of contraction at 120 minutes is only 2/900%. At this stage the contraction starts again rapidly at first and then very gradually reaching the value 17/900% at 400 minutes with 30 minute reading as the datum.

Fig.85 shows the total length change of specimens

Nos. 11 to 14 with 6.5% water-cement ratio. The mortar contracts initially reaching the value 15/9000% at 70 minutes after which it starts expanding, the value of expansion obtained being 1/100% at 400 minutes with 30 minute reading as the datum.

Figs. 86 & 87 show the temperature changes of specimens Nos. 1 to 5 with 8.5% water-cement ratio by weight. Figs. 88 & 89 show the temperature changes of specimens Nos. 6 to 10 with 10.5% water-cement ratio by weight. Figs. 90 & 91 show the temperature changes of specimens Nos. 11 to 14 with 6.5% water-cement ratio by weight.

All these curves are plotted (as has already been mentioned in connection with the other three series) with the lowest temperature reached as 0. 8.5% water-cement ratio seems to be the optimum ratio for this series as the amount of heat evolved initially as well as finally is much greater for this percentage. The temperature reached initially for this percentage must be much greater than 6.5% specimens as can be seen from the shape of the cooling curve which is more sharp for 8.5% than 6.5%. The temperature reaches a maximum earlier in 8.5% specimens and starts falling at a greater rate than 6.5% specimens. That is why in the absence of the curve from 0 to 30 minutes, it seems as if the heat evolved by 6.5% is greater initially. The heat evolved initially and finally

with 10.5% is much less as could have been expected. No temperature correction has been applied to length change values obtained for the reasons already mentioned in the three preceding series.

Table XLIII shows the temperature and humidity variations during series No. 4. The maximum temperature variation for the duration of a whole test period of a specimen was 2°F. and the humidity variation 8 degrees. For the whole series, the temperature varied from 55.9°F. to 61.7°F. and humidity from 58.4 to 81.0 degrees. For the reasons already mentioned for the other three series, it is also assumed in this series that the cellaphane envelope did afford sufficient protection to the specimen from temperature and humidity changes of the outside atmosphere.

An indication of the suitability of the apparatus for volume-change observations is obtained from the study of variations in results between the individual specimens in a set (Figs. 31 to 91). It is found that that individual variation is relatively small, particularly so when it is remembered that it is practically impossible to ensure the identical amount of each constituent of the mix in each of the companion specimens. The variation shown is therefore probably due more to the variation in the constituents of the mix than to the method of observation. The

TABLE XLIII.

Temperature and Humidity Variations - Series No. 4.

Specimen No.	Temperature °F.	Degree of Humidity - Saturation = 100.
1	55.9 - 57.9	64.6 - 70.0
2	56.5 - 58.2	66.7 - 68.7
3	56.1 - 57.9	65.0 - 67.1
4	57.8 - 59.8	60.4 - 68.5
5	60.0 - 61.7	70.0 - 73.0
6	58.3 - 60.0	62.8 - 69.5
7	58.5 - 60.1	77.0 - 78.7
8	59.9 - 61.2	78.0 - 81.0
9	59.3 - 61.3	70.3 - 74.5
10	59.5 - 61.3	71.0 - 76.5
11	58.0 - 59.6	61.0 - 63.3
12	56.9 - 59.0	61.0 - 67.5
13	57.8 - 59.9	66.8 - 69.5
14	58.9 - 60.0	58.4 - 66.5

results indicate that the very simple apparatus and the small specimens used in this investigation served for observations of volume changes.

CHAPTER XII.

CONCLUSIONS.

FIG. — 92

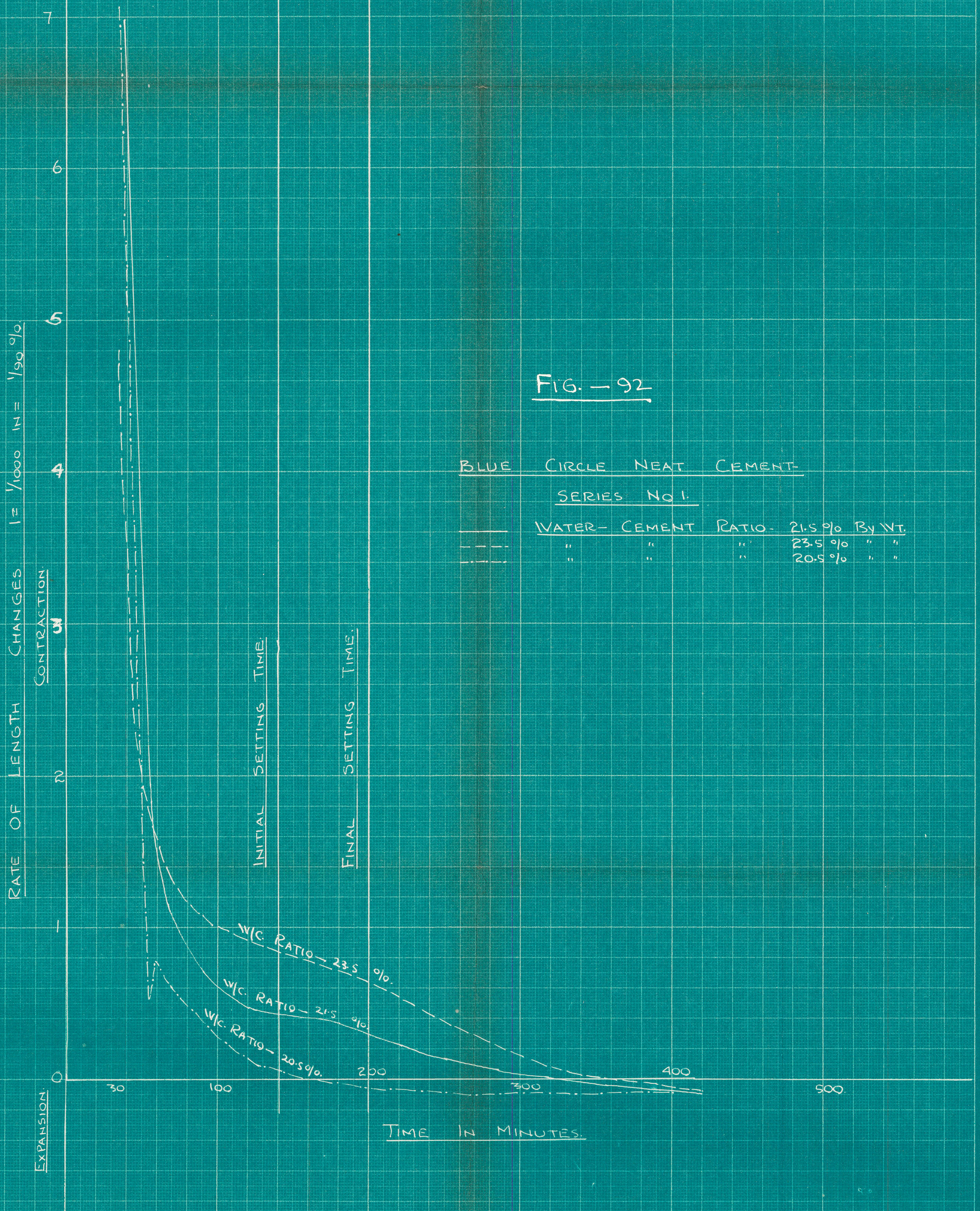
BLUE CIRCLE NEAT CEMENT-

SERIES No 1.

———— WATER- CEMENT RATIO- 21.5 % By WT.

– – – – " " " 23.5 % " "

– · – · – " " " 20.5 % " "



W/C. RATIO — 23.5 %.

W/C. RATIO — 21.5 %.

W/C. RATIO — 20.5 %

BLUE CIRCLE NEAT CEMENT.

SERIES NO. 1.

———	WATER- CEMENT	RATIO	21.5 %	By Wt.
- - - -	"	"	23.5 "	"
-.-.-	"	"	20.5 "	"

FIG. —93

CHANGE — 1" = 1/1000 IN = 1/90 %.

TOTAL LENGTH CONTRACTION.

25
20
15
10
5
0

INITIAL SETTING TIME.

FINAL SETTING TIME.

30
100
200
300
400.

TIME IN MINUTES.

FIG. - 94

BLUE CIRCLE NEAT CEMENT-
WATER - CEMENT RATIO -
21.5 % BY WT.

⊙ AVERAGE OF SERIES No. 1
SPEMENS NOS. 5 TO 7 & 11.

INITIAL PORTION OF THE
CURVE PLOTTED ON
REDUCED TEMPERATURE
SCALE.

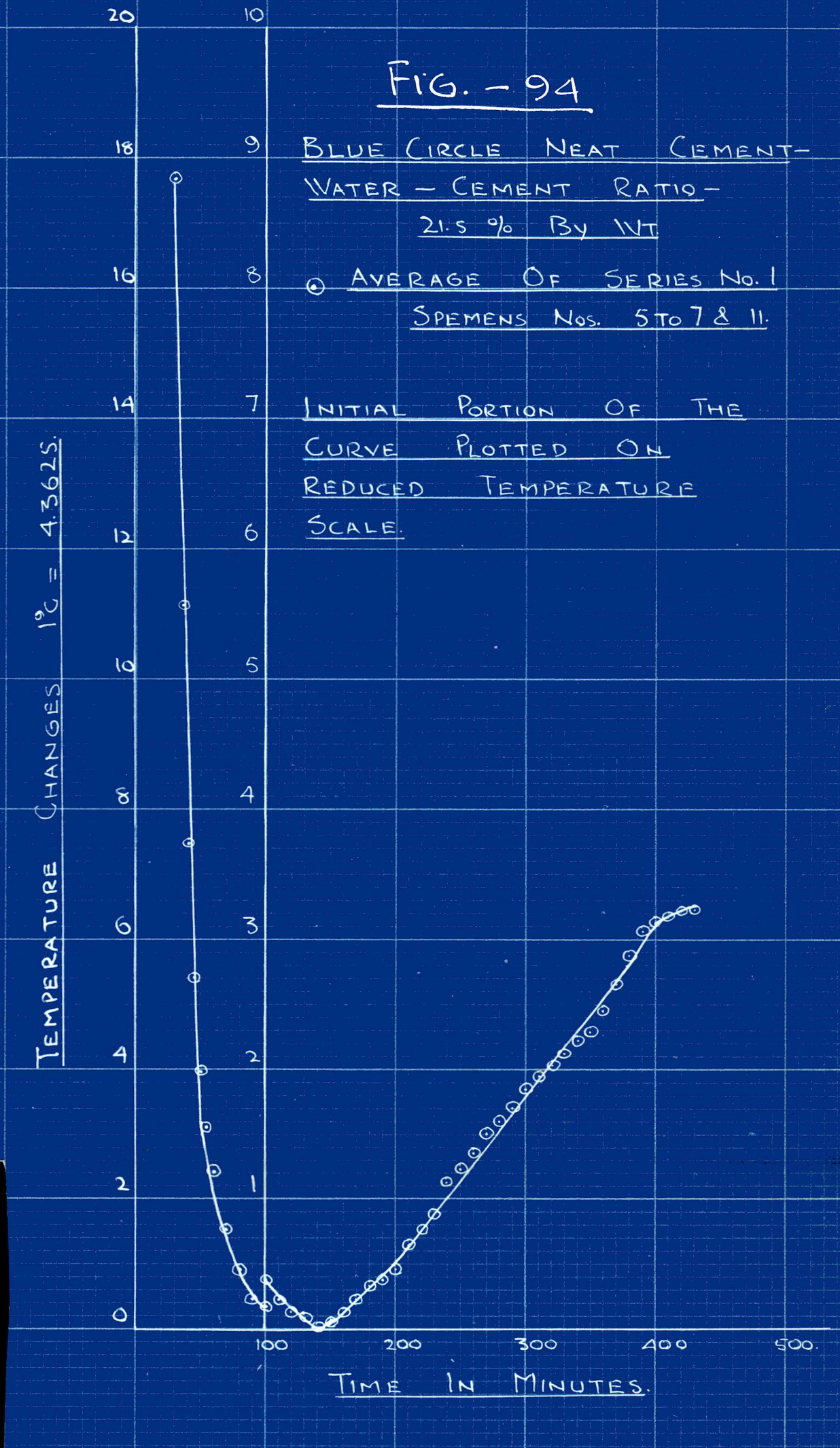
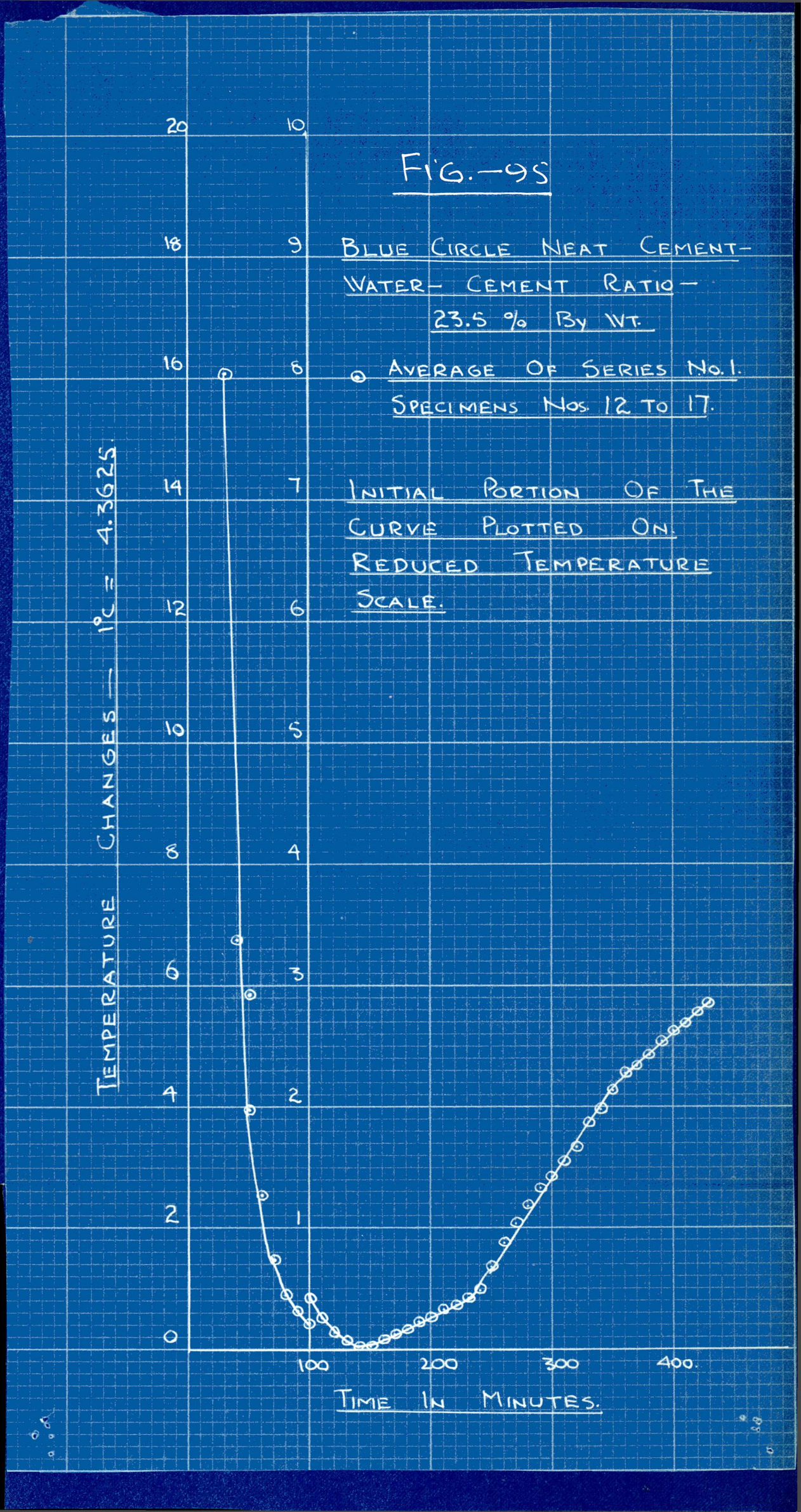


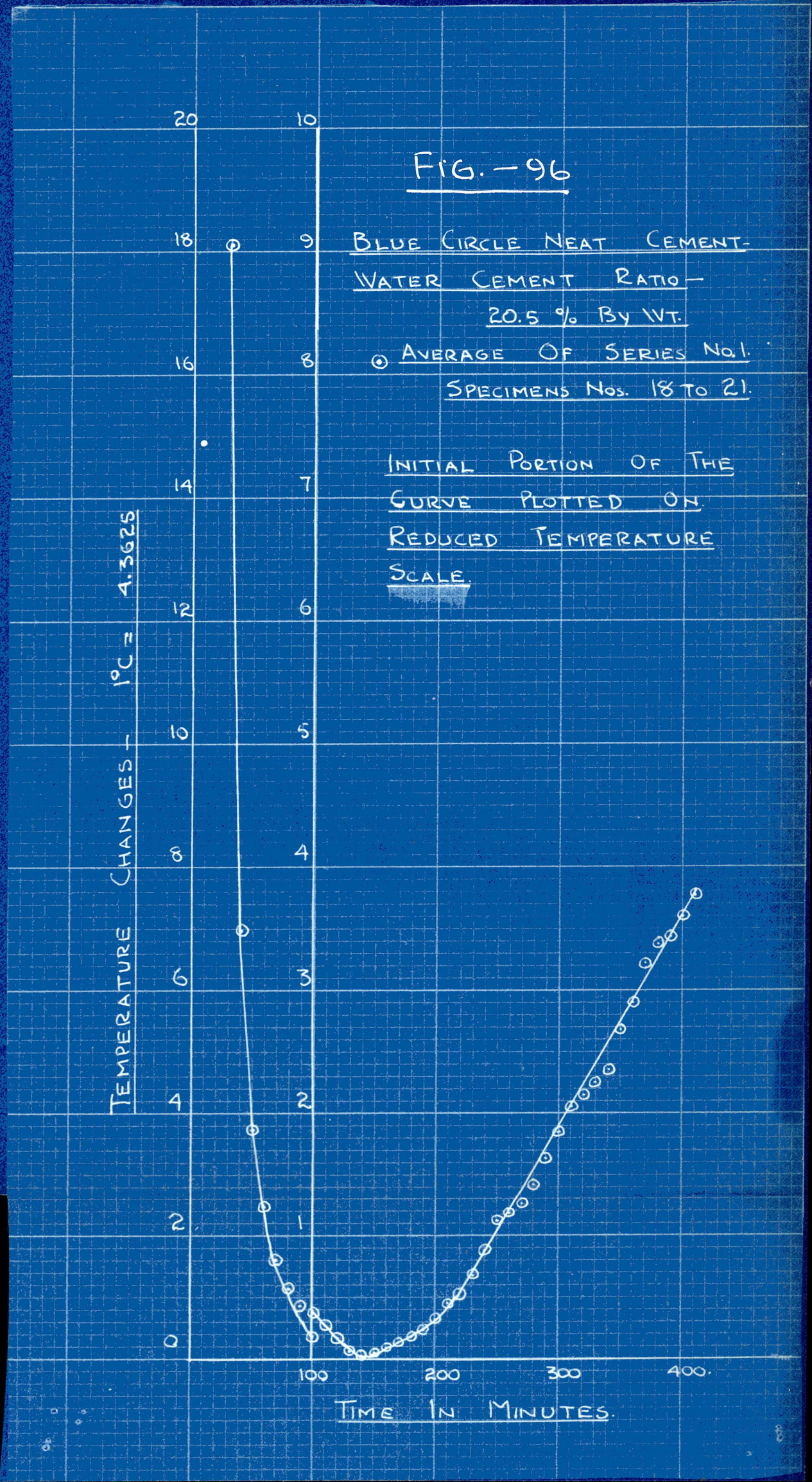
FIG.—9S

BLUE CIRCLE NEAT CEMENT—
WATER— CEMENT RATIO—
23.5 % BY WT.

○ AVERAGE OF SERIES No. 1.
SPECIMENS Nos. 12 TO 17.

INITIAL PORTION OF THE CURVE PLOTTED ON REDUCED TEMPERATURE SCALE.




FIG.-96
BLUE CIRCLE NEAT CEMENT-
WATER CEMENT RATIO-
20.5 % BY WT.
⊙ AVERAGE OF SERIES No.1.
SPECIMENS Nos. 18 TO 21.
INITIAL PORTION OF THE
CURVE PLOTTED ON
REDUCED TEMPERATURE
SCALE.
TEMPERATURE CHANGES - 1°C = 4.3625
20
18
16
14
12
10
8
6
4
2
0
10
9
8
7
6
5
4
3
2
1
100
200
300
400.
TIME IN MINUTES.

BLUE CIRCLE CEMENT—

STANDARD SAND

1:3 MORTAR.

SERIES No. 2.

		By Wt.
———	WATER-CEMENT RATIO—	7.9% "
– – –	" " "	9.9% "
–·–·–	" " "	5.9% "

FIG. — 97

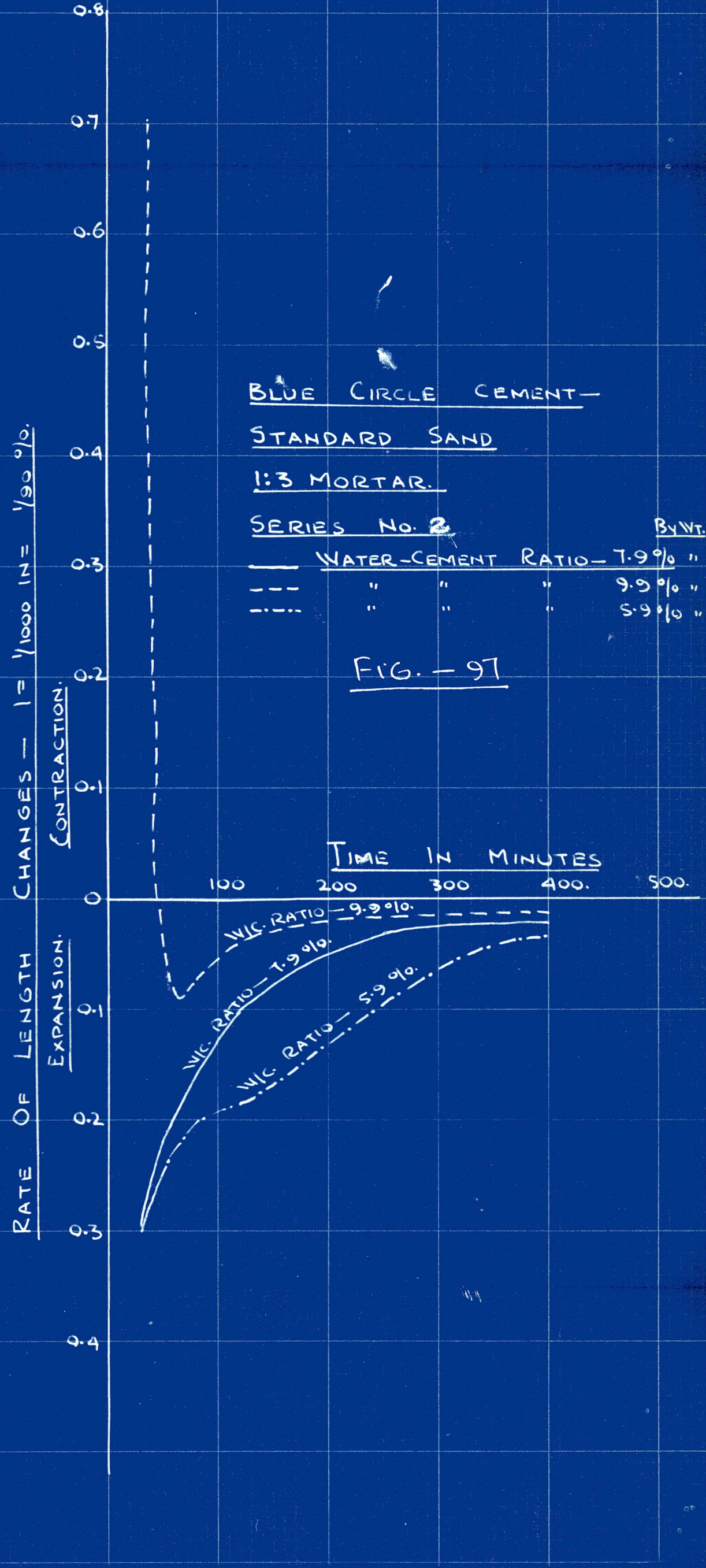


FIG. — 98

BLUE CIRCLE- CEMENT — STANDARD SAND.

1:3 MORTAR.

SERIES No. 4.

——— WATER-CEMENT RATIO — 7.9 % BY WT.

– – – – " " " 9.9 % " "

–·–·– " " " 5.9 % " "

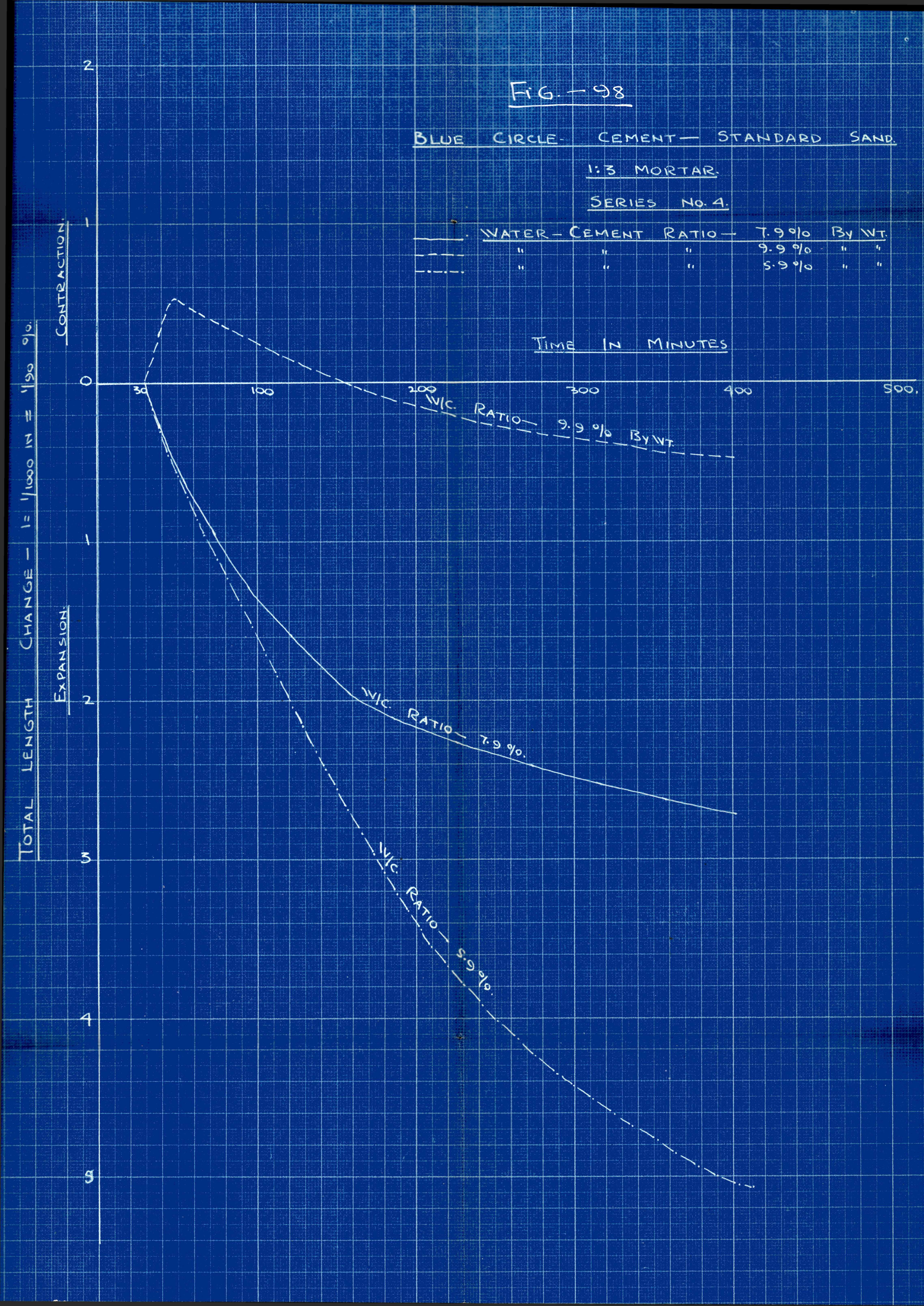


FIG.- 99

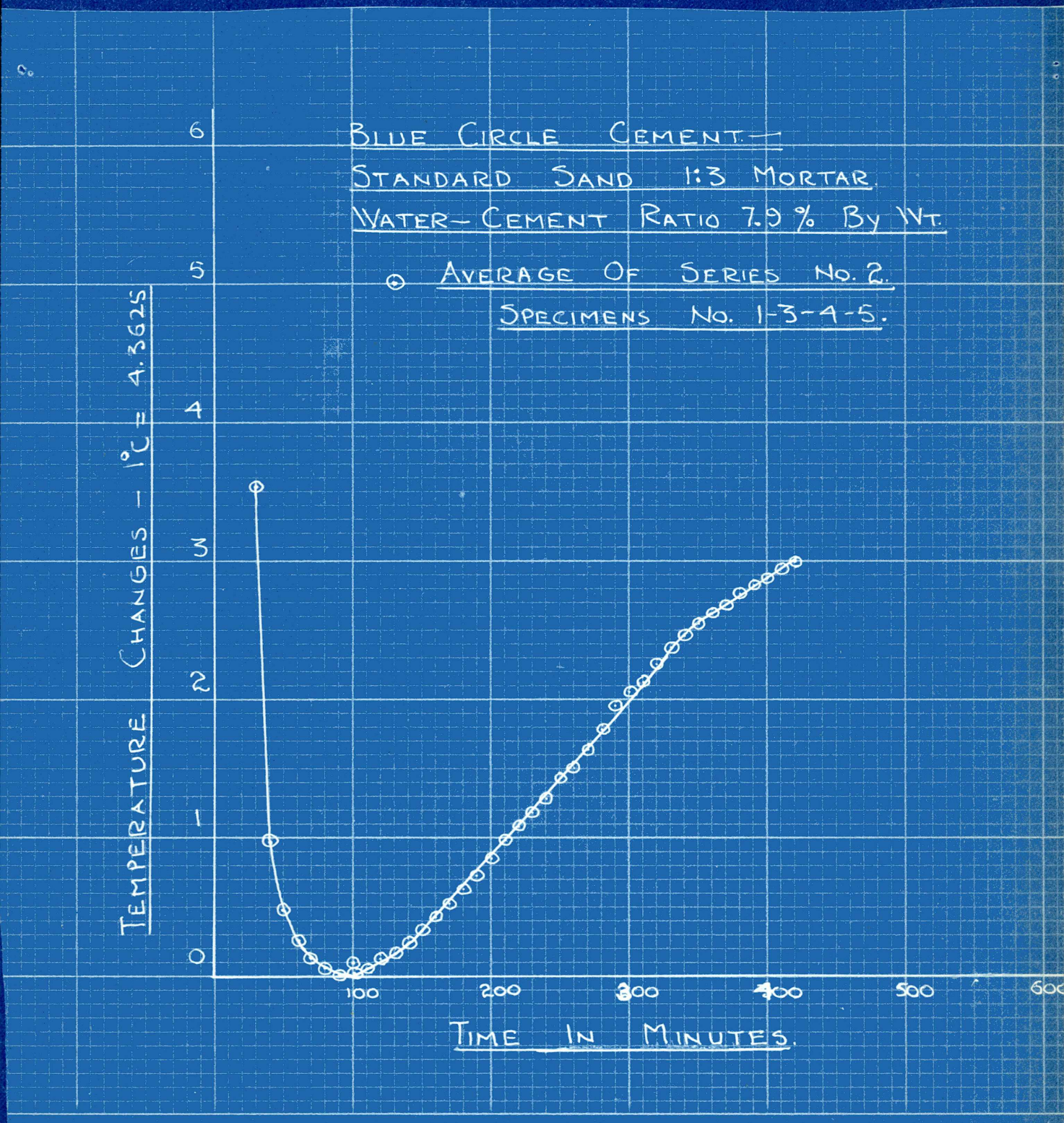
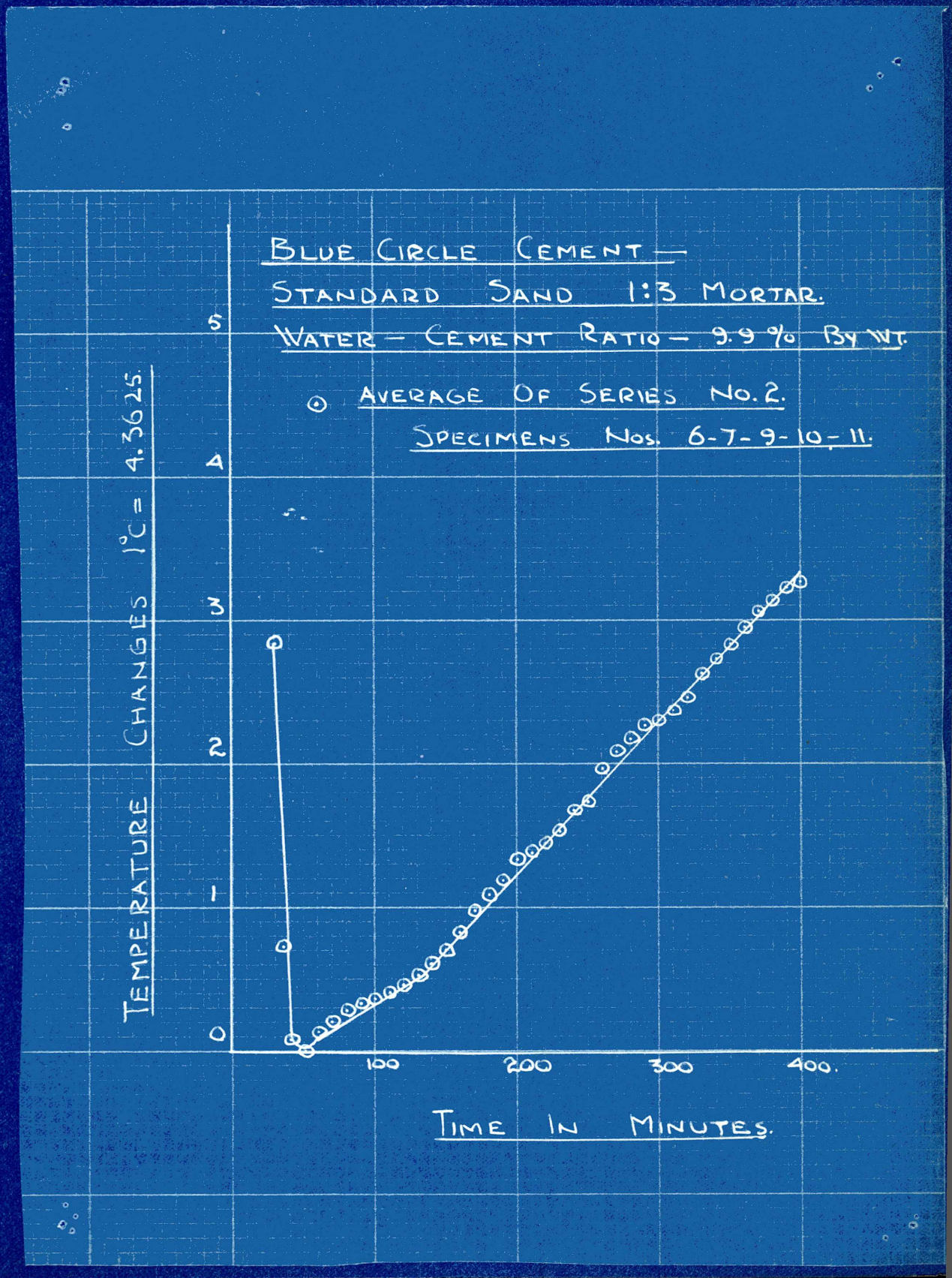
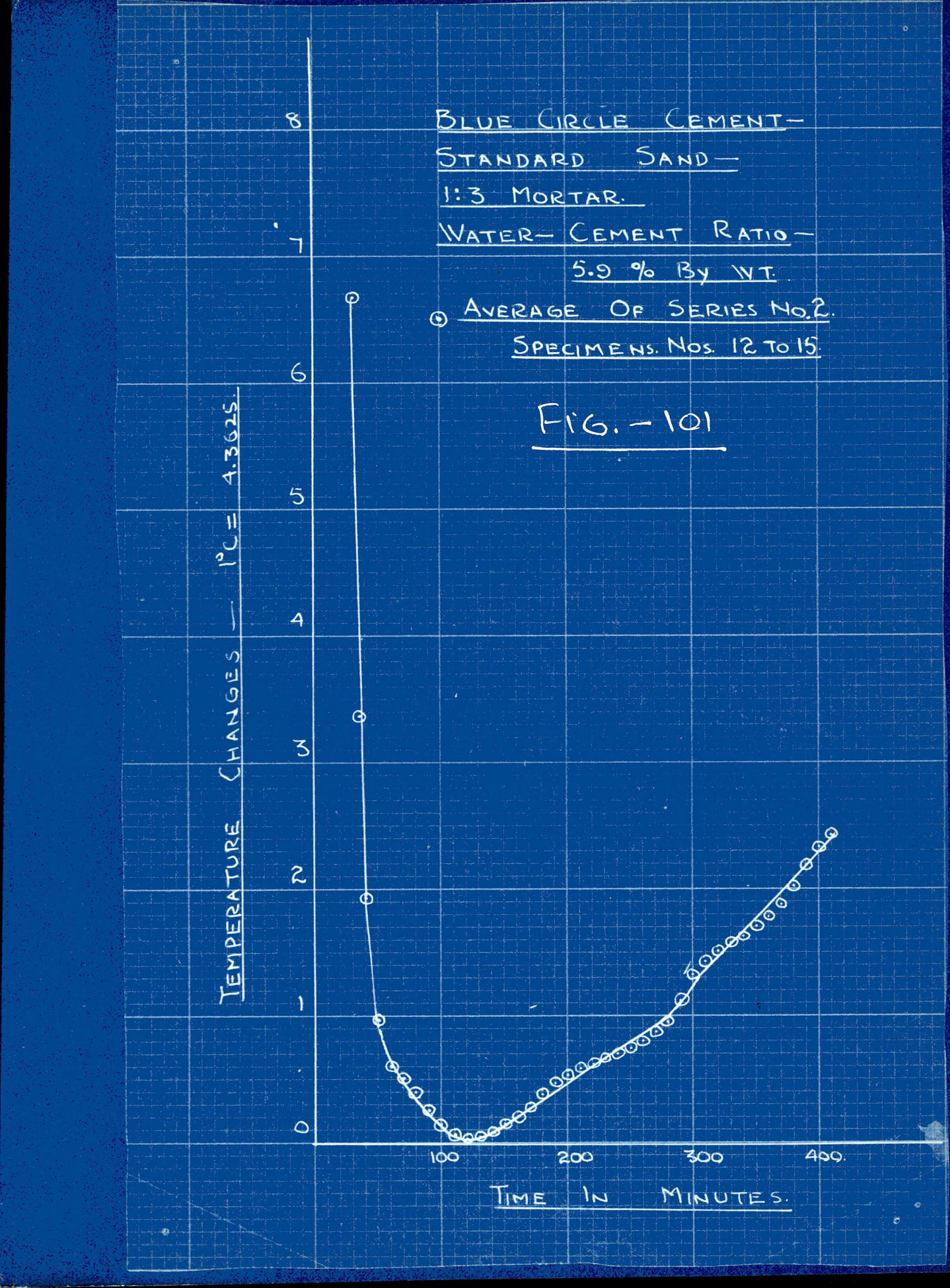

BLUE CIRCLE CEMENT.—
STANDARD SAND 1:3 MORTAR.
WATER-CEMENT RATIO 7.0 % BY WT.
⊙ AVERAGE OF SERIES No. 2.
SPECIMENS No. 1-3-4-5.
TEMPERATURE CHANGES — 1°C = 4.3625
0
1
2
3
4
5
6
100
200
300
400
500
600
TIME IN MINUTES.

FIG. – 100

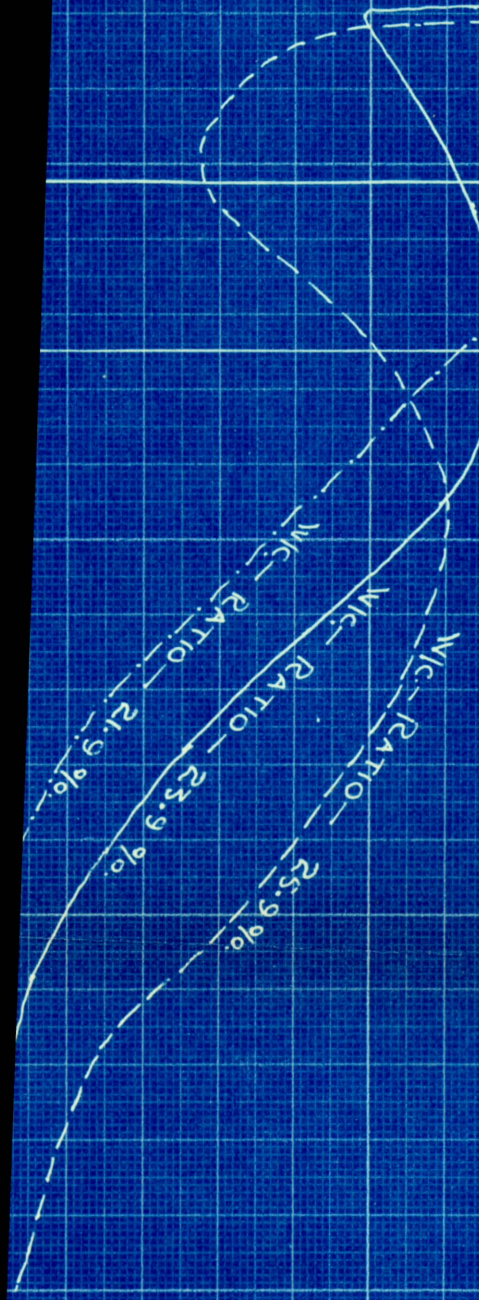

BLUE CIRCLE CEMENT –
STANDARD SAND 1:3 MORTAR.
WATER – CEMENT RATIO – 9.9 % BY WT.
⊙ AVERAGE OF SERIES No. 2.
SPECIMENS Nos. 6-7-9-10-11.
TEMPERATURE CHANGES 1°C = 4.3625.
5
4
3
2
1
0
100
200
300
400.
TIME IN MINUTES.


BLUE CIRCLE CEMENT—
STANDARD SAND—
1:3 MORTAR.
WATER—CEMENT RATIO—
5.9 % BY WT.
AVERAGE OF SERIES No. 2.
SPECIMENS. NOS. 12 TO 15.
FIG.—101
TEMPERATURE CHANGES — 1°C = 4.3625.
8
7
6
5
4
3
2
1
0
100
200
300
400.
TIME IN MINUTES.

RATE OF LENGTH CHANGES 1" = 1/1000 IN = 1/90 0/0.

CONTRACTION.

1 2 3 4 5 6 7 8



INITIAL SETTING TIME.

FINAL SETTING TIME.

FIG- 102

FERROCRETE NEAT CEMENT.

SERIES NO. 3.

WATER- CEMENT RATIO- 23.9 0/0 BY WT.
" " " 25.9 0/0 " " "
" " " 21.9 0/0 " " "

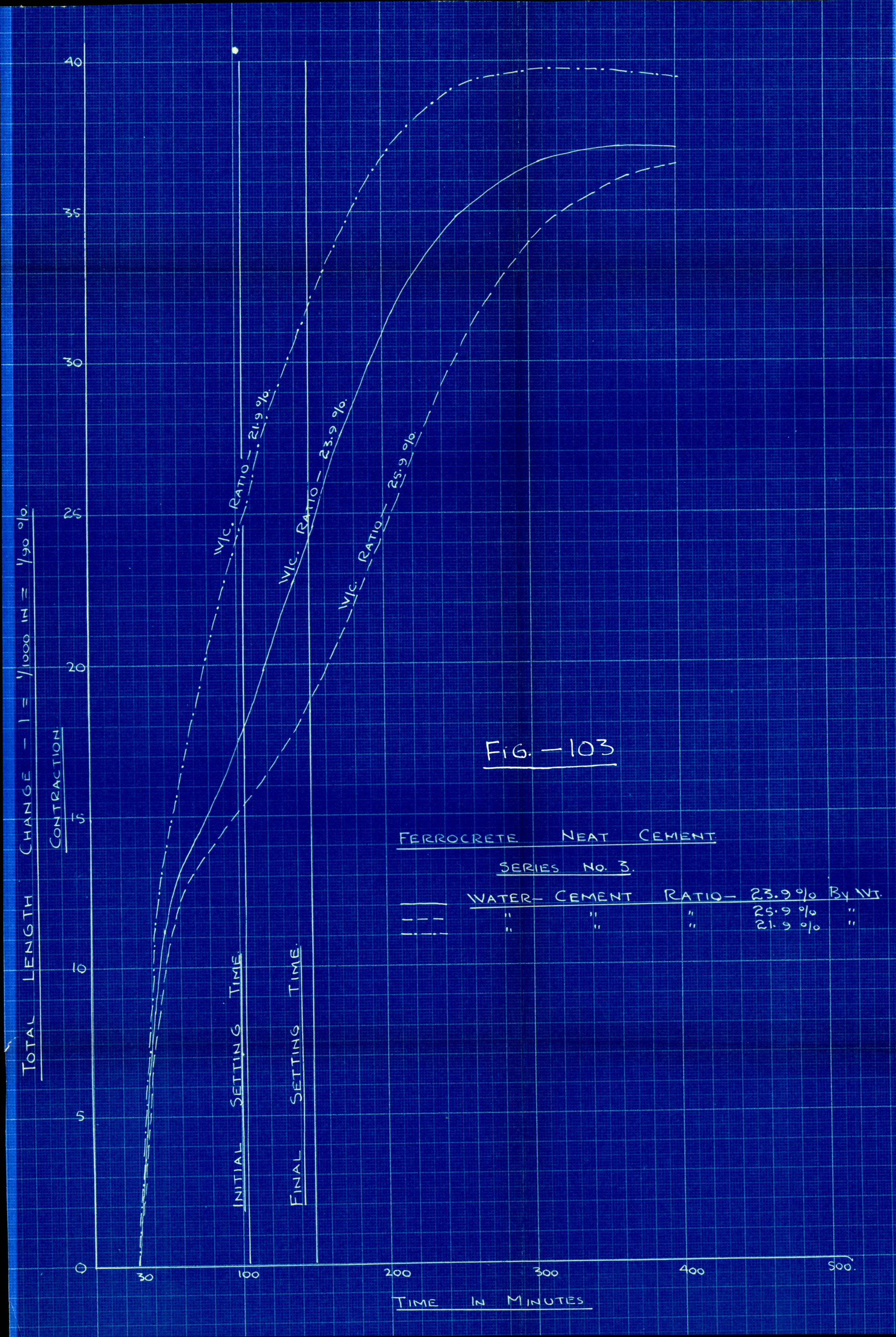

Total Length Change — 1 = 1/1000 in = 1/90 o/o.
Contraction
40
35
30
25
20
15
10
5
0
30
100
200
300
400
500.
Time in Minutes
Initial Setting Time.
Final Setting Time.
Vic. Ratio — 21.9 o/o.
Vic. Ratio — 23.9 o/o.
Vic. Ratio — 25.9 o/o.
Ferrocrete Neat Cement
Series No. 3.
Water-Cement Ratio — 23.9 o/o By Wt.
" " " 25.9 o/o "
" " " 21.9 o/o "

Fig. — 103

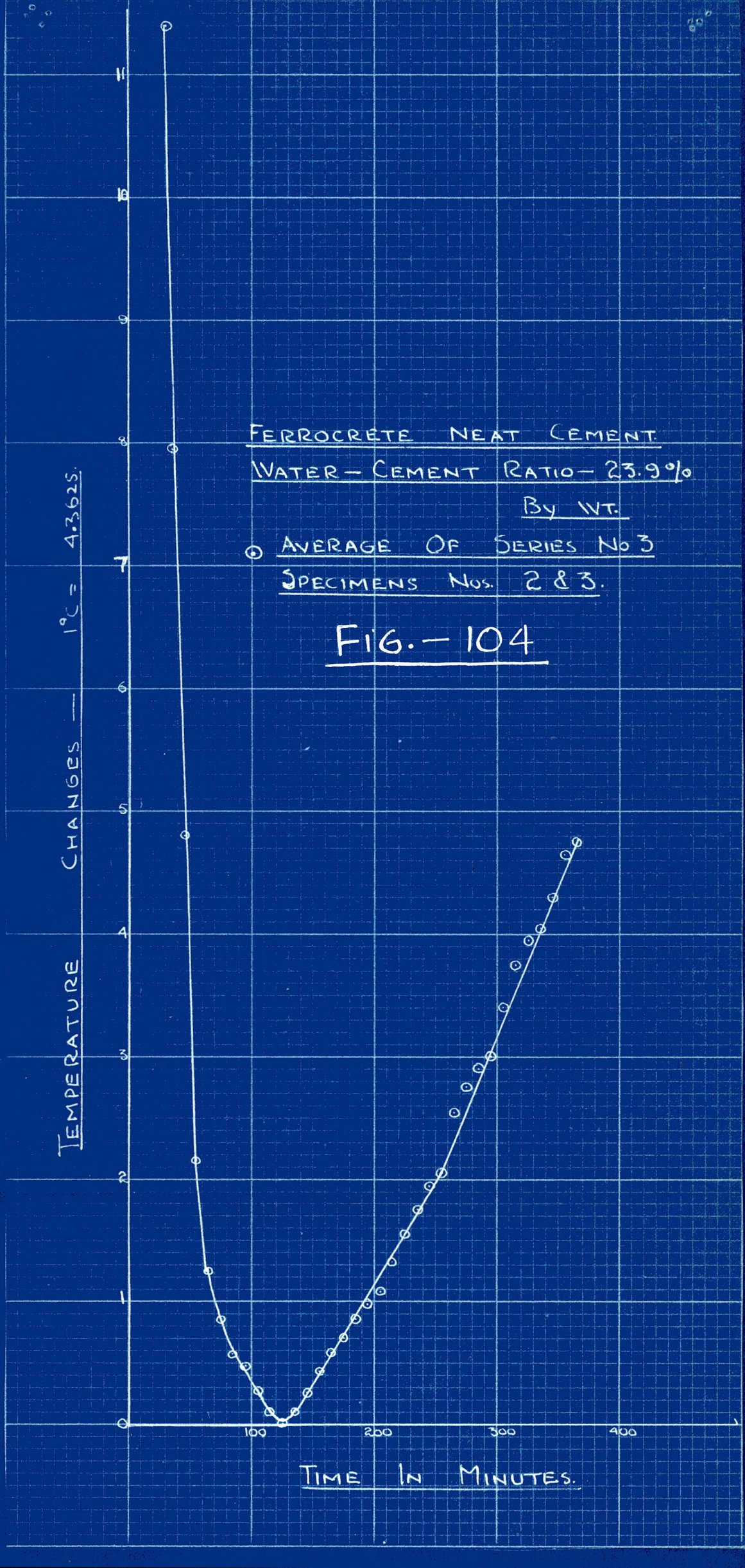
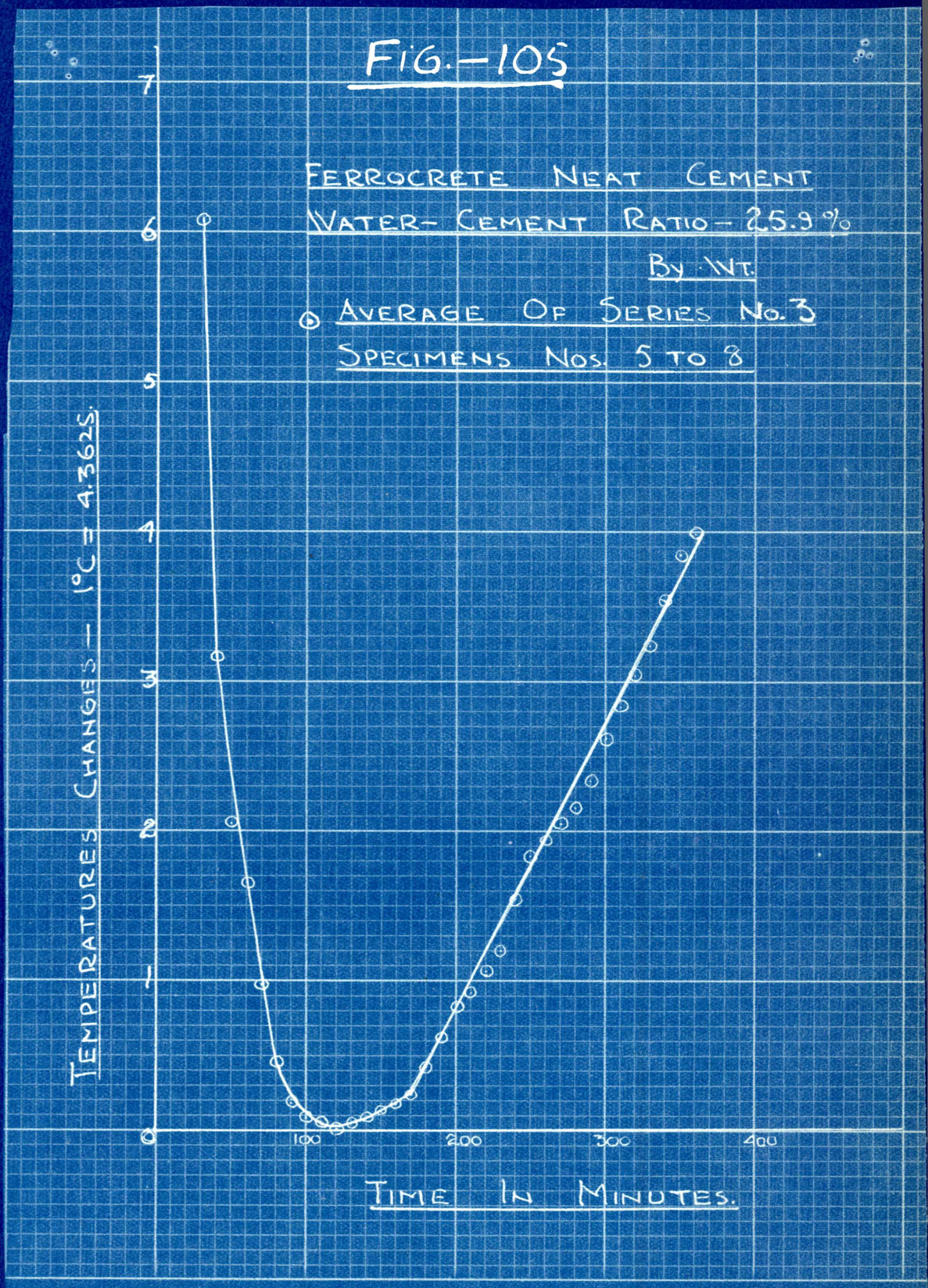
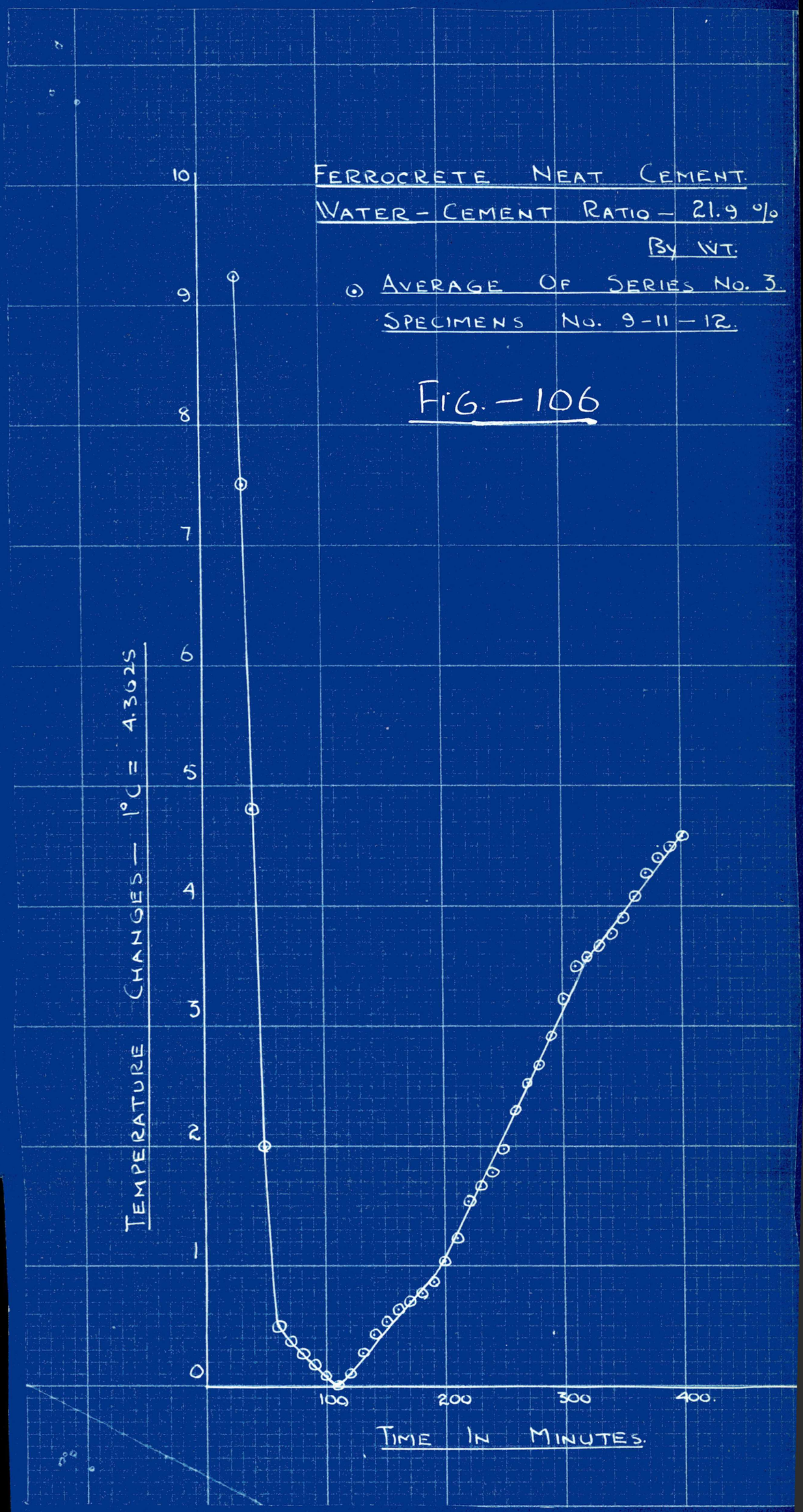

FERROCRETE NEAT CEMENT.
WATER – CEMENT RATIO – 23.9%
By WT.
⊙ AVERAGE OF SERIES No 3
SPECIMENS Nos. 2 & 3.
TEMPERATURE CHANGES — 1°C = 4.3625.
TIME IN MINUTES.
0
1
2
3
4
5
6
7
8
9
10
11
100
200
300
400

FIG. – 104

FIG.–105

FERROCRETE NEAT CEMENT
WATER–CEMENT RATIO – 25.9 %
BY WT.
○ AVERAGE OF SERIES No. 3
SPECIMENS NOS. 5 TO 8




FERROCRETE NEAT CEMENT.
WATER-CEMENT RATIO — 21.9 % BY WT.
⊙ AVERAGE OF SERIES No. 3
SPECIMENS No. 9-11-12.
FIG.-106
TEMPERATURE CHANGES — 1°C = 4.302S
0
1
2
3
4
5
6
7
8
9
10
100
200
300
400.
TIME IN MINUTES.

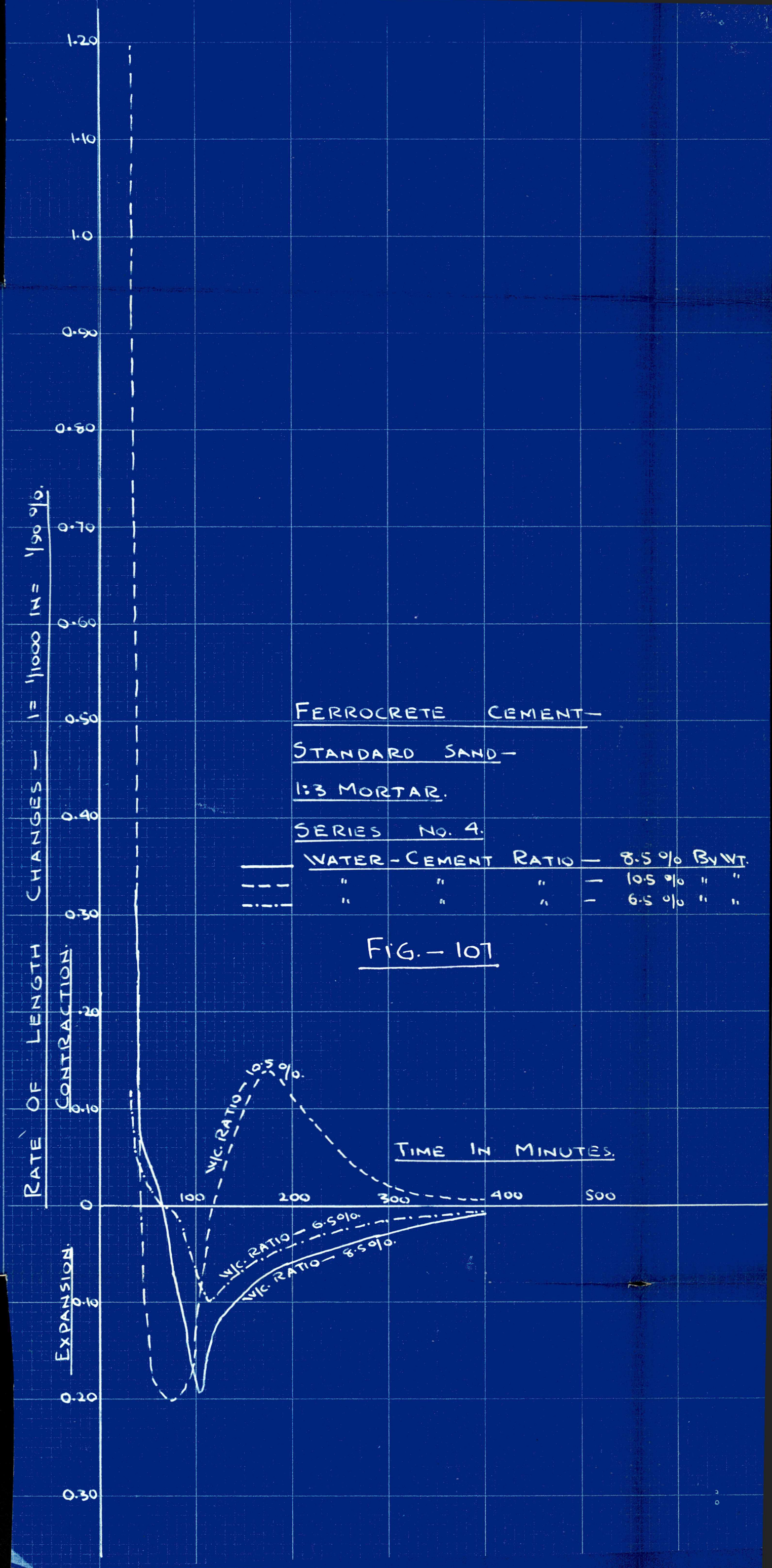

1.20
1.10
1.0
0.90
0.80
0.70
0.60
0.50
0.40
0.30
1" = 1/1000 IN = 1/90 o/o.
RATE OF LENGTH CHANGES — CONTRACTION.
EXPANSION.
0.10
0.20
0.30
0
100
200
300
400
500
TIME IN MINUTES.
W/C. RATIO — 10.5 o/o.
W/C. RATIO — 6.5 o/o.
W/C. RATIO — 8.5 o/o.
FERROCRETE CEMENT —
STANDARD SAND —
1:3 MORTAR.
SERIES NO. 4.
WATER-CEMENT RATIO — 8.5 o/o BY WT.
" " " — 10.5 o/o " "
" " " — 6.5 o/o " "

FIG. — 107

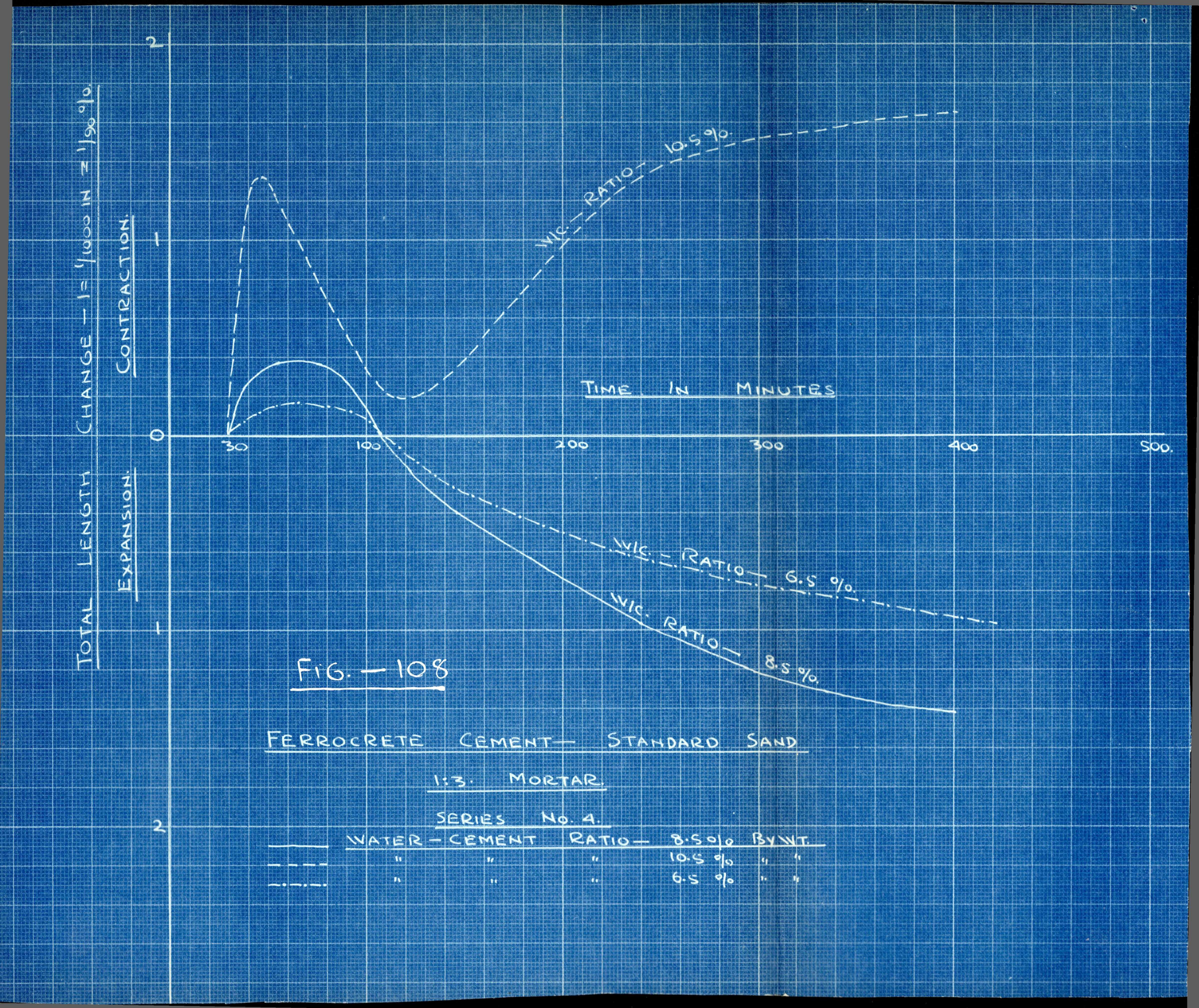


FIG. — 108

FERROCRETE CEMENT — STANDARD SAND

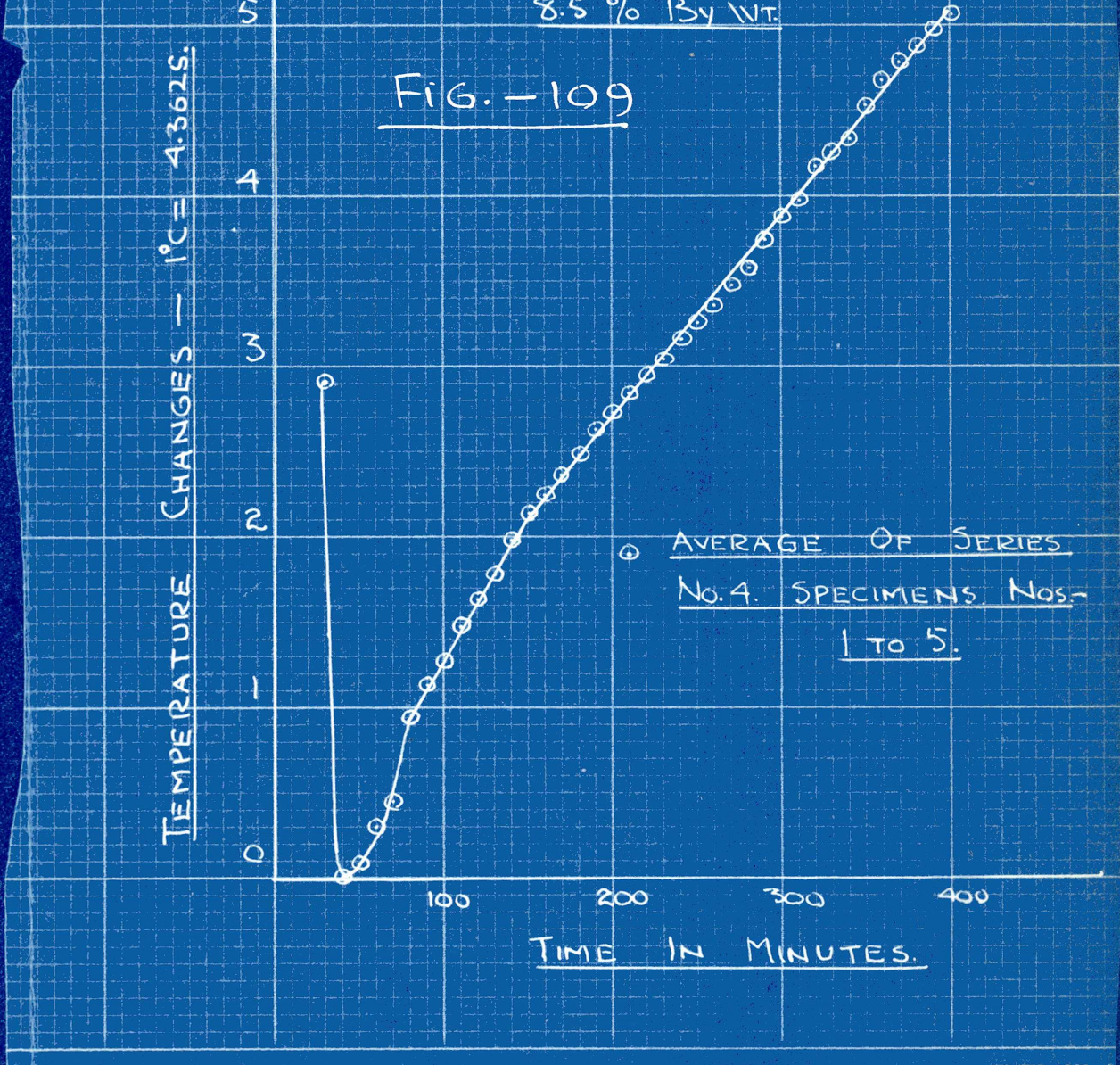
1:3. MORTAR.

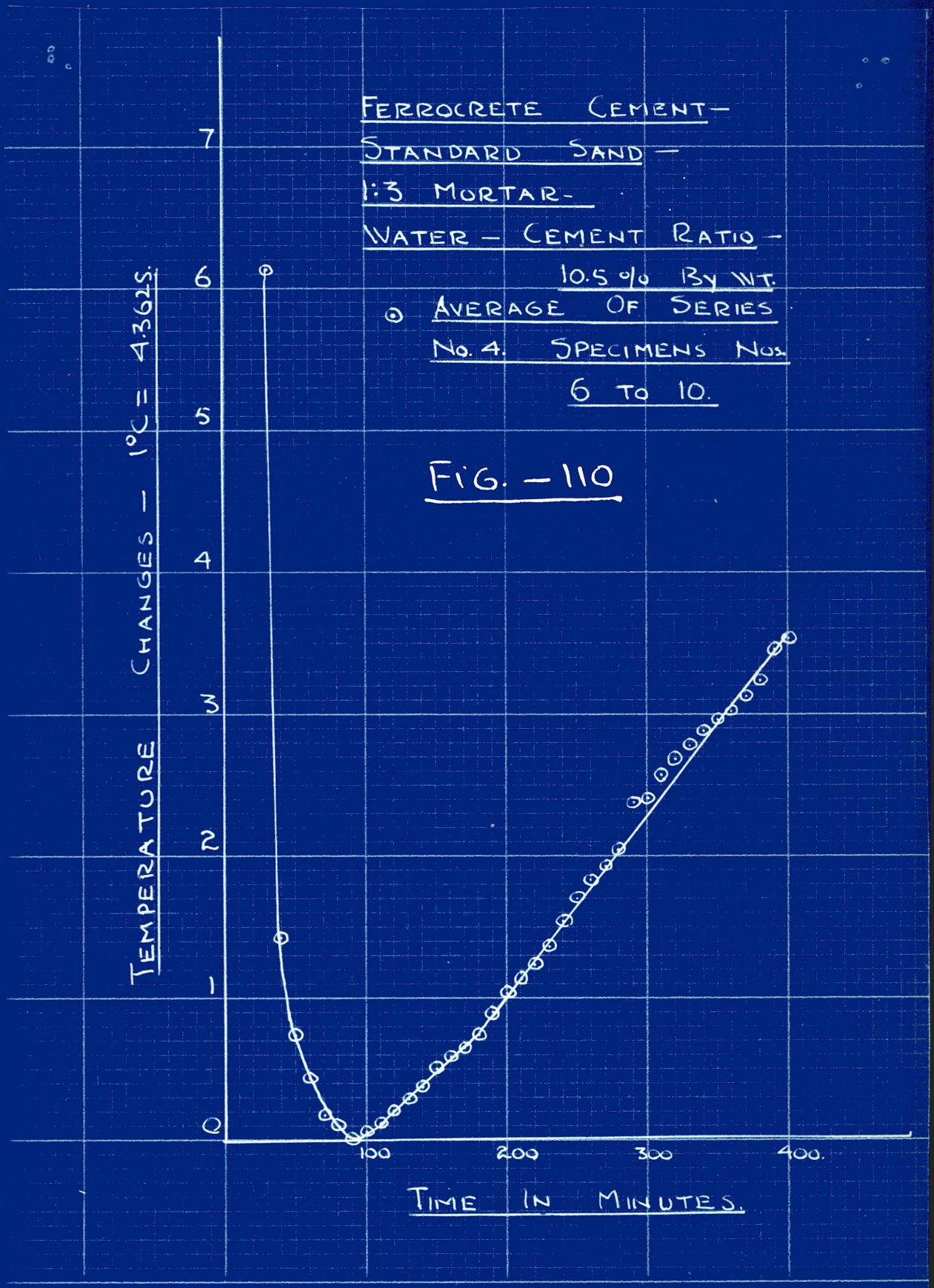
SERIES No. 4.

——— WATER-CEMENT RATIO — 8.5 % BY WT.
– – – " " " 10.5 % " "
–·–·– " " " 6.5 % " "

FERROCRETE CEMENT—
STANDARD SAND
1:3 MORTAR-
WATER— CEMENT RATIO—
8.5 % BY WT.

FIG.—109



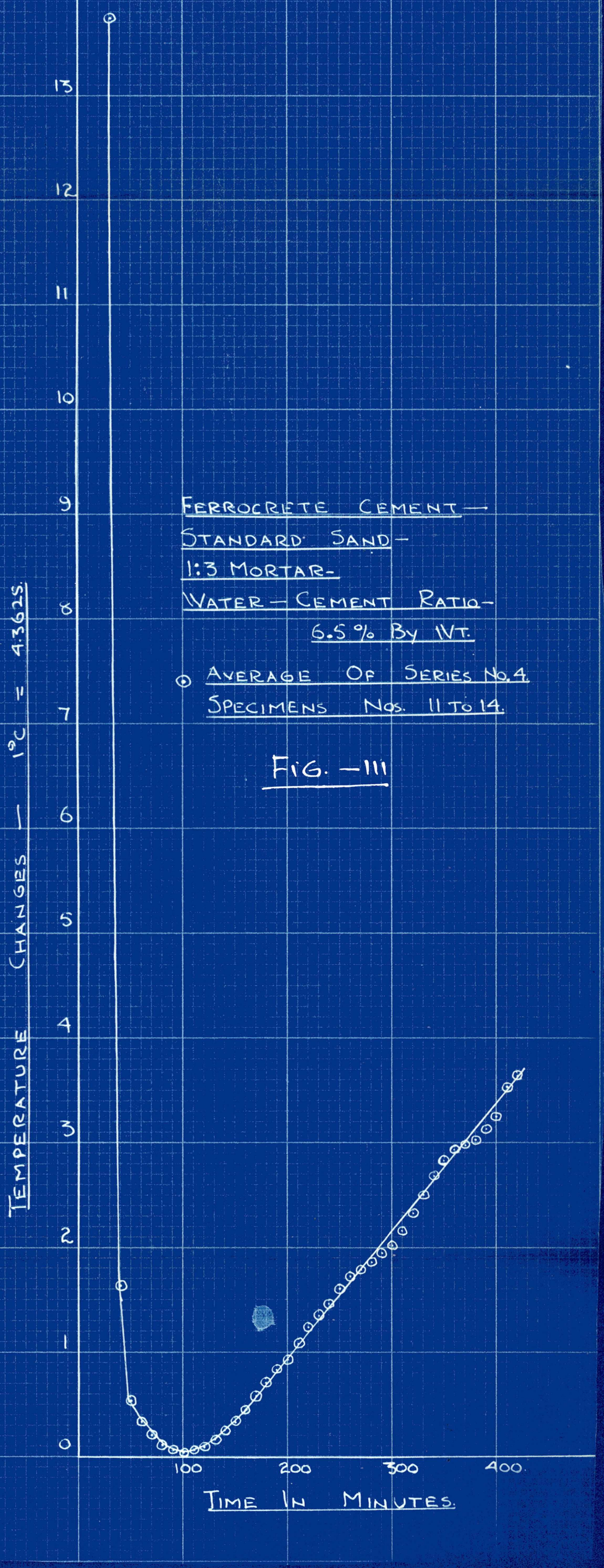


BRITISH MADE

FERROCRETE CEMENT —
STANDARD SAND —
1:3 MORTAR —
WATER — CEMENT RATIO —
6.5 % BY WT.

⊙ AVERAGE OF SERIES No. 4.
SPECIMENS Nos. 11 TO 14.

FIG. — III



Chapter XII.

Results.

Series No. 1.

Fig. 92 shows the rate of change of length in ten minutes of Series No.1. It is seen from this figure that the rate of change of length decreases rapidly for all the three mixes initially. The initial rate of change of the driest mix is the greatest and it decreases as the mixes become wetter. A break is observed in the driest mix, i.e. 20.5%, which is not observed in the other two mixes. The expansion starts earliest in the driest mix.

Fig. 93 shows the total length change of Series No.1 with 30 minute reading as the datum. It is seen that the initial contraction of the driest mix is the greatest, but finally the greatest contraction is observed with the wettest mix. The curves of shrinkage are all continuous between 30 to 400 minutes and no definite break is observed near the initial or the final setting time according to the Vicat needle test.

Figs. 94, 95 and 96 show the average temperature changes for this Series plotted as has been already mentioned with the lowest temperature recorded as 0. It is seen that the optimum percentage of water for this Series for the heat evolution is 20.5%. Next comes 21.5%

and the last 23.5%.

Series No. 2.

Fig.97 shows the rate of change of length in ten minutes of Series No.2. It is seen that the initial contraction is only observed in the 9.9% mix. In the other two mixes, which are drier than this, no initial contraction is observed. On the other hand, initial expansion is observed with the drier mixes, which increases as the percentage of water is reduced. The final rate of expansion is the greatest for the driest mix and decreases with larger quantities of mixing water.

Fig. 98 shows the total length changes of Series No.2. It is seen that the wettest mix contracts initially while the other two mixes expand from the beginning. After about 45 minutes, all the mixes expand. The total expansion is the least with the wettest mix and increases with lesser quantities of mixing water.

Figs. 99, 100 and 101 show the average temperature variations for this Series. It is seen that 9.9% is the optimum percentage of water for this Series for heat evolution, and the heat evolved decreases with the lesser percentages of mixing water.

Series No.3.

Fig.102 shows the rate of length changes in ten minutes for the Series No.3. It is seen that the initial rate of contraction is the greatest for the driest mix which decreases rapidly initially until a stage is reached when the rates of all the three mixes start increasing.

A similar break to that observed in the driest mix of the Blue Circle Cement, Series No.1, is observed for the driest mix in this Series also. But finally the rate of contraction is the greatest with the wettest mix and it decreases with the percentage of water.

Fig. 103 shows the total length changes of Series No.3. It is seen that the driest mix shrinks the most, though as far as the rate of shrinkage is concerned, larger amounts of mixing water reduce initial shrinkage and increase final shrinkage.

Figs. 104, 105 and 106 show the average temperature variations for this Series. It is seen that 23.9% is the optimum percentage for this Series. Next is 21.9% and the last - 25.9%.

Series No.4.

Fig.107 shows the rate of change of length in ten minutes of Series No.4. It is seen that all the three mixes shrink initially. The driest mix has the least initial shrinkage and the wettest has the greatest initial shrinkage. The rate of shrinkage decreases very rapidly initially and the mixes start expanding. The greatest rate of expansion is also observed with the wettest mix which decreases very rapidly and the wettest mix starts contracting once again which increases till it reaches a peak at about 180 minutes after which it goes on decreasing gradually. For the other two mixes, only expansion is observed and the rate is greater for the wetter of the two mixes.

Fig. 108 shows the total length changes of Series No.4 with 30 minute reading as the datum. It is seen that the nature of the curve is the same for all the three mixes up to 100 minutes. Till then the wettest has the greatest initial rate of contraction and expansion which decreases with the lower percentage of water. After that the wettest starts contracting while the other two still expand. Of the other two mixes, the expansion of the drier one is less than that of the wetter one.

Figs.109, 110 and 111 show the average temperature

variations for this Series. It is seen that 8.5% is the optimum percentage for this Series and the next is 10.5% and 6.5% the last.

Conclusions.

(1) It is observed that for both Blue Circle Portland Cement as well as Ferrocrete Rapid-hardening Cement, larger quantities of mixing water reduce the initial rate of shrinkage and increase the final rate of shrinkage. This is in agreement with Dr.Kuhl's observations.

(2) As regards the total shrinkage, it is seen that with 30 minute reading as a datum larger amounts of water reduce the shrinkage initially and increase it finally for Blue Circle Portland Cement. For Ferrocrete Cement, larger amounts of mixing water reduce the total shrinkage initially as well as finally.

(3) It is seen that for both the cements, all the mixes tried contract initially. Drier mixes start expanding earlier than the wetter ones.

(4) The initial as well as the final rate of shrinkage are much greater for Ferrocrete cement than Blue Circle Cement with the same workability, i.e. the percentage of water necessary for the normal consistency of cement according to the B.S.Specification No.12 (1931).

(5) A break is observed in the rate of shrinkage curve of the driest mix of both the cements. No such break at about that time is observed in the other two wetter mixes of the Blue Circle cement. For Ferrocrete a gentler break is observed for the other two wetter mixes.

(6) A change in the rate of shrinkage is observed near the final setting time in the rate of shrinkage curves of both the cements.

(7) The total shrinkage curves for both the cements for all mixes are continuous, showing that the terms "initial" and "final" set as given by the Vicat-needle test are empirical points of use for practical purposes but not existing in fact and that the normal setting in cement is a continuous process without any fixed or defined points.

(8) For Blue Circle Cement, the larger amounts of mixing water (for the percentages tried) decrease the heat evolved, the initial rate of shrinkage and initial total shrinkage. The same relation is not observed with the final rate of shrinkage or final total shrinkage.

(9) For Ferrocrete Cement, larger amounts of mixing water (for the percentages tried) decrease the initial rate of shrinkage and total shrinkage. The

 for heat evolution

optimum percentage of water is 23.9%, the next 21.9% and the last 25.9%. So the same relation that was observed for Blue Circle Cement between percentage water, heat evolution and shrinkage does not hold good for the initial or final rates of shrinkage or total shrinkage.

(10) For the Blue Circle Cement mortar, it is found that the mortar contracts with ~~water~~ wetter mixes and expands with the drier mixes initially. In the end, the drier the mix the greater the expansion.

(11) The same type of relation that was observed for Blue Circle Cement between percentage of water, heat evolved and volume changes holds good for Blue Circle cement mortars also.

(12) For Ferrocrete Cement mortars, it is observed that all the mixes contract initially, the rate of contraction increasing with the percentage of water. This initial contraction decreases rapidly, the rate of decrease increasing with the percentage of water until all start expanding. The wettest reaches the peak value. After this, the rate of expansion decreases, the rate of decrease increasing with the percentage of water till the wettest mix starts contracting again.

(13) No relation was found to exist between the percentage of mixing water, heat evolution and volume changes for Ferrocrete mortar as has been the case with

Ferrocrete cement also.

(14) The heat evolved by the Ferrocrete mortars is greater than the Blue Circle mortars, while the volume change movements are greater for Blue Circle Cement mortars.

No attempt has been made in this investigation to give any quantitative values of shrinkage for the various mixes and the percentage of water, etc., as it would be realised that this investigation is merely an attempt to obtain some qualitative information about autogeneous shrinkage, about which practically no unequivocal data exists due to the difficulty of taking measurements while the cement is in a plastic state, by devising a simple and suitable apparatus for obtaining a curve of shrinkage as near the wetting time as possible. This investigation merely forms a very small part of research that will have to be carried out about the autogeneous shrinkage of cements and the effect on it of the attendant circumstances, such as fineness of cements, size and shape of the specimen, aggregates, temperature and humidity of the surrounding air, etc., before any definite results can be obtained which would enable us to formulate a basic theory which would account for all - creep, shrinkage, plastic flow, setting, etc. as a guide to structural practice into which this important material enters.

APPENDIX A.

TABLES Nos. 44 to 62.

(Note:- As the total number of specimens was 62, only 10 tables for Series I have been given, and only representative table for each of the other Series with each percentage of water.)

Notes:-

(1) Series No. 1. Specimens Nos.1 to 11 - Blue Circle Neat Cement Specimens - water-cement ratio, 21.5% by weight.
Tables 44 to 51 for specimens Nos.1 to 8.

Series No.1. Specimens Nos. 12 to 17.- Blue Circle Neat Cement Specimens - water-cement ratio, 23.5% by weight.
Representative Table 52 for Specimen No.12.

Series No.1. Specimens Nos. 18 to 21. - Blue Circle Neat Cement Specimens - water-cement ratio, 20.5% by weight.
Representative Table 53 for Specimen No.20.

(2) Series No.2. Specimens Nos. 1 to 5.- Blue Circle Cement -Standard sand - 1:3 Mortar, water-cement ratio, 7.9% by weight.
Representative Table 54 for Specimen No.1.

Series No.2. Specimens Nos. 6 to 11.- Blue Circle Cement - Standard sand - 1:3 mortar, water-cement ratio, 9.9% by weight.
Representative Table 55 for Specimen No.6.

Series No.2. Specimens Nos.12 to 16.- Blue Circle Cement - Standard sand - 1:3 mortar, water-cement ratio, 5.9% by weight.
Representative Table 56 for Specimen No.15.

(3) Series No.3. Specimens Nos. 1 to 4. - Ferrocrete Neat Cement Specimens - water-cement ratio, 23.9% by weight.
Representative Table 57 for Specimen No.1.

Series No.3. Specimens Nos. 5 to 8.-Ferrocrete Neat Cement Specimens - water-cement ratio, 25.9% by weight.
Representative Table 58 for Specimen No.8.

Series No.3. Specimens Nos. 9 to 12.- Ferrocrete Neat Cement Specimens - water-cement ratio, 21.9% by weight.
Representative Table 59 for Specimen No.12.

(4) Series No.4. Specimens Nos. 1 to 5.- Ferrocrete Cement - Standard sand - 1:3 mortar, water-cement ratio, 8.5% by weight. Representative Table 60 for Specimen No.1.

Series No.4. Specimens Nos. 6 to 10.- Ferrocrete Cement - Standard sand - 1:3 mortar, water-cement ratio, 10.5% by weight. Representative Table 61 for Specimen No.10.

Series No.4. Specimens Nos. 11 to 14.- Ferrocrete Cement - Standard Sand - 1:3 mortar, water-cement ratio, 6.5% by weight. Representative Table 62 for Specimen No.14.

(5) The temperature of the mixing water was maintained at 15° C. throughout all the four series.

(6) Rate of length change readings represent 1 = 1/1000 in.= 1/90% in ten minutes. For convenience of typing and to include all the readings for a specimen on one page, rate of length change values are given in line with scale and time readings, e.g. reading given at 30 minutes represents the values of the rate of length changes between 30 and 40 minutes.

(7) Total length change readings represent 1 = 1/1000 in. = 1/90%.

(8) Total length change readings are given with 30 minutes readings from wetting the mix as datum.

(9) Plus represents contraction; minus, expansion in all the Tables.

(10) Galvanometer deflection readings represent, 4.3625 = 1°C.

(11) Hygrometrical Tables adapted to the use of Dry and Wet bulb thermometers by James Glaisher, were referred for finding degree of humidity from thermometer readings.

- - - - - - -

TABLE XLIV.

16/12/35.

Series No.1. Specimen No. 1.
Blue Circle Neat Cement Specimen. + contraction.
Water-cement ratio,21.5% by weight. - expansion.
Temp.of mixing water,-15° C.

Time.	Time in mins. from wetting the mix.	Scale Reading.	Rate of length changes in 10 mins.	Total Length Changes	Atmospheric Temperatures		Degree of Humidity Satn.= 100.	Ames Dial Reading.
					Dry Bulb °F.	Wet Bulb °F.		
		1 = 1/1000 in. = 1/90%						
11.50	---	Mixing ---						
12.20	30	6.28		0	56.0	50.0	65	8.858
12.25	35	10.3	+7.0	+4.02				
12.30	40	13.28	+3.70	+7.0				
12.40	50	16.98	+1.34	+10.70				
12.50	60	18.32	+1.12	+12.04				
1.0	70	19.44	+ .87	+13.16				
1.10	80	20.31	+ .75	+14.03				
1.20	90	21.06	+ .66	+14.78				
1.30	100	21.72	+ .54	+15.44				
1.40	110	22.26	+ .46	+15.98				
1.50	120	22.72	+ .40	+16.44				
2.0	130	23.12	+ .31	+16.84	56.2	50.0	64.2	8.858
2.10	140	23.43	+ .32	+17.15				
2.20	150	23.75	+ .37	+17.47				
2.30	160	24.12	+ .28	+17.84				
2.40	170	24.40	+ .27	+18.12				
2.50	180	24.67	+ .26	+18.39				
3.0	190	24.93	+ .24	+18.65				
3.10	200	25.17	+ .28	+18.89				
3.20	210	25.45	+ .22	+19.17				
3.30	220	25.67	+ .30	+19.39				
3.40	230	25.97	+ .23	+19.69				
3.50	240	26.20	+ .17	+19.92				
4.0	250	26.37	+ .16	+20.09	56.5	50.8	67.0	8.858
4.10	260	26.53	+ .14	+20.25				
4.20	270	26.67	+ .11	+20.39				
4.30	280	26.78	+ .08	+20.50				
4.40	290	26.86	+ .06	+20.58				
4.50	300	26.92	+ .06	+20.64				
5.0	310	26.98	+ .04	+20.70	56.3	50.7	67.3	8.858
5.10	320	27.02	+ .02	+20.74				
5.20	330	27.04	0	+20.76				
5.30	340	27.04	0	+20.76				
5.40	350	27.04		+20.76				
17/12/35.								
10.40	1370	25.45		+19.17	53.6	47.7	64.5	8.858

TABLE XLV.

17/12/35.

Series No. 1. Specimen No. 2.
Blue Circle Neat Cement.
Water-cement ratio, 21.5% by weight.
Temp. of mixing water - 15° C.

Time.	Time in mins. from wetting the mix.	Scale Reading.	Rate of length changes in 10 mins.	Total Length Changes	Atmospheric Temperatures		Degree of Humidity Satn. = 100.	Ames Dial Reading.
		1 = 1/1000 in. = 1/90%.			Dry Bulb °F.	Wet Bulb °F.		
11.45	---	Mixing						
12.7	22	5.5			55.3	49.7	67.3	11.182
12.10	25	9.1						
12.15	30	11.64		0				
12.20	35							
12.25	40	18.54	+4.3	+ 6.9				
12.30	45	20.54		+ 8.9				
12.35	50	21.57	+2.68	+ 9.93				
12.40	55	23.22		+11.58				
12.45	60	24.30	+1.86	+12.66				
12.50	65	25.08		+13.44				
12.55	70	25.73	+1.24	+14.09				
1.0	75	26.32		+14.68	55.3	49.8	67.8	11.182
1.5	80	26.81	+ .80	+15.17				
1.10	85	27.12	+ .77	+15.48				
1.20	95	27.89		+16.25				
1.25	100	28.11	+ .67	+16.47				
1.30	105	28.56		+16.92				
1.35	110	28.93	+ .55	+17.29				
1.40	115	29.11		+17.47				
1.45	120	29.38	+ .48	+17.74				
1.50	125	29.59		+17.95				
1.55	130	29.80	+ .45	+18.16				
2.0	135	30.04		+18.40				
2.5	140	30.24	+ .48	+18.60	55.8	49.8	66.3	11.182
2.10	145	30.52		+18.88				
2.20	155	30.95	+ .39	+19.31				
2.30	165	31.34	+ .30	+19.70				
2.40	175	31.64	+ .29	+20.0				
2.50	185	31.93	+ .23	+20.29				
3.0	195	32.16	+ .20	+20.52	56.0	50.2	66.0	11.182
3.10	205	32.36	+ .19	+20.72				
3.20	215	32.55	+ .19	+20.91				
3.30	225	32.74	+ .17	+21.10				
3.40	235	32.91	+ .09	+21.27				
3.50	245	33.0	+ .08	+21.36				
4.0	255	33.08	+ .07	+21.44	56.0	50.2	66.0	11.182
4.10	265	33.15	+ .09					
4.20	275	33.24	+ .05	+21.60				
4.30	285	33.29	+ .01	+21.65				
4.40	295	33.30	+ .01	+21.66				
4.50	305	33.31	+ .01	+21.67				
5.0	315	33.32		+21.68	56.0	50.2	66.0	11.182
18/12/35.								
10.40	1375	31.02		+19.38	49.0	48.0		11.182

TABLE 46.

8/1/36.

Series No. 1. Specimen No. 3.
Blue Circle Neat Cement Specimen.
Water-cement ratio, 21.5% by weight.
Temp. of mixing water - 15° C.

Time.	Time in mins. from wetting the mix.	Scale Reading.	Rate of length changes in 10 mins.	Total Length Changes	Atmospheric Temperatures		Degree of Humidity Satn.= 100.	Ames Dial Reading.
		1 = 1/1000 in. = 1/90%			Dry Bulb °F	Wet Bulb °F		
11.5	---	Mixing ---						
11.25	20	5.60			59.7	56.0	78.5	9.363
11.30	25	8.01	+4.0					
11.35	30	9.60	+6.8	0				
11.45	40	16.40		+6.80				
11.50	45	18.50	+2.52	+8.90				
12.0	55	21.02	+ .96	+11.42	59.5	56.0	79.5	9.363
12.10	65	21.98	+ .82	+12.38				
12.20	75	22.80	+ .71	+13.20				
12.30	85	23.51	+ .69	+13.91				
12.40	95	24.20	+ .58	+14.60				
12.50	105	24.78	+ .51	+15.18				
1.0	115	25.29	+ .43	+15.69	60.0	56.2	77.2	9.363
1.10	125	25.72	+ .41	+16.12				
1.20	135	26.13	+ .39	+16.53				
1.30	145	26.52	+ .37	+16.92				
1.40	155	26.89	+ .37	+17.29				
1.50	165	27.26	+ .39	+17.66				
2.0	175	27.65	+ .31	+18.05	60.0	56.2	77.2	9.363
2.10	185	27.96	+ .27	+18.36				
2.20	195	28.23	+ .33	+18.63				
2.30	205	28.56	+ .10	+18.96				
2.40	215	28.66	+ .23	+19.06				
2.50	225	28.89	+ .21	+19.29				
3.0	235	29.10	+ .15	+19.50	60.0	56.2	77.2	9.363
3.10	245	29.25	+ .13	+19.65				
3.20	255	29.38	+ .13	+19.78				
3.30	265	29.51	+ .06	+19.91				
3.40	275	29.57	+ .08	+19.97				
3.50	285	29.65	+ .07	+20.05				
4.0	295	29.72	+ .04	+20.12	60.0	56.2	77.2	9.363
4.10	305	29.76	+ .05	+20.16				
4.20	315	29.81	+ .02	+20.21				
4.30	325	29.83		+20.23				
9/1/36.								
10.50	1425	28.09		+18.59				

TABLE 47.

10/1/36.
Series No. 1. Specimen No. 4.
Blue Circle Neat Cement Specimen.
Water-cement ratio - 21.5% by weight.
Temp. of mixing water, 15° C.

Time.	Time in mins. from wetting the mix.	Scale Reading.	Rate of length changes in 10 mins.	Total Length Changes	Atmospheric Temperatures		Degree of Humidity Satn. = 100.	Ames Dial Reading.
					Dry Bulb °F.	Wet Bulb °F.		
		1 = 1/1000 = 1/90%.		in.				
11.36	---	Mixing	---					
12.0	24	4.0			59.8	56.0	78.0	6.093
12.6	30	5.25		0				
12.10	34	8.95	+4.8	+3.70				
12.20	44	13.75	+3.2	+8.50				
12.30	54	16.95	+1.36	+11.70				
12.40	64	18.31	+1.09	+13.06				
12.50	74	19.40	+.74	+14.15				
1.0	84	20.14	+.73	+14.89				
1.10	94	20.87	+.60	+15.62				
1.20	104	21.47	+.60	+16.22				
1.30	114	22.07	+1.08	+16.82	60.0	56.0	76.0	6.093
1.40	124	23.15	+.04	+17.90				
1.50	134	23.19	+.49	+17.94				
2.0	144	23.68	+.39	+18.43				
2.10	154	24.07	+.39	+18.82				
2.20	164	24.46	+.41	+19.21				
2.30	174	24.87	+.36	+19.62				
2.40	184	25.23	+.35	+19.98				
2.50	194	25.50	+.27	+20.31				
3.0	204	25.83	+.27	+20.58	60.3	56.0	74.5	6.093
3.10	214	26.10	+.27	+20.85				
3.20	224	26.37	+.23	+21.12				
3.30	234	26.60	+.12	+21.35				
3.40	244	26.72	+.08	+21.47				
3.50	254	26.80	+.06	+21.55				
4.0	264	26.86	+.06	+21.61	60.3	56.0	74.5	6.091
4.10	274	26.92	+.03	+21.67				
4.20	284	26.95	+.01	+21.70				
4.30	294	26.96	0	+21.71				
4.40	304	26.96	-.01	+21.71				
4.50	314	26.95	-.015	+21.70				
5.0	324	26.935		+21.685	60.3	56.0	74.5	6.093
13/1/36.								
10.45	4269	26.10		+20.85				

TABLE 48.

30/3/36.

Series No.1. Specimen No.5.
Blue Circle Neat Cement Specimen.
Water-cement ratio, 21.5% by weight.
Temp. of mixing water, 15° C.

Time.	Time in mins. from wetting the mix.	Scale Readings. 1 = 1/1000 in. = 1/90%	Rate of length changes in 10 mins.	Total length Changes.	Galvanometer Deflection Scale Readings.	Temp. Changes. 1°C = 4·3625	Atmospheric Temp. Dry Bulb °F.	Atmospheric Temp. Wet Bulb °F.	Degree of Humidity. Satn. = 100.	Ames Dial Reading.
10.30	---	Mixing ---								
11.0	30	14.20		0	98.10	17.9	60.8	56.3	73.8	21.662
11.5	35	17.65	+6.61	+3.45	91.30	11.1				
11.10	40	20.81		+6.61	87.60	7.4				
11.15	45	22.98	+3.87	+8.78	85.80	5.6				
11.20	50	24.68		+10.48	84.40	4.2				
11.25	55	25.81	+2.12	+11.61	83.50	3.3				
11.30	60	26.80	+1.5	+12.60	82.90	2.7				
11.40	70	28.30	+1.0	+14.10	82.0	1.8				
11.50	80	29.30	+ .70	+15.10	81.20	1.0				
12.0	90	30.0	+ .60	+15.80	80.70	.5	61.0	56.9	76.5	21.662
12.10	100	30.60	+ .58	+16.40	80.60	.4				
12.20	110	31.18	+ .58	+16.98	80.45	.25				
12.30	120	31.76	+ .50	+17.56	80.30	.10				
12.40	130	32.26	+ .45	+18.06	80.20	0				
12.50	140	32.71	+ .39	+18.51	80.20	0				
1.0	150	33.10	+ .38	+18.90	80.25	.05				
1.10	160	33.48	+ .37	+19.28	80.30	.10				
1.20	170	33.85	+ .43	+19.65	80.40	.20				
1.30	180	34.28	+ .35	+20.08	80.50	.30				
1.40	190	34.63	+ .35	+20.43	80.60	.40				
1.50	200	34.98	+ .33	+20.78	80.70	.50				
2.0	210	35.31	+ .23	+21.11	80.90	.70	61.1	57.3	78.0	21.662
2.10	220	35.54	+ .23	+21.34	81.0	.80				
2.20	230	35.77	+ .22	+21.57	81.10	.90				
2.30	240	35.99	+ .20	+21.79	81.35	1.15				
2.40	250	36.19	+ .18	+21.99	81.45	1.25				
2.50	260	36.37	+ .16	+22.17	81.60	1.40				
3.0	270	36.53	+ .08	+22.33	81.70	1.50	62.2	57.5	78.5	21.662
3.10	280	36.61	+ .13	+22.41	81.80	1.60				
3.20	290	36.74	+ .07	+22.54	81.90	1.70				
3.30	300	36.81	+ .08	+22.61	82.0	1.80				
3.40	310	36.89	+ .03	+22.69	82.10	1.90				
3.50	320	36.92	0	+22.72	82.20	2.00				
4.0	330	36.92	- .005	+22.72	82.30	2.10				
4.10	340	36.915	-.035	+22.75	82.40	2.20				
4.20	350	36.88	-.04	+22.68	82.50	2.30				
4.30	360	36.84	- .05	+22.64	82.70	2.50				
4.40	370	36.79	- .04	+22.59	82.90	2.70				
4.50	380	36.75	-.035	+22.55	83.10	2.90				
5.0	390	36.715	-.065	+22.51	83.30	3.10	61.2	57.2	77.0	21.662
5.10	400	36.65	-.035	+22.45	83.55	3.15				
5.20	410	36.615	-.075	+22.41	83.40	3.20				
5.30	420	36.54		+22.34	83.45	3.25	61.2	57.2	77.0	21.662
31/3/36.										
10.0	1410	35.89		+21.69						

TABLE 49.

31/3/36.
Series No. 1. Specimen No. 6.
Blue Circle Neat Cement Specimen.
Water-cement ratio, 21.5% by weight.
Temp. of mixing water, 15° C.

Time.	Time in mins. from wetting the mix.	Scale Readings.	Rate of length changes in 10 mins.	Total Length Changes.	Galvanometer Deflection Scale Readings.	Temp. Changes. 1°C=4.3625	Atmospheric Temp. Dry Bulb °F.	Atmospheric Temp. Wet Bulb °F.	Degree of Humidity. Sat. = 100	Ames Dial Reading
		1 = 1/1000 in. = 1/90%.								
10.30	---	Mixing ---								
11.0	30	8.95		0	99.1	17.3	61.1	57.0	76.5	15.991
11.5	35	12.81	+6.87	+3.86	92.6	10.8				
11.10	40	15.82		+6.87	89.0	7.2				
11.15	45	17.99	+3.58	+9.04	87.0	5.2				
11.20	50	19.40		+10.45	85.80	4.0				
11.25	55	20.42	+1.79	+11.47	85.0	3.2				
11.30	60	21.19	+1.38	+12.24	84.0	2.2				
11.40	70	22.57	+1.10	+13.62	83.10	1.3				
11.50	80	23.67	+.79	+13.72	82.70	.90				
12.0	90	24.46	+.64	+15.51	82.20	.40	61.6	57.1	74.5	15.991
12.10	100	25.10	+.60	+16.15	82.10	.30				
12.20	110	25.70	+.55	+16.75	81.95	.15				
12.30	120	26.25	+.47	+17.30	81.90	.10				
12.40	130	26.72	+.41	+17.77	81.90	.10				
12.50	140	27.13	+.49	+18.18	81.80	0				
1.0	150	27.62	+.41	+18.67	81.90	.10	61.8	57.8	77.0	15.991
1.10	160	28.03	+.48	+19.08	81.95	.15				
1.20	170	28.51	+.36	+19.56	82.0	.20				
1.30	180	28.87	+.385	+19.92	82.10	.30				
1.40	190	29.255	+.37	+20.305	82.15	.35				
1.50	200	29.625	+.39	+20.615	82.25	.45				
2.0	210	30.015	+.315	+21.065	82.45	.65	62.0	58.0	77.0	15.991
2.10	220	30.33	+.30	+21.38	82.55	.75				
2.20	230	30.63	+.29	+21.68	82.70	.90				
2.30	240	30.92	+.21	+21.97	82.90	1.10				
2.40	250	31.13	+.20	+22.18	83.0	1.20				
2.50	260	31.35	+.19	+22.38	83.10	1.30				
3.0	270	31.52	+.105	+22.57	83.50	1.50	62.0	57.5	74.5	15.991
3.10	280	31.625	+.10	+22.675	83.40	1.60				
3.20	290	31.725	+.095	+22.775	83.50	1.70				
3.30	300	31.82	+.05	+22.87	83.70	1.90				
3.40	310	31.87	+.045	+22.92	83.50	2.0				
3.50	320	31.915	+.0075	+22.965	83.90	2.10				
4.0	330	31.9225	+.0025	+22.9725	84.0	2.20	62.0	57.5	74.5	15.991
4.10	340	31.9250	+.0025	+22.9750	84.05	2.25				
4.20	350	31.9275	-.005	+22.9775	84.10	2.50				
4.30	360	31.9225	-.0025	+22.9725	84.20	2.40				
4.40	370	31.920	-.02	+22.97	84.50	2.70				
4.50	380	31.90	-.055	+22.95	84.70	2.90				
5.0	390	31.845	-.025	+22.895	84.90	3.10	62.0	57.2	73.0	15.991
5.10	400	31.82	-.0075	+22.87	84.95	3.15				
5.20	410	31.8125	-.0425	+22.8625	85.0	3.20				
5.30	420	31.77	-.0475	+22.82	85.01	3.21				
5.40	430	31.7225		+22.7725	85.015	3.215	62.0	57.2	73.0	15.991
1/4/36.										
10.10	1420	31.65		+22.68						

TABLE 50.

1/4/36
Series No.1. Specimen No. 7.
Blue Circle Neat Cement Specimen.
Water-cement ratio, 21.5% by weight.
Temp. of mixing water, 15°C.

Time.	Time in mins. from wetting the mix.	Scale Readings.	Rate of length changes in 10 mins.	Total Length Changes.	Galvanometer Deflection Scale Readings.	Temp. Changes. 1°C=4.3625	Atmospheric Temp. Dry Bulb °F.	Atmospheric Temp. Wet Bulb °F.	Degree of Humidity. Sat.=100	Ames Dial Reading.
		1 = 1/1000 in. = 1/90%								
10.30	---	Mixing --+-								
11.0	30	4.21		0	101.1	18.4	61.2	57.9	80.5	16.18
11.5	35	8.09	+7.0	+3.88	94.8	12.1				
11.10	40	11.21		+7.0	90.2	7.5				
11.15	45	13.69	+4.19	+9.48	87.9	5.2				
11.20	50	15.40		+11.19	86.10	3.4				
11.25	55	16.53	+1.99	+12.52	85.20	2.5				
11.30	60	17.59	+1.105	+13.18	84.80	2.1				
11.40	70	18.495	+1.105	+14.285	83.90	1.2				
11.50	80	19.60	+.83	+15.59	83.40	.70				
12.0	90	20.43	+.67	+16.22	83.0	.30	61.7	58.0	78.5	16.18
12.10	100	21.10	+.53	+16.89	83.0	.30				
12.20	110	21.63	+.51	+17.42	82.90	.20				
1230	120	22.14	+.45	+17.93	82.85	.15				
12.40	130	22.59	+.43	+18.38	82.80	.10				
12.50	140	23.02	+.43	+18.81	82.70	0				
1.0	150	23.45	+.43	+19.24	82.80	.10	61.9	58.3	79.3	16.18
1.10	160	23.88	+.40	+19.67	82.90	.20				
1.20	170	24.28	+.47	+20.07	83.0	.30				
1.30	180	24.75	+.41	+20.54	83.05	.35				
1.40	190	25.16	+.31	+20.95	83.075	.375				
1.50	200	25.47	+.29	+21.26	83.10	.40				
2.0	210	25.76	+.27	+21.55	83.30	.60	62.0	58.2	78.0	16.18
2.10	220	26.03	+.33	+21.82	83.50	.80				
2.20	230	26.56	+.26	+22.15	83.60	.90				
2.30	240	26.62	+.25	+22.41	83.90	1.2				
2.40	250	26.87	+.23	+22.66	84.0	1.3				
2.50	260	27.10	+.13	+22.89	84.10	1.40				
3.0	270	27.23	+.13	+23.02	84.30	1.60	62.0	58.2	78.0	16.18
3.10	280	27.36	+.08	+23.15	84.40	1.70				
3.20	290	27.44	+.07	+23.23	84.50	1.80				
3.30	300	27.51	+.03	+23.30	84.60	1.90				
3.40	310	27.54	+.015	+23.33	84.70	2.0				
3.50	320	27.555	+.005	+23.345	84.75	2.05				
4.0	330	27.56	-.02	+23.35	84.80	2.10	62.0	58.6	80.0	16.18
4.10	340	27.54	-.02	+23.33	84.95	2.25				
4.20	350	27.52	-.06	+23.31	85.05	2.35				
4.30	360	27.46	-.03	+23.25	85.20	2.50				
4.40	370	27.43	-.03	+23.22	85.35	2.65				
4.50	380	27.40	-.0675	+23.19	85.60	2.90				
5.0	390	27.3325	-.0725	+23.1225	85.75	3.05	62.0	58.4	79.0	16.18
5.10	400	27.51	-.08	+23.10	85.85	3.15				
5.20	410	27.23	-.025	+23.02	85.90	3.20				
5.30	420	27.205		+22.995	85.95	3.25	62.0	58.4	79.0	16.18
2/4/36.										
10.10	1420	26.880		+22.670						

TABLE 51.

13/1/36.
Series No. 1. Specimen No. 8.
Blue Circle Neat Cement Specimen.
Water-cement ratio, 21.5% by weight.
Temp. of mixing water, 15° C.

Time.	Time in mins. from wetting the mix.	Scale Readings. 1 = 1/1000 in. = 1/90%	Rate of length changes in 10 mins.	Total Length Changes.	Galvanometer Deflection Scale Readings.	Temp. Changes. 1°C=4.3625	Atmospheric Temp. Dry Bulb ° F.	Atmospheric Temp. Wet Bulb ° F.	Degree of Humidity	Ames Dial Reading.
11.26	---	Mixing ---								
11.52	26	3.0					56.5	51.2	67.5	7.888
11.56	30	4.80		0	85.70	17.6				
12.0	34	7.90	+5.40	+3.10	78.50	10.5	56.5	51.2	67.5	7.888
12.10	44	13.30	+2.60	+8.50	75.50	7.5				
12.20	54	15.90	+1.30	+11.10	73.0	5.0				
12.30	64	17.20	+1.0	+12.40	72.20	4.2				
12.40	74	18.20	+.80	+13.40	70.0	2.0				
12.50	84	19.0	+.70	+14.20	69.10	1.1				
1.0	94	19.70	+.60	+14.90	68.60	.60	56.6	51.0	68.5	7.888
1.10	104	20.30	+.60	+15.50	68.40	.40				
1.20	114	20.90	+.50	+16.10	68.30	.30				
1.30	124	21.40	+.48	+16.60	68.10	.10				
1.40	134	21.88	+.60	+17.08	68.0	0				
1.50	144	22.48	+.43	+17.68	68.05	.05				
2.0	154	22.91	+.40	+18.11	68.10	.10	56.8	50.8	65.8	7.888
2.10	164	23.51	+.34	+18.51	68.15	.15				
2.20	174	23.65	+.33	+18.85	68.20	.20				
2.30	184	23.98	+.23	+19.18	68.30	.30				
2.40	194	24.21	+.24	+19.41	68.40	.40				
2.50	204	24.45	+.22	+19.65	68.60	.60				
3.0	214	24.67	+.19	+19.87	68.80	.80	51.3	51.3	65.3	7.888
3.10	224	24.86	+.15	+20.06	68.85	.85				
3.20	234	25.01	+.15	+20.21	69.0	1.0				
3.30	244	25.16	+.20	+20.36	69.10	1.10				
3.40	254	25.36	+.07	+20.56	69.20	1.20				
3.50	264	25.43	+.09	+20.63	69.30	1.30				
4.0	274	25.52	+.06	+20.72	69.45	1.45	57.3	51.8	67.8	7.888
4.10	284	25.58	+.03	+20.78	69.70	1.70				
4.20	294	25.61	+.01	+20.81	69.80	1.80				
4.30	304	25.62	+.01	+20.82	69.90	1.90				
4.40	314	25.63	0	+20.83	70.00	2.0				
4.50	324	25.63	-.005	+20.83	70.10	2.10				
5.0	334	25,625	-.015	+20.825	70.20	2.20	57.8	51.8	65.8	7.888
5.10	344	25.61	-.02	+20.81	70.40	2.40				
5.20	354	25.59	-.04	+20.79	70.60	2.60				
5.30	364	25.55		+20.75	70.70	2.70				
14/1/36										
11.10	1424	23.79		+18.99						
11.20	1434	23.78		+18.98						
11.30	1444	23.77		+18.97						
12.5	1479	23.76		+18.96						
1.0	1534	23.73		+18.93						
2.20	1614	23.725		+18.925						
3.30	1684	23.72		+18.92						
15/1/36.										
11.10	2864	23.81		+19.01						

TABLE 52.

Representative Table, Series No.1. Water-cement ratio 23.5% by weight.

30/1/36.
Series No.1. Specimen No. 12.
Blue Circle Neat Cement Specimen.
Temp. of mixing water, 15° C.

Time.	Time in mins. from wetting the mix.	Scale Readings.	Rate of length changes in 10 mins.	Total Length Changes.	Galvanometer Deflection Scale Readings.	Temp. Changes.	Atmospheric Temp. Dry Bulb ° F.	Atmospheric Temp. Wet Bulb ° F.	Degree of Humidity.	Ames Dial Reading.
		1 = 1/1000 in. = 1/90%				1°C = 4·3625				
12.0	---	Mixing	---							
12.30	30	1.66	+4.62	0	88.0	15.1	58.5	53.6	71.5	9.095
12.40	40	6.28	+2.55	+4.62	79.50	6.6				
12.50	50	8.83	+1.83	+7.17	76.90	4.0				
1.0	60	10.66	+1.30	+9.0	75.50	2.6				
1.10	70	11.96	+1.20	+10.30	74.20	1.30				
1.20	80	13.16	+1.0	+11.50	73.80	.90				
1.30	90	14.16	+.90	+12.50	73.40	.50	58.7	54.0	72.5	9.095
1.40	100	15.06	+.90	+13.40	73.30	.40				
1.50	110	15.96	+.85	+14.30	73.20	.30				
2.0	120	6.81	+.80	+15.15	73.05	.15				
2.10	130	17.61	+.70	+15.95	73.0	.10				
2.20	140	18.31	+.75	+16.65	72.90	0				
2.30	150	19.06	+.74	+17.40	72.90	0				
2.40	160	19.80	+.70	+18.14	72.95	.05				
2.50	170	20.50	+.71	+18.84	73.0	.10				
3.0	180	21.21	+.69	+19.55	73.05	.15	59.0	54.2	72.0	9.095
3.10	190	21.90	+.65	+20.24	73.10	.20				
3.20	200	22.55	+.60	+20.89	73.15	.25				
3.30	210	23.15	+.55	+21.49	73.20	.30				
3.40	220	23.70	+.50	+22.04	73.25	.35				
3.50	230	24.20	+.48	+22.54	73.30	.40				
4.0	240	24.68	+.49	+23.02	73.375	.475				
4.10	250	25.17	+.39	+23.51	73.70	.80				
4.20	260	25.56	+.31	+23.90	73.80	.90				
4.30	270	25.87	+.27	+24.21	73.90	1.0				
4.40	280	26.14	+.25	+24.48	74.20	1.30				
4.50	290	26.39	+.17	+24.73	74.30	1.40				
5.0	300	26.56	+.14	+24.90	74.40	1.50	59.8	54.8	71.0	9.095
5.10	310	26.70	+.12	+25.04	74.50	1.60				
5.20	320	26.82	+.10	+25.16	74.60	1.70				
5.30	330	26.92	+.08	+25.26	74.80	1.90				
5.40	340	27.0		+25.34	74. 90	2.0	59.8	54.8	71.0	9.09
31/1/36.										
11.35	1415	26.57		+24.91						
3/2/36.										
10.15	5655	26.97		+25.31						

TABLE 53.

Representative Table, Series No.1. Water-cement ratio, 20.5% by weight.

7/4/36.
Series No.1. Specimen No.20.
Blue Circle Neat Cement Specimen.
Temp. of mixing water, 15° C.

Time.	Time in mins. from wetting the mix.	Scale Readings. 1 = 1/1000 in. = 1/90%.	Rate of length changes in 10 mins.	Total Length Changes.	Galvanometer Deflection Scale Readings.	Temp. Changes. 1°C = 4·3625	Atmospheric Temp. Dry Bulb ° F.	Atmospheric Temp. Wet Bulb ° F.	Degree of Humidity Sat = 100	Ames Dial Reading.
11.10	---	Mixing	---							
11.38	28	13.5		-	-					
11.39	29	14.35		-	-					
11.40	30	15.80		0	87.05	17.85	58.9	53.0	66.5	18.19
11.45	35	20.60	+7.06	+4.8	80.05	10.85				
11.50	40	22.86		+7.06	76.25	7.05				
11.55	45	23.70	+5.70	+9.35	74.05	4.85				
12.0	50	26.56		+10.76	73.05	3.85	58.9	53.0	66.5	18.19
12.5	55	26.61	+.85	+11.26	72.15	2.95				
12.10	60	27.41	+.97	+11.61	71.75	2.55				
12.20	70	28.38	+.60	+12.58	70.85	1.65				
12.30	80	28.98	+.40	+13.18	70.25	1.05				
12.40	90	29.38	+.33	+13.58	70.05	.85				
12.50	100	29.71	+.22	+13.91	69.60	.40				
1.0	110	29.93	+.17	+14.13	69.50	.30	59.8	53.0	62.8	18.19
1.10	120	30.10	+.11	+14.30	69.40	.20				
1.20	130	30.21	+.10	+14.41	69.30	.10				
1.30	140	30.31	+.06	+14.51	69.20	0				
1.40	150	30.37	+.04	+14.57	69.25	.05				
1.50	160	30.41	+.02	+14.61	69.275	.075				
2.0	170	30.43	0	+14.63	69.30	.10				
2.10	180	30.43	-.01	+14.63	69.35	.15				
2.20	190	30.42	-.04	+14.62	69.40	.20				
2.30	200	30.38	-.01	+14.58	69.45	.25				
2.40	210	30.37	-.04	+14.57	69.65	.45				
2.50	220	30.33	-.03	+14.53	69.75	.55				
3.0	230	30.30	-.06	+14.50	69.90	.70	59.3	53.0	64.8	18.19
3.10	240	30.24	-.03	+14.44	70.05	.85				
3.20	250	30.21	-.08	+14.41	70.50	1.10				
3.30	260	30.13	-.07	+14.33	70.55	1.15				
3.40	270	30.06	-.09	+14.26	70.45	1.25				
3.50	280	29.97	-.04	+14.17	70.55	1.35				
4.0	290	29.93	-.0425	+14.13	70.80	1.60	59.0	53.0	66.0	18.195
4.10	300	29.8875	-.0475	+14.0875	71.05	1.85				
4.20	310	29.84	-.0225	+14.04	71.30	2.10				
4.30	320	29.8175	-.0775	+14.0175	71.35	2.15				
4.40	330	29.74	-.025	+13.94	71.45	2.25				
4.50	340	29.715	-.075	+13.915	71.55	2.35				
5.0	350	29.64	-.055	+13.84	71.90	2.70	59.5	53.1	64.5	18.195
5.10	360	29585	-.065	+13.785	72.10	2.90				
5.20	370	29.52	-.09	+13.72	72.40	3.20				
5.30	380	29.45	-.04	+13.63	72.50	3.30				
5.40	390	29.39	-.04	+13.59	72.60	3.40	59.1	53.0	65.6	18.195
5.50	400	29.35		+13.55	72.80	3.60				
8/4/36										
10.0	1370	27.695		+12.165						

TABLE 54.

Representative Table, Series No.2. Water-cement ratio, 7.9% by weight.

5/2/56.
Series No.2 Specimen No.1.
Blue Circle Cement - Standard sand - 1:3 Mortar.
Temp. of mixing water 15° C.

Time.	Time in mins. from wetting the mix.	Scale Readings. 1 = 1/1000 in. = 1/90%.	Rate of length changes in 10 mins.	Total Length Changes.	Galvanometer Deflection Scale Readings.	Temp. Changes. (1 = 2.96 x 10⁻⁴ Cal)	Atmospheric Temp. Dry Bulb ° F.	Atmospheric Temp. Wet Bulb ° F.	Degree of Humidity Sat. = 100.	Ames Dial Readings.
10.40	---	Mixing ---								
11.10	30	20.48	-.29	0	65.60	3.75	57.5	49.4	56.6	9.296
11.20	40	20.19	-.29	-.29	62.40	.55				
11.30	50	19.90	-.28	-.58	62.20	.35				
11.40	60	19.62	-.20	-.86	62.0	.15				
11.50	70	19.42	-.20	-1.06	61.90	.05				
12.0	80	19.22	-.19	-1.26	61.85	0	57.9	49.8	56.6	9.296
12.10	90	19.03	-.14	-1.45	61.85	0				
12.20	100	18.89	-.10	-1.59	61.85	0				
12.30	110	18.79	-.9	-1.69	61.90	.05				
12.40	120	18.70	-.07	-1.78	62.0	.15				
12.50	130	18.63	-.08	-1.85	62.0	.15				
1.0	140	18.55	-.06	-1.93	62.0	.15	58.5	50.2	55.8	9.296
1.10	150	18.49	-.04	-1.99	62.10	.25				
1.20	160	18.45	-.05	-2.03	62.20	.35				
1.30	170	18.40	-.03	-2.08	62.30	.45				
1.40	180	18.37	-.03	-2.11	62.40	.55				
1.50	190	18.34	-.03	-2.14	62.50	.65				
2Ø.0	200	18.31	-.025	-2.17	62.60	.75	58.9	50.6	55.8	9.296
2.10	210	18.285	-.025	-2.195	62.80	.95				
2.20	220	18.26	-.05	-2.22	62.90	1.05				
2.30	230	18.21	-.02	-2.27	63.0	1.15				
2.40	240	18.19	-.04	-2.29	63.10	1.25				
2.50	250	18.15	-.04	-2.33	63.20	1.35				
3.0	260	18.11	-.03	-2.37	63.30	1.45	59.0	51.0	57.0	9.296
3.10	270	18.08	-.4	-2.40	63.50	1.65				
3.20	280	18.04	-.035	-2.44	63.70	1.85				
3.30	290	18.005	-.025	-2.475	63.85	2.0				
3.40	300	17.98	-.04	-2.50	63.95	2.10				
3.50	310	17.94	-.035	-2.54	64.0	2.15				
4.0	320	17.905	-.025	-2.575	64.10	2.25	58.8	51.0	57.8	9.296
4.10	330	17.88	-.03	-2.60	64.20	2.35				
4.20	340	17.85	-.04	-2.63	64.25	2.40				
4.30	350	17.81	-.01	-2.67	64.30	2.45				
4.40	360	17.80	-.02	-2.68	64.40	2.55				
4.50	370	17.78	-.03	-2.70	64.50	2.65				
5.0	380	17.75	-.01	-2.73	64.60	2.75	58.7	50.9	57.8	9.296
5.10	390	17.74	-.01	-2.74	64.65	2.80				
5.20	400	17.73	-.005	-2.75	64.70	2.85				
5.30	410	17.725	-.005	-2.755	64.80	2.95				
5.40	420	17.72	-	-2.76	64.85	3.0	58.6	50.9	57.8	9.296
6/2/56.										
10.15	1415	16.97		-3.51						

TABLE 55.

Representative Table, Series No.2. Water-cement ratio, 9.9% by weight.

10/2/36.
Series No.2. S pecimen No. 6.
Blue Circle Cement - Standard sand - 1:3 Mortar.
Temp. of Mixing Water 15° C.

Time.	Time in mins. from wetting the mix.	Scale Readings. (1 = 1/1000 in. = 1/90")	Rate of length changes in 10 min.	Total Length Changes.	Galvanometer Deflection Scale Readings.	Temp. Changes. (1°C = 4·3625)	Atmospheric Temp. Dry Bulb ° F.	Atmospheric Temp. Wet Bulb ° F.	Degree of Humidity. Sat. = 100.	Ames Dial Readings
11.10	---	Mixing	---							
11.40	30	17.02	+.30	0	51.40	2.60	53.0	46.0	59.0	0.592
11.50	40	17.32	+.08	+.30	48.8	0				
12.0	50	17.40	+.02	+.38	48.8	0	53.0	46.0	59.0	0.592
12.10	60	17.42	0	+.40	48.90	.10				
12.20	70	17.42	-.03	+.40	48.95	.15				
12.30	80	17.39	-.02	+.37	49.0	.20				
12.40	90	17.37	-.01	+.35	49.05	.25				
12.50	100	17.36	-.03	+.34	49.10	.30				
1.0	110	17.33	-.04	+.31	49.20	.40	54.0	47.0	59.0	0.592
1.10	120	17.29	-.02	+.27	49.30	.50				
1.20	130	17.27	-.035	+.25	49.40	.60				
1.30	140	17235	-.055	+.215	49.60	.80				
1.40	150	17.18	-.035	+.16	49.70	.90				
1.50	160	17145	-.045	+.125	49.80	1.0				
2.0	170	17.10	-.06	+.08	49.80	1.0	54.0	47.0	59.0	0.592
2.10	180	17.04	-.03	+.02	49.90	1.10				
2.20	190	17.01	-.04	-.01	50.0	1.20				
2.30	200	16.97	-.02	-.05	50.10	1.30				
2.40	210	16.95	-.04	-.07	50.125	1.325				
2.50	220	16.91	-.06	-.11	50.15	1.35				
3.0	230	16.85	-.04	-.17	50.20	1.40	54.0	47.0	59.0	0.592
3.10	240	16.81	-.02	-.21	50.40	1.60				
3.20	250	16.79	-.02	-.23	50.50	1.70				
3.30	260	16.77	-.03	-.25	50.60	1.80				
3.40	270	16.74	-.03	-.28	50.80	2.0				
3.50	280	16.71	-.02	-.31	50.90	2.10				
4.0	290	16.69	-.01	-.33	51.0	2.20	54.0	47.0	59.0	0.592
4.10	300	16.68	-.02	-.34	51.05	2.25				
4.20	310	16.66	-.03	-.36	51.10	2.30				
4.30	320	16.63	-.025	-.39	51.20	2.40				
4.40	330	16.605	-.015	-.415	51.25	2.45				
4.50	340	16.59	-.01	-.43	51.30	2.50				
5.0	350	16.58	-.005	-.44	51.35	2.55	54.0	47.0	59.0	0.592
5.10	360	16.575	-.005	-.445	51.50	2.70				
5.20	370	16.57	-.0025	-.45	51.65	2.85				
5.30	380	16.5675	-.0025	-.4525	51.70	2.90				
5.40	390	16.565	-.005	-.455	51.90	3.10				
5.50	400	16.56		-.46	51.95	3.15	54.0	47.0	59.0	0.592
11/2/36.										
10.0	1380	16.285		-.735						
12/2/36.										
10.30	2840	16.31		-.71						

TABLE 56.

Representative Table, Series No.2. Water-cement Ratio, 5.9% by weight.

7/5/36.
Series No. 2. Specimen No. 15.
Blue Circle Cement - Standard Sand - 1:3 Mortar.
Temp. of Mixing water, 15° C.

Time.	Time in mins. from wetting the mix.	Scale Readings. 1 = 1/1000 in. = 1/90%.	Rate of length Changes in 10 min.	Total Length Changes.	Galvanometer Deflection Scale Readings.	Temp. changes. 1°C=4.3625	Atmospheric Temp. Dry Bulb °F.	Atmospheric Temp. Wet Bulb °F.	Degree of Humidity. Sat. = 100.	Ames Dial Readings.
10.40	---	Mixing ---								
11.0	20	27.89				15.6	62.9	58.6	75.5	18.392
11.5	25	27.69	-.34			9.6				
11.10	30	27.55		0	88.70	6.3				
11.15	35	27.41	-.28	-.14	85.70	3.2				
11.20	40	27.27		-.28	84.20	1.80				
11.25	45	27.11	-.27	-.44	83.90	1.50				
11.30	50	27.0		-.55	83.30	.90				
11.35	55	26.95	-.23	-.65	83.05	.65				
11.40	60	26.77	-.20	-.78	83.0	.60				
11.50	70	26.57	-.19	-.98	82.95	.55				
12.0	80	26.38	-.22	-1.17	82.90	.50	62.6	58.6	77.0	18.392
12.10	90	26.16	-.21	-1.39	82.80	.40				
12.20	100	25.95	-.20	-1.60	82.60	.20				
12.30	110	25.75	-.21	-1.80	82.50	.10				
12.40	120	25.54	-.2125	-2.01	82.45	.05				
12.50	130	25.3275	-.2075	-2.2225	82.40	0				
1.0	140	25.12	-.20	-2.43	82.45	.05	62.7	58.9	78.0	18.392
1.10	150	24.92	-.195	-2.63	82.55	.15				
1.20	160	24.725	-.195	-2.825	82.60	.20				
1.30	170	24.53	-.16	-3.02	82.70	.30				
1.40	180	24.37	-.145	-3.18	82.80	.40				
1.50	190	24.225	-.145	-3.325	82.90	.50				
2.0	200	24.08	-.120	-3.47	82.95	.55	62.8	59.0	78.0	18.392
2.10	210	23.96	-.13	-3.59	83.0	.60				
2.20	220	23.85	-.12	-3.72	83.05	.65				
2.30	230	23.71	-.10	-3.84	83.075	.675				
2.40	240	23.61	-.08	-3.94	83.10	.70				
2.50	250	23.53	-.09	-4.02	83.10	.70				
3.0	260	23.44	-.10	-4.11	83.15	.75	63.0	59.1	77.5	18.392
3.10	270	23.34	-.09	-4.21	83.20	.80				
3.20	280	23.25	-.07	-4.30	83.30	.90				
3.30	290	23.18	-.06	-4.37	83.50	1.10				
3.40	300	23.12	-.09	-4.43	83.70	1.30				
3.50	310	23.03	-.05	-4.52	83.80	1.40				
4.0	320	22.98	-.055	-4.57	83.90	1.50	63.1	59.4	78.6	18.392
4.10	330	22.925	-.075	-4.625	83.95	1.55				
4.20	340	22.85	-.03	-4.70	84.0	1.60				
4.30	350	22.82	-.055	-4.73	84.05	1.65				
4.40	360	22.765	-.04	-4.785	84.10	1.70				
4.50	370	22.725	-.065	-4.825	84.20	1.80				
5.0	380	22.66	-.035	-4.89	84.30	1.90	63.5	59.8	79.0	18.392
5.10	390	22.625	-.035	-4.925	84.40	2.0				
5.20	400	22.59		-4.96	84.60	2.20	63.5	59.8	79.0	18.392
8/5/36.										
10.10	1410	21.58		-5.97						

TABLE 57.

Representative Table, Series No.3. Water-cement ratio, 23.9% by weight.

18/2/36.
Series No.3. Specimen No.1.
Ferrocrete Neat Cement.
Temp. of mixing water 15° C.

Time.	Time in mins. from wetting the mix.	Scale Readings. 1/ = 1/1000 in. = 1/90.%	Rate of length Changes in 10 min.	Total Length Changes.	Galvanometer Deflection Scale Readings.	Temp. changes. 1°C=4·3625	Atmospheric Temp. Dry Bulb °F.	Atmospheric Temp. Wet Bulb °F.	Degree of Humidity. Sat. = 100.	Ames Dial Readings.
10.46	---	Mixing ---								
11.16	30	8.59		0	82.2	11.4	57.0	53.8	79.8	8.654
11.20	34	11.09	+7.105	+2.50	79.0	8.2				
11.30	44	18.195	+2.815	+9.605	75.0	4.2				
11.40	54	21.01	+1.40	+12.42	73.10	2.3				
11.50	64	22.41	+1.05	+13.82	72.10	1.3				
12.0	74	23.46	+1.09	+14.87	71.65	.85	57.2	54.0	80.0	8.654
12.10	84	24.55	+1.15	+15.96	71.35	.55				
12.20	94	25.70	+1.23	+17.11	71.20	.40				
12.30	104	26.93	+1.19	+18.34	71.0	.20				
12.40	114	28.12	+1.22	+19.53	70.9	.10				
12.50	124	29.34	+1.25	+20.75	70.8	0				
1.0	134	30.59	+1.37	+22.0	70.95	.15	57.7	54.2	78.7	8.654
1.10	144	31.96	+1.25	+23.37	71.10	.30				
1.20	154	33.24	+1.32	+24.65	71.20	.40				
1.30	164	34.56	+1.38	+25.97	71.30	.50				
1.40	174	35.94	+1.34	+27.35	71.40	.60				
1.50	184	37.28	+1.27	+28.69	71.70	.90				
2.0	194	38.35	+1.11	+29.96	71.80	1.0	58.0	54.3	77.5	8.654
2.10	204	39.66	+1.03	+31.07	72.0	1.20				
2.20	214	40.69	+1.03	+32.10	72.20	1.40				
2.30	224	41.72	+.74	+33.13	72.40	1.60				
2.40	234	42.46	+.62	+33.87	72.60	1.80				
2.50	244	43.08	+.47	+34.49	72.80	2.0				
3.0	254	43.55	+.46	+34.96	72.90	2.10	58.2	54.7	78.5	8.654
3.10	264	44.01	+.35	+35.42	73.30	2.50				
3.20	274	44.36	+.31	+35.77	73.55	2.75				
3.30	284	44.67	+.27	+36.08	73.70	2.90				
3.40	294	44.94	+.21	+36.35	73.80	3.0				
3.50	304	45.15	+.12	+35.56	74.30	3.50				
4.0	314	45.27	+.15	+36.68	74.60	5.80	58.8	54.8	76.0	8.654
4.10	324	45.42	+.07	+36.83	74.90	4.10				
4.20	334	45.49	+.08	+38.90	75.0	4.20				
4.30	344	45.57	+.015	+36.98	75.10	4.30				
4.40	354	45.585	+.045	+36.995	75.40	4.60				
4.50	364	45.63	+.02	+37.04	75.80	5.0				
5.0	374	45.65	+.005	+37.06	76.0	5.20	58.9	54.7	75.0	8.654
5.10	384	45.655	0	+37.065	76.10	5.30				
5.20	394	45.655	0	+37.065	76.20	5.40				
5.30	404	45.655		+37.065	76.30	5.50	58.9	54.7	75.0	8.654
19/2/36.										
10.20	1414	46.53		+37.94						

TABLE 58.

Representative Table, Series No.3. Water-cement ratio, 25.9% by weight.

25/2/36.
Series No.3. Specimen No. 8.
Ferrocrete Neat Cement Specimen.
Temp. of mixing water - 15° C.

Time.	Time in mins. from wetting the mix.	Scale Readings. 1 = 1/1000 in. = 1/90%.	Rate of length Changes in 10 min.	Total Length Changes.	Galvanometer Deflection Scale Readings.	Temp. changes. 1°C = 4·3625	Atmospheric Temp. Dry Bulb °F.	Atmospheric Temp. Wet Bulb °F.	Degree of Humidity. Sat. = 100.	Ames Dial Readings.
10.50	---	Mixing ---								
11.20	30	5.54	+6.28	0	71.2	6.20	57.05	51.9	69.3	9.792
11.30	40	11.82	+5.28	+6.28	68.5	3.50				
11.40	50	15.10	+2.50	+9.56	67.2	2.20				
11.50	60	17.60	+1.30	+12.06	66.7	1.70				
12.0	70	18.90	+.75	+13.36	66.0	1.0	57.7	52.1	67.7	9.792
12.10	80	19.65	+.48	+14.11	65.5	.50				
12.20	90	20.13	+.565	+14.59	65.2	.20				
12.30	100	20.695	+.795	+15.155	65.10	.10				
12.40	110	21.49	+.71	+15.95	65.05	.05				
12.50	120	22.20	+.71	+16.66	65.0	0				
1.0	130	22.91	+.96	+17.37	65.0	0	57.9	52.2	67.4	9.792
1.10	140	23.87	+1.07	+18.33	65.05	.05				
1.20	150	24.94	+.96	+19.40	65.10	.10				
1.30	160	25.90	+1.08	+20.36	65.15	.15				
1.40	170	26.98	+1.11	+21.44	65.20	.20				
1.50	180	28.09	+1.11	+22.55	65.30	.30				
2.0	190	29.20	+1.10	+23.66	65.60	.60	58.2	52.4	67.2	9.792
2.10	200	30.30	+1.17	+24.76	65.80	.80				
2.20	210	31.47	+1.11	+25.93	65.90	.90				
2.30	220	32.58	+1.04	+27.04	66.0	1.0				
2.40	230	33.62	+1.06	+28.08	66.10	1.10				
2.50	240	34.68	+.93	+29.14	66.50	1.50				
3.0	250	35.61	+.94	+30.07	66.80	1.80	57.85	52.2	67.6	9.792
3.10	260	36.55	+.83	+31.01	66.90	1.90				
3.20	270	37.38	+.76	+31.84	67.0	2.0				
3.30	280	38.14	+.565	+32.60	67.20	2.20				
3.40	290	38.705	+.555	+33.165	67.30	2.30				
3.50	300	39.26	+.48	+33.72	67.50	2.50				
4.0	310	39.74	+.35	+34.20	67.70	2.70	58.0	52.1	70.5	9.792
4.10	320	40.09	+.26	+34.55	67.90	2.90				
4.20	330	40.35	+.25	+34.81	68.0	3.0				
4.30	340	40.60	+.20	+35.06	68.40	3.40				
4.40	350	40.80	+.16	+35.26	68.70	3.70				
4.50	360	40.96	+.13	+35.42	68.90	3.90				
5.0	370	41.09	+.10	+35.55	69.0	4.0	58.5	52.3	69.5	9.792
5.10	380	41.19	+.09	+35.65	69.10	4.10				
5.20	390	41.28	+.08	+35.74	69.15	4.15				
5.30	400	41.36		+35.82	69.20	4.20	58.5	52.3	69.5	9.792
26/2/36.										
10.10	1400	42.62		+37.08						

TABLE 59.

Representative Table, Series No.3. Water-cement ratio, 21.9% by weight.

26/2/36.
Series No. 3. Specimen No. 12.
Ferrocrete Neat Cement Specimen.
Temp. of Mixing Water - 15° C.

Time.	Time in mins from wetting the mix.	Scale Readings.	Rate of length Changes in 10 min.	Total Length Changes.	Galvanometer Deflection Scale Readings.	Temp. changes. 1°C = 4·3625	Atmospheric Temp. Dry Bulb °F.	Atmospheric Temp. Wet Bulb °F.	Degree of Humidity. Sat. =100.	Ames Dial Readings.
		1 = 1/1000 in. = 1/90%.								
11.30	---	Mixing ---								
12.0	30	2.66	+8.73	0	75.2	9.0	57.9	51.4	63.4	9.848
12.10	40	11.39	+4.51	+8.73	70.20	4.70				
12.20	50	15.90	+2.85	+13.24	68.20	2.0				
12.30	60	18.75	+2.14	+16.09	66.80	.60				
12.40	70	20.89	+2.26	+18.23	66.60	.40				
12.50	80	23.15	+2.16	+20.49	66.50	.30				
1.0	90	25.31	+1.95	+22.65	66.40	.20	57.9	51.2	63.2	9.848
1.10	100	27.26	+1.82	+24.60	66.30	.10				
1.20	110	29.08	+1.67	+26.42	66.20	0				
1.30	120	30.75	+1.55	+28.09	66.30	.10				
1.40	130	32.30	+1.40	+29.64	66.50	.30				
1.50	140	33.70	+1.36	+31.04	66.70	.50				
2.0	150	35.06	+1.20	+32.40	66.80	.60	58.2	51.4	60.2	9.848
2.10	160	36.26	+1.10	+33.60	66.85	.65				
2.20	170	37.36	+.93	+34.70	66.95	.70				
2.30	180	38.29	+.81	+35.63	67.0	.80				
2.40	190	39.10	+.70	+36.44	67.10	.90				
2.50	200	39.80	+.59	+37.14	67.20	1.0				
3.0	210	40.39	+.42	+37.73	67.40	1.20	58.0	51.1	61.5	9.848
3.10	220	40.8	+.29	+38.15	67.70	1.50				
3.20	230	41.10	+.33	+38.44	67.80	1.60				
3.30	240	41.43	+.24	+38.77	68.0	1.80				
3.40	250	41.67	+.14	+39.01	68.40	2.20				
3.50	260	41.81	+.10	+39.15	68.60	2.40				
4.0	270	41.91	+.095	+39.25	68.80	2.60	58.1	51.1	61.1	9.848
4.10	280	42.005	+.035	+39.345	69.0	2.80				
4.20	290	42.04	+.05	+39.38	69.10	2.90				
4.30	300	42.09	+.01	+39.43	69.40	3.20				
4.40	310	42.10	+.005	+39.44	69.60	3.40				
4.50	320	42.105	0	+39.445	69.70	3.50				
5.0	330	42.105	-.005	+39.445	69.80	3.60	57.7	50.8	61.4	9.848
5.10	340	42.10	-.01	+39.44	69.90	3.70				
5.20	350	42.09	-.02	+39.43	70.0	3.80				
5.30	360	42.07	-.03	+39.41	70.15	3.95				
5.40	370	42.04	-.04	+39.38	70.35	4.15				
5.50	380	42.0	-.045	+39.34	70.50	4.30				
6.0	390	41.955		+39.295	70.65	4.45	57.6	50.7	61.4	9.848
27/2/36										
10.10	1360	42.42		+39.76						

TABLE 60.

Representative Table, Series No.4. Water-cement ratio, 8.5% by weight.

2/3/36.
Series No.4, Specimen No. 1.
Ferrocrete Cement - Standard Sand - 1:3 Mortar.
Temp. of Mixing Water - 15° C.

Time.	Time in mins. from wetting the mix.	Scale Readings. 1 = 1/1000 in. = 1/90%.	Rate of length changes in 10 min.	Total Length Changes.	Galvanometer Deflection Scale Readings.	Temp. changes. $t = 4.375 - 2.5$	Atmospheric Temp. Dry Bulb °F.	Atmospheric Temp. Wet Bulb °F.	Degree of Humidity. Sat. = 100.	Ames Dial Readings.
10.50	---	Mixing	---							
11.20	30	25.27	+.30	0	62.30	2.80	55.9	50.9	70.0	9.782
11.30	40	25.57	+.03	+.30	59.50	0				
11.40	50	25.60	+.02	+.33	59.55	.05				
11.50	60	25.62	+.01	+.35	59.60	.10				
12.0	70	25.63	-.04	+.36	59.70	.20	56.0	50.9	69.5	9.782
12.10	80	25.59	-.09	+.32	60.0	.50				
12.20	90	25.50	-.15	+.23	60.30	.80				
12.30	100	25.35	-.20	+.08	60.50	1.0				
12.40	110	25.15	-.14	-.12	60.70	1.20				
12.50	120	25.01	-.10	-.26	60.90	1.40				
1.0	130	24.91	-.06	-.36	61.0	1.50	56.6	51.1	68.5	9.782
1.10	140	24.85	-.08	-.42	61.10	1.60				
1.20	150	24.77	-.09	-.50	61.20	1.70				
1.30	160	24.68	-.06	-.59	61.30	1.80				
1.40	170	24.62	-.06	-.65	61.60	2.10				
1.50	180	24.56	-.08	-.71	61.80	2.30				
2.0	190	24.48	-.07	-.79	61.90	2.40	57.1	51.0	64.6	9.782
2.10	200	24.41	-.06	-.86	61.95	2.45				
2.20	210	24.35	-.08	-.92	62.00	2.50				
2.30	220	24.27	-.10	-1.0	62.05	2.55				
240	230	24.17	-.09	-1.10	62.10	2.60				
2.50	240	24.08	-.09	-1.19	62.20	2.70				
3.0	250	24.04	-.06	-1.23	62.30	2.80	57.2	51.3	65.7	9.782
3.10	260	23.98	-.02	-1.29	62.40	2.90				
3.20	270	23.96	-.05	-1.31	62.60	3.10				
3.30	280	23.91	-.03	-1.36	62.70	3.20				
3.40	290	23.88	-.02	-1.39	62.90	3.40				
3.50	300	23.86	-.03	-1.41	62.95	3.45				
4.0	310	23.83	-.04	-1.44	63.0	3.50	57.9	51.9	65.9	9.782
4.10	320	23.79	-.02	-1.40	63.20	3.70				
4.20	330	23.77	-.015	-1.50	63.30	3.80				
4.30	340	23.755	-.005	-1.515	63.40	3.90				
4.40	350	23.75	-.03	-1.52	63.80	4.30				
4.50	360	23.72	-.02	-1.55	63.90	4.40				
5.0	370	23.70	-.015	-1.57	63.95	4.45	57.9	51.9	65.9	9.782
5.10	380	23.685	-.02	-1.585	64.0	4.50				
5.20	390	23.665	-.015	-1.605	64.10	4.60				
5.30	400	23.65		-1.62	64.20	4.70	57.9	51.9	65.9	9.782
3/3/36.										
10.20	1410	23.37		-1.90						

TABLE 61.

Representative Table, Series No. 4. Water-cement ratio, 10.5% by weight.

25/3/36.
Series No. 4. Specimen No. 10.
Ferrocrete Cement - Standard Sand - 1:3 Mortar.
Temp. of Mixing Water 15° C.

Time.	Time in mins from wetting the mix.	Scale Readings. 1 = 1/1000 in. = 1/90%.	Rate of length changes in 10 min.	Total Length Changes.	Galvanometer Deflection Scale Readings.	Temp. changes. 1°C = 4·3625	Atmospheric Temp. Dry Bulb ° F.	Atmospheric Temp. Wet Bulb ° F.	Degree of Humidity. Sat. = 100.	Ames Dial Readings.
10.40	---	Mixing ---								
11.5	25	11.54			-	-	59.5	54.5	71.0	16.15
11.10	30	12.48	+1.20	0	78.35	6.25				
11.20	40	13.68	+.08	+1.20	73.05	.95				
11.30	50	13.76	-15	+1.28	72.70	.60				
11.40	60	13.61	-.20	+1.13	72.35	.28				
11.50	70	13.41	-.22	+.93	72.20	.10				
12.0	80	13.19	-.21	+.71	72.15	.05	60.1	55.1	71.0	16.15
12.10	90	12.98	-.19	+.50	72.10	0				
12.20	100	12.79	-.10	+.31	72.15	.05				
12.30	110	12.69	-.01	+.21	72.20	.10				
12.40	120	12.68	+.005	+.20	72.40	.30				
12.50	130	12.685	+.105	+.205	72.50	.40				
1.0	140	12.79	+.10	+.31	72.60	.50	61.0	56.2	73.0	16.15
1.10	150	12.89	+.10	+.41	72.70	.60				
1.20	160	12.99	+.09	+.51	72.80	.70				
1.30	170	13.08	+.105	+.60	72.85	.75				
1.40	180	13.185	+.095	+.705	73.0	.90				
1.50	190	13.28	+.09	+.80	73.30	1.20				
2.0	200	13.37	+.10	+.89	73.40	1.30	62.0	56.5	74.5	16.15
2.10	210	13.47	+.11	+.99	73.60	1.50				
2.20	220	13.58	+.07	+1.10	73.70	1.60				
2.30	230	13.65	+.08	+1.17	73.80	1.70				
2.40	240	13.73	+.04	+1.25	73.85	1.75				
2.50	250	13.77	+.05	+1.29	74.0	1.90				
3.0	260	13.82	+.03	+1.34	74.20	2.10	61.1	56.9	76.0	16.15
3.10	270	13.85	+.02	+1.37	74.30	2.20				
3.20	280	13.87	+.02	+1.39	74.40	2.30				
3.30	290	13.89	+.03	+1.41	74.50	2.40				
3.40	300	13.92	+.0075	+1.44	74.80	2.70				
3.50	310	13.9275	+.0125	+1.4475	74.90	2.80				
4.0	320	13.94	+.02	+1.46	75.0	2.90	61.3	57.0	75.5	16.15
4.10	330	13.97	+.02	+1.49	75.10	3.0				
4.20	340	13.99	+.01	+1.51	75.20	3.10				
4.30	350	14.0	+.01	+1.52	75.30	3.20				
4.40	360	14.01	+.0075	+1.53	75.40	3.30				
4.50	370	14.0175	+.0075	+1.5375	75.50	3.40				
5.0	380	14.025	+.005	+1.545	75.60	3.50	61.2	57.1	76.5	16.15
5.10	390	14.03	+.01	+1.55	75.70	3.60				
5.20	400	14.04		+1.56	75.75	3.65	61.2	57.1	76.5	16.15
24/3/36.										
9.50	1390	13.955		+1.475						

TABLE 62.

Representative Table, Series No.4. Water-cement ratio, 6.5% by weight.

18/3/36.
Series No. 4. Specimen No. 14.
Ferrocrete Cement - Standard Sand - 1:3 Mortar.
Temp. of Mixing water, 15° C.

Time.	Time in mins. from wetting the mix.	Scale Readings. (1 = 1/1000 in. = 1/90%)	Rate of length changes in 10 min.	Total Length Changes.	Galvanometer Deflection Scale Readings.	Temp. changes (1°C = 4.3625)	Atmospheric Temp. Dry Bulb ° F.	Atmospheric Temp. Wet Bulb ° F.	Degree of Humidity. Sat. = 100.	Ames Dial Readings.
10.50	---	Mixing ---								
11.0	30	18.52	+.10	0	80.90	13.5	58.9	53.0	66.5	16.17
11.10	40	18.62	+.005	+.10	68.50	1.40				
11.20	50	18.625	-.005	+.105	67.70	.60				
11.30	60	18.62	-.005	+.10	67.40	.30				
11.40	70	18.615	-.01	+.095	67.30	.20				
11.50	80	18.605	-.015	+.085	67.25	.15				
12.0	90	18.59	-.095	+.07	67.15	.05	59.5	53.0	64.0	16.17
12.10	100	18.495	-.095	-.025	67.10	0				
12.20	110	18.40	-.07	-.12	67.15	.05				
12.30	120	18.33	-.05	-.19	67.20	.10				
12.40	130	18.28	-.04	-.24	67.30	.20				
12.50	140	18.24	-.04	-.28	67.45	.35				
1.0	150	18.20	0	-.32	67.60	.50	59.9	53.0	62.4	16.17
1.10	160	18.20	-.005	-.32	67.70	.60				
1.20	170	18.195	-.05	-.325	67.80	.70				
1.30	180	18.145	-.04	-.375	67.90	.80				
1.40	190	18.105	-.025	-.415	68.0	.90				
1.50	200	18.08	-.06	-.44	68.10	1.0				
2.0	210	18.02	-.02	-.50	68.30	1.20	60.0	53.1	62.4	16.17
2.10	220	18.0	-.02	-.53	68.70	1.60				
2.20	230	17.98	-.03	-.54	68.75	1.65				
2.30	240	17.95	-.035	-.57	68.85	1.75				
2.40	250	17.915	-.01	-.605	65.90	1.80				
2.50	260	17.90	-.005	-.615	68.95	1.85				
3.0	270	17.90	-.02	-.62	68.97	1.87	59.8	52.2	63.8	16.17
3.10	280	17.88	-.03	-.64	69.0	1.90				
3.20	290	17.85	-.02	-.67	69.05	1.95				
3.30	300	17.83	-.015	-.69	69.10	2.0				
3.40	310	17.815	-.01	-.705	69.25	2.15				
3.50	320	17.805	-.005	-.715	69.30	2.20				
4.0	330	17.80	-.01	-.72	69.50	2.40	60.0	52.9	61.6	16.17
4.10	340	17.79	-.03	-.73	69.80	2.70				
4.20	350	17.76	-.03	-.76	69.90	2.80				
4.30	360	17.73	-.02	-.79	70.0	2.90				
4.40	370	17.71	-.01	-.81	70.05	2.95				
4.50	380	17.70	-.0025	-.82	70.10	3.0				
5.0	390	17.6975	-.0175	-.8225	70.20	3.10	59.9	52.2	58.4	16.17
5.10	400	17.68	-.03	-.84	70.40	3.30				
5.20	410	17.65	-.04	-.87	70.60	3.50				
5.30	420	17.61		-.91	70.65	3.55	59.9	52.2	58.4	16.17
19/3/36.										
10.10	1420	17.52		-1.0						

APPENDIX B.

MIRROR EXTENSOMETER.

A mirror extensometer was used for obtaining a magnification of 393.6 times. The mirror extensometer was fixed on a ¼" knife edge which was mounted between the two notches of the invar bar of the plug of the specimen and the invar block. (Fig. 30).

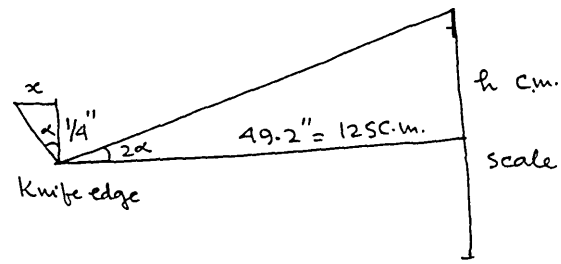


Fig – 112 – (Not to Scale)

$\text{Sin}\,\alpha = \alpha = \frac{x}{k}$, where k = knife edge ..... (1)

$\text{Sin}\,2\alpha = 2\alpha = \frac{h}{49.2}$

$\therefore \quad = \frac{h}{98.4}$ ..... (2)

From (1) and (2),

$$\frac{x}{k} = \frac{h}{98.4}$$

$$\therefore \quad x = \frac{h}{393.6}$$

when h = 1 Division of the scale

= 1 cm.

$$x = \frac{1}{393.6 \times 2.54}$$

$$= \frac{1}{1000} \text{ in.}$$

Therefore movement of one division of the scale = 1/1000 in. = 1/90% as the specimen is 9 ins. long. The scale could be read up to 1/10 m.m. and so the readings were obtained up to $\frac{1}{100,000}$ in.

APPENDIX C.

CALIBRATION OF THERMOCOUPLE.

FIG — 113

CALIBRATION OF THERMOCOUPLE.

EUREKA & COPPER WIRES. (S.W.G 30).

HEATING CURVE —

4.3625 Div = 1°C.

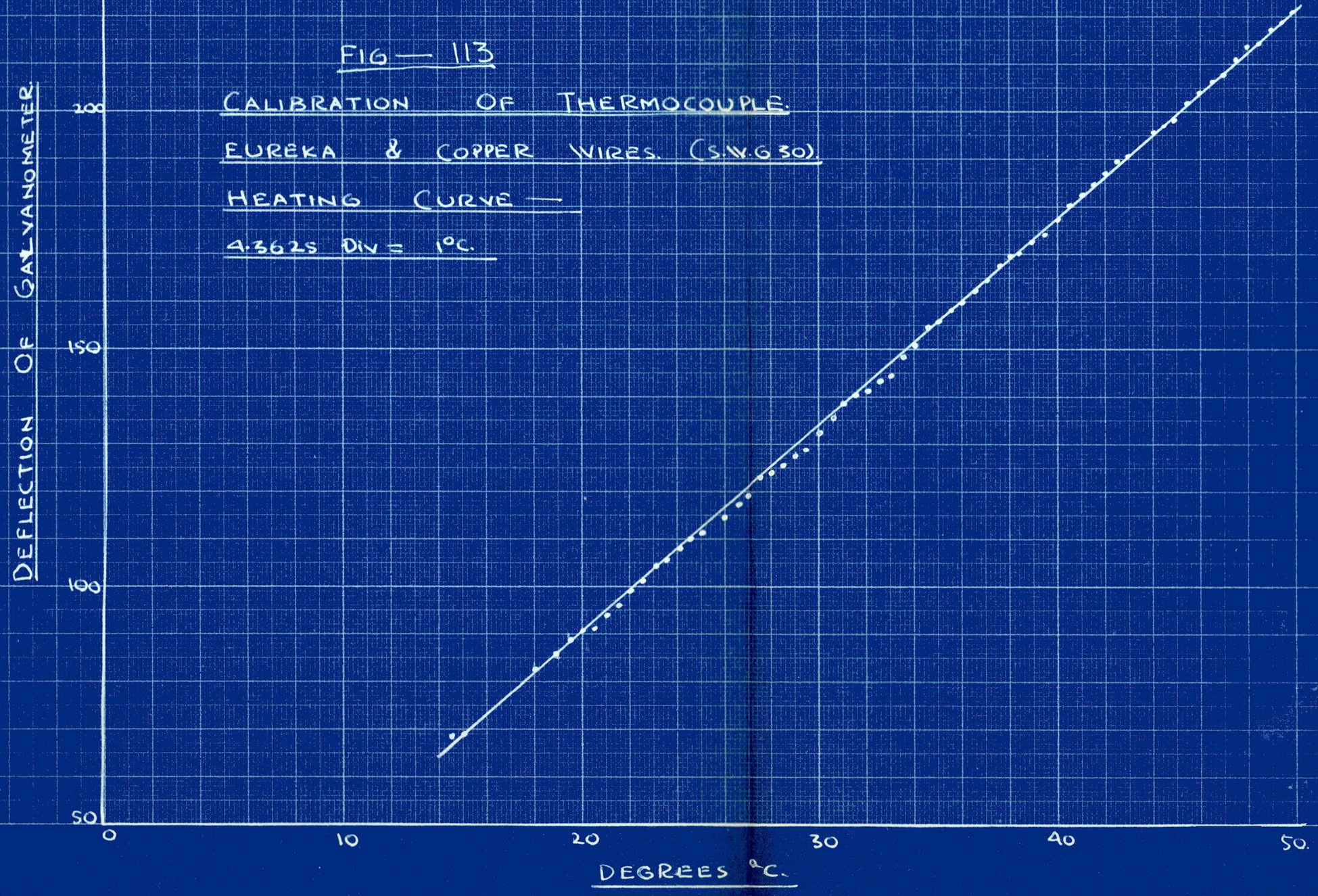


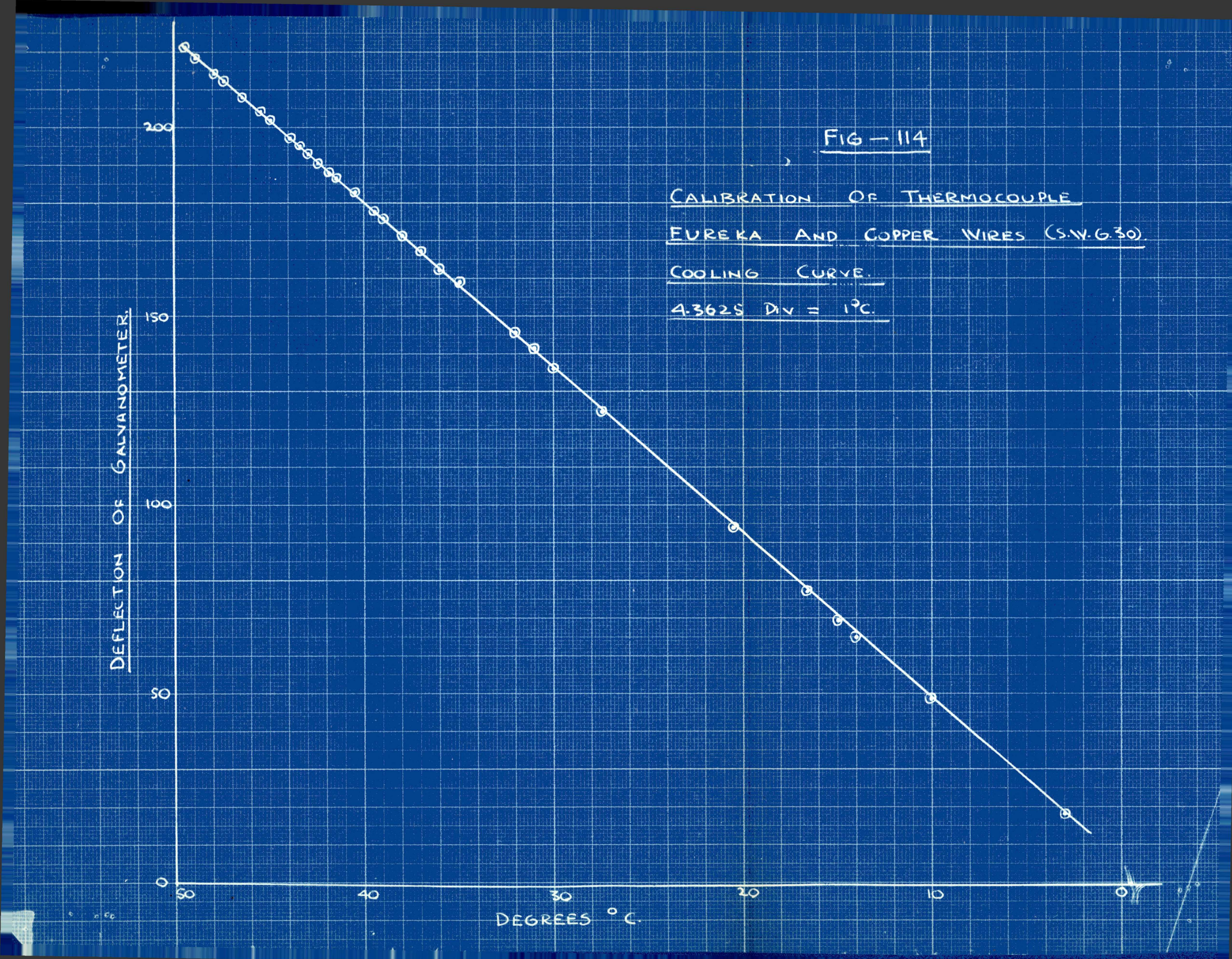
FIG — 114

CALIBRATION OF THERMOCOUPLE

EUREKA AND COPPER WIRES (S.W.G.30)

COOLING CURVE.

4.3625 Div = 1°C.



Calibration of Thermocouple.

The thermocouple consisted of Eureka and Copper Wires (S.W.G. 30). It was calibrated with reference to the direct reading scale of the galvanometer by putting it first in water and then raising the temperature of the water and noting the deflections of the galvanometer on the scale. These readings are given in Table 106. After this the water was allowed to cool and the deflections of the galvanometer on the scale read with the fall in temperature. Table 107. Both sets of readings are plotted in Figs. No. 113 and 114. The mean calibration obtained from the two figures was 4.3625 Div. = 1° C.

TABLE 106.

Calibration of Thermocouple.

Cold Junction in ice.
Hot Junction in water which is gradually heated up.

Temp. of water. °C.	Deflection of Galvanometer. Scale readings.
14.5	68
15.0	68.5
18	82.1
19	84.0
19.5	88.0
20	89.0
20.5	90.9
21	93.9
21.5	95.5
22	99.0

Continued.

Table 106 (Continued)

Temp. of water. °C.	Deflection of Galvanometer. Scale Readings.
22.5	100.9
23.0	103.2
23.5	105.2
24.0	107.5
24.5	109,8
25	111.0
25.5	-
26	114.0
26.5	117.0
27	118.4
27.5	122.5
28.0	123.5
28.5	125.5
29.0	127.0
29.5	129.0
30.0	132.0
30.5	135.0
31.0	138.9
31.5	140.0
32.0	141.0
32.5	143.0
33.0	144.0
33.5	148.0
34.0	150.4
34.5	154.5
35.0	155.5
35.5	158.5
36.0	159.1
36.5	162.1
37.0	164.5
37.5	167.4
38.0	169.5
39.0	123.0
39.5	124.0
40.0	128.5
40.5	180.5
41.0	182.8
41.5	185.0
42.0	187.0
42.5	189.8
43.0	191.0
43.5	193.2
44.0	195.5
44.5	197.0

Continued.

Table 106. (Continued)

Temp. of water. °C.	Deflection of Galvanometer. Scale Readings.
45.0	198.0
45.5	2o2.0
46.0	204.0
46.5	206.4
47.0	207.7
47.5	210.7
48.0	213.6
48.5	214.2
49.0	217.5
49.5	218.7
50.0	221.0

Table 107.

Calibration of Thermocouple.

Cold junction in ice;
Hot junction in hot water which is cooled.

Temp. of Water. °C.	Deflection of Galvanometer. Scale Readings.
50.9	222.9
49.5	221.4
49.0	218.6
48.0	214.8
47.5	212.9
47.0	210.5
46.5	208.0
46.0	207.9
45.5	204.5
45.0	202.0
44.0	197.2
43.5	195.0
43.0	193.0

Continued.

Table 107. (Continued).

Temp. of water °C.	Deflection of Galvanometer. Scale Readings.
42.5	190.5
41.9	188.0
41.5	186.8
40.5	183.0
40.0	179.7
39.5	178.0
39.0	176.0
38.4	173.2
38.0	171.1
37.0	167.5
36.2	164.2
36.0	162.0
35.0	158.9
32.5	147.0
32.0	145.7
31.0	141.1
30.0	136.0
27.5	124.6
27.2	124.0
26.1	119.5
24.9	113.2
20.5	94.0
16.6	77.5
15.0	69.7
14.0	65.0
3.0	18.95

APPENDIX D.

TESTS OF BLUE CIRCLE PORTLAND CEMENT.

Table 108.

Tests of "Blue Circle" Portland Cement.

(1) Fineness of Grinding -

Residue per cent. on British Standard Sieves:

Mesh No. 170	4.8%
Mesh No. 72	-

(2) Setting Time - Minutes:

Initial	140 minutes.
Final	200 minutes.

(3) Soundness - Le Chatelier Test.

Without aeration.

Expansion in m.m.	2 m.m.

(4) Tensile strength (lbs./sq.in.)

3 parts Standard Sand,
1 part Cement.

3 days	560 lbs./sq.in.
7 days	638 lbs./sq.in.

(5) Approximate Analysis - %

Loss on Ignition -	1.91%
SiO_2	21.37%
I.R.	0.34%
Al_2O_3	6.29%
Fe_2O_3	2.30%
CaO	64.05%
SO_3	2.00%
MgO	1.01%
Alkalies and loss	0.73%

APPENDIX E.

TESTS OF "FERROCRETE". THE RAPID HARDENING PORTLAND CEMENT.

Table 109.

Tests of "Ferrocrete". The Rapid Hardening Portland Cement.

(1) Fineness of Grinding.

Residue per cent. on British Standard Sieves:

Mesh No. 110	0.22
Mesh No. 12	-

(2) Setting Time.

Initial	105 minutes.
Final	150 minutes.

(3) Soundness - Le Chatelier Test - without aeration.

Expansion in m.m.	2 m.m.

(4) Tensile strength (lbs./sq.in.) -

3 parts Standard sand,
1 part Cement.

1 day	636 lbs./sq.in
3 Days	721 lbs/sq.in.
7 days	826 lbs/sq.in.

(5) Approximate analysis - %.

Loss on Ignition	1.87%
SiO_2	21.24%
I.R.	0.30%
Al_2O_3	6.39%
Fe_2O_3	2.25%
CaO	64.37%
SO_3	2.25%
MgO	0.85%
Alkalies and Loss	0.48%