Ph.D. Thesis

SEGREGATION AND SEPARATION IN CONCRETES AND MORTARS AND THEIR EFFECTS ON STRENGTH.

Accompanied by Book of Prints.

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ABSTRACT.

In the introductory discussion, evidence indicating water-cement ratio as the principal factor affecting strength is commented on and the view is advanced that the effects of grading and proportions are due to inequalities in cement distribution conditioned by them.

Sections of mortars and concretes are shown and commented on. Evidences of cavity formation are found under the larger fragments in badly graded mixtures. It appears, however, that this is an extreme condition which is not evident in mortars.

Tests of remixed concretes and mortars are then described. In these, segregations were reduced by the increased paste viscosity obtained by re-mixing after a suitable storage period. The control of paste viscosity by this means was somewhat uncertain but reduced cavitation was obtained, accompanied by increased strength. Increases in mortar strengths obtain by re-mixing were much less marked and it was concluded that cavity formation, as a factor affecting strength, was important only in badly graded concretes. It is suggested that inequalities in the density of the cementing paste have considerable influence on strength and may explain the usual grading and proportion effects which occur in normal mixtures.

Mortar tests are then described and discussed from this point of view, together with mortar voids information. Rapid Hardening Portland cement was used. Specimens were water cured and broken at 7 days. Previous experience had indicated that the behaviour of this cement at this curing period was similar to that of Ordinary Portland at 28 days, and the shorter curing period simplified storage arrangements.

The following formula for crushing stress S was evolved,

$$S = 14100\,K\left\{\frac{c}{w} - 0.42K\right\}\ \text{lb/ins.}^2$$

and $K = 1 - 1.11\frac{c}{V_b}$

where V_b = basic voids for the mixture,

c = basic voids - basic voids for neat cement

c = cement content

ω = effective water content

The extension of the tests to include concretes is preceded by a discussion of basic voids and the description of a method of estimating their magnitude. This method is presented, not as a formal study of grading phenomena, but as an expedient to enable the concrete results to be reduced. It was required by circumstances but it is otherwise desirable as it makes unnecessary the somewhat troublesome process of obtaining basic voids experimentally.

As the formula does not cover cavity formation, it was expected that it would not apply to concretes of outstandingly bad gradings. This was found to be so, calculated strengths agreeing closely with observed strengths for normally graded mixtures but exceeding them when grading was obviously poor.

Cavitation is discussed under the heading of "Particle Interference".

Workability is then discussed, slump is related approximately to ?

The writer wishes to draw attention to the fact that the method appears to be quite general, including neat pastes, mortars and concretes under the same rule.

INTRODUCTORY STATEMENT.

Concrete, as one of the most generally employed structural materials, has outstanding claims on the attention of engineers. From the point of view of intrinsic interest also, it claims attention by its peculiar composition and method of preparation. It is remarkable that, by the simple addition of water, it should be possible to build up with certainty a cementing material capable of transforming a random arrangement of stone fragments and a finely ground clinker into concrete of a strength which may be as great as that of a good quality stone.

Primarily this is an achievement of the cement industry; and the part which its technical chemists have played in advancing concrete to its present importance must be acknowledged. It must also be acknowledged that the solutions of many problems in the use of cement must be sought in pure chemistry or in physical chemistry. According to the work done be H.M. Building Research Station, the explanation of volumetric changes in concrete due to changes in moisture content appears to be found in the influence of water on silica gels. As another illustration, the degree of fire resistance possessed by a concrete appears to be determined chiefly by the amount of free lime produced by the hardening reactions.

In such matters the engineer may look to specialists for his facts. In other cases the classification of the problem may not be so apparent. The study of the strength of concrete appears to fall in the latter category as this property is dependent on chemical action and also on the physical effects of aggregate grading and proportions. On the chemical side, the active constituents are the mixing water and cement and it appears that the hardening reactions are condition:ed to some extent by the relative quantities of these materials. The influence of grading and cement proportion is evidently physical. This subject is, however, a legitimate one for engineering research as it appears that the effect of chemical action may be treated by ordinary engineering methods, as far as strength is concerned. This consideration, coupled with some experience of the methods employed by investigators in the same field, induced the writer to commence the work which is to be described. A brief outline of the position as it appeared to him at the time of commencing the work and a statement of the lines he proposed to follow should here be in order.

The most widely known of the simple rules for the strength S of concrete are Abrams'[1] $S = \frac{A}{B^{\frac{w}{c}}}$ and Bolomey's[2] $S = K(\frac{c}{w} - L)$. Although bulk volumes were used by Abrams, c and w may be the respective weights of cement and mixing water or, with appropriate changes in the constants, the absolute volume of cement and the volume of water. A, B, K and L are constants for any selected cement and method and duration of curing. For the practical range of $\frac{c}{w}$ values, the rules are actually alternative ways of expressing the same relation, as pointed out by Dutron. They may be classed as water-ratio relations. Although it appears that, by adjustment of the constants, they may be made to fit the results obtained by varying the water-ratio in any given cement-aggregate mixture, they are evidently incapable of allowing for variations of aggregate grading and proportions. Their authors do not claim this for them. Abrams gives his rule as a mean relation applying to workable non-segregating concretes. The form attributed to Bolomey was given by him as an approximate alternative to a more general rule.

In other investigations, methods have been developed capable of making some allowance for variations in aggregates and proportions, in addition to the chemically active constituents. Feret,[3] in his pioneer work on mortars, used paste density $\frac{c}{1-s}$ as an index of strength S in a formula of the type $S' = K\left(\frac{c}{1-s}\right)^2$. Here c and s are the absolute volumes of cement and sand in unit volume of mortar and represents unit voids ν , (water + air) in the consolidated mortar. Voids are definitely connected with grading and proportions when the mixtures lie within the stiff to plastic range since ν here is greater than the mixing water ω , by an amount depending on grading, grain shape and proportions. It has been found, however, that the relation between paste density and strength differs for different aggregates.[4] There is also the further objection that in wet mixtures air voids disappear and the aggregate effect vanishes, paste density becoming simply a variant of water-ratio.

In their development of Feret's work Talbot and Richart[5] added a reduction factor which removed the latter objection and gave an improved relation between paste density and strength. They stated that at basic water content ω_b (the water content giving minimum voids) strength was given by an equation of Feret's type. At higher water contents ω , strengths correspond:ed with a reduction factor multiplied by the value for strength which the appropriate paste density would give at basic water content. The reduction factor was dependent on relative water content $\frac{\omega}{\omega_b}$ and increase of water over the basic amount decreased strength both by increasing the reduction factor and reducing paste density.

The validity of the paste density rule for strength at basic water content was questioned however by later investigators. The Building Research Station[6] adopted Abram's type of rule for basic water content but they stated that the constants A and B changed to some extent with changes in materials and proportions. As a general rule they gave a modified water-ratio form $S' = \frac{A}{B^{\frac{\omega_b}{c}+2r}}$ where $r = \frac{\omega}{c} - \frac{\omega_b}{c}$. This, of course, is subject to the uncertainties of the basic rule.

In the foregoing methods the grading factors are indirect, being associated with paste density or relative water content. Their determination involves rather lengthy voids tests and they are therefore inconvenient for specification or for comparison of aggregates. Direct grading factors which have been used are Abrams' Fineness Modulus and Surface Area. They are based on sieve analysis. Fineness modulus, given by the sum of the fractions coarser than each of the sieves of the Tyler series, is an empirical measure stated by Abrams to have been arrived at by trial. He claims that aggregates of the same fineness modulus and of similar grain shape are equivalent in their effect on consistency. He uses fineness modulus in his formula connecting water-ratio, aggregates and relative water content. This implies some connection between fineness modulus and strength.

Surface area of the aggregate particles was used initially by Edwards[7] in his method of estimating the amount of mixing water required to produce normal water content. Being therefore connected with relative water content, it has also some bearing on strength. Combining Abrams' and Edwards' work, Young[8-9] used the quantity cement/surface area to establish a connection between strength, water-ratio and consistency. His methods are claimed to have been used with success in work carried out by the Hydro-Electric Power Commission of Ontario. In later work cement/surface area, under the name of cement factor has been employed in various investigations. Further discussion of surface areas will be necessary in connection with the present work but it can be postponed with advantage until a certain amount of experimental work has been described.

The impression gained from a study of the foregoing investigations is that in workable mixtures the basic influence is that of water-ratio. It appears further that relative water content, fineness modulus and surface area are individually inadequate to define the modifying effect of aggregates on strength. Further work on fundamental aspects of these effects appeared to be justified. The following brief statement should serve to indicate the lines it was proposed to follow.

The fact that concrete mixtures are aggregations of materials in unstable physical equilibrium becomes very evident when they are examined. One cubic foot of workable good quality concrete, suitable for reinforced construction, may contain about 107 lb. of aggregate, 25 lb. of cement and 1.3 gallons of water. A leaner mixture, suitable for mass concrete, may contain 120 lb. of aggregate, 13 lb. cement and one gallon of water. In handling, the mass depends for cohesion, partly on surface tension at the boundaries and partly on internal friction. When it is realised that the cement and water still retain their independent physical states of granular impervious clinker and free water it becomes evident that the association of all the constituents is unstable and that inequalities must occur. The precise composition of any small volume of the material must differ, to some small extent at least, from that of any other. In addition to such chance inequalities, there will be systematic effects. In all mixtures there must be tendencies to modification by segregation. In a badly proportioned mixture relatively large quantities of cement and water may separate and, in placing, zones of materials having different proportions may form. Such a condition might be termed general segregation.

As grading is improved these effects will become less apparent and more localised. A well proportioned mixture will be expected to exhibit no material general segregation but there may be local segregations more or less uniformly distributed throughout the mixture.

Object of Work and Arrangement.

The writer's object was primarily the examination of concretes and mortars for effects which might throw further light on the relations between the strengths and compositions of mixtures. Examination for segregation effects appeared to be a promising starting-point. From this, the work described here has developed and its nature precluded any comprehensive scheme being laid down at the outset. The results of the examinations of mixtures suggested tests on remixed materials. These were carried as far as was thought desirable at the time. In theory they should give valuable information on segregation effects - in practise they are rather difficult to control.

It appeared finally to be necessary to accumulate experimental data regarding mortar and concrete strengths in order to examine the indications obtained from the earlier tests. A number of materials of uniform particle size were included in the mortar series as they promised easier analysis. Also mortar voids investigations of the fine aggregates were made, following the methods of Talbot and Richart, as these appeared to offer promise of usefulness in investigations of the equilibrium of the constituents of mixtures.

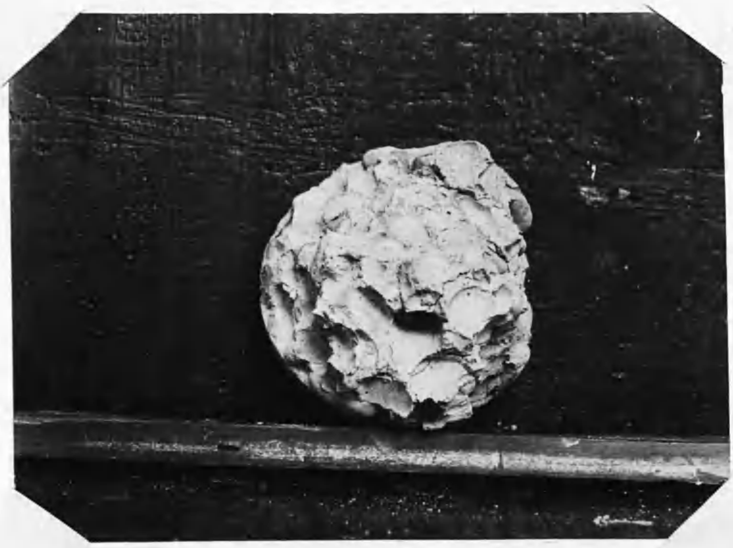
PART 1.

Examination of Mixtures for Segregation.

Remixed Mortars and Concretes.

Segregation Effects.

8" × 4" Cylinders.



Gravel Coarse Agg.

Upper Lower

Coarse Agg. 1½" Whin - no intermediate sizes
Broken in Bending.

Upper Lower

Coarse Agg. - Whin, graded from 1½"
Broken in Bending

EXAMINATION OF SPECIMENS FOR SEGREGATION.

Local segregations of water in concrete have been noted and commented on at various times. They are described in two papers by Edwards(7) in 1918 and are mentioned also by Hollister in Johnson's Reinforced Concrete Handbook of the same year. The latter also discusses the subject in two papers to the American Concrete Institute, the last of these appearing in the 1930 Proceedings. Powers(10) in his paper of the previous year, also mentions the characteristic looseness and poor contact of the cementing material under the larger aggregate fragments which is the most striking evidence of gravitational segregation.

Comment(11) has also been made on marked decreases in bond due to segregations of this type at the surfaces of bars placed horizontally in concrete. In such cases the effect seems to be enhanced by the relative immobility of the bars.

In the later 'particle interference' theory of Weymouth(12)(13) it is sought to establish a connection between grading and tendencies to form segregations of the above type. This work will be discussed in detail later.

Poor adhesion of the mortar to the undersides of the aggregate fragments appears most clearly in transverse fractures. It is illustrated in the three photographs on the opposite page. The first one is of the lower part of an 8" x 4" cylinder and the two others show similar cylinders broken in bending at seven days age. It was noticed that the effect was less marked in specimens broken after a longer curing period.

These concretes were badly graded and were selected to show in a marked degree effects which were present to some extent in normal types of mixture.

Examination of concretes broken up soon after stiffening disclosed similar effects. Mortar adhered much better to the upper sides of the aggregate fragments than the lower. No definite accumulations of water were observed in

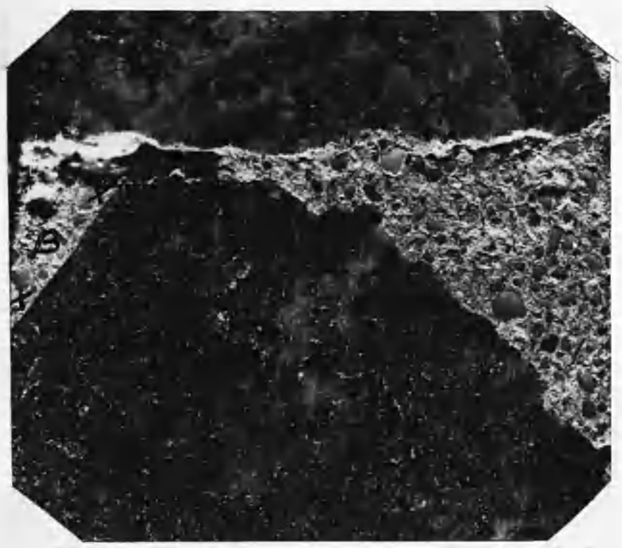


Fig. 2

Showing segregation gaps

x 8

Fig 5.

¼" Gravel + Paste - W.R. 0·5 (by wt.)
Polishing material has filled gap (dark area)

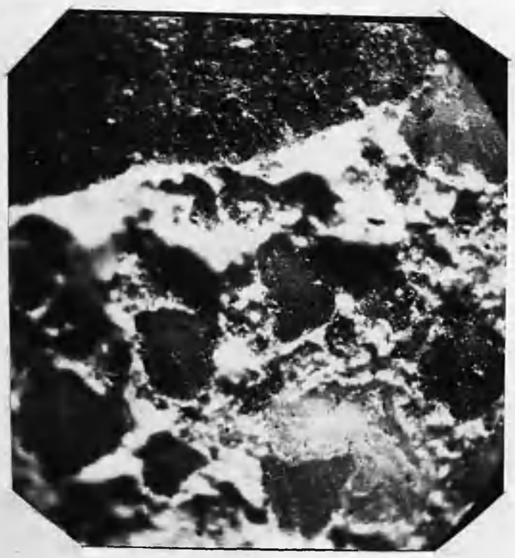
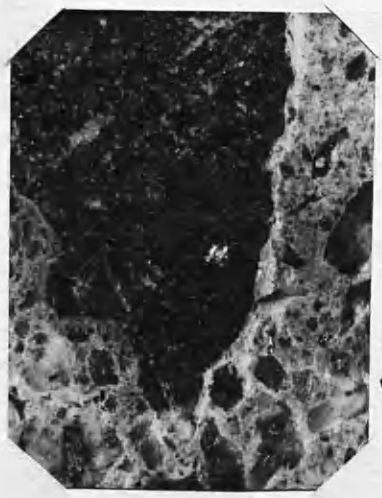


Fig. 3

Enlarged View at A

x 60



Outer side

Fig 7

Spun Concrete Pipe

Fig 4

Enlarged View at B
showing normal contact.
x 60

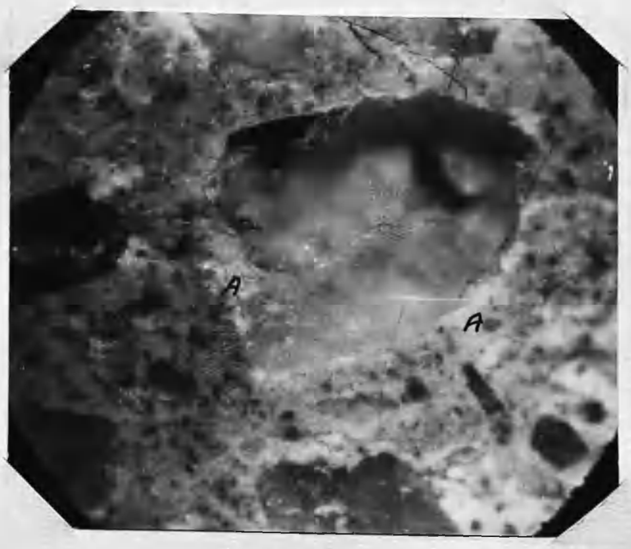


Fig 6

Polished Mortar
Loose binding at A

the sockets left by removal of pieces of aggregate although the surfaces disclosed appeared wetter than adjacent fracture surfaces in the mortar. As the concretes were rather harsh and had water-ratios ranging up to 0·8 (by weight) segregation was less evident than might have been expected in view of the free rejection of water from high water-ratio cement pastes. At water-ratios over 0·6, water was observed to collect at the surfaces of pastes even when they were spread out in thin layers. In 3" x 2½" cylindrical moulds, settlement of cement with rejection of water to the top occurred with water-ratios of 0·5 and over. (see separate sheet) Fig.1 shows the thickness of the water layer about half-an-hour after filling the moulds. ?

To permit further study of segregation, pieces of mortar and concrete were rubbed down on carborundum blocks. Sections prepared in this way were preferred to the thin translucent sections used in petrology. Such sections had been used in a previous investigation and it had then become apparent that suitably prepared surfaces would serve the purpose better. They permit a more certain classification of voids and the surface can be further broken down to clear up uncertainties which may appear on the first examination.

Some of the mortars were given an optical polish although in general this was undesirable as it filled the voids with a material which was hardly distinguishable from cement. One of the sands used (sand A) contained transparent quartz grains and, in the polished mortars, contact between grain surface and cementing material could be examined through some of the grains. These contact surfaces had the white flocculent appearance of laitance. No differences were observed at upper and lower surfaces of the grains. In section, some indication of abnormal conditions at contact between cementing material and grains were observed, as mentioned later.

Appearances on the plane sections are illustrated in figs. 2 to 6. In concretes, definite gaps bordered by looser mortar were found in badly graded mixtures under some of the coarse aggregate fragments. As would be expected the gaps are more frequent in harsh mixtures, but even in these mixtures they were not numerous and their discovery by hand grinding was laborious.

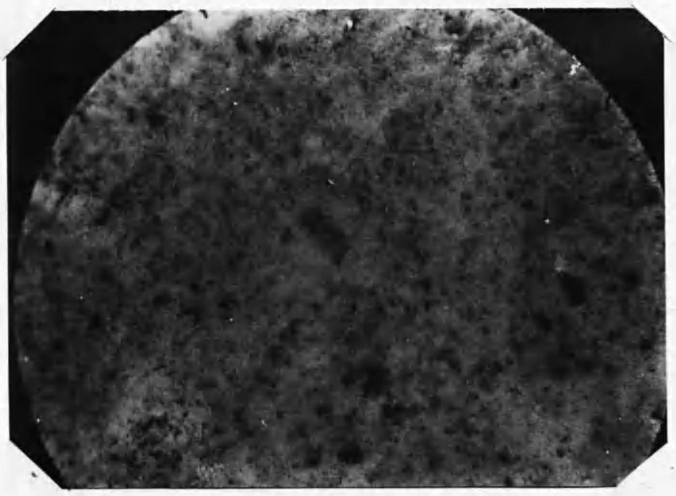
Fig.7 was obtained from the material of a spun concrete pipe. It does not show any definite gap but the binding on the outer (right) side of the large fragment of aggregate was less dense than the normal. 'Binding' is used to describe the hardened cementing material as it seems desirable to differentiate it from the dry cement and the fluid cementing paste.

For inspection of the smaller grains mortars were used principally. No well-defined segregation gaps were seen under fragments passing a No.4 sieve. In mixes of high water content there seemed to be a general looseness of contact between the binding and some of the grains, rather than definite cavities under them. The appearance suggested that some factor other than gravitational segregation produced envelopes of water round these grains. According to the Building Research Station's work on the hardening of silica gels,[14] shrinkage of the gel occurs accompanied by syneresis or rejection of water. It is possible that this may explain the formation of water envelopes round aggregate grains, however, as these envelopes appeared to occur irregularly, it is likely that other agencies contributed water and influenced its distribution.

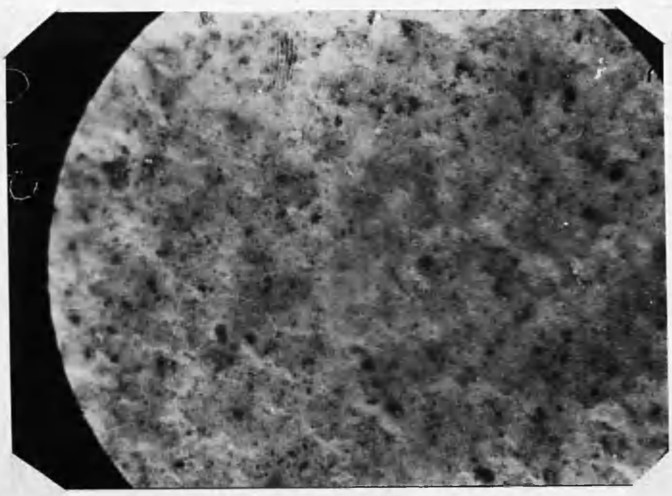
Variations in the texture of the bindings were observed, the materials in adjacent 'voids' frequently showing marked differences in apparent density. In some mortars of high water-ratio, made with fine sand, discontinuities of the binding were noticed in some of the smaller voids. Some time was spent on a study of bindings of different water-ratios in an endeavour to obtain some index of paste density which would assist in examining the condition of the material in the voids in mixtures. Bindings have no regular structure. They appear to consist of darker centres embedded in an amorphous material

Neat Cement Pastes. ×40

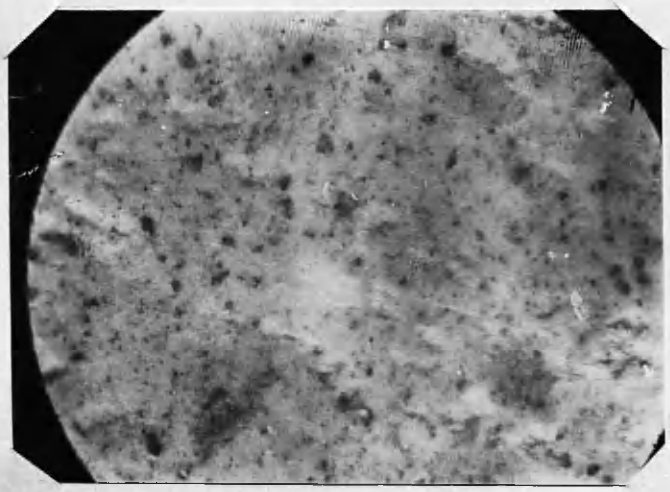
Water-ratios by weight.



Water-ratio 0·5



Water-ratio 0·6



Water-ratio 0·7

Fig 8 ?

of colour which becomes lighter as water-ratio is increased (fig.8) plate?. The dark centres are presumably unchanged grain-material and their sizes indicate that in most cases they are composed of groups of grains. Appearances changed with changes in the angle of illumination producing the impression that some of the dark centres were seen through a partly translucent material. Because of the indefiniteness of position and structure of the dark centres it did not appear to be practicable to estimate cement concentration by count but a rough comparison could be obtained from the appearance.

To summarise briefly, it is evident that segregation gaps occur under aggregate fragments in unsuitably graded con::cretes which may have a serious effect on strength. In mortars (whether isolated or in concrete) there is the possibility of loss of strength through imperfect contact between the binding and some of the aggregate grains and there is also evidence of fluctuations in the density of the binding from point to point.

In addition to the above effects there is the possibility of general segregation. This condition is of interest only as a limit at which any method of calculating the effects on strength of the above local phenomena must break down.

Remixed Mortars and Concretes.

It seemed probable that mortars and concretes, remixed after initial set had taken place, might be of assistance in the study of segregations. It appears to be well established that modern cements of the Portland type are not affected in strength by remixing, provided that hardening has not proceeded too far to permit them to be reduced to a workable state. The paste formed will be more viscous than the original, its condition depending on how far hardening has progressed and on how much it has been worked. Greater paste viscosity will reduce gravitational segregation in mixtures and it should be possible to eliminate these segregations by remixing carefully at a suitable time. It was thought to be useless to arrange a comprehensive programme designed to correlate strength loss with segregation until more definite indications of the possibility of success in this direction had been obtained. Accordingly some tests were made to obtain figures showing how far strength differences due to differences in proportions and grading could be removed by remixing. (See [illegible] book)

The concrete mixtures of fig.9 give ranges of proportions extending from dificiency of coarse material to excess (i.e. harshness). The harsh mixtures were expected to show maximum gap formation and therefore the maximum recovery of strength on remixing. At the other extreme, evidences of general segregation were expected.

Mortar tests, shown in fig. 10 were made at the same time and some neat cement tests, fig.11, were also included. Subsequently the additional mortars of fig.12 were made.

The fine aggregates are described as sands A, B, C and D. Particulars of these sands are given in the appendix.

Details of Preparation of Test Pieces.

Cement:- Rapid Hardening Ferrocrete.

Curing:- All specimens were kept 24 hours in the moulds and then stored in water for 6 days, being broken at 7 days.

Preparation of specimens :- The concretes were mixed in a metal tray about 3ft. x 4ft. x 4in. deep. Solids were measured by weight and the water by volume. Test ? pieces consisted of cylinders 4in. diameter and 8 in. long. They were cast in C.I. moulds on glass plates, their upper faces being finished, after stiffening, with a layer of cement paste which was scraped plane and parallel with the bottom after it had hardened sufficiently.

Three test pieces were made from each mixture. In all but the last five mixtures they were cast at intervals, the first immediately after mixing and the others after the storage times shown in the table, fig.9. To allow for possible effects of time of mixing, when each mixture was made up the portion for the first specimen was separated from the heap and given an additional amount of mixing corresponding roughly to that which the rest would undergo in remixing. The material for the second specimen was treated similarly. During storage the material was covered with a damp sack, kept from contact with it by pieces of steel bar, to minimise evaporation.

In the last five groups the moulds were filled with freshly mixed concrete and the second and third of each were inverted at the times shown. It was thought that freedom from suspicion of evaporation losses could be thus obtained and local segregation effects separated from those of general segregation.

The mortars were mixed in a vessel which was covered by a lid during storage.

The testing machine was a hand-operated one working on oil pressure. The load on the specimen was read by gauges, one reading to 5 tons and the other to 50 tons.

CONCRETES.

It would have been preferable if the figures for strength had been based on the results of three test pieces. As only three 8" x 4" cylinder moulds were available and as it was considered desirable to make each group of normal and remixed specimens from a single mixture, single test pieces had to be used. Very uniform results had been obtain previously from the 8" x 4" cylinders and, as only general indications were sought, it was thought that they would serve the purpose here.

It would also have been preferable to keep the storage times uniform. At the time of making the tests circumstances did not permit this. "Time-strength" diagrams have been plotted for those groups showing the greatest departures from the mean storage times.

Water-ratios given in the table have been corrected for absorption and absorbed water.

Discussion of the normal strengths of the specimens (col. No.1) belongs properly to a later part of the work and it is felt that to attempt it at this stage would result in needless complication. For the present it may be mentioned that they are in accordance with previous work which had been done on these materials. It should perhaps be mentioned also that sand D, which is very fine and capable of holding a high proportion of paste, had been found to be capable of giving very high strengths.

Most of the remixed concretes show gains in strength which may be due to the elimination of segregation. In support of the view that strength loss is entirely due to segregation

Mix 29

Segregation gap in normal specimen.

Fig. 9A

Mix. 29

Segregation gap in inverted specimen.

Mortar has collapsed to fill it partly.

Fig. 9B

which can be dispersed by remixing, some of the groups, of the same water-ratios and materials but of different proportions, reach the same final strengths, e.g. 3 & 4, 5 & 6, 13 & 14 and 19 & 20. However, there are exceptions, 1 & 2 differ from 3 & 4 and 10 from 9 & 8. It does not appear that the same remixed strengths will be obtained for a selected water-ratio when the materials differ (e.g. 3 & 4 and 21 & 22). In one case, group 23, the final specimen shows a very low strength owing to the mixture having become too stiff. Groups 25 to 29 are those in which the moulds were simply inverted and tapped to promote movement. It is thought that the gains obtained are due entirely to the dispersal of gravitational segregation. The object of the special treatment given to these groups was to disturb the concrete no more than necessary to disperse gravitational segregations. The photographs, figs. 9a, 9b, from additional specimens of the group 29 mixture indicate that dispersal was incomplete.

Neat Cements and Mortars.

The neat cement tests confirm that remixing has no effect on the strength of cement paste. In the last two sets (0.52 & 0.56 water-ratios) the small increases obtained are probably due to the dispersal of slight general segregations. The mortars do not give such marked increases on remixing as the concretes. This would appear to indicate that the concrete gains are due to the dispersal of gravitational segregations as these were observed to occur in concretes but not in mortars.

The tables figs. 12 & 13 represent a closer study of sand A. This was based on the following considerations. A typical curve for the variation of mortar strength with constant aggregate and different proportions of pasteof constant water-ratio is shown in fig.14. This curve, illustrating the effect of cement content or mix factor, is typical of graded aggregate. The sized grains of fig.12 give maxima farther to the left. General segregation is a plausible explanation for the lower strengths at low A/C values. The diminution of strength towards the highest A/C values occurs with paste contents more than sufficient to fill the aggregate voids and so is not due to incomplete void filling. Weymouth's discussion of his particle interference theory indicates that he would attribute strength losses here to gravitational segregation. If both these views are correct it ought to be possible to raise the strengths throughout the range to the maximum value by remixing.

The natural grading of sand A was used for the mortars of fig.13. Storage periods of 6 hours for the 0.5 and 0.6 water ratios and 7½ hours for the 0.8 water-ratio were chosen as it had been found that the mortars could be placed up to these times. Two storage periods at each water-ratio were used for the sized materials of fig.12 as they had not been tried previously. Very little difference appears between the normal and remixed strengths in both sets, indicating that gravitational segregation does not have much influence. Considering the earlier results it seems that this conclusion may be extended to cover all mortars.

Note on other work on distrubed concrete. The writer's figures appear to be in general agreement with published figures for remixed mortars and concretes. Gonnerman and Woodworth (15) obtained slightly increased strengths for storage periods up to about four hours, maximum increases being about 10% for some mixtures, for others, less. Gains in mortar strength are reported only at higher water-ratios. In comparison, some of the writer's figures are high but these refer to mixtures of abnormal gradings. Gonnerman and Woodworth used only well-graded mixtures such as would be employed in good practice and they did not use high water-ratios.

With regard to concrete distrubed during setting, Giesche's (16) re-rodded concretes and Hough's (17) 'rotated' specimens may be mentioned. In the former case a proportion of the specimens were re-rodded in the moulds 5 times at 30 minute intervals, water freed being allowed to escape. Gains in strength varying from 8% to 80%, which were obtained, are attributed to the expulsion of water and air. As the gains are not closely related to the increases in density, which are also reported, reduction of air and water contents does not afford a complete explanation. Hough used cylindrical specimens, covering the ends of the moulds and altering their positions during stiffening. They were first inverted and then laid on their sides and given a quarter turn at intervals. He reports gains ranging from 10% for water-ratio 0.7 (Abrams' rating) to 40% for water-ratio 1.1. He also comments on the improved adhesion of the mortar to the aggregate fragments.

Summary and Conclusions.

The remixing tests indicate that local segregation affords only a partial explanation of the influence of aggregate grading and cement content on strength. Provided that aggregate grading is not definitely bad it would appear possible to ignore their effect in strength investigations of such mixtures. The relations obtained might be influenced to a slight extent but it is likely that the residual effects due to variations in the characteristics of the mixtures would be negligible. The effects in mortars are even less apparent. This is in agreement with the rarity of apparent segregation gaps in the mortars examined.

On the assumption that the strength of a mixture depends only on the strength of the binding, there remained only the observed inequalities in bindings, which are referred to earlier, to explain the influences of grading and cement content on strength. These inequalities persisted in remixed mortars. It is suggested that in them an explanation of grading and cement content effects may be found.

A similar view appears to have found acceptance as an explanation of the effect on strength of the cement factor (cement/surface area of aggregate). This quantity represents the nominal thickness of the cement envelope round each aggregate fragment (neglecting the cement absorbed by the residual voids) and it is held that increases in cement factor increase strength by permitting movement of the grains in placing with less disturbance of the cement envelopes. Cement factor explains the increases in strength which usually occur as cement content is increased but its influence is not so apparant when grading is changed. Increases in cement factor produced by replacing an aggregate by a coarser one may result in loss of strength. Cement factor, in conjuction with cement-water ratio and mix factor, has been used in statistical investigations of concrete strength. The primary difficulty here is in obtaining factors capable of defining the concrete making characteristics of the materials and proportions. For instance, mixtures of different aggregates, of the same surface area and cement content, may behave very differently.

It therefore appeared to be worth while pursuing the idea of a binding inequality - strength connection along different lines. It was therefore decided to try to trace some connection between strength fluctuations and mixture characteristics which might be related to the mobility of the cementing paste in the void spaces of the aggregate. Tests of the strengths of mixtures in conjunction with mortar voids investigation along the lines of Talbot and Richart's work seemed to offer the best starting point. Accordingly the work described in the following pages was undertaken.

PART 2.

Application to Mortars and Concretes.

NORMAL TESTS OF MORTARS AND CONCRETES.

Cement:- Ferrocrete Rapid Hardening cement was used as before. As the tests were unavoidably spread over a considerable time the matter of cement control was of special moment. Glanville[18] comments on the variations which may be found in the material from a single container. In the present work the cement was taken from different consignments and used after varying storage periods. Control was obtained by overlapping or repeating tests. Some of these control figures are shown in the tabulated results.

It was found necessary to make control tests at both ends of the water-ratio range, in order to check the effects of aeration. Although the cement was stored in metal containers the usual aeration phenomena were observed, colour becoming lighter and the material somewhat softer to the touch with prolonged storage. It was possible to keep the material in fairly good condition, from the practical point of view, for at least six months, the strength at 7 days age showing material diminution at the higher water-ratios only. Fresh cement of some consignments gave higher results than the average. At storage periods between one and three months the cement appeared to be in the most stable condition and the mortar results given are taken from mixtures in which cements from this storage range were used.

Allowance being made for storage phenomena, the writer found Ferrocrete cement to be remarkably uniform in quality.

The value of 3.05 adopted for specific gravity may also be considered to show aeration effects. It is the mean value obtained from a series of measurements.

Aggregates:-

Fine Aggregate:- The principal aggregates were sands A and C. Sand A is a dredged granite sand composed of irregular granite fragments with rounded edges. It was well graded from $\frac{3}{8}$" down to material passing a No.100 sieve. Different consignments showed very little variation in grading, however, practically all of this material used in the concrete tests reported here came from a single 15 cwt. consignment.

Sand C is a siliceous pit sand of rounded grain shape. It contained a high proportion of fine material and was deficient in intermediate sizes. It was chosen to provide a marked contrast to sand A.

Sand D is also a siliceous pit sand of rounded grain shape. It is composed chiefly of very fine material and was used here only in mortar tests.

The grain materials of these sands were of sufficient strength to ensure that grain failure would not precede binding failure in the mixtures.

The sands were also clean, giving only a slight discoloration when washed and when subjected to the caustic soda test for organic impurity.

Coarse Aggregates:-

$\frac{3}{4}$" to $\frac{3}{8}$" and $\frac{3}{8}$" to No.4 crushed granite of good quality.

$\frac{3}{4}$" to $\frac{3}{8}$" and $\frac{3}{8}$" to No.4 siliceous gravel.

$\frac{3}{4}$" down granite gravel - this was screened in the laboratory and used in graded concretes.

Sieve analysis and other properties of the aggregates are given in the appendix, page 52.

Mortars:- All materials were measured by weight. The drier mortars were mixed on a steel plate and the wetter in a large bowl. The specimens were 3" x $1\frac{1}{2}$" cylinders, cast in C.I. moulds which had their upper and lower faces machined plane and parallel. The moulds were set on plate glass slabs and the upper ends of the cylinders were capped with neat cement paste after stiffening. The top was scraped flush with the upper surface of the mould after the cement had hardened sufficiently. The behaviour of the specimens under test indicated this finish to be satisfactory. After 24 hours in the moulds the specimens were removed and stored in water for 7 days, temperature 58° to 62° F. They were broken immediately after removal from the water without the interposition of packing of any sort between their faces and the platens of the machine.

Concretes:- Solids were measured by weight and the water in a graduated measure. The materials were mixed in a metal tray 3' x 4' x 4" deep. To avoid loss of water, this was kept clean and the surface damped by sponging over with a wet cloth before making each mixture. The specimens were 8" x 4" cylinders. Similar C.I. moulds were used and the specimens finished, cured and broken in the same way as the mortars.

Testing:- The specimens were tested in the hand operated oil machine mentioned previously. A number of tests were, however, duplicated on a 100-Ton steelyard machine as a check on the smaller machine.

Each value used is the mean of three tests.

The concrete and mortar tests were made concurrently. Mortar voids measurements were also made covering the range of mortars. As the reductions of the concrete tests are based on the results obtained for the mortars, it will be convenient to consider the latter first, in conjunction with the mortar voids data. Particulars of these will therefore be given now.

MORTARS .

Mortar Tests.

Mortar Voids.

Discussion of Results and Reduction.

MORTARS.

The particulars of these tests are prefaced by a diagram showing the strengths of neat cement at various water contents. It was desired particularly to get figures for the higher water contents. For these, remixed pastes were used as the freshly mixed pastes are unstable. The results are shown plotted against $\frac{c}{w}$ in fig. 15 and those of fig. 11 are also included.

The averaging line conforms to the $S = A(\frac{c}{w} - b)$ type of equation. The value 14100 lb. per sq. in. has been adopted for A and 0.42 for b.

Notation:- c = absolute volume of cement.

w = volume of effective mixing water.

S = crushing stress of 3" x 1½" cylinders at 7 days, water cured.

Particulars of the mortar tests are given in figs. 16 to 26. Mixing water has been corrected for absorption in all cases. As the quantities handled were small it was possible to dry the materials for each mix and so avoid corrections for water in aggregates.

The strengths are plotted against $\frac{c}{w}$. The points for each mix lie approximately on a straight line, the slopes of the lines decreasing with cement content and grain size (i.e. decreasing with cement factor).

On each diagram the neat cement line has been shown.

Below, the materials used are given, numbered for convenience in reference.

```
No.1 - Sand A )
 " 2 -   "  C )   Screened through No.4 sieve.
 " 3 -   "  D )
Sand A fractions
No.4 - 4/8 screenings 1 part,28/48 screenings 1 part (by
 " 5 -  "       "     2 parts  "          "     1  "  wt.)
 " 6 -  "       "     3.5 "    "          "     1  "
 " 7 - 28/48    "     2   "  48 down      "     1  "
 " 8 - 4/8
 " 9 - 8/14
 "10 - 14/28
 "11 - 28/48
```

Discussion of these results follows the statement of the mortar voids figures.

MORTAR VOIDS MEASUREMENTS.

The method consisted in filling a vessel of known volume with the mortar to be tested. Having obtained the weight of this volume of mortar and knowing the proportions of the mixture and the specific gravities of the constituents, the volume of the solids can be obtained. The difference between this quantity and the volume of the vessel gives the voids (i.e. the space filled by water and air).

As the water content of a mortar is increased air voids decrease and water voids increase. Minimum or Basic voids occur usually at a water content giving a stiff-plastic mortar.

Some time was spent on preliminary tests of methods of placing and type of measuring vessel, special attention being paid to basic voids.

A number of aggregates were investigated, using glass specimen tubes $1\frac{1}{2}$" diameter by 4" long. These tubes were too easily broken by the filling methods necessary for stiff mixtures to be convenient for routine use but they enabled filling methods to be studied. Pockets of loose material were observed to form readily at the walls of the vessel and, if due to separation of the constituents, they were very difficult to disperse. It was evident also that uniformity in methods of placing had a restricted value when applied to mixtures of varying types. Talbot and Richart filled their vessel, which was 4" deep, in three layers, rodding each layer 20 times with a $\frac{1}{2}$" square, pointed, wooden rod. In the present work it was found that greater uniformity was obtained by rodding each layer 40 times with a similar implement. Also special care was taken to avoid separation, each layer being introduced in small quantities which were spread and pressed into place with piece of $\frac{1}{4}$" steel bar cut square at the end. This departure from Talbot and Richart's procedure was justified as it was not intended to use their methods of applying the results. For routine work metal vessels were tried; an aluminium cylinder about 3" deep was finally adopted as it combined lightness and rigidity.

Procedure was on the lines followed by Talbot and Richart. In dealing with an aggregate, the richest mortar, usually 1/1 by weight, was taken first. This was mixed on a metal plate, using a water content less than basic. The mould was filled and weighed and the contents returned to the batch. This was remixed and mould filling and weighing repeated. If the two weights compared satisfactorily, the mean was taken, if not, a third determination was made.

Additional water was then added and the weight of the filled mould determined as before. For further measurement at this aggregate-cement proportion, a fresh batch of mortar was made up as evaporation loss generally became apparent after four fillings of the moulds. This was checked by overlapping some of the batches.

The whole procedure was repeated for other aggregate-cement ratios.

The balance available weighed from one pound to 0.001 lb. In the circumstances, the units of weight were quite immaterial. For convenience in reduction, unit volume was taken as the volume of 1 lb. of water at laboratory temperature. The weight of the empty vessel was 0.115 lb. and about 0.8 lb. filled with mortar. A difference of 0.001 lb. due to a difference in the quantity of solids represents a volume difference of 0.00037, assuming an average sp.gr. of 2.7. The minimum void content of mortar in the vessel was about 0.08 so that, at the worst, 0.001 lb. difference due to packing variations represented an error of about 0.2% in voids. These discrepancies were usually well under 0.005 lb. If over, additional determinations were made.

Reduction of Mortar Voids Observations.

Absolute volume of sand in batch = a

" " " cement = c

Volume of gross mixing water = ω_g ? see p. 25

Weight of sand = W_s

" " cement = W_c ?

" " water = ω_g

Wt. of mortar filling mould = W_m

Volume of mould = V

" " batch = V_b = $\frac{V}{W_m}(W_s + W_c + \omega_g)$?

" " water absorbed by aggregate = ω_a

" " cement in unit vol. of mortar = $c' = \frac{c}{V_b}$

Effective" " aggregate " " " " = $a' = \frac{a + \omega_a}{V_b}$

" " " water " " " " = $\omega' = \frac{\omega_g - \omega_a}{V_b}$

Voids per unit vol. of mortar = $v' = 1 - (a' + c')$

Air voids " " " " = $v' - \omega'$

Voids at basic water denoted by v_b ?

In the specimen table of reductions, fig.27, the procedure has been varied by making the absorption corrections after reduction to volumes per unit volume of mortar. ?

The essential information obtained from mortar voids tests of the mortar aggregates is shown in the diagrams headed "Voids per unit vol. of mortar", figs.27 to 37.
Curves for $\frac{v_b}{c}$ are also shown.

It will be noted that air voids are present in appreciable amounts at water contents considerably higher than basic. Their persistence is especially marked in the finer sands Figs. 29, 33 & 37. Strength tests for the material of Fig.37 (48/100) are not included. A few were made but as they showed no special characteristics and as the sieving of such fine fractions took considerable time, it was not considered worth while to complete the series.

DISCUSSION OF MORTARS.

Figs. 16 to 26 show that mortar strength may be above or below neat cement strength for the same water-ratio. This might be due to some indirect effect. Tensile strength, for instance, might be expected to be affected by the cement factor, if the bond between aggregate and binding is less strong than the aggregate itself. There are obvious difficulties in applying such an explanation to the effects shown in figs.16 to 26.

Here it is intended to work on the assumption that strength of the mixture is entirely dependent on the strength of the binding and to endeavour to find, in the observed inequalities of the binding, an explanation of the strength phenomena.

The binding in mortars is not a uniform mass of density controlled by the water-ratio, but an aggregation of elements of greater and less density than the mean. To pursue this idea further, consider a specimen of binding of height λ and of uniform cross-sectional area. Assuming that the air voids in the paste are of negligible amount, the cross-sectional area of the specimen will be $\frac{c+\omega}{\lambda}$, where c and ω are the absolute volumes of cement and water used in its manufacture. As bindings have been observed to obey the strength law $A(\frac{c}{\omega} - b)$ down to $\frac{c}{\omega} = 0.42$, the crushing load L for the specimen will be given by $\frac{c+\omega}{\lambda} A(\frac{c}{\omega} - b)$ within the same limit.

Now let the water be assumed to concentrate at various points uniformly distributed throughout the paste, and, for discussion, assume that the result is to divide the binding into two components, one of uniform higher water-ratio and the other of a uniform lower one. A cross-section will cut areas of the respective pastes which are proportional to their volumes and the resultant crushing load will be assumed to be the sum of the quantities obtained by multiplying these areas by their respective crushing stresses.* The last statement assumes that the ultimate strains of the pastes are equal. This appears to be justifiable.

Two cases will require to be considered:-

(1) When the water-ratio of the weaker component is above 0·42.

(2) When the water-ratio of the weaker component is below 0·42.

<u>Case (1)</u>. Let the paste be assumed to divide into two fractions r and $(1-r)$ and let a volume of water s be transferred from one to the other,

	Stronger component.	Weaker component.
Sectional area:-	$\frac{r(c+\omega)-s}{\lambda}$	$\frac{(1-r)(c+\omega)-s}{\lambda}$
<u>Cement</u>:- Water	$\frac{cr}{\omega r-s}$	$\frac{c(1-r)}{\omega(1-r)+s}$
Crushing:- Stress	$A\left[\frac{(c+\omega)r-s}{\lambda}\left\{\frac{cr}{\omega r-s}-z\right\}\right]$	$A\left[\frac{(c+\omega)(1-r)+s}{\lambda}\left\{\frac{c(1-r)}{\omega(1-r)+s}-z\right\}\right]$

Denoting the mean crushing stress on the section by S'

$$S'\frac{c+\omega}{\lambda}=A\left[\frac{(c+\omega)r-s}{\lambda}\left\{\frac{cr}{\omega r-s}-z\right\}+\frac{(c+\omega)(1-r)+s}{\lambda}\left\{\frac{c(1-r)}{\omega(1-r)+s}-z\right\}\right]$$

This reduces to ,

$$S'=A\left\{\frac{c}{\omega}\left(1+\frac{cs^2}{(c+\omega)(\omega r-s)\{\omega-(\omega r-s)}\right)-z\right\}$$

<u>Case 2</u>. Here it will be assumed that a volume of water s , is rejected from the paste, producing water voids of zero strength, and that these voids are uniformly distributed throughout the paste. By reasoning similar to that employed previously,

$$S(c+\omega)=\left[(c+\omega-s)\left(\frac{c}{\omega-s}-z\right)\right]$$

giving finally,

$$S'=A\left\{\frac{c}{\omega}\left(1+\frac{c}{c+\omega}\cdot\frac{s}{\omega-s}-z\left(1-\frac{s}{c+\omega}\right)\right\}$$

These equations are based on simplifying assumptions but they are sufficiently representative of conditions to indicate that a pastewhich has uniformly distributed variations in density will be stronger than the corresponding mean paste. They are, in any case, limited, as they do not allow for included air. Air is present in the upper ranges of these

* *This assumption envisages roughly spherical inclusions of weaker paste in mass of stronger, in Case I* W.H.

mortars and also in neat pastes of $\frac{c}{\omega}$ values greater than about 0·9, indicating that the equation $S' = A(\frac{c}{\omega} - b)$ is not entirely a density-strength relation. It is thought, however, that the consequences of binding inequalities have been indicated formally.

Inspection of figs. 16 to 26 indicates that the strength difference d between a mortar and the corresponding paste will be given by an equation of the type,

$$d = R(\bar{X} - \tfrac{c}{\omega})$$

where R is the difference between the slopes of the mortar and neat cement lines and $\bar{X}$ the $\frac{c}{\omega}$ value at which mortar and neat strengths are equal.

The corresponding difference for case 1 is,

$$d = A \cdot \frac{c}{\omega} \cdot \frac{c}{c+\omega} \cdot \frac{s^2}{(\omega r - s)\{\omega - (\omega r - s\}}$$

and for case 2,

$$d = A\frac{c}{\omega}\left\{\frac{c}{c+\omega} \cdot \frac{s}{\omega - s} + \frac{bs}{c+\omega}\right\}$$

It appeared that a closer examination of these equations would be justified only if some means could be found of estimating ω_x, the water content corresponding to $\bar{X}$ of the first equation and zero s values of the second and third. If no air inclusions are present this might be expected to equal basic voids. In figs. 16 to 26 the $\frac{\omega}{c}$ values at which mortar and neat strengths are equal have been tabulated. Reference to figs. 27 to 36 shows that corresponding $\frac{v}{c}$'s are larger. Due to air inclusions ω_x may be less than basic voids for the mix. There is however a general correspondence between $\frac{\omega_x}{c}$ and $\frac{v_x}{c}$ in which, however, the influence of grading is evident. No relation sufficiently close to be of value was noted.

Discarding these equations, therefore, as indications for the construction of an expression connecting strength with mixture characteristics, the results were examined for other possibilities. It was noted that the slopes of the lines appeared to bear some relation to the constant b intercepted on the $\frac{c}{\omega}$ axis. These constants and also the slopes of the lines are shown tabulated in figs. 16 to 26. Slopes are plotted against the constants in fig. 38. The averaging line runs from the value for neat cement to the origin, indicating direct proportionality. Some of the points are considerably off the line; however these erratic values relate to abnormal mixtures, as indicated by the notes on the diagram. Sand D in particular diverges completely in lean mixtures. Abnormality may be expected here as this sand contained a relatively high proportion of grains of sizes comparable with those of the cement grains.

The assmuption that the δ values are directly proportional to the slopes is, therefore, thought to be permissible.

With regard to the slopes, the maximum values occur with neat cement and diminish generally with cement factor. Various factors were examined for correspondence. The best appeared to be $\frac{V_g}{c}$. The quantity $\frac{V_g}{qc}$ might be regarded as a measure of the constraint to which the cement is subjected in its position in the voids of the aggregate. Here qc represents basic voids for neat cement, giving the constraint unity for this material. The introduction of aggregate, by imposing an arrangement on the cement grains in contact with its surfaces, increases the basic voids and the constraint. This will apply as long as the cement is sufficient to fill the voids but it may represent conditions beyond this point approximately. Fig. 40 shows graphically the state of a 3 to 1 mortar of sand A in this respect. The V_g line and constraint are shown on a modification of the type of diagram which the writer believes was first used by Richart and Bauer.

Slopes are shown plotted against $\frac{V_g}{c}$ in fig. 39. Here again there are erratic points corresponding generally with those of fig. 38 but the more normal mixtures are averaged fairly well by the curve which has been drawn. There were indications that a simpler relation would be obtained if slope difference, $A - A'$ were plotted against $\frac{c}{V_g}$

Here A = slope of neat cement line.

A' = " " mortar "

e = excess of basic voids for mortar over basic voids for neat cement.

$\frac{e}{c} = \frac{V_b}{c} - q$ where q = basic voids in neat cement divided by the absolute volume of the cement.

Values for q ranging from 0·765 for maximum consolidation to 0·84 for consolidation by Talbot and Richart's methods, had been obtained. It was thought desirable therefore to obtain q from the results shown in fig. 39. Accordingly if (fig.41) $(A - A')\frac{V_b}{c}$ is plotted against $\frac{V_b}{c}$. A straight line is obtained, represented by the equation,

$$(A - A')\frac{V_b}{c} = 15600\left\{\frac{V_b}{c} - 0{\cdot}8\right\}$$

This gives the value 0·8 for q.

Therefore, $(A - A')\frac{V_b}{c} = 15600\frac{e}{c}$

$$\therefore A' = 14100 - 15600\frac{e}{V_b}, \text{ inserting the value of } A \text{ from Fig. 15}$$
$$= 14100(1 - 1{\cdot}11\frac{e}{V_b})$$

Or, replacing $1 - 1{\cdot}11\frac{e}{V_b}$ by k

$$A' = 14100k.$$

In the equation for strength, $S' = A'(\frac{c}{w} - b')$ it has been suggested on the previous page that b' is directly proportional to A', and the equation may therefore be rewritten.

$$S = 14100k(\frac{c}{w} - 0{\cdot}42k)$$

where 14100 and $0{\cdot}42$ are respectively the slope and the constant for neat cement.

Although the assumption of the dependence of strength on binding inequalities has been used in selecting the factors for this formula, the validity of the formula is in no way affected by the truth or error of the assumption.

The formula represents a combination of Talbot and Richart's, Bolomey's and other methods and must stand or fall by its correspondence with observed results. The reasoning is an endeavour to make it rational rather than empirical.

Estimation of Basic Voids.

Estimation of Basic Voids.

To apply the formula evolved to the concrete tests which had been made it was necessary to obtain basic voids. for the mixturesused. Values were of course obtainable for the mortars of sands A and C but it was not evident that these apply to the mortars in position in the aggregate voids.

In discussing the application of their methods, Talbot and Richart suggest, with reservations, that mortar voids in concretes may be assumed the same as those of similar isolated mortars. The reservations appear to be of particular importance with reference to voids at basic water content. The implication that the strength of a concrete equals the strength of the corresponding mortar is not supported by experimental work which has been done. Mortar strength may exceed concrete strength or fall short of it. It may be that the strength of a concrete is that of the mortar which is present in the void spaces but this mortar may differ very materially from an isolated mortar composed of the same sand, cement and water proportions. Direct measurement or calculation of basic voids for each concrete appeared to be necessary therefore.

Measurement of basic voids for concretes can be carried out in the same way as for mortars. A larger measuring vessel is required; probably the American rule for the minimum diameter of compression cylinders (diameter at least four times that of the largest aggregate fragment) would serve. The method of placing would require investigation.

For the present work it appeared desirable to try to evolve some method of estimating basic voids.
There were two reasons for this.

(1) A variety of aggregate combinations had been used and much time would have been consumed and some difficulty experienced in repeating all of the mixtures.

(2) It was desired to get the results into some form which

might be useful in practice and it is thought that the elimination of mortar voids measurements is a step in this direction.

This problem was approached by voids measurements on combinations of sand A fractions, some dry, others wet. As far as the writer could ascertain there appeared to be no solution available to suit the requirements. Something on the lines of the swell factor, used by Furnas[19] in his careful and elaborate investigation of grading for maximum density, would have served but he only refers to this factor casually as a figure to be determined experimentally. Here it is not desired to go into the general question of grading, so the relations observed are stated and comparison of observed and calculated values provided in justification.

Symbols used:- Absolute volume of coarse material $= a_c$

$\dfrac{\text{Voids in coarse material}}{a_c} = v_c$

Absolute volume of fine material $= a_f$

$\dfrac{\text{Voids in fine material}}{a_f} = v_f$

$\dfrac{\text{Voids in mixture of } a_c + a_f}{a_c + a_f} = v$

To present the information in a convenient form, let $\frac{a_f}{a_c + a_f}$ be plotted along PQ and v vertically, fig. 42. On the assumption of no swell, v will be given by the line AC from P to C'. At this point the voids in the coarse, $v_c a_c$, will be just filled by the fine with its voids.

i.e. $a_c v_c = a_f(1 + v_f)$, $\therefore \frac{a_f}{a_c} = \frac{v_c}{1 + v_f}$ or $\frac{a_f}{a_c + a_f} = \frac{v_c}{1 + v_f + v_c}$

Beyond C', voids are given by line CE. for no swell.

The curves marked 4/8, 8/14, 14/28 and 28/48 show the voids obtained on mixing these fractions of sand A as a_c materials, with varying proportions of the 48/100 fraction as a_f.

Mortar voids methods were used. Most of the mixtures were dry. A point which it is desired to stress is the extreme difficulty of preventing separation in "well graded" or harsh mixes (i.e. mixtures in which, at some point, the fine material is no more than sufficient to fill the voids in the coarser). With such mixtures, rodding or shaking was found to result only in separation. The best proceedure appeared to be the introduction of the material in small quantities which were spread and pressed into position with the fingers. Some of the harsh mixtures were improved by the addition of sufficient water to make them coherent. These were treated by the usual mortar voids methods. The dotted parts of the curves shown in fig.42 were obtained in this way and the results indicate improved distribution of the fine materials. Similar results were obtained for $\frac{3}{8}$"/4, 4/8, 8/14 and 14/28 as coarse and 28/48 as fine and with other combinations of two sizes.

The ordinate differences between the tangents ER to the voids curves at E fig.42 and the line PE, which will be referred to as the tangent swells, t, increase as the grain sizes become more nearly equal. For $\frac{a_f}{a_f + a_c}$ values down to 0·5 the voids curves follow these tangents closely. It is suggested that swells over this range are due principally to constraint of the fine particles at the surfaces of the coarse.

Tangent swells, t are given closely by, $t = m a_c \frac{d_c}{d_c + d_f}$ for range $\frac{a_c}{a_f} = 0$ to $\frac{a_c}{a_f} = 1$

A^{ins^2} = Surface area of 1 ins³ (absolute vol.) of coarse.

Diam. of coarse grain $= d_c$

" " fine " $= d_f$

m is a factor depending on grain shape and diameter.

The value $m = \frac{d_f}{6}$ was obtained for the sand A fragments and it appeared to apply also to the other fine aggregates used.

<u>Note on Surface Area</u>*. An absolute volume of a cubic inches of material of uniform spherical grains of diameter d has a surface area $\frac{6a}{d}$. Flattened or elongated grains may have a considerably larger surface area; in these cases statistical diameter may be adopted with advantage but they are not of great importance in concerte work as these shapes are avoided. Here, all the fine aggregates had rounded fragments of similar

* Comprehensive account of work done on this subject will be found in Heywood's paper mentioned on page 56.

shapes and they have been considered spherical. The surface areas of the crushed granites used in some of the concretes have been assumed 50% greater than given by the spherical assumption. Particulars of the sand A fractions are given in the upper table, fig.44.

In fig.43 basic mortar voids for sand A fractions and rapid hardening cement are shown. The voids given by corresponding dry mixtures are larger. As no essential difference appears between these results and those of the aggregates, they will be treated in the same way. The correspondence of minimum voids with point C is better however. This correspondence has been commented on by numerous invest:igators. Numerous examples will be found in recent work on grading of aggregates for bituminous road mixtures, the binder in these mixtures taking the place of the cement in concrete. e.g. (20)

In fig.44 values of m and d_f have been obtained from the four curves by the usual least squares solution for indirectly observed quantities. The value for d_f is obtained as 0.0017". This should correspond with the effective mean diameter of a cement grain. Taking an example of cement analysed by sedimentation from Kuhl's book, the dominant particle diameter works out at 38.3μ i.e. 0.00151". It was found later that better correspondence with average results was obtained by increasing m to ·00033 and d_f to ·002".

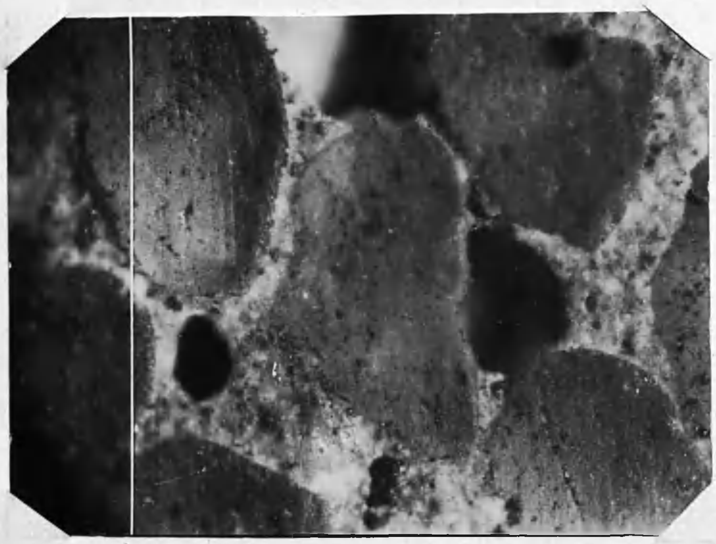
In pursuance of the view that swell between E and F is due to constraint of the fine aggregates at the surfaces of the coarse, the increasing swells to the left of F, fig.45, might be expected to correspond the diminution of the fine aggregate to a quantity insufficient to space the coarse fragments by an amount equal to the diameter of the fine grains. This critical value of d_f would be given by:-

$$a_f = \frac{a_c(1+v_c)\left\{\frac{d_c+d_f}{d_c}\right\}^3 - a_c}{1+v_f+\text{swell}}$$

Inspection of fig.42 indicates that other factors overrule this condition. If it were the principal one, the point F

Distribution of Fine Material

1 & 2 show zones of paste deficiency in 3 to 1 Standard Mortars

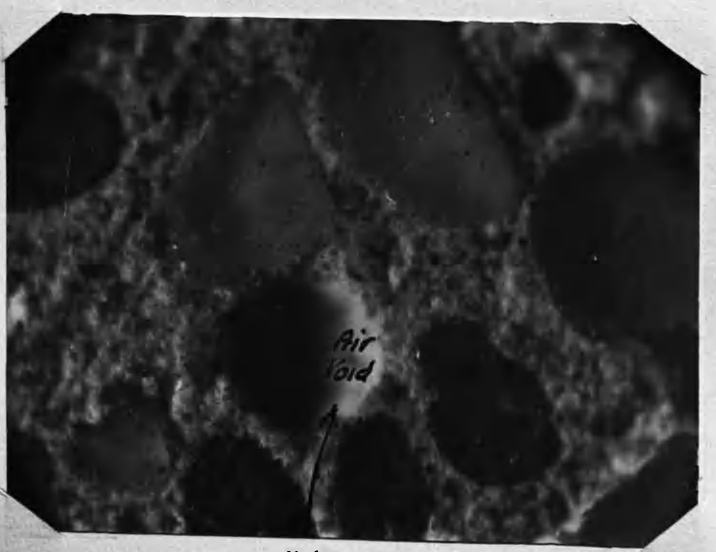


×60

1

×40

2



×60

Same Mortar

about 1·4 Relative Water Content

ought to approach the minimum voids point as $\frac{d_c}{d_f}$ increases. Although this tendency is shown in fig.43, it is not evident in fig.42. It is thought that irregularities in the distribution of the fine material is the principal factor determining swell at the smaller $\frac{a_c}{a_f}$ values and that the problem is statistical rather than geometrical. A sufficiently accurate approximation appears to be obtainable as follows.

Referring to fig.45, GH appears to equal HC for smaller values of t and it diminishes as t increases. The assumption is made that,

$$HG = HC\frac{KC - HC}{KC} = HC\left(1 - \frac{HC}{KC}\right)$$

HC = tangent swell, t', at C

and $$t' = mA\frac{d_c}{d_f + d_c} \cdot \frac{1 + v_f}{1 + v_f + v_c}$$

tangent swell at P $= t_p = mA\frac{d_c}{d_c + d_f}$, $\therefore t' = t_p \frac{1 + v_f}{1 + v_f + v_c}$

Also, $$KC = v_c\frac{1 + v_f}{1 + v_f + v_c}$$

$$\therefore HG = t'\left(1 - \frac{t_p}{v_c}\right)$$

G is a critical point in the series of the two aggregate mixtures. The critical coarse aggregate proportion $\frac{a_c'}{a_f} = \frac{1 + v_f}{v_c}$. Considering any mixture to the right of G, a_c is less than a_c'.

Let $r = \frac{a_c}{a_c'}$

It is assumed that the excess of the total swell, s, over the tangent swell is $t\left(1 - \frac{t_p}{v_c}\right)r^2$

$$\therefore \text{Swell, } s = t\left\{1 + \left(1 - \frac{t_p}{v_c}\right)r^2\right\}$$

$$\text{and } \frac{v}{a_f} = v_f + t\left\{1 + \left(1 - \frac{t_p}{v_c}\right)r^2\right\}\cdot\frac{1}{a_f}$$

Considering a mixture to the left of G, a_c is greater than a_c'.

Let $r' = \frac{a_c'}{a_c}$

It is assumed that the excess of the total swell, s, over $v_c a_c$ is $CG \times r'^2$

$$= t'\left\{1 + \left(1 - \frac{t_p}{v_c}\right)\right\}r'^2$$

$$\therefore \frac{v}{a_f} = \frac{v_c a_c}{a_f} + t'\left\{2 - \frac{t_p}{v_c}\right\}\frac{r'^2}{a_f}$$

These formulae do not, of course, give a continuous curve at G. However, they are thought to give values which are sufficiently close.

So far only mixtures of two particle sizes have been considered (if variation in cement particle size be neglected). When the aggregates are graded the relations are less simple; this is implied by the statements already made. However, the following modifications were found to give what are thought to be serviceable rules.

In the expression for t, $A\frac{d_c}{d_c+d_f}$ occurs. In the table in fig.46, the surface areas of the fractions have been multiplied by $\frac{d_c}{d_c + \cdot 002''}$ giving the modified surface areas tabulated under the heading N. In calculating the modified surface area N of a graded aggregate the fractions may be multiplied by the corresponding tabular N values and the results summed.

Tangent swell is now given by $0{\cdot}00033\,Na$ when cement, $d_f = \cdot 002''$ is used as the fine material. As mentioned on page 35, the above values for m and d_f were finally selected for cement. Restricting the statement finally to cement as fine, a suitable value for v_f appears to be 0·8.

The critical coarse aggregate ratio, $\frac{a'}{c} = \frac{1{\cdot}8}{v_a}$, denoting $\frac{\text{agg. voids}}{a}$ by v_a in place of v_c.

When a is less than a',

$$r = \frac{a}{a'}$$

$$\text{and} \quad \frac{v_b}{c} = 0{\cdot}8 + 0{\cdot}00033\, N\frac{a}{c}\left\{1 + (1 - \frac{0{\cdot}00033N}{v_a} r^2\right\}$$

When a is greater than a',

$$r' = \frac{a'}{a}$$

$$\text{and} \quad \frac{v_b}{c} = \frac{a}{c}v_a + 0{\cdot}00033\, N\frac{a'}{c}\left(2 - \frac{0{\cdot}00033\,N}{v_a}\right)r'^2 - 1$$

Two examples of the application of this method of basic voids estimation to concretes are given in fig.46. It will be noted that the calculated results are slightly higher than those obtained from actual concrete voids tests which are given below them. With regard to the first example, in which the aggregate was below the critical quantity, the fact that the gravel aggregate used gave very easily worked mixtures might account for the small discrepancy. The discrepancy in case 2, in which aggregate over the critical amount is used, is probably due to the figure for dry aggregate voids being slightly high. The difficulty of avoiding separation, which was mentioned in connection with fine aggregates, is even greater when coarse material is included. Separation, of course, increases voids. These two mixtures are average - not selected - examples. Others were tried and will be shown under concrete results (page 43). The table, fig.47, gives a comparison of calculated mortar voids and experimental voids from figs.27 to 36, for six of the fine aggregates. The results for the other fine aggregates show a similarly good correspondence although the single sized fractions of sand A show the effect of the increase in m in the richer mixes.

The writer's method of expressing voids as a fraction of the absolute volume of the material is unusual but it is adopted for convenience. The figures are, of course, higher than their equivalents expressed in the usual way as fractions of the bulk volume.

In obtaining the relations described, the unit of volum~~n~~ used was the volume of one pound of water. However, as volumes appear merely as ratios and, as dimensions of particles are in inches and surface areas in inches^2, the dimensions of the coefficient m are inches. N, the surface area per unit volume of aggregate is $\frac{ins^2}{ins^3}$; therefore the tangent swell ~~mN~~ coefficient mN is a numerical factor. The unit of tangent swell mNa is that of the aggregate volume a.

Concretes.

Additional Notes on Mixtures.

Description of Mixtures.

Discussion of Results.

Particle Interference

Workability.

Concluding Remarks.

Concrete Mixtures.

It has been suggested on page 18 that particle interference, or cavitation under the coarse aggregate fragments, appears to influence strength materially in concretes only. The strengths of concretes should, therefore, fall below the values given by the formula evolved for mortars when particle interference occurs. A number of the concrete mixtures which were made will, therfore, be examined for indications as to how far the mortar formula is applicable to concretes. Two series of mixtures have been taken.

Procedure in making and testing was as described on pages 21 & 22 but it will be convenient to make the following comments on placing and effective cement water ratio here.

Placing.

In the remarks columns of the tabulated information, figs.48 to 53, slumps and methods of placing are given. Workable mixtures were rodded, a ½" diameter steel rod with a rounded point being employed. Normally the moulds were filled in three layers. Each layer was rodded but it received only the minimum amount of rodding sufficient to dispel air and give the material a homogeneous appearance. This departure from the usual procedure of giving the layers each a uniform number of rodding strokes was adopted because the range of mixtures included some with more or less marked tendencies to separation, and, with these, rodding had the effect of packing the coarser material in the lower part of the specimen.

A number of very stiff mixtures were included and it is desired to draw attention to these as their results are discordant. A one-inch square bar with a slightly rounded end was employed to ram these into coherence. Again it was found undesirable to adopt any standard method. Most of these mixtures had to be placed in one-inch thick layers and ramming was continued until the appearance of uniformity was obtained.

Effective Cement-water Ratio.

The $\frac{c}{w}$ values tabulated in figs. 48 to 53 are based on gross mixing water, less deductions for absorption and rejected water. There is, of course, in all workable concretes, the tendency to reject water, and the writer's experience is that a layer of water formed on the surface usually at slumps greater than about $1\frac{1}{2}$", when watertight moulds were employed. If the moulds are not watertight the effect is masked by loss of water but is shown by settlement. The behaviour of concrete in this respect has been frequently commented on. There is a slow settlement with rejection of water to the surface. The writer's procedure with workable mixtures was to fill the moulds completely and finish off the surface flush with the end by straight edge so settlement could be conveniently observed and measured. Settlements were of the order, usually, of 0·05" but the largest noted was 0·16" occurring with mixture No.3 of fig.48 (slump 10"). There appears to be absorption of some sort as the surface of the rejected water was usually slightly below the top of the mould. This may be due to a slow saturation of the aggregates although attempts to reproduce the effect in a long-necked specific gravity flask indicated that the aggregates in use became saturated within a minute or so of wetting. It was therefore concluded that a sufficiently accurate estimate of the water rejected could be obtained by measuring the settlements. This was done and rejected water calculated at the rate of 0·453 lb. per inch of settlement. Opinions as to the significance of rejected water differ. It is held by some that it is contributed mainly by the upper layer of the mixture and has little effect on strength.[22] However, the strengths obtained here indicated that rejected water should be deducted so settlements were measured, specimens weights, the rejected water reduced to loss per batch.

First Series - Mixtures 1 to 36.

The aggregates consisted of granite gravel, siliceous gravel and screenings of sands A and C. They were artificially graded. Four principal gradings were adopted, arranged on the lines indicated by Furnas for good workability. The volume relations r_g between successively larger sieve analysis fractions, which were adopted, were 1·0, 1·1, 1·2 and 1·3 between No.48 and $\frac{3}{4}$" sieves. The material below No.48 was reduced slightly, as shown in figs. 48 to 50.

Aggregate voids, v_a , were measured directly and basic voids calculated for various $\frac{a}{c}$ values for each grading. Basic voids curves are plotted in the figures mentioned above.

The smoothness of working of the mixtures of this series merits special comment. Undoubtedly it was due partly to the rounded shapes of the aggregate particles but it was also evident that the gradings which were used conferred good working characteristics. Tendencies to separation were not noticeable during rodding - the tendency to packing shown by the coarse material in mixtures of irregular grading has already been commented on.

Second Series - Mixtures 37 to 100.

Sands A and C combined with various proportions of $\frac{3}{4}$" and $\frac{3}{8}$" crushed granite formed the aggregate. Mixtures of sand A and the crushed granites were used in concretes 37 to 78. Voids, v_a , for all combinations of these materials are shown in a diagram of the type employed by Feret for such purposes, (fig. 51A). These were employed in the calculation of the v_z figures used in tables 51 and 52. Fig.51 relates to concretes of water ratios about 0·5 by weight. It has been divided into two groups. To explain this classification it may be stated that sand A, which is deficient in fine material, produces rather harsh mixtures when the standard one fine to two coarse combination is used. At the moderate water-ratio of 0·5 there is too little fine material to absorb the paste and the result is a wet mortar, from which paste readily escapes. Particle interference occurs under the larger fragments. Mixtures 47 to 49 are examples. Mixtures 37 to 46, on the other hand, have sufficient fine material to form a stable mortar. The classification is rough, however, and the results will be discussed in greater detail later.

Mixtures 57 to 71 are similar to 37 to 46, but of water-ratios about 0·6 and 72 to 78 are of water-ratios about 0·8.

In mixtures 79 to 100 sand C has been employed alone or in combination with sand A to obtain mixtures constrasting with the earlier ones.

<u>Comments on Results</u>.

With reference to the tables figs. 48 to 53, all quantities are absolute volumes or ratios of absolute volumes, except where otherwise stated.

The values $\frac{c}{w}$ and $\frac{v_s}{c}$ have already been commented on.

Values of $\frac{e}{c} = \frac{v_s}{c} - 0{\cdot}8$

" " $k = 1 - 1{\cdot}11\frac{e}{v_s}$

Calculated strengths are obtained from the formula arrived at on page 31, $S = 14100\,k\left(\frac{c}{w} - 0{\cdot}42k\right)$.

An example is given in the Appendix, page 52.

First Series of Mixtures. (figs. 48, 49 and 50).

The correspondence in the workable mixtures between calculated and observed strengths is thought to be good. It is suggested that, so far, the conclusions may be drawn that the formula applies to concretes and also that there is no serious particle interference in these mixtures. The only point which appears to call for comment is the excess of observed over calculated strength in the stiff mixtures which were placed by ramming. The only reason which could be detected for this was loss of water. This conclusion was reached after examination of the volumetric compositions of these mixtures, calculated from the weights of the test pieces on the assumption that the materials were present in the mix proportions. The compositions below were obtained for the stiff mixtures. These mixtures are near basic water content so their $\frac{v}{c}$ values have also been tabulated along with the calculated $\frac{v_b}{c}$ values as a further check on the method of calculating basic voids.

Mixture No.	Vols. per unit vol. of concrete Aggregate	Cement	Water	Voids	Voids. Cem.	v /c
7	0·763	0·070	0·166	0·170	2·43	2·42
15	0·697	0·116	0·176	0·193	1·66	1·37
18	0·752	0·070	0·168	0·178	2·54	2·40
21	0·750	0·085	0·154	0·165	1·94	2·02
24	0·731	0·109	0·164	0·160	1·46	1·41
29	0·757	0·087	0·158	0·156	1·79	2·00
32	0·729	0·112	0·170	0·159	1·42	1·36

Loss of water is indicated by the close approach of the ω values to the v values. Air inclusions should be larger than indicated by the differences. In mixtures 24, 29 and 32 the figures obtained for ω are actually slightly in excess of v. To afford some comparison with probable water losses in the workable mixtures the figures below are given. These show the volumes of voids and water for a test cylinder, calculated on the mean weight of the three cylinders of each mix, on the assumption that the proportions of the specimen are the same as those of the mix. Very little air is inlcuded in these workable mixtures so the figures serve to show that water losses are small here. In mixture 23 only is there definite indication of loss.

Mixture No.	Volumes of:- Voids	Water	Slump.
19	0·693	0·670	¼"
20	0·803	0·788	6"
22	0·705	0·662	2½"
23	0·753	0·771	8"
25	0·693	0·670	1"
26	0·786	0·768	3½"

It is believed therefore that there is material loss of water in the stiff mixtures. The mixtures formed loose heaps in the tray and in most cases the filling of the three moulds occupied half an hour against five minutes or so for the rodded mixtures, so that evaporation would be greater.

Second Series. Figs. 51, 52 and 53. In these, crushed granite coarse aggregate and sands A and C were used.

The mixtures showing good correspondence between calculated and test values of strength through each range of cement contents have been grouped together. Those showing deficiency of test strength are classified separately as showing particle interference. In some cases, e.g. mixtures 47, 48 and 49 this classification was justified by inspection. On breaking down parts of the fractured specimens looseness of contact on the undersides of the large aggregate fragments was unmistakable. Weymouth's method of analysis will be applied to some of the mixtures.

In the first place, to describe the method briefly, consider a sieve analysis fraction of diameter D in a mixture. The bulk volume of this fraction in an isolated state will be given by nkD^3 where,

n = number of particles

and k = a factor depending on particle shape and voids.

The density of the isolated fraction = $d_o = \frac{a}{nkD^3}$ where a is the absolute volume of the material.

Using the writer's notation $d_o = \frac{1}{1 + v_a}$. Aggregate voids v_a were found to vary from 0·625 for granite gravel (sized) to 0·85 for sized crushed granite in the present work. Figures given by Coultas [21] reduce to 0·65 for gravel to 0·93 for crushed granite.

If the particles of the fraction are now imagined to be spaced a distance t apart (i.e. each particle imagined to be enclosed in a shell of similar shape of diameter $D + t$), the bulk volume of n spaced particles becomes $nk(t + D)^3$ and the density $d_a = \frac{a}{nk(t + D)^3}$

Therefore $\frac{d_o}{d_a} = \frac{(t + D)^3}{D^3}$

Weymouth assumes that particle interference occurs when t is less than the diameter of the next smaller particle plus an allowance for the thickness of the cement film. The allowance suggested varies from 0·001" to 0·002".

For ¾" to ⅜" crushed granite, mean diameter is 0·56" and for sand A screened on No.4 sieve mean diameter of largest particle group is 0·141". Voids u_g for the granite is 0·85 and density $d_o = \frac{1}{1\cdot 85} = 0\cdot 541$

$$d_a = \frac{0\cdot 541 \times 0\cdot 56^3}{(0\cdot 56 + 0\cdot 141 + 0\cdot 002)^3} = 0\cdot 272$$

As in the mixtures dealt with here, ¾" to ⅜" is the maximum aggregate size, the above result means that particle interference may be expected if the absolute volume of coarse aggregate per unit volume of concrete exceeds 0·242. ?

The tabulated figures below give the volumetric compositions of mixtures 47, 49, 50 and 52. The last two contain a small proportion of ⅜" to No.4 material but so little that they may be included with 47 and 49 in this discussion.

Mix Number.	Aggregates Coarse	Fine	Cement	Water
47	0·472	0·229	0·125	0·147
49	0·424	0·206	0·154	0·216
50	0·354	0·351	0·125	0·170
52	0·287	0·284	0·178	0·251

The absolute volume of coarse exceeds 0·272 in all cases, indicating particle interference.

Taking now one of the mixtures classified as showing no particle interference, mixture number 37, this contains ⅜" to No.4 material, mean particle diameter 0·28".

Trying for particle interference in the ¾" to ⅜" group,

$$d_a = 0\cdot 542 \left\{\frac{\cdot 56}{\cdot 56 + \cdot 28 + \cdot 002}\right\}^3 = 0\cdot 157$$

For the $\frac{3}{8}$" to No.4 group,

$$d_a = \cdot 547 \left\{\frac{\cdot 28}{\cdot 28 + \cdot 141 + \cdot 002}\right\}^3 = 0\cdot 158$$

The volumetric compositions are as below.

Aggregate Coarse	Aggregate Fine	Cement	Water
0·196	0·166	0·119	0·162

Particle interference is indicated for the $\frac{3}{4}$" group.

For the $\frac{3}{8}$" group, density = $\frac{\cdot 166}{\cdot 166 + \cdot 119 + \cdot 162} = 0\cdot 206$

This exceeds the limit of 0·158, therfore particle interference is again indicated.

Weymouth's condition appears to be rather severe. It will show particle interference with the gradings recommended by Walsh[(23)] and it will condemn the 1:2:4 mixes so largely used in British practice.

This disability could probably be easily enough removed by substituting some less exacting requirement for the condition that the particles of each group must be spaced by a distance at least equal to the diameter of the next smaller size. Possibly the dominant diameter of the finer material would serve.

In the writer's view, a more serious criticism of Weymouth's method may be based on the performances of mixtures, such as those examined, as paste content at constant water ratio is increased. From groups such as (47, 48, 49), (50, 51, 52) and (53, 54, 55, 56), it will be seen that strength deficiencies become more marked as paste content is increased. According to Weymouth, particle interference ought to diminish as paste content increases. Stiff mixtures show the excess of strength which has already been commented on.

It is evident that other properties of the finer component are operative.

The high values of basic voids which obtain when cement is below the critical proportion, show diminished strengths by the writer's formula and cover cases of strength loss cited by Weymouth as examples of particle interference.(12)

With regard to the cases of unmistakable particle interference occurring with the higher paste contents mentioned above, the mortars were obviously too wet. The gradings of these mixtures were also obviously bad and it is suggested that behaviour in the slump test, as discussed in the following section, is the simplest indication of the probability of particle interference.

Slump Tests.

Harsh Mix - workable but no slump

Collapse of same mix with increased water

Semi-plastic - some escape of water

Plastic mix.

Proportioned from Abrams' curves.

Range of Water Contents. Comment on the relations between slump, mixture and water content will be made principally to define the limits within which the strength formula may be expected to apply. It was not intended to investigate slumps.

The behaviour of slump specimens indicated that conditions differed with different mixtures. When adequate fine material was present and water contents were adequate, plastic slumps were obtained, due to radial flow of the concrete. These were regular, in that consistent figures could be obtained in repeated tests of a mixture. In harsher mixtures of water contents sufficient to give considerable workability, the slumps differed. At moderate slumps the semifluid mortar was forced out from between the coarse fragments. Instead of showing a smooth plastic subsidence, these mixtures "sat down" immediately on removal of the mould. The evidence was marked, in many cases, of a sudden transition from fluid suspension to support by bearing of the coarse fragments on each other. At greater water contents such mixtures simply collapsed and the slump figure ceased to have meaning.

As the writer's mixtures included both plastic and harsh concretes it was not anticipated that slumps, on the whole, would conform to any law, and notes were made of their characteristics only in a few cases.

In fig.54 slumps are tabulated against $\frac{w}{v_b}$. The latter are the reciprocals of the products of the tabular $\frac{c}{w}$ and $\frac{v_b}{c}$ values. Slumps are roughly proportional to $\frac{w}{v_b} - 1$ In fig.54 slumps of the continuously graded mixtures, 1 to 34, are plotted against $\frac{w}{v_b}$. The points for each grading may be averaged roughly by straight lines which are steeper and farther to the left the greater the quantity of fine material present. However, too much significance cannot be attached to this as other factors such as cement content and water ratio, which are likely to exert an influence, are not included.

The crushed granite-sand combination, 37 to 100, have not been plotted. They show the same general tendencies as the former mixtures but there are greater irregularities. This is to be expected as diversities in grading and grain shape are greater. Irregularities are noticeable particularly where cement content is less than the critical value, $\frac{v_z}{1.8}$ and where there are deficiencies in fine material.

As a rough mean rule it might be taken that,

$$\text{Slump in inches} = 10\left(\frac{\omega}{v_z} - 1\right)$$

The strength rule may be taken to apply to workable plastic mixtures having $\frac{\omega}{v_z}$ values ranging between 1·0 and 1·6, i.e. slumps up to about 6". Particle interference effects may occur in harsh mixtures, causing strength to drop below the figure given by the formula.

One feature of the equation $S = Ak\left(\frac{c}{\omega} - kz\right)$ calls for comment. This is the very rapid diminution in strength which it shows for diminishing $\frac{c}{\omega}$ values when k is near unity.

$$k = 1 - 1.11\frac{c}{v_z}$$

$$= 1 - \frac{1.11(v_z - 0.8c)}{v_z}$$

$$= \frac{0.888c - 0.11v_z}{v_z}$$

$$\text{For } \frac{c}{\omega} - kz = 0, \qquad \frac{c}{\omega} = z\,\frac{0.888c - 0.11v_z}{v_z}$$

Neglecting the term $0.11v_z$ and inserting 0·42 for z,

$$\frac{\omega}{v_z} = 2.68$$

This is much beyond the largest $\frac{\omega}{v_z}$ value used in the mixtures tested. Material rejection of water usually occurs when $\frac{\omega}{v_z}$ exceeds 1·5 or 1·6 so that the above limit may be taken to represent a mixture which cannot exist. As far as the writer's experience goes, when $\frac{c}{\omega} - kz$ becomes small it indicates that the mixture is too wet. Test results in such a case will be higher owing to rejection of water but the mixture will be undesirable for practical use and will probably develop general segregation.

Concluding Notes.

The methods of voids and strength estimation described here have been applied by the writer satisfactorily to interpolations of strengths for varied aggregate gradings in relation to concretes for reinforced concrete bridge work on which he was consulted. For 6" cubes of concretes made with Ordinary Portland Cement, at 7 days age the relation $k = 1 - 1.11\frac{c}{v_z}$ appeared still to apply. The strength relation was $6880\,k\left(\frac{C}{W} - 2.06k\right)$ lb/ins.^{2}, and C and W being, in this case, measured by weight. At 28 days the results were uniformly 50% greater.

As far as Ferrocrete cement is concerned some tests at 14 and 28 days, made in the course of the writer's own investigations indicated that the relations for greater ages are different to some extent. This is in line with the findings of the Building Research Station.

In conclusion, the writer wishes to state that no finality is claimed for the results given here. They represent the best combination of the available facts and figures which he was able to obtain after extensive trials of other methods. It is hoped that they represent some new view points.

The view that paste inequalities form the primary cause of strength differences in different mixtures of the same water-ratio appears to be capable of explaining the observed phenomena. Factors such as tensile strength and bond between paste and aggregates will be affected by paste inequalities and explanations of strength variations employing these factors need not be entirely at variance with the views expressed here.

The strength equation, as already mentioned, is not dependent on the above conception. It appears to provide a satisfactory connection between neat cement, mortar and concrete strengths.

dependent on the above conception. It appears to provide a satisfactory connection between neat cement, mortar and concrete strengths.

Although the method developed for basic voids calculation is regarded merely as an expedient to obtain a necessary quantity, it appears to give satisfactory results and the further connection between basic voids, water and slump appears to be of considerable interest.

The work on concretes and mortars was done at the Royal Technical College, Glasgow.

Sectioning of concretes and mortars, microscopic examination and photography were done at the writer's home with his own apparatus.

Finally, the writer desires to acknowledge his indebtedness to Professor Moncur for materials and facilities for the work and for his interest in it.

Acknowledgements are also due to Professor Mellanby for the continuance of these priviliges.

It is desired also to record indebtedness to the late Professor Cormack for his interest and encouragement.

Appendix Nº 1.

Sieve Analyses of Fine Aggregates.

Sand D and earlier samples of sands A and C (screened Nº 4) used in Mortar and Mortar Voids Tests.

Mesh No.	Clear Opening ins.	Mean Opening d ins	N for unit vol.	Sand A Fraction	Sand A N	Sand C Fraction	Sand C N	Sand D Fraction	Sand D N
3/4"	·75								
		·56	10·7						
3/8"	·375								
		·281	21						
4	·187								
		·141	42	·137	5·8	·086	3·6	·019	1
8	·094								
		·0701	83·5	·198	16·6	·078	6·5	·024	2
14	·047								
		·0351	162	·268	43·5	·086	13·9	·104	17
28	·0232								
		·0174	310	·247	76·5	·250	77·6	·353	110
48	·0117								
		·0088	556	·123	68·5	·400	222·0	·370	206
100	·0059								
		·0044 assumed	950	·027	25·7	·100	95·0	·130	125
				Sums	236·6		418·6		461

N values are modified surface areas.

They are given by $\frac{6}{d + \cdot 002''}$.

Absorption of Sand A = ·011 by weight. Sp. Gr 2·63
" " " C = ·009 " " " " 2·635
" " D = ·014 " " 2·60

Absorptions were obtained by the paraffin-salt-solution method described in University of Illinois Bulletin No. 7

Sands A and C used in Concretes (A screened thro' Nº 4 Sieve.) (C " " Nº 8 ")

These later and larger deliveries contained less fine material than the earlier samples above.

Mesh Nº	Sand A Fraction	Sand A N	Sand C Fraction	Sand C N
4				
	·212	8·8		
8				
	·257	21·4	·145	12·1
14				
	·275	44·5	·182	29·5
28				
	·200	62·0	·308	95·5
48				
	·049	27·0	·270	150
100				
	·008	7·5	·095	90
Sums		171·2		377·1

Coarse Aggregates:-

The specific Gravities of both the crushed granites and the gravel were 2·60.

The absorptions are taken at ·006 by weight for both. This figure was obtained by surface drying saturated samples with blotting paper, weighing, drying and again weighing.

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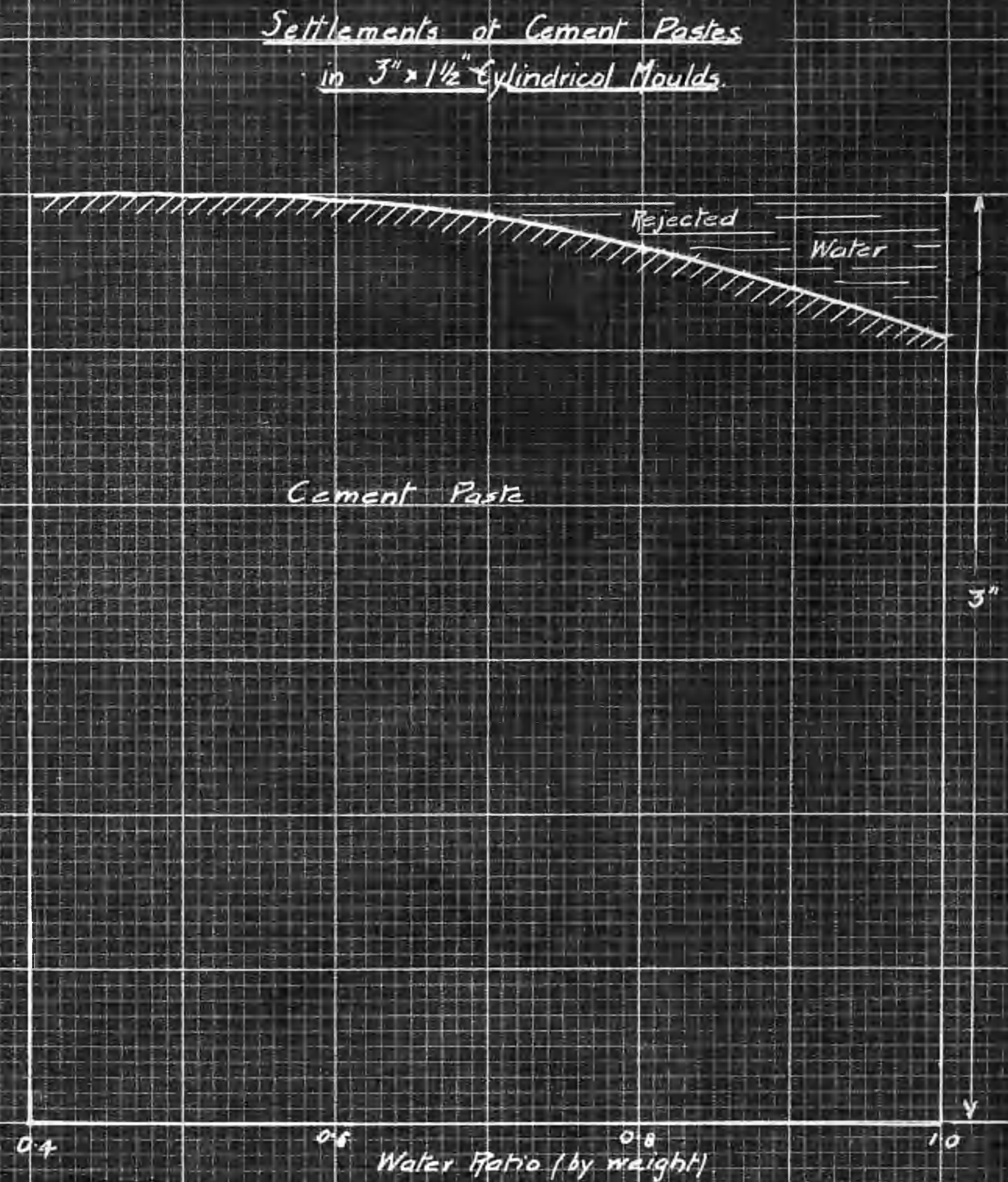

Settlements of Cement Pastes
in 3" x 1½" Cylindrical Moulds.
Rejected
Water
Cement Paste
3"
0·4
0·6
0·8
1·0
Water Ratio (by weight)
Fig. 1

Rapid Hardening Cement – 8" × 4" Cylinders – 7 days age.

Nos. 1 to 24 – Remixed Concretes.

Nos. 25 to 29 – 2nd. + 3rd Cyls. inverted when stiffening.

Group No.	Proportions by Weight: Cement	Sand	Coarse Agg.	Water Ratio by Weight	No. 1 Compve. Strength lbs/ins²	No. 2 Storage Time Hours	No. 2 Compve. Strength lbs/ins²	No. 3 Storage Time Hours	No. 3 Compve. Strength lbs/ins²	Sand	Coarse Agg.
1	1	2.0	4.5	·75	1550	0.8	1720	2.5	1720	C	1
2	1	2.3	4.7	·76	1340	4.5	2160	6.3	2640	"	"
3	1	2.4	3.8	·75	1680	2.5	1970	5.0	2070	"	"
4	1	2.4	2.4	·77	1660	2.3	2020	4.9	2070	"	"
5	1	2.0	2.8	·71	1640	3.0	2050	5.3	2000	B	2
6	1	2.0	2.5	·71	1410	1.8	1960	4.6	2190	"	"
7	1	2.0	4.3	·73	1500	3.0	1970	5.5	2320	"	"
8	1	2.0	2.5	·57	2680	1.0	2740	3.0	3040	C	1
9	1	1.6	2.0	·58	2980	3.0	3300	4.3	3220	"	"
10	1	1.6	2.5	·56	3700	0.9	3570	4.8	4050	"	"
11	1	2.0	3.5	·64	2610	3.0	3040	6.3	3260	D	3
12	1	2.0	2.4	·66	2980	4.8	3300	6.8	3500	"	"
13	1	2.4	3.7	·65	1860	2.0	2170	6.2	2170	C	1
14	1	1.8	3.7	·68	1360	1.0	1670	2.5	2180	"	"
15	1	2.8	2.8	·63	2820	3.0	2750	4.8	3020	B	2
16	1	2.0	2.8	·76	2180	3.0	2280	7.0	2520	D	1
17	1	2.5	3.0	·74	2180	3.0	2160	7.0	2410	D	4
18	1	2.0	4.0	·67	2060	2.8	3000	4.8	2860	D	4
19	1	2.0	4.0	·63	3400	3.7	3700	5.4	3250	D	1
20	1	2.0	4.0	·63	2220	2.8	2620	5.0	3040	D	2
21	1	2.0	4.0	·74	1710	1.6	1790	6.0	2610	D	3
22	1	2.0	4.0	·75	2060	2.8	2430	6.0	2810	D	2
23	1	2.0	4.0	·55	4020	3.0	4050	5.8	1250	D	2
24	1	1.1	2.0	·48	3600	1.9	3640	4.6	4230	C	1
25	1	2.0	4.0	·82	1175	1.0	1460	2.0	1425	C	3
26	1	2.0	4.0	·67	2360	2.5	2760	2.5	3220	D	4
27	1	2.0	4.0	·78	1040	3.0	1290	3.0	1360	D	4
28	1	2.0	4.0	·68	1360	2.0	1470	2.0	1720	C	4
29	1	2.0	4.0	·67	1520	2.0	1630	2.0	1920	A	1

Aggregates.

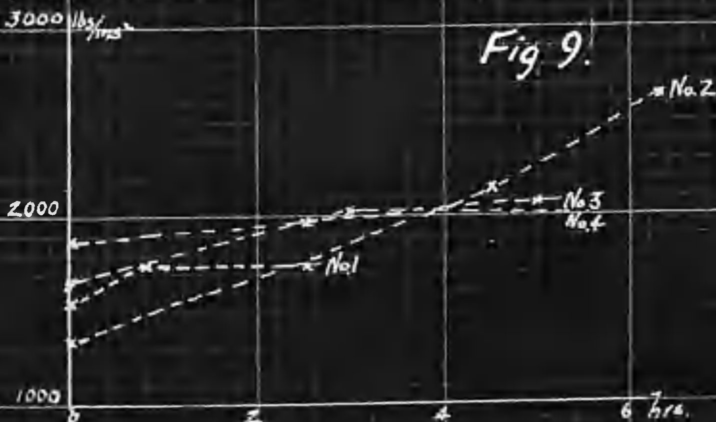
No. 1 – ¼" to ¾" Whin.

No. 2 – ⅛" to ½" Gravel

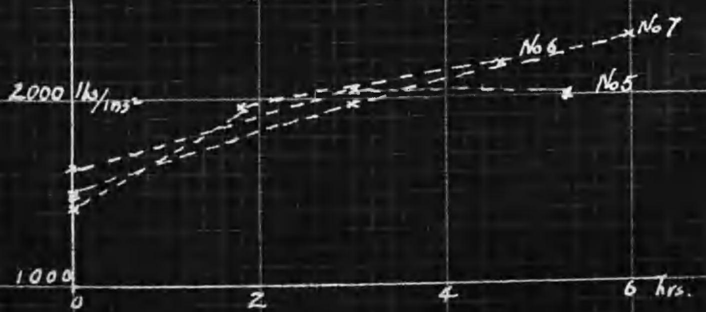
No. 3 – ¼" to ¾" Granite

No. 4 – ½" to 1½" Whin.

Fig. 9.



Strength – Time Diagrams.



Rapid Hardening Cement – Neat and Mortar Tests.

7 Days Water Cured

No. 1 – Freshly mixed specimen – Nos 2 + 3 remixed at times given

Each compression value mean of two 3" × 1½" cylinders.

Each tension value mean of 3 standard briquettes.

	Water Ratio by Weight	No. 1 Comp. Strength lbs/ins²	No. 1 Tensile Strength lbs/ins²	No. 2 Storage Time Hours	No. 2 Comp. Strength lbs/ins²	No. 2 Tensile Strength lbs/ins²	No. 3 Storage Time Hours	No. 3 Comp. Strength lbs/ins²	No. 3 Tensile Strength lbs/ins²
Neat Cement	·33	——	457	0·8	——	400	2·5	——	455
	·36	——	387	0·8	——	310	2·5	——	363
	·40	5600	383	1·7	5530	333	4·5	5420	396
	·44	4680	337	2·5	4540	350	5·0	4760	333
	·48	4140	250	2·5	4100	243	6·0	3220	287
	·52	2760	257	2·5	3360	285	5·5	3220	257
	·56	2410	220	1·5	2570	235	5·5	2790	230

Fig. 11

	Cem. Wt. / Sand Wt.	Water Ratio by Weight	No. 1 Compressive Strength lbs/ins²	No. 2 Storage Time Hours	No. 2 Compressive Strength lbs/ins²	No. 3 Storage Time Hours	No. 3 Compressive Strength lbs/ins²	Sands.
Mortars	1:4	·53	2220	2·5	2290	5·0	3050	
	1:3	·54	2770	2·5	3020	6·5	3200	
	1:2	·558	2220	0·8	2290	2·8	2570	
	1:2·3	·640	1400	1·1	1680	3·0	1820	C
	1:2	·655	1520	0·8	1500	2·8	1720	
	1:1·7	·65	1300	1·1	1700	3·0	1780	
	1:2	·54	2570	2·5	3020	6·5	2820	B
	1:1·6	·56	1970	1·5	2240	4·3	2480	
	1:3	·70	1940	2·8	1840	4·8	2110	
	1:4	·58	1710	1·6	1710	5·0	2610	
	1:3	·61	2510	1·8	2540	5·0	2730	
	1:3	·52	3180	2·3	3330	4·5	3300	
	1:2·5	·53	3500	2·3	3870	4·5	3870	
	1:3	·70	1940	2·8	1840	4·8	2110	
	Tension	Briq.	278		278		250	
	1:2	·57	2290	2·8	2870	5·8	3170	D
	Tension	Briq.	330		300		370	
	1:1·7	·63	2540	1·6	2670	5·6	2920	
	Tension	Briq.	310		330		290	
	1:1·6	·56	3070	5·5	3370	——	——	
	Tension	Briq.	390		410		——	

Fig. 10

Sand A Mortars.

Rapid Hardening Cement.

BRITISH MADE

Normal and Remixed Mortars of complete sand

6 hrs storage period
All figures are mean values from three cylinders 3" × 1½" diam.
broken after 1 day in moulds + 6 days in water.

Weight of Cem / Wt of Sand	W.R. 0·5 Strengths lbs/ins² Normal	W.R. 0·5 Remixed	W.R. 0·6 Strengths lbs/ins² Normal	W.R. 0·6 Remixed	W.R. 0·8 Strengths lbs/ins² Normal	W.R. 0·8 Remixed
1:1	3580	3480	—	—	—	—
1:2	3750	3600	2290	2320	—	—
1:3	3580	3550	2520	2490	1580	1300
1:4	—	—	2350	2300	1440	1200
1:6	—	—	—	—	890	1090

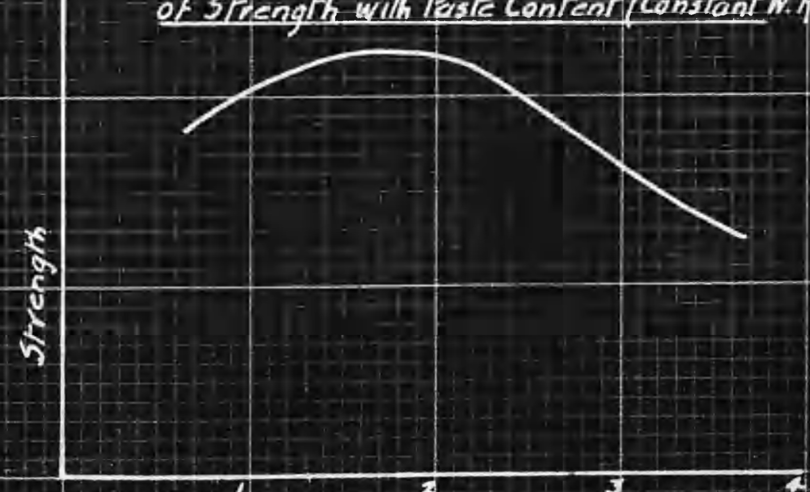
Fig. 13

Normal and Remixed Mortars of sand A fractions intercepted between sieves shown in column on left.
All figures are mean values from three 3" × 1½" cylinders broken at 7 days

Sand Fraction	Wt. of Cem. / Wt. of Sand	W.R. 0·5 Strengths lbs/ins² Normal	W.R. 0·5 3 hrs Storage	W.R. 0·5 7 hrs. Storage	Cem. / Sand	W.R. 0·6 Strengths lbs/ins² Normal	W.R. 0·6 5 hrs. Storage	W.R. 0·6 10 hrs Storage
4 to 8 mesh	1:1	3500	3700	3300	1:2		2290	2290
	1:2	3150	3300	3160	1:3	1460	2100	2090
8 to 14 mesh	1:1	4000	4320	3560	1:2	2500	2540	2410
	1:2	3800	4070	3560	1:3	2120	2290	2340
14 to 28 mesh	1:1	3700	3580	3510	1:2	2600	2500	2800
	1:2	3550	3950	3500	1:3	2200	2140	2180
28 to 48 mesh	1:1	4300	3870	3200				
	1:2	4100	4000	3470				

Fig. 12

Diagram showing typical Fluctuation of Strength with Paste Content (Constant W.R.)



$$\frac{A}{C} = \frac{\text{Wt. of sand}}{\text{Wt of Cem.}}$$

Fig. 14

Neat Cement Compression Tests.

3" × 1½" Cylinders – 7 days – Water cured.

Wetter pastes remixed after storage times sufficient to prevent separation of water.

$\frac{c}{\omega}$	Crushing Stress lbs/ins²
1·33	12000
0·972	7860
0·785	5070
0·657	3300
0·557	1770
0·489	1530
0·437	1080

c = absolute vol. of cement
ω = volume of water
S = Crushing stress, lbs/ins²

Equation for averaging line:-

$$S = 14{,}030\left(\frac{c}{\omega} - \cdot 417\right)$$

Values from above table shown thus ·
" " table fig 11, page shown thus +

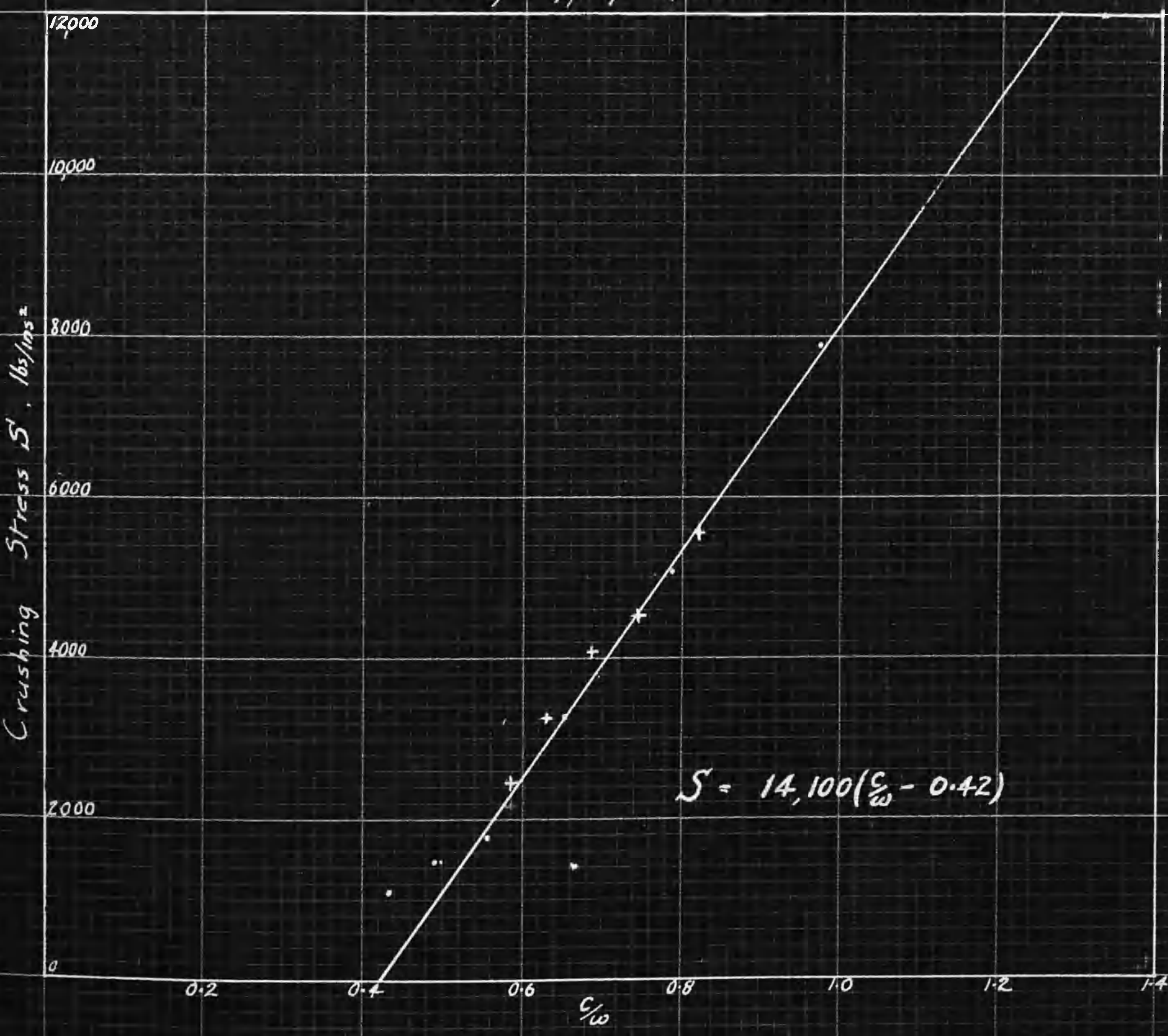


Fig 15.

Compressive Strengths of Normal Mortars

Sand A - Natural Grading. (No 1)

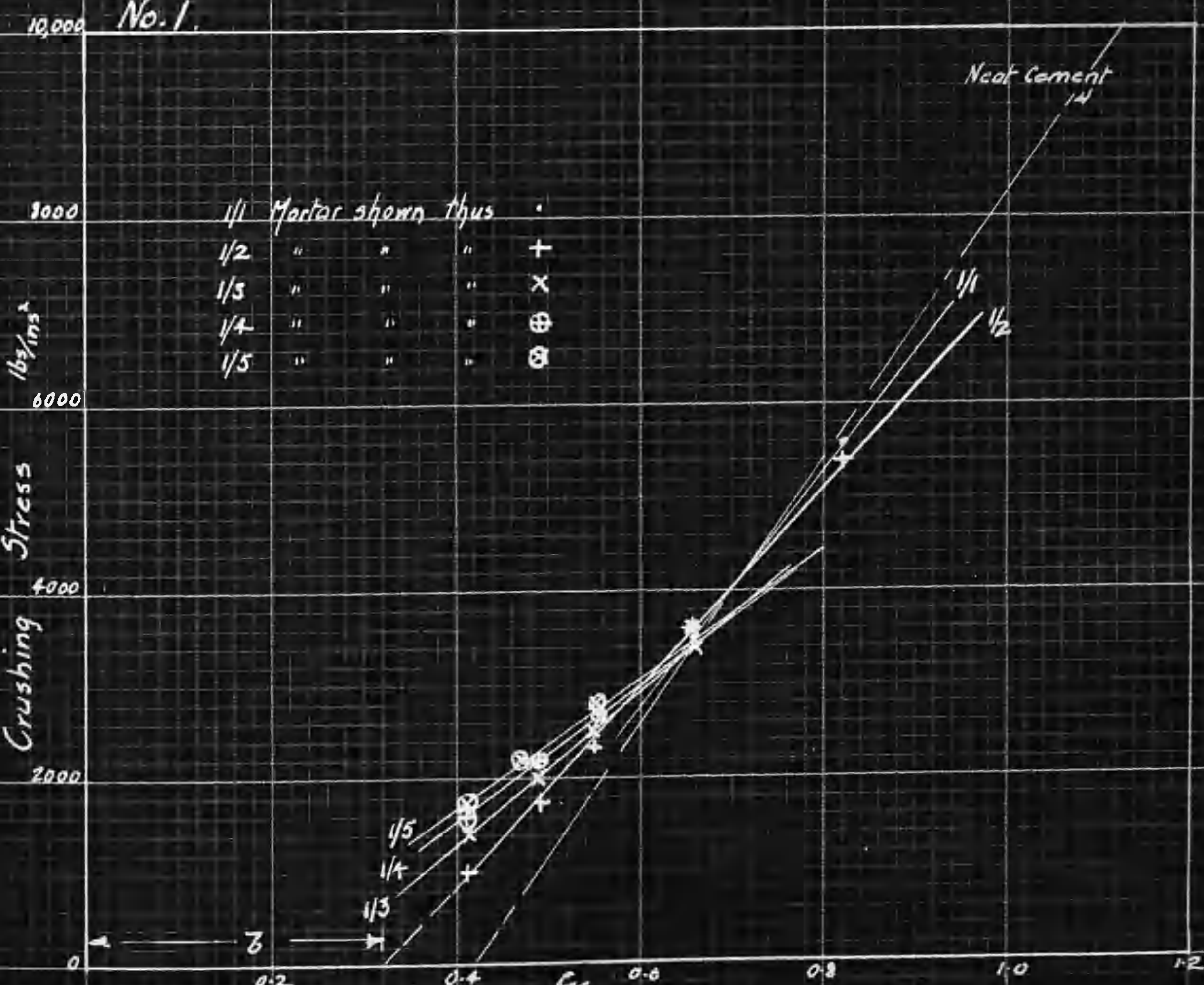
3" x 1½" cylinders at 7 days age - Water cured.

Each value mean of 3 Tests.

Fig 16.

Wt of Cem. / W. of Sand	1/1	1/2		1/3		1/4		1/5	
C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²
0·82	5600	0·82	5400	0·66	3600	0·66	3450	0·66	3400
0·66	3580	0·66	3660	0·55	2520	0·55	2650	0·55	2800
0·55		0·55	2320	0·47	2000	0·47	2200	0·47	2200
0·47		0·47	1750	0·41	1550	0·41	1600	0·41	1600
0·41		0·41	1000						

No. 1.



Abstract

Mix.	1/1	1/2	1/3	1/4	1/5
w/c value for equal mortar and neat strengths	1·33	1·39	1·52	1·54	1·54
Slope of Averaging Line	12,500	10,560	8120	7200	6600
z	0·38	0·32	0·25	0·20	0·16

Compressive Strengths of Normal Mortars.

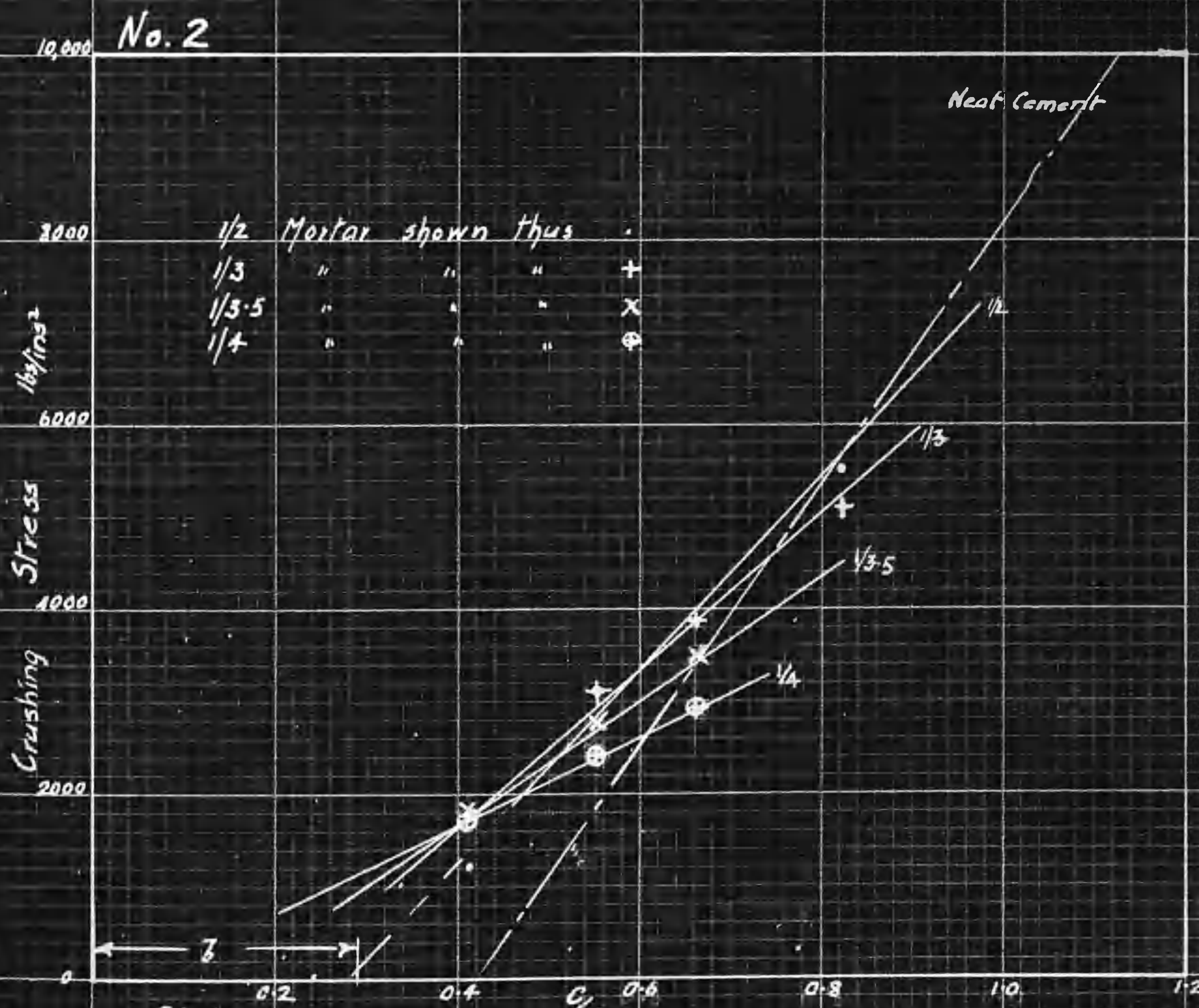
Sand C – Natural Grading. (No. 2.)

3" × 1½" cylinders at 7 days age – Water cured.

Each value mean of 3 Tests.

Fig. 17.

Wt. of Cem. / Wt. of Sand	1/2		1/3		1/3.5		1/4
C/ω	Crushing Stress lbs/ins²	C/ω	Crushing Stress lbs/ins²	C/ω	Crushing Stress lbs/ins²	C/ω	Crushing Stress lbs/ins²
0·82	5500	0·82	5100	0·66	3500	0·66	2850
0·66	3900	0·66	3900	0·55	2860	0·55	2450
0·55	3100	0·66	3100	0·41	1800	0·41	1800
0·41	1200	0·41	1700				



Abstract

Mix	1/2	1/3	1/3·5	1/4
C/ω value for equal mortar and neat strengths	1·21	1·33	1·49	1·64
Slope of Averaging Line	10,500	8500	6700	4720
z	0·29	0·21	0·17	0·06

Compressive Strengths of Normal Mortars.

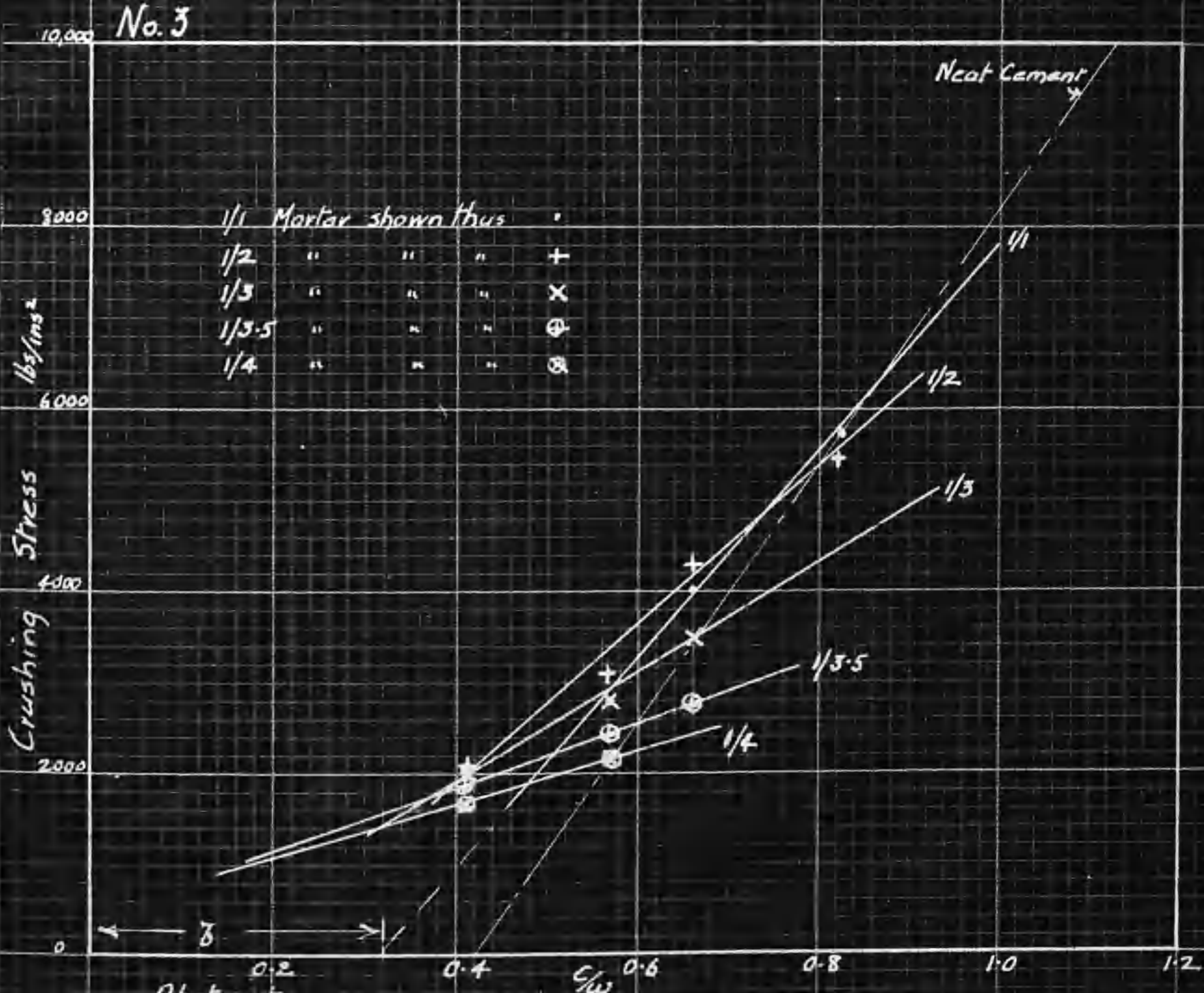
Sand D – Natural Grading. (No 3.)

3" × 1½" cylinders at 7 days age – Water cured.

All values mean of 3 Tests

Fig 18.

Wt. of Cem. / Wt. of Sand	1/1	1/2		1/3		1/3·5		1/4	
C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²
0·82	5750	0·82	5450	0·66	3500	0·66	2750	0·57	2200
0·66	4000	0·66	4300	0·57	2800	0·57	2450	0·41	1650
0·57	2800	0·57	3100	0·41	2050	0·41	1950		
		0·41	2100						



Abstract

Mix.	1/1	1/2	1/3	1/3·5	1/4
C/W value for equal mortar and neat strengths	1·20	1·25	1·50	1·68	1·76
Slope of Averaging Line	11,300	8700	6000	3500	2900
b	0·32	0·19	0·09	-0·10	-0·14

Compressive Strengths of Normal Mortars.

Sand A fractions – 4 to 8 fraction 1 part, 28 to 48 fraction 1 part. (by weight) (No 4)

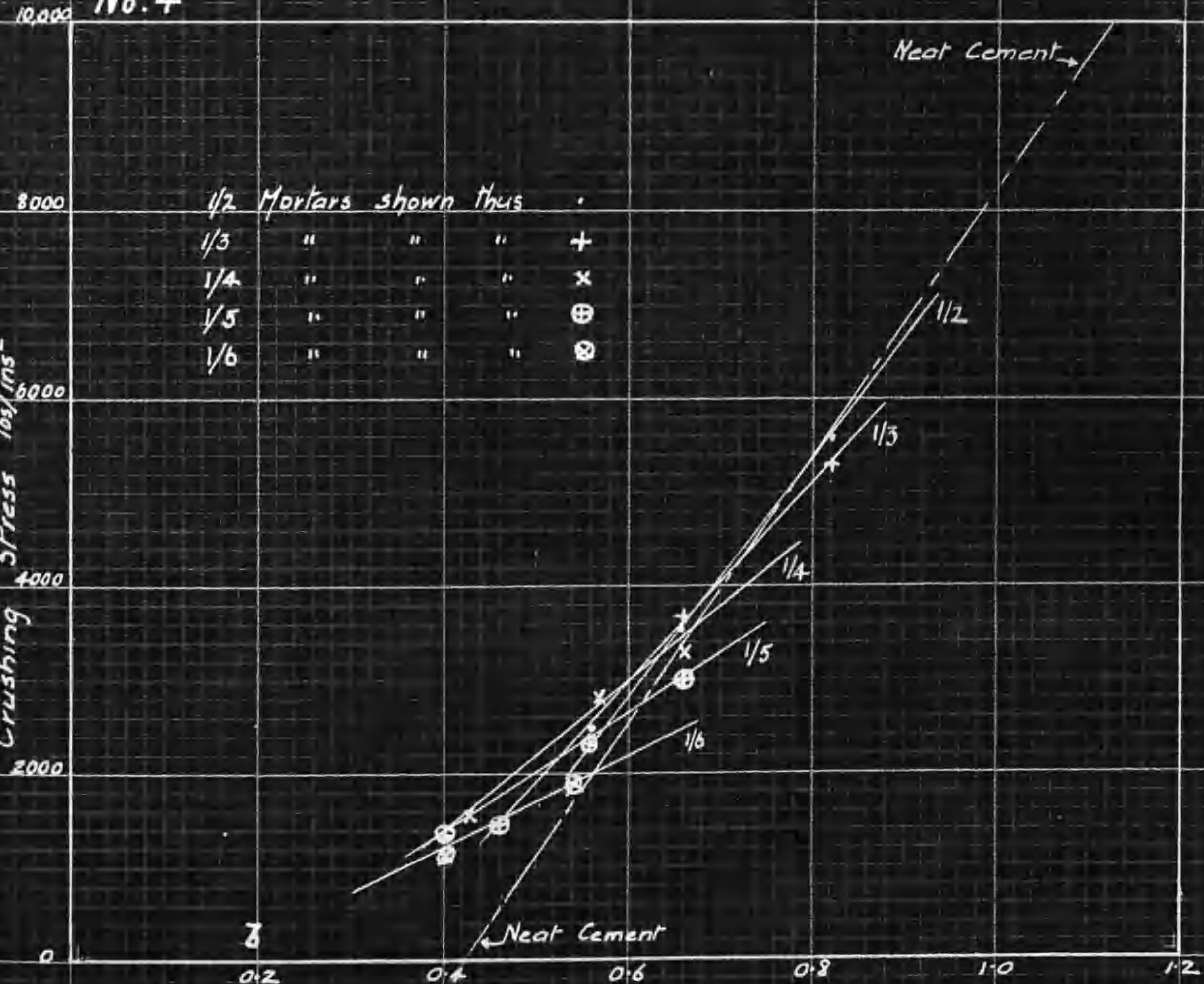
3"×1½" Cylinders at 7 days age – Water cured.

Each value mean of 3 Tests.

Fig. 19

Wt of Cem / Wt of Sand: ½		⅓		¼		⅕		⅙	
C/ω	Crushing Stress lbs/ins²	C/ω	Crushing Stress lbs/ins²	C/ω	Crushing Stress lbs/ins²	C/ω	Crushing Stress lbs/ins²	C/ω	Crushing Stress lbs/ins²
0·82	5600	0·82	5300	0·66	3320	0·66	3000	0·54	1900
0·66	3500	0·66	3680	0·57	2820	0·56	2460	0·40	1100
0·56	2390	0·56	2460	0·43	1560	0·40	1380		
		0·46	1420						

No. 4



Abstract.

Mix	1/2	1/3	1/4	1/5	1/6
ω/c value for equal mortar and neat strengths	1·25	1·37	1·49	1·64	1·79
Slope of Average Line	12,800	10,700	7,900	6400	4900
b̄	0·38	0·32	0·23	0·18	0·14

Compressive Strengths of Normal Mortars.

Sand A fractions – 4 to 8 2 parts, 28 to 48 1 part (by weight)

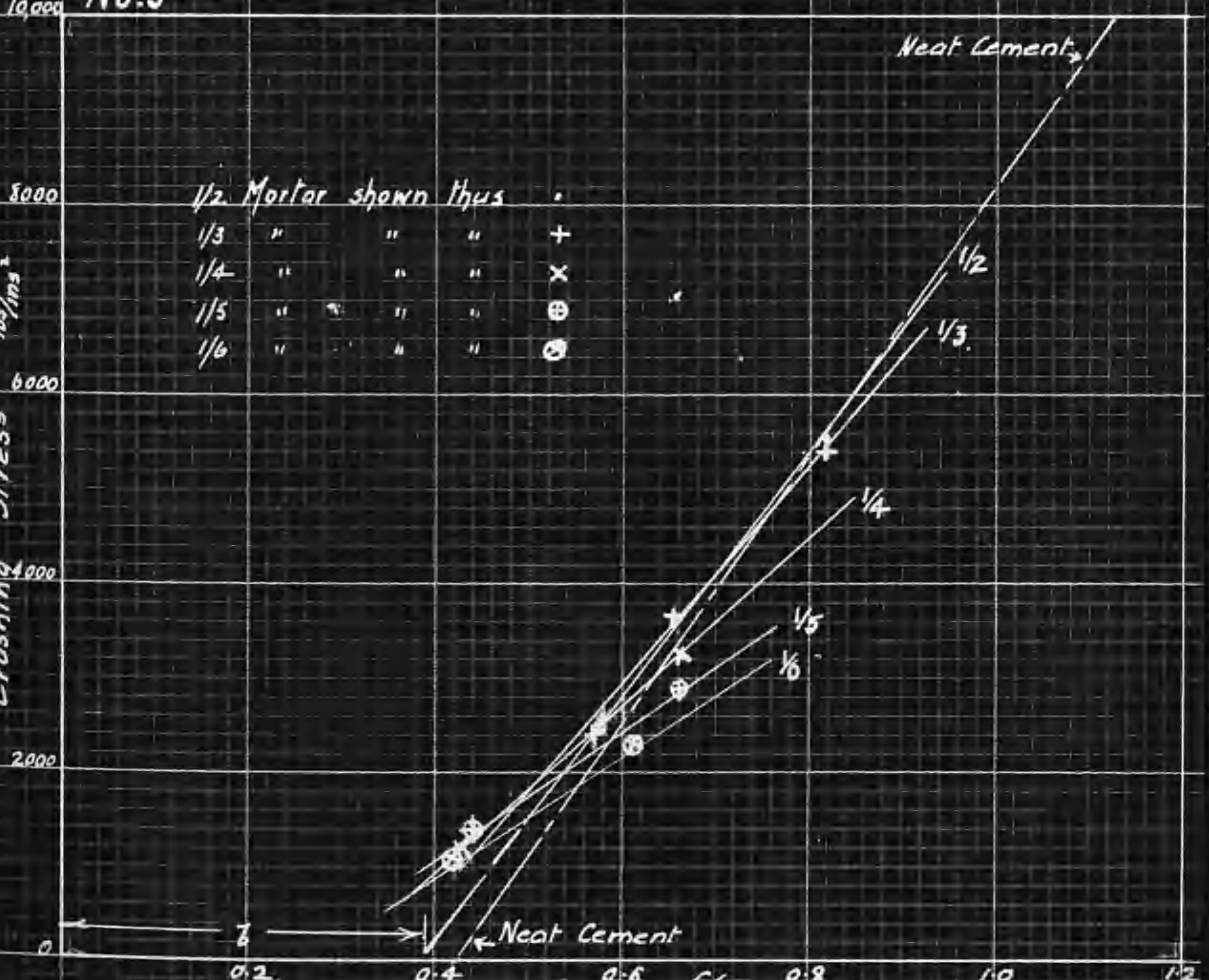
3" × 1½" cylinders at 7 days age – water cured. No. 5.

Each value mean of 3 Tests

Fig 20

Wt. of Cem. / Wt. of Sand	1/2	1/3		1/4		1/5		1/6	
C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²
0·82	5600	0·82	5400	0·66	3320	0·66	2900	0·61	2350
0·66	3600	0·66	3660	0·57	2550	0·60	2700	0·43	1200
0·57	2370	0·58	2470	0·43	1180	0·44	1390		
		0·42	1000						

No. 5



Abstract

Mix	1/2	1/3	1/4	1/5	1/6
W/C value for equal mortar and neat strengths	1·18	1·32	1·57	1·87	2·0
Slope of Average Line	13,000	11,600	8800	6800	6500
b	0·39	0·35	0·30	0·24	0·24

Compressive Strengths of Normal Mortars.

Sand A Fractions – 4 to 8 3·5 parts, 28 to 48 1 part by weight

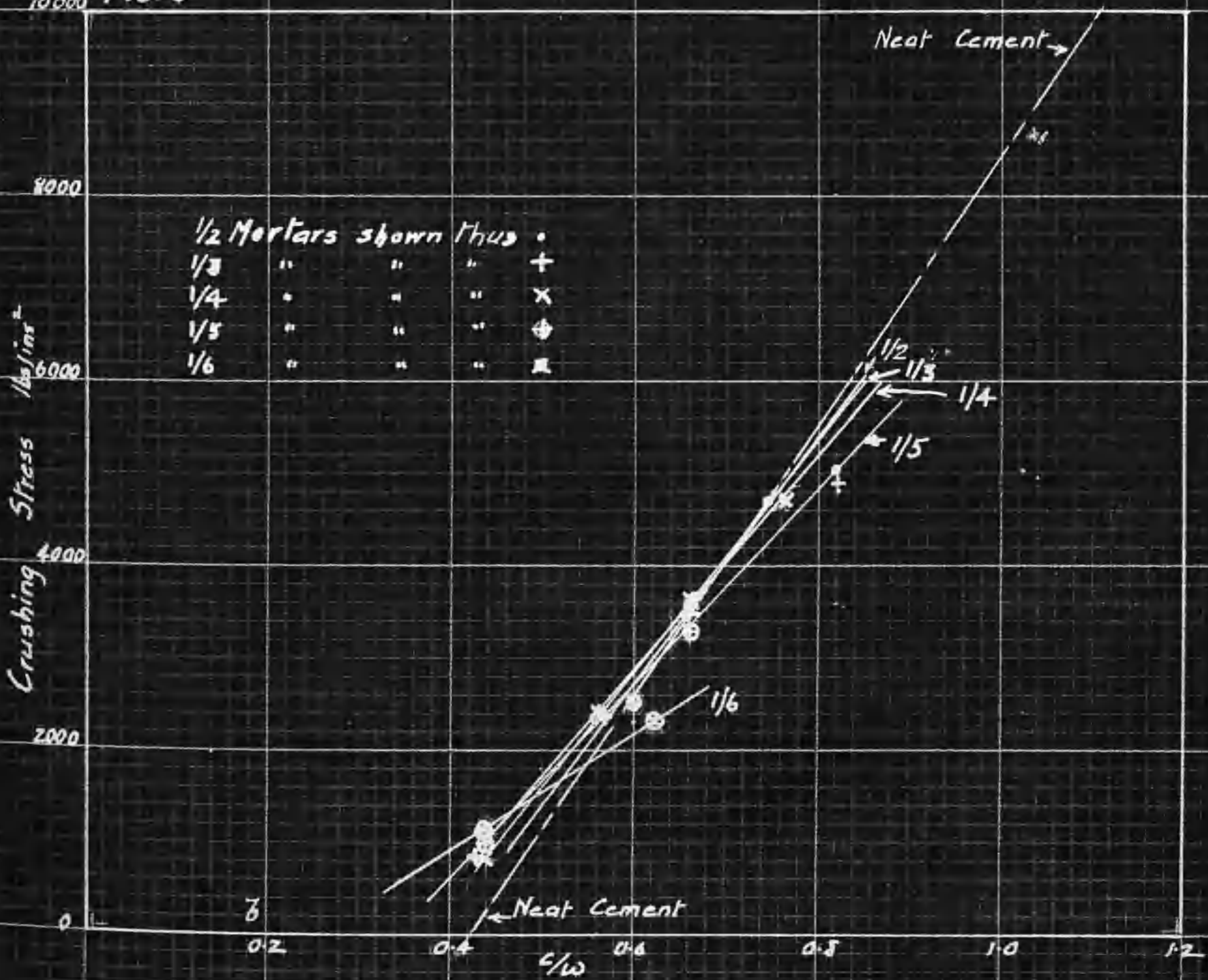
3" x 1½" cylinders at 7 days age – Water cured **No. 6**

Each value mean of 3 Tests

Fig 21

Wt. of Cem / Wt. of Sand ½		1/3		1/4		1/5		1/6	
C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²
0·82	5000	0·82	4900	0·76	4700	0·66	3300	0·62	2300
0·75	4800	0·66	3550	0·66	3600	0·60	2500	0·44	1050
0·66	3300	0·57	2380	0·56	2400	0·44	1000		
		0·43	800	0·44	950				

No. 6



Mix	1/2	1/3	1/4	1/5	1/6
W/C value for equal mortar and neat strengths	1·39	1·43	1·52	1·67	1·82
Slope of Averaging Line	13,000	12,600	11,500	10,000	6350
b	0·40	0·38	0·35	0·33	0·26

Compressive Strengths of Normal Mortars.

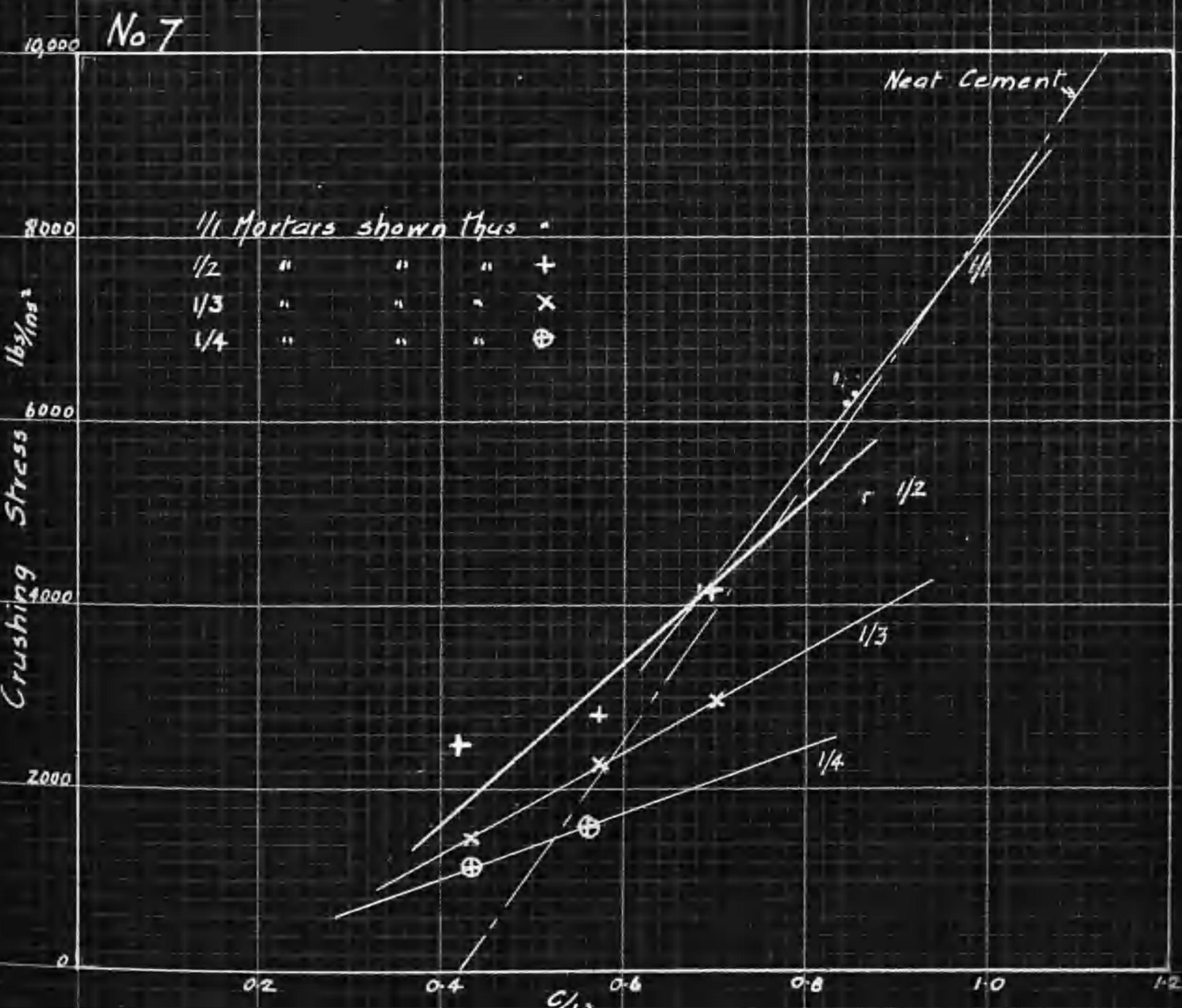
Sand A fractions – 28 to 48 2 parts – 48 down 1 part (by weight)

3" x 1½" cylinders at 7 days age – Water cured No. 7.

Each value mean of 3 Tests.

Fig. 22

Wt. of Cem. / Wt. of Sand 1/1		1/2		1/3		1/4		1/6	
C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²	C/W	Crushing Stress lbs/ins²
0·85	6280	0·86	5200	0·70	2960	0·56	1600		
0·84	6220	0·68	4080	0·57	2270	0·43	1130		
0·67	4000	0·57	2630	0·43	1410				
		0·42	2500						

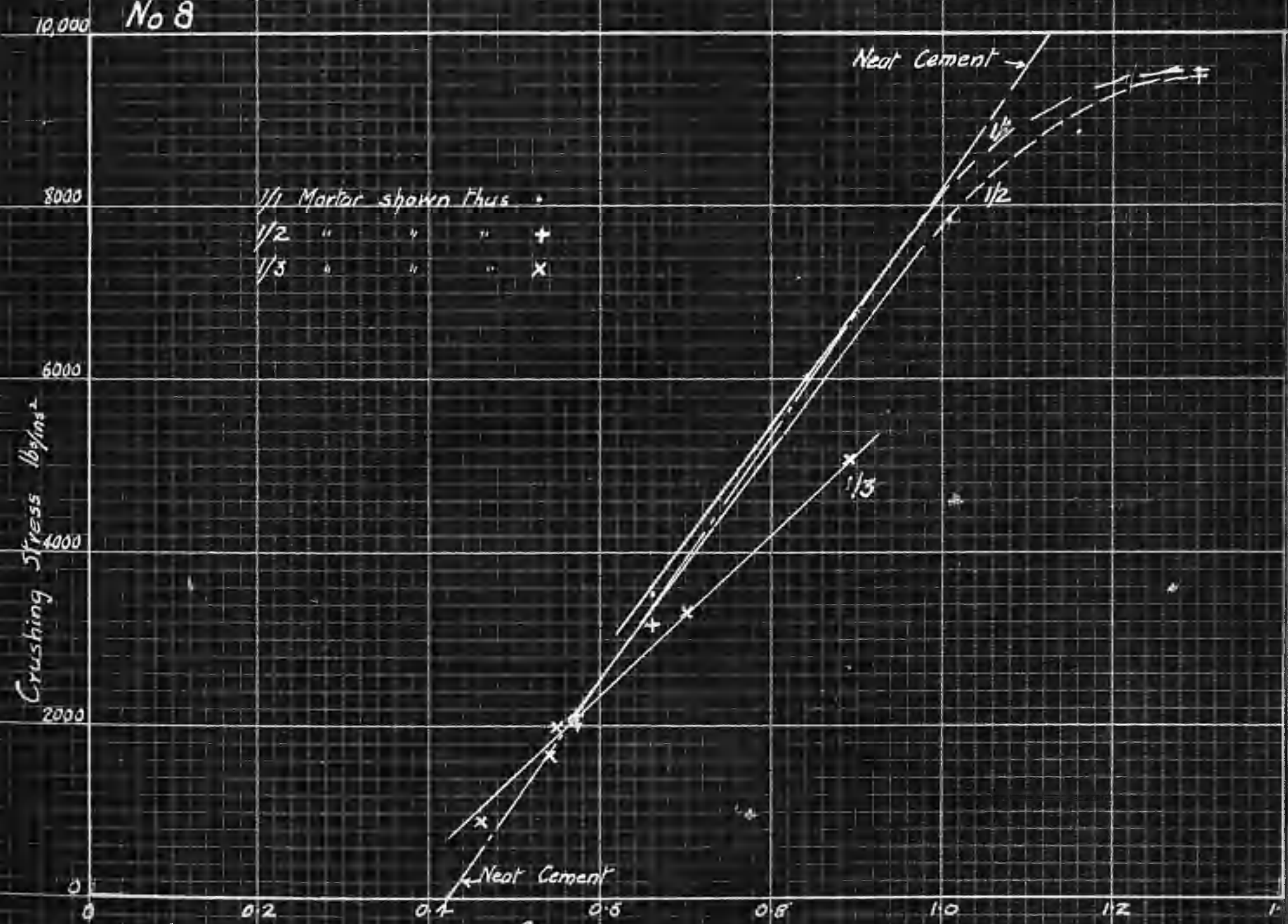


Mix.	1/1	1/2	1/3	1/4	1/6
W/C value for equal mortar and neat strengths	1·05	1·35	1·72	1·90	
Slope of Averaging Line	12,600	8900	5500	3560	
γ	0·36	0·22	0·17	0·13	

Compressive Strengths of Normal Mortars.
Sand A fractions – Material between Sieves Nos 4 + 8
3" x 1½ Cylinders at 7 days age – Water Curing No. 8
Each value mean of 3 Tests.

Fig. 23

Wt. of Cem. / Wt. of Sand: 1/1		1/2		1/3		1/4	
c/w	Crushing Stress lbs/ins²	c/w	Crushing Stress lbs/ins²	c/w	Crushing Stress lbs/ins²	c/w	Crushing Stress lbs/ins²
1.3	9570	1.3	9500	0.89	5070	—	—
1.16	8850	1.05	7820	0.70	3320	—	—
0.84	6000	0.66	3180	0.66	2800	—	—
0.66	3560	0.57	2090	0.54	1660	0.54	1230
0.66	3660	0.57	2000	0.55	2000	—	—
0.65	3490	0.66	3200	0.46	890	—	—



Abstract.

Mix	1/1	1/2	1/3
w/c value for equal mortar and neat strengths	1.05	1.54	1.78
Slope of Average Line	13400	12700	9400
b	0.39	0.40	0.33

Compressive Strengths of Normal Mortars.

Sand A Fractions — Material between Sieves Nos. 8 and 14.

3" × 1½" cylinders at 7 days age — Water cured. № 9

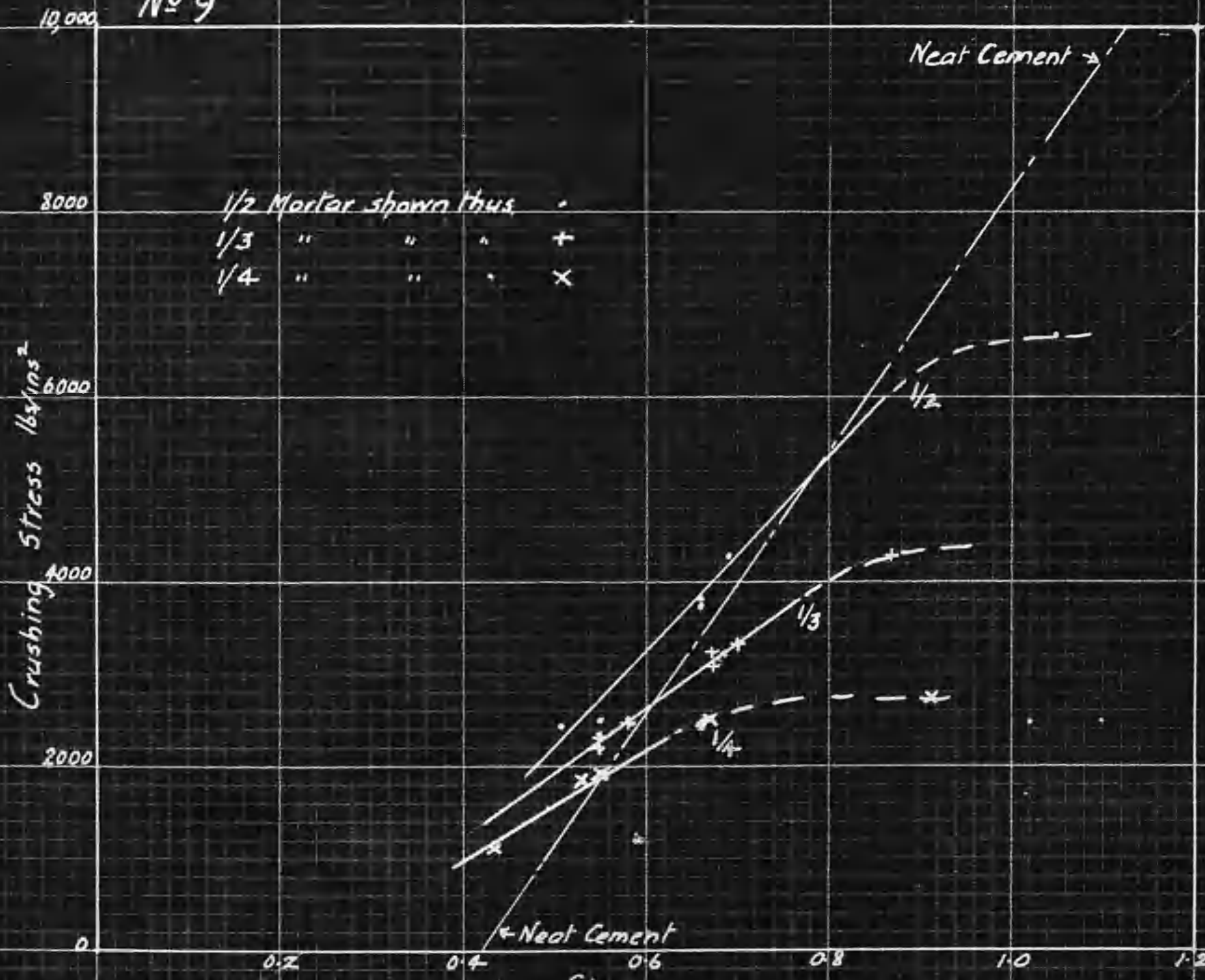
Each value mean of 3 Tests.

Fig. 24

Wt. of Cem. / Wt. of Sand ½		⅓		¼	
c/ω	Crushing Stress lbs/ins²	c/ω	Crushing Stress lbs/ins²	c/ω	Crushing Stress lbs/ins²
1·05	6650	0·97	4270	0·912	2790
0·69	4290	0·70	3310	0·664	2480
0·51	2460	0·66	3260	0·523	1820
0·66	3770	0·58	2460	0·432	1036
0·66	3800	0·66	3120	0·55	1920
0·55	2500	0·55	2200		
0·55	2500	0·55	2300		

Repeated figures are control test values

№ 9



Abstract

Mix	½	⅓	¼
ω/c value for equal mortar and neat strengths	1·27	1·64	1·82
Slope of average line	10,400	7200	5900
b	0·30	0·23	0·22

Compressive Strengths of Normal Mortars.

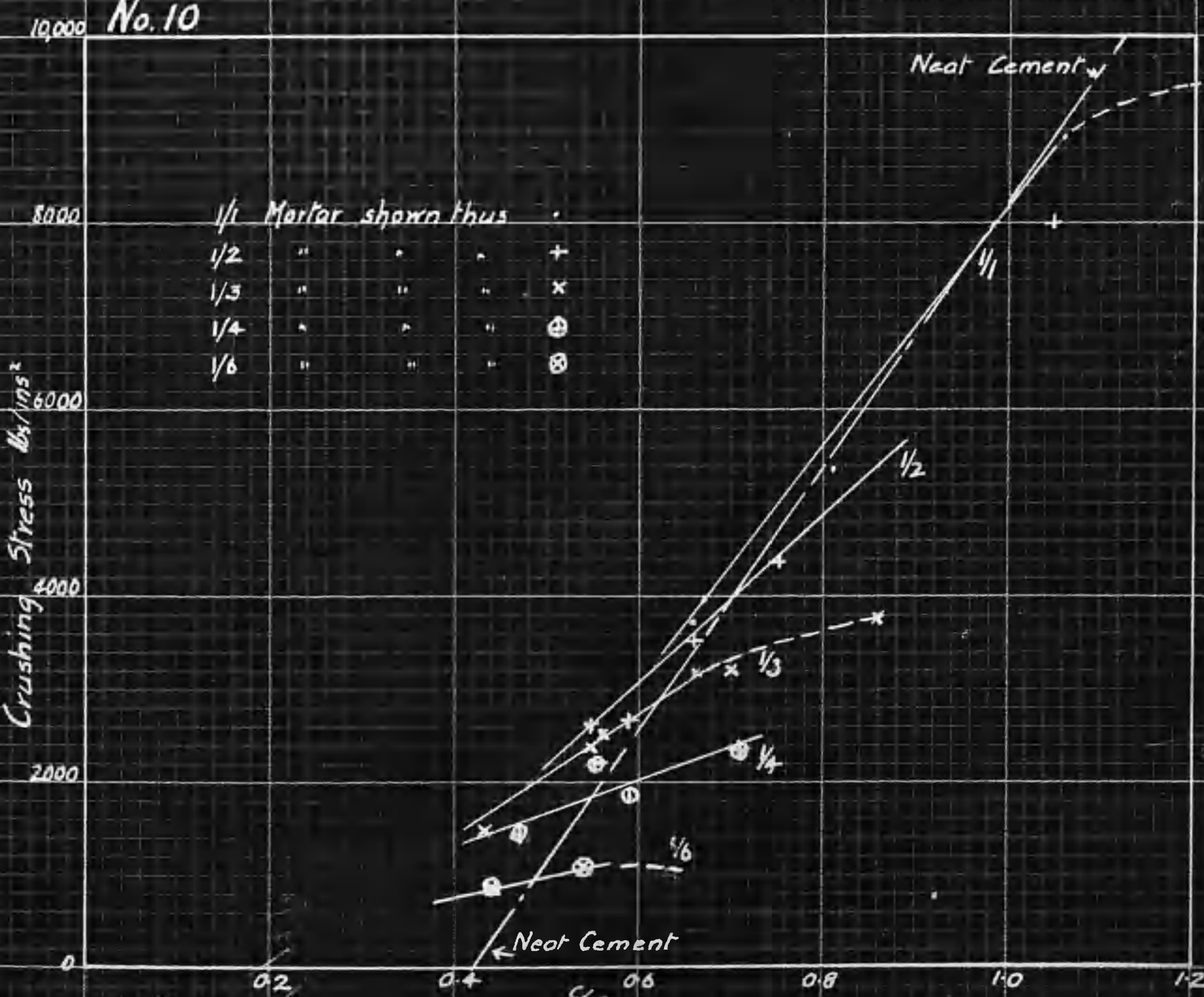
Sand A fractions — Material between Sieves Nos. 14 + 28

3" × 1½" cylinders at 7 days age — Water cured. No. 10.

Each value mean of 3 Tests

Wt. of Cem / Wt. of Sand 1/1		1/2		1/3		1/4		1/6	
c/ω	Crushing Stress lbs/ins²	c/ω	Crushing Stress lbs/ins²	c/ω	Crushing Stress lbs/ins²	c/ω	Crushing Stress lbs/ins²	c/ω	Crushing Stress lbs/ins²
1·28	9500	1·28	8720	0·88	3790	0·71	2180	0·63	1050
1·06	8980	1·05	8000	0·70	3210	0·59	1850	0·54	1036
0·81	5329	0·75	4350	0·58	2480	0·469	1630	0·42	936
0·67	3980	0·59	2670	0·43	1340	0·55	2260		
0·66	3770	0·66	3520	0·66	3200				
		0·55	2610	0·55	2370				

Fig. 25



Abstract

Mix	1/1	1/2	1/3	1/4	1/6
$\frac{\omega}{c}$ value for equal mortar and neat strengths	1·06	1·43	1·61	1·82	2·04
Slope of average line	12800	9000	7300	3740	2140
γ	0·37	0·26	0·19	0·06	0·06

Compressive Strengths of Normal Mortars.

Sand A fractions – Material between Sieves Nos. 28 + 48.

3" x 1½" cylinders at 7 days age – Water cured **No. 11**

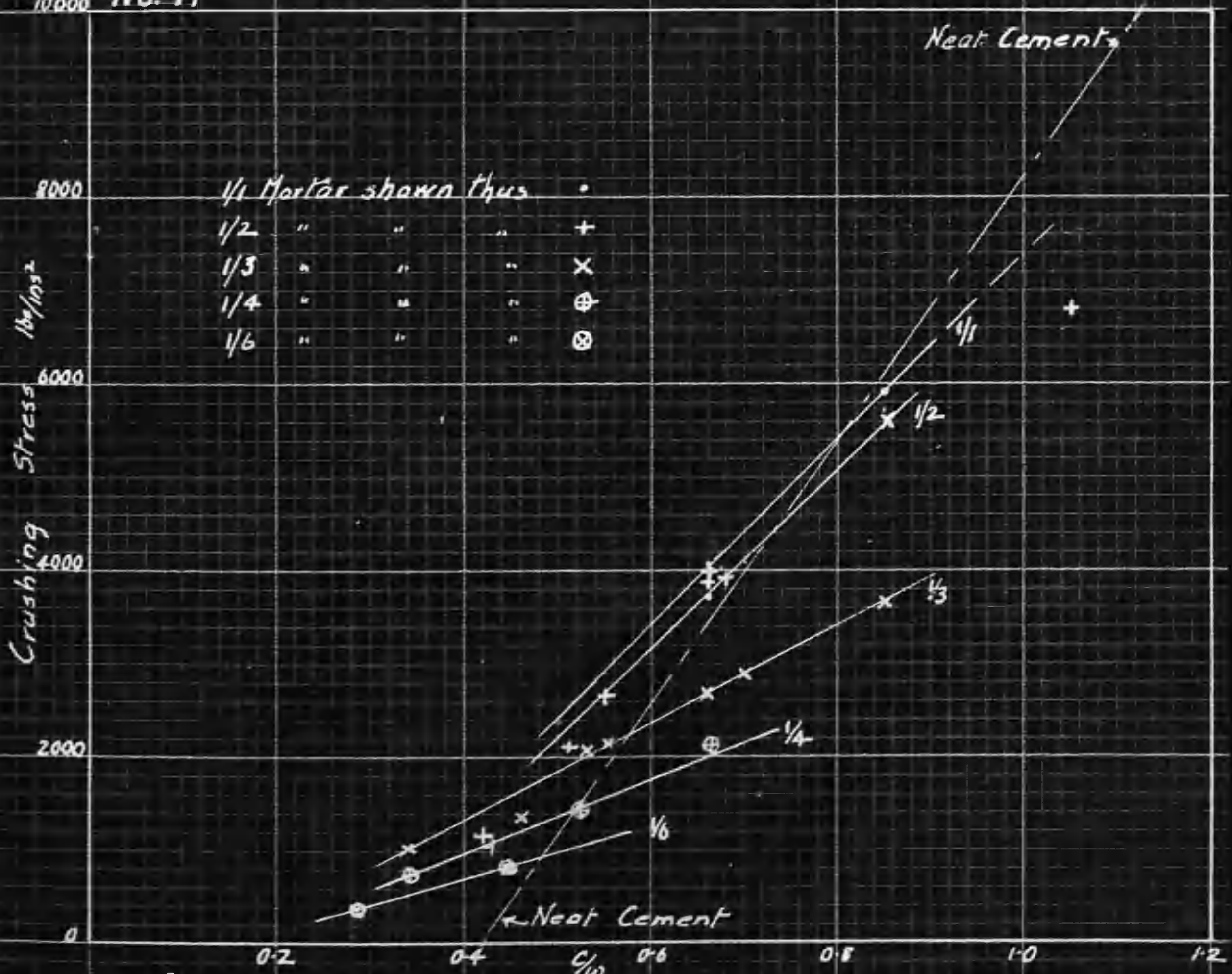
Each value mean of 3 Tests

Fig. 26

Wt. of Cem. / Wt. of Sand: 1/1		1/2		1/3		1/4		1/6	
c/w	Crushing Stress lbs/ins²	c/w	Crushing Stress lbs/ins²	c/w	Crushing Stress lbs/ins²	c/w	Crushing Stress lbs/ins²	c/w	Crushing Stress lbs/ins²
1·13	8363	1·05	6800	0·85	3690	0·66	2170	0·44	823
0·85	5910	0·68	3920	0·70	2800	0·53	1430	0·29	354
0·67	4070	0·51	2100	0·53	2050	0·43	1044		
0·5	2390	0·42	1180	0·46	1390	0·34	748		
0·66	4040	0·66	4130	0·34	1010	0·55	1960		
0·66	3700	0·66	3900	0·66	2660				
0·55	2900	0·55	2670	0·55	2160				

Repeated figures are control test values.

No. 11



Abstract

Mix.	1/1	1/2	1/3	1/4	1/6
w/c value for equal mortar and neat strengths	1·24	1·36	1·73	1·92	2·09
Slope of Average Line	10,000	9400	5200	3900	2900
b	0·26	0·27	0·15	0·15	0·16

Mortar Voids — Sand A (No 1) Sp. Gr 2·65.

Absolute vol. of sand = a do. do. per unit vol of mortar = a'

" " " cement = c " " " " " " " = c'

Voids in unit bulk vol of dry sand = $\frac{V_a - \cdot 324 V_a}{a}$ = v_a ; Voids in unit vol of mortar = v'

Unit volume = volume of 1 lb of water

Mix.	Water w_s lbs	Wt of Fill of Vessel lbs.	Wt. of Batch lbs.	Vol. of Batch	Water in Batch	Vols in Unit vol of Mortar: a'	Absorbed Water	Eff. a'	c'	Effective Water w'	v'
1/1 by wt.	0·30	0·698	2·30	1·046	0·30	0·364	0·010	0·374	0·312	0·277	0·314
a = ·381 (1 lb)	0·34	0·710	2·34	1·047	0·34	0·364	0·010	0·374	0·312	0·304	0·314
c = ·328 (1 lb)	0·38	0·697	2·38	1·083	0·38	0·351	0·010	0·361	0·303	0·341	0·336
a/c = 1·16	0·42	0·680	2·42	1·131	0·42	0·337	0·009	0·346	0·290	0·362	0·364
Absorbed Water ·01	0·48	0·670	2·48	1·171	0·48	0·325	0·009	0·334	0·279	0·400	0·387
1/2 by wt.	0·15	0·655	1·65	0·812	0·15	0·469	0·013	0·482	0·202	0·171	0·316
a = ·381 (1 lb)	0·17	0·705	1·67	0·756	0·17	0·508	0·014	0·522	0·217	0·210	0·261
c = ·164 (·5 lb)	0·18	0·718	1·68	0·745	0·18	0·512	0·014	0·526	0·220	0·227	0·254
a/c = 2·32	0·21	0·713	1·71	0·762	0·21	0·500	0·014	0·514	0·215	0·261	0·271
Absorbed Water 0·011 lbs	0·24	0·706	1·74	0·784	0·24	0·486	0·014	0·500	0·209	0·292	0·291
1/3 by wt.	0·10	0·627	1·433	0·727	0·10	0·524	0·015	0·539	0·150	0·122	0·311
a = ·381	0·12	0·689	1·453	0·672	0·12	0·567	0·016	0·583	0·163	0·162	0·254
c = ·109 (1 lb)	0·14	0·715	1·473	0·656	0·14	0·582	0·017	0·599	0·167	0·197	0·234
a/c = 3·49 (1/3 lb)	0·16	0·713	1·493	0·667	0·16	0·572	0·016	0·588	0·164	0·223	0·248
Absorbed Water = ·011 lbs.	0·18	0·700	1·513	0·688	0·18	0·554	0·015	0·569	0·159	0·246	0·272
	0·22	0·695	1·553	0·712	0·22	0·535	0·015	0·550	0·154	0·294	0·286
1/4 by wt.	0·09	0·644	1·34	0·662	0·09	0·591	0·017	0·608	0·124	0·119	0·268
a = ·381 (1 lb)	0·11	0·682	1·36	0·634	0·11	0·617	0·017	0·634	0·129	0·156	0·237
c = ·082 (1/4 lb)	0·13	0·700	1·38	0·627	0·13	0·623	0·017	0·640	0·131	0·196	0·229
a/c = 4·64	0·15	0·696	1·40	0·640	0·15	0·612	0·017	0·629	0·128	0·217	0·243
Absorbed Water = ·011 lbs	0·17	0·689	1·42	0·656	0·17	0·597	0·017	0·614	0·125	0·243	0·261
1/5 by wt.	0·08	0·647	1·28	0·629	0·08	0·606	0·017	0·623	0·104	0·110	0·273
a = ·381 (1 lb)	0·10	0·690	1·30	0·599	0·10	0·637	0·018	0·655	0·110	0·148	0·235
c = ·0657 (0·2 lb)	0·12	0·701	1·32	0·599	0·12	0·637	0·018	0·655	0·110	0·182	0·235
a/c = 5·8	0·14	0·701	1·34	0·608	0·14	0·627	0·018	0·645	0·108	0·213	0·247
Absorbed	0·16	0·692	1·36	0·626	0·16	0·609	0·017	0·626	0·105	0·238	0·269
Water = ·011 lbs	0·18	0·689	1·38	0·638	0·18	0·597	0·017	0·614	0·103	0·265	0·283

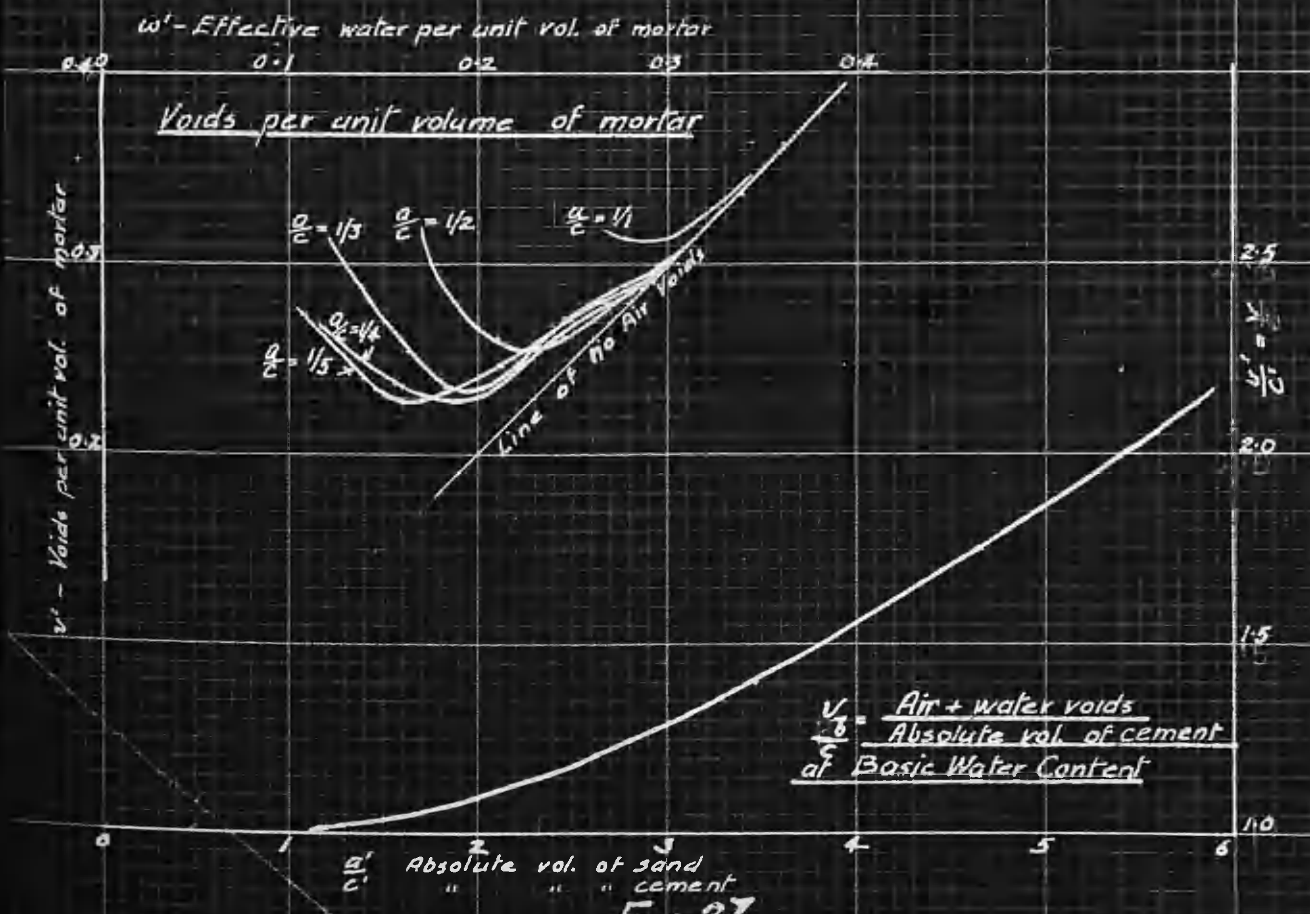


Fig. 27

Mortar Voids – Sand C – Sp. Gr 2·63 (No 2)

Absolute vol. of sand = a , vol. of effective water ω

" " " cement = c , Mortar voids (air + water) = v , do. do. at Basic Water = V_b

Dry sand voids = V_a = 0·6

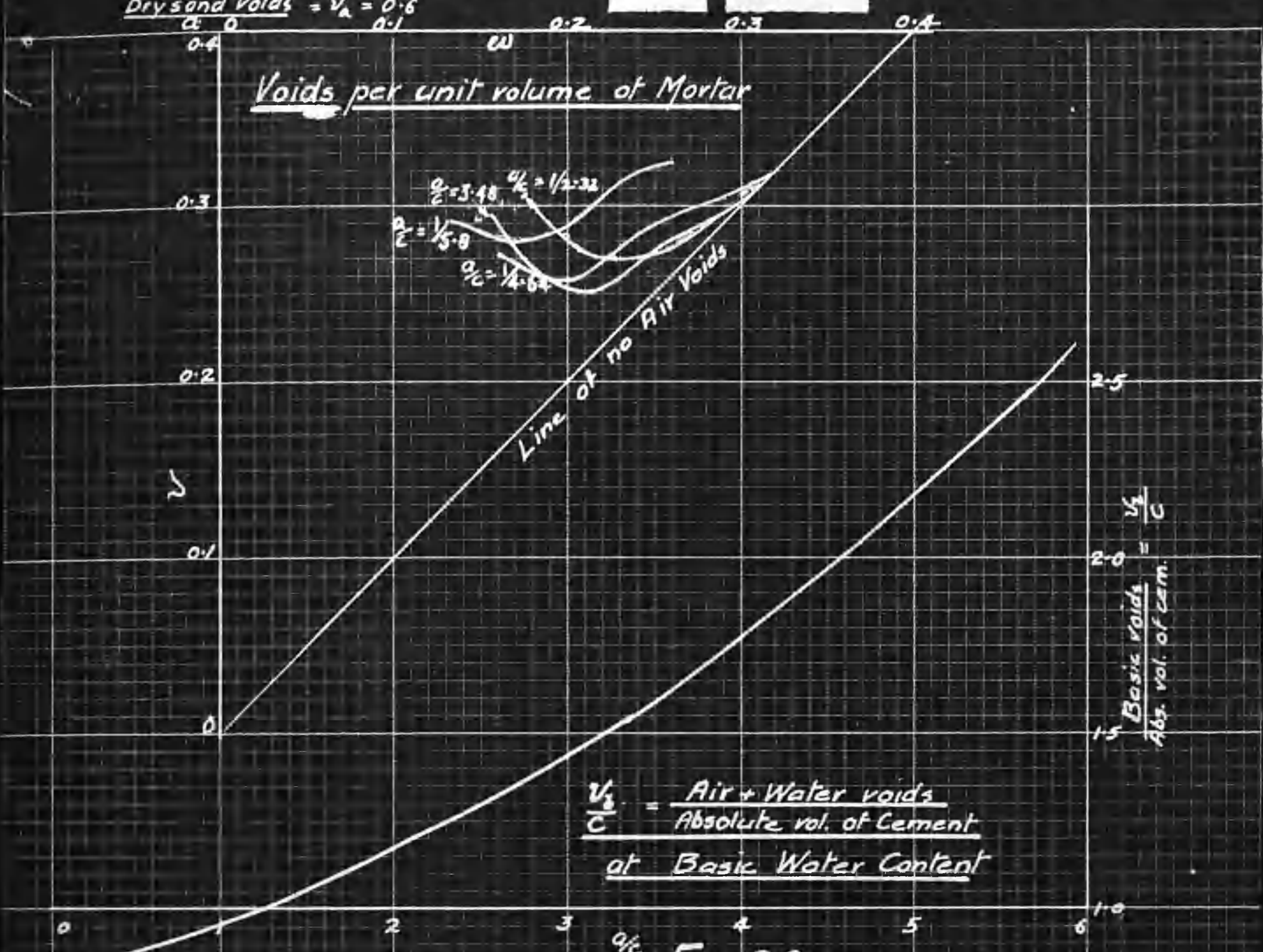


Fig. 28.

Sand D – Sp. Gr. 2·60 No 3

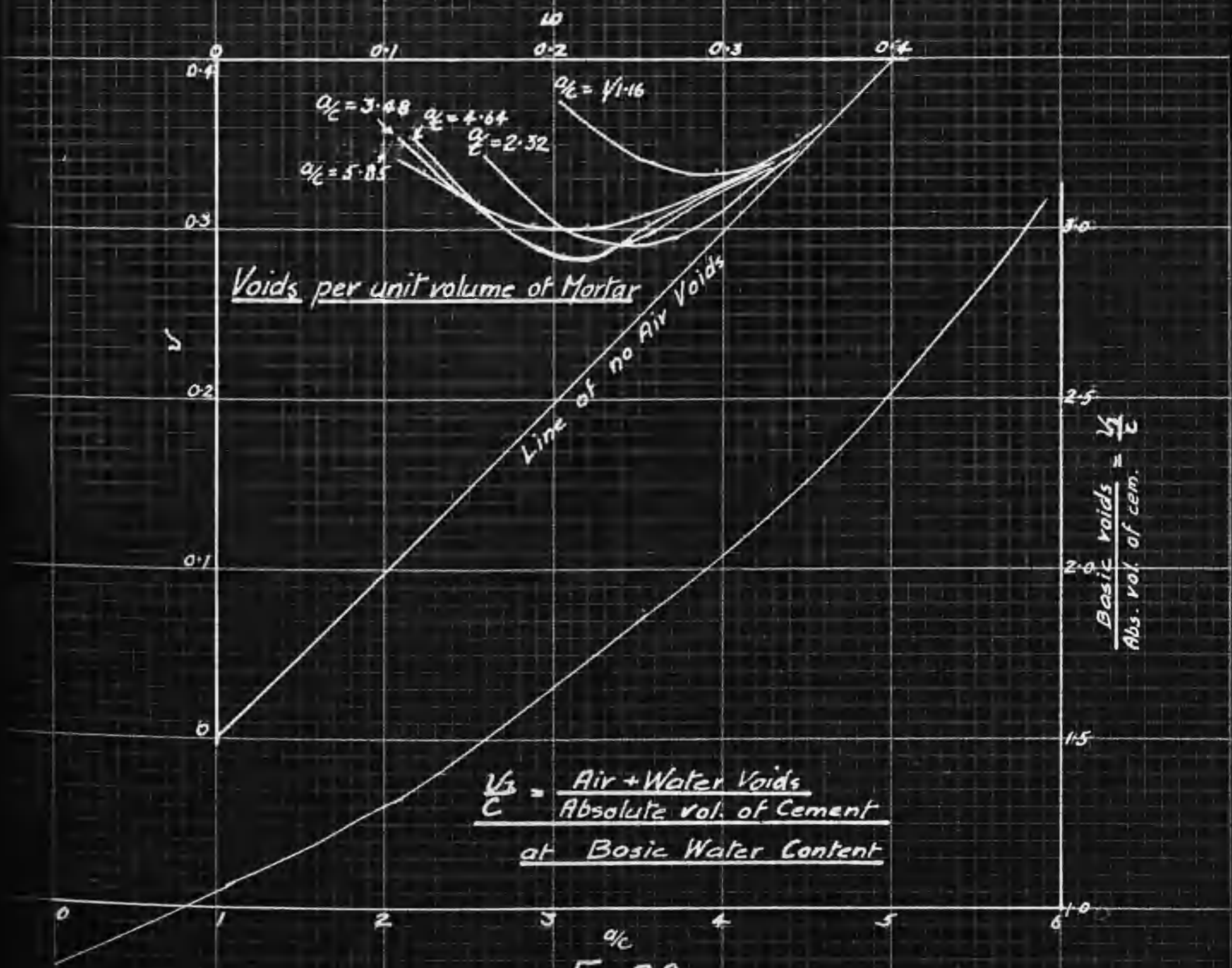


Fig 29.

Mortar – Voids – Sand A Fractions.

Absolute vol. of sand = a, Vol. of effective water w.

" " " cement = c, Mortar voids (air + water) = v, do. do. at Basic Water = v_B

Dry sand voids = v_a

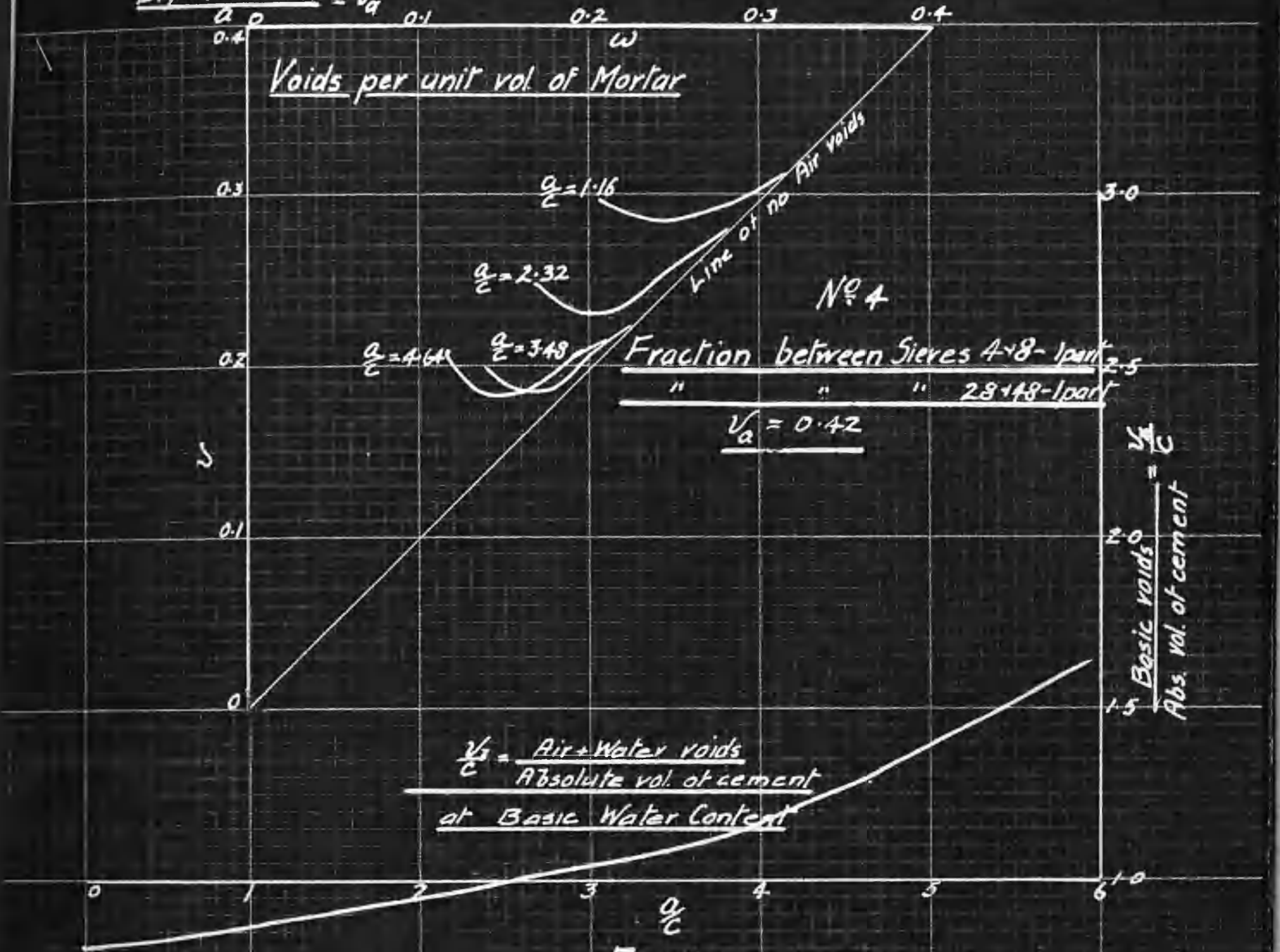


Fig. 30.

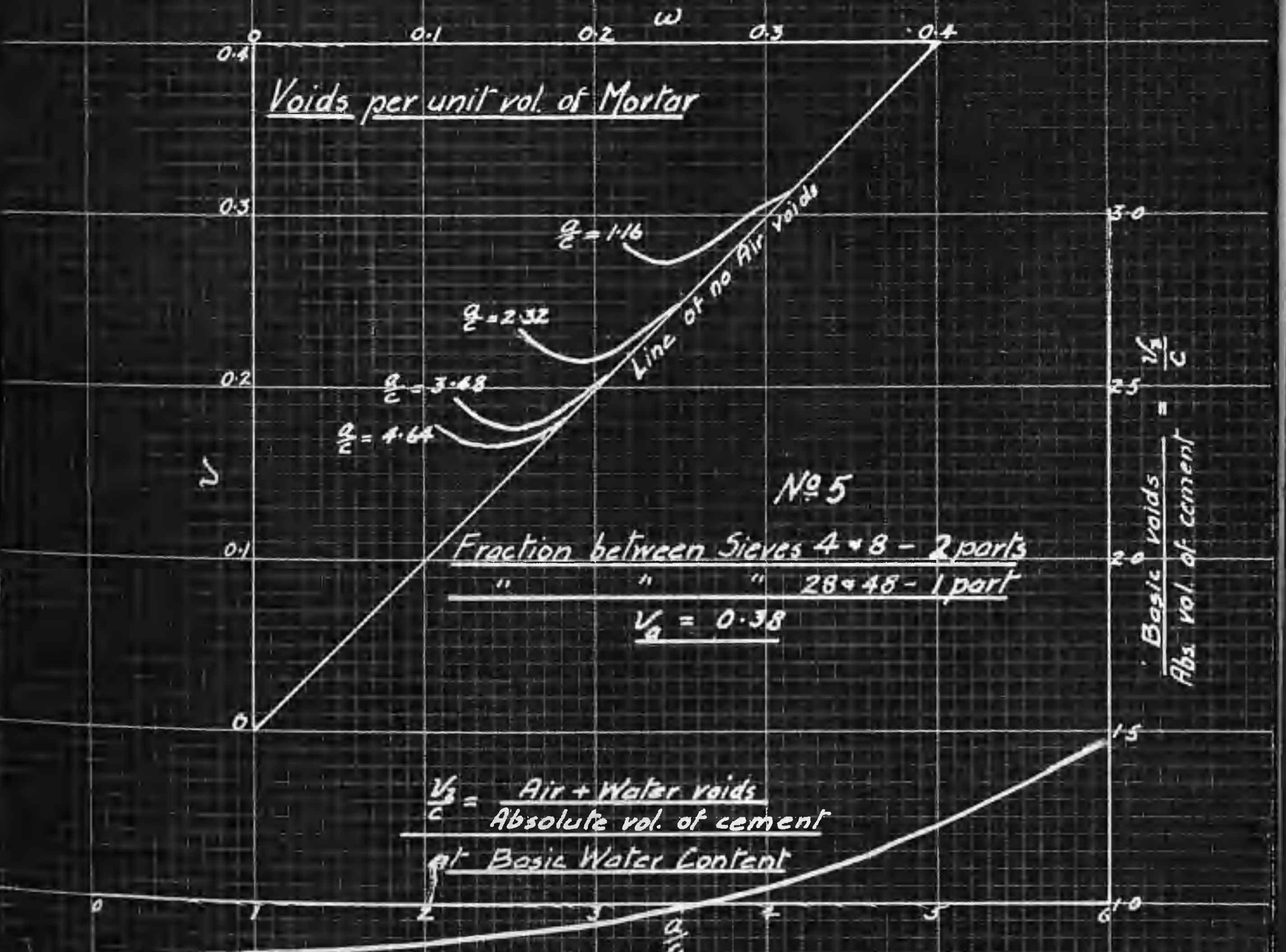


Fig. 31.

Mortar Voids – Sand A Fractions.

Absolute vol. of sand = a, Vol. of effective water = w

" " " cement = c, Mortar voids (air + water) = v, do. do. at Basic Water = v_b

Dry sand voids = v_a

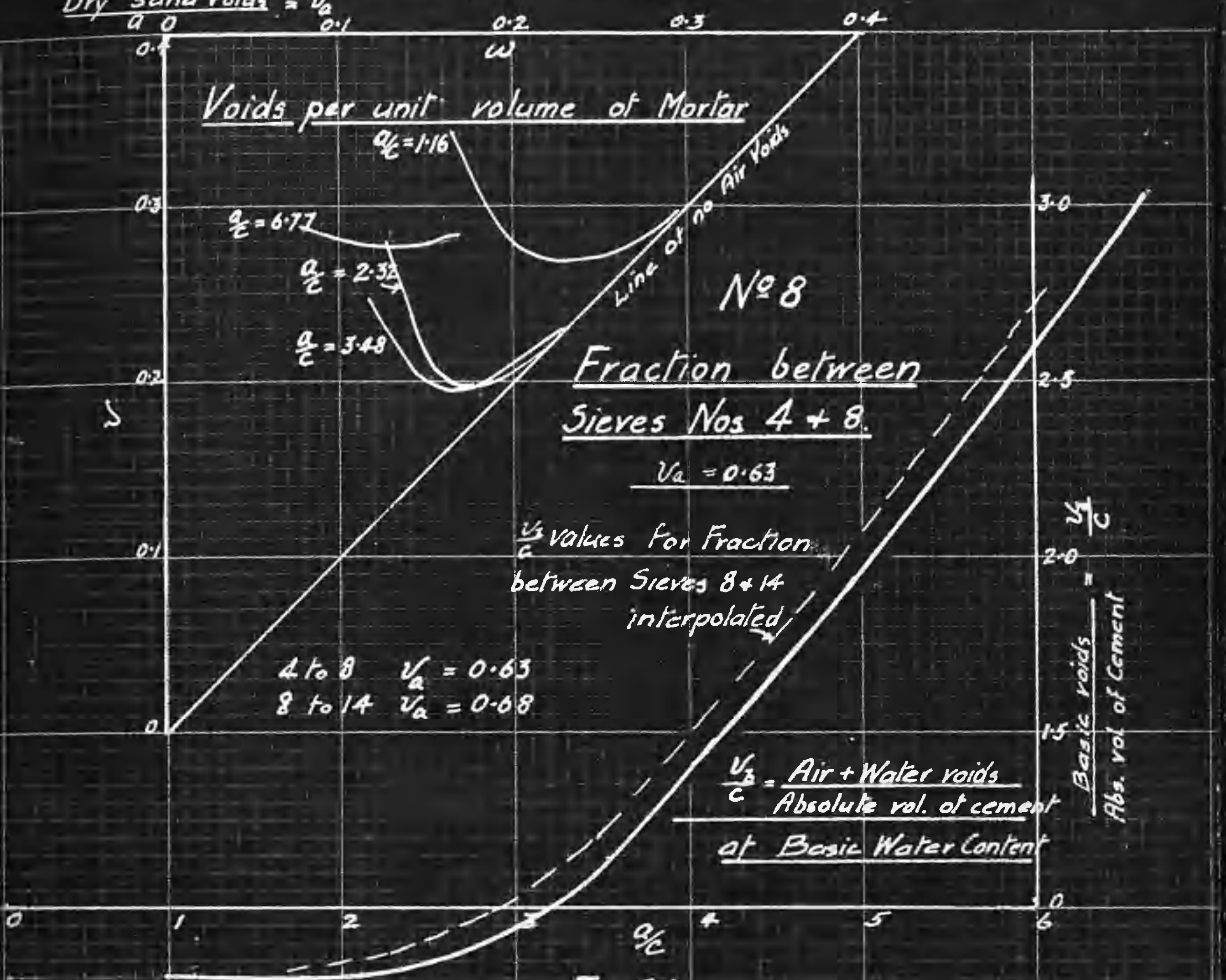


Fig. 34

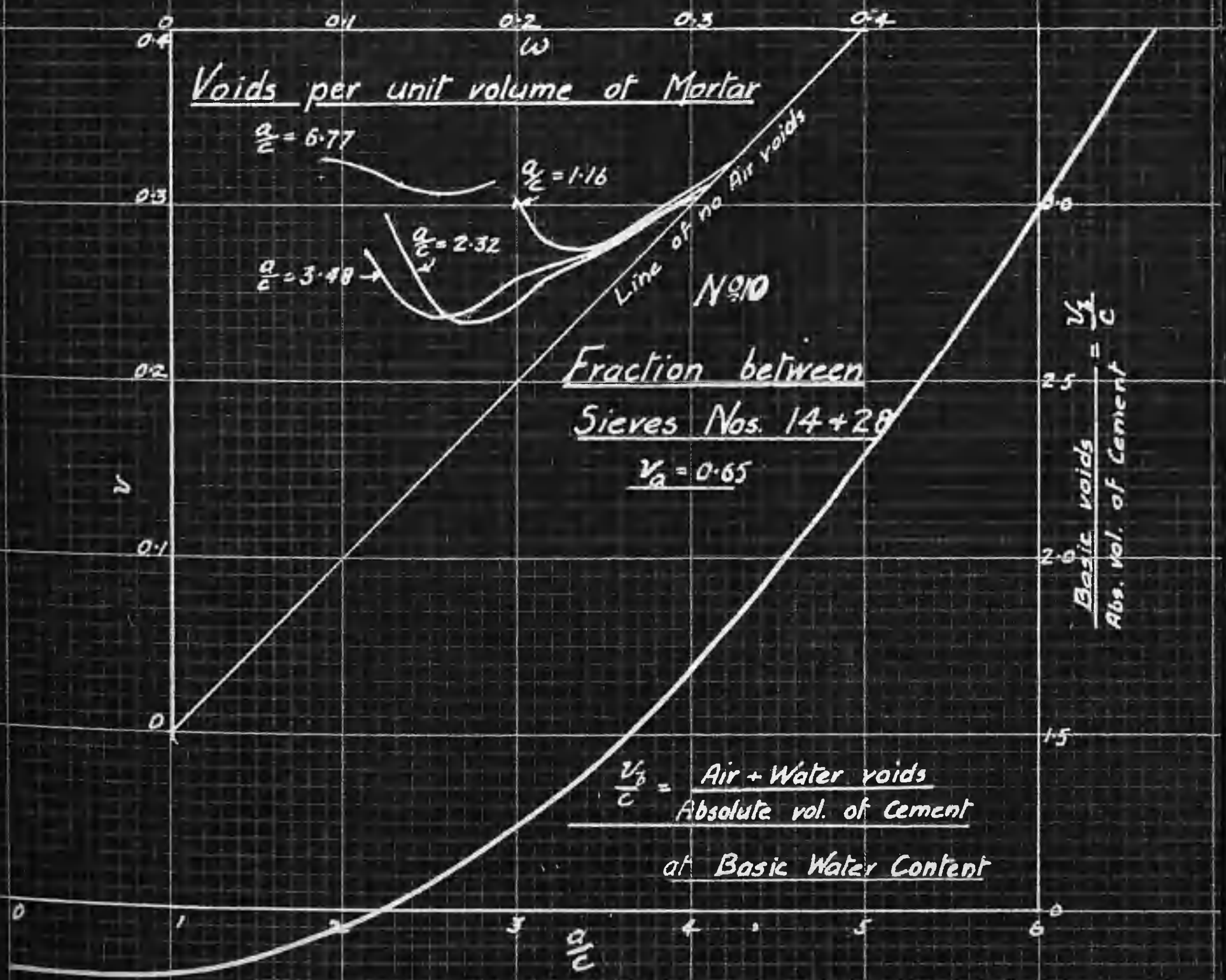


Fig 35

Mortar Voids – Sand A Fractions.

Absolute vol. of sand = a , Vol. of effective water = ω

" " " cement = c , Mortar voids (air + water) = v, do. do. at Basic Water

Dry sand voids = v_a [redacted]

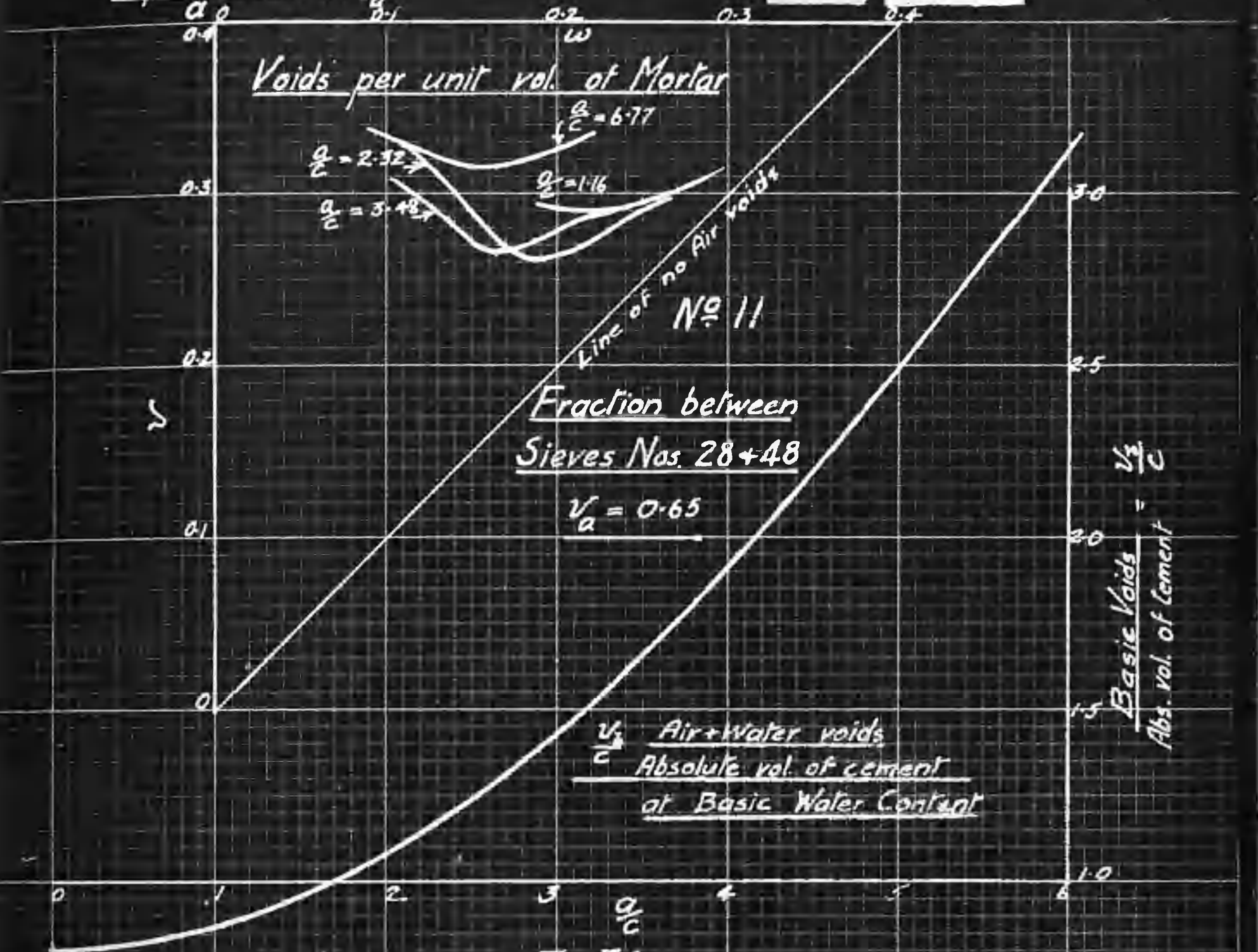


Fig. 36

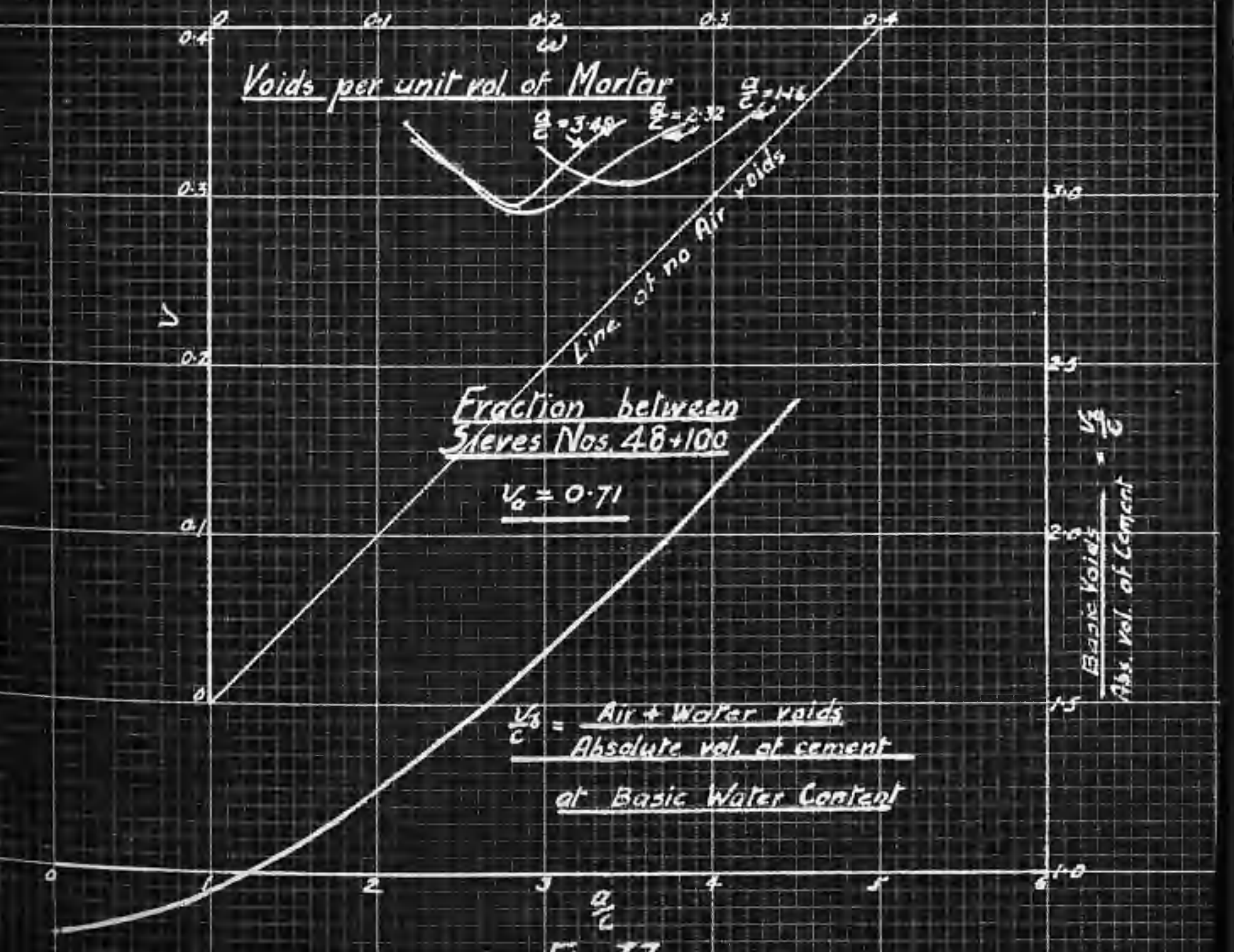


Fig. 37.

Diagram showing the constants b plotted against slopes A of equation $S = A\left(\frac{c}{w} - b\right)$ for mortar strength.

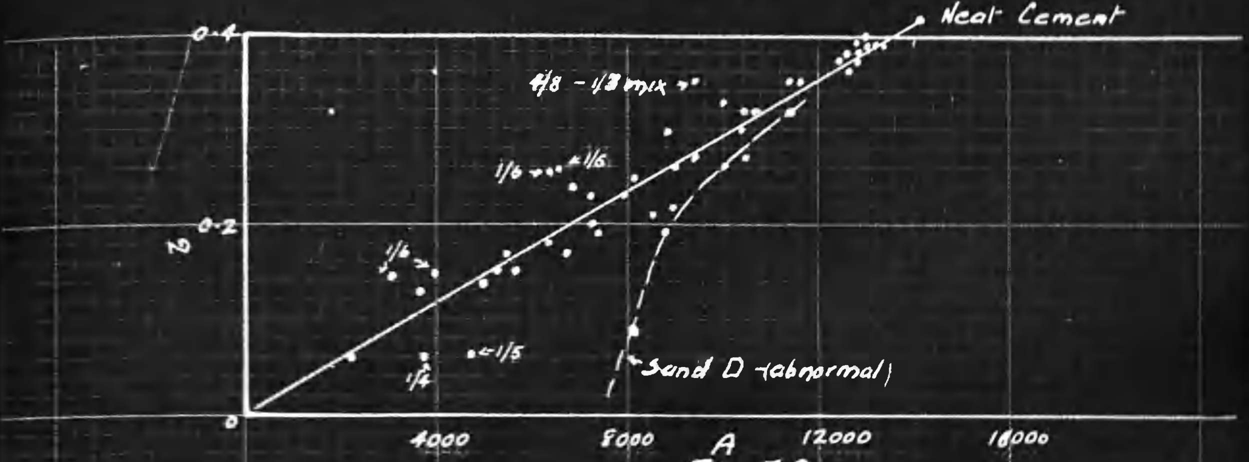
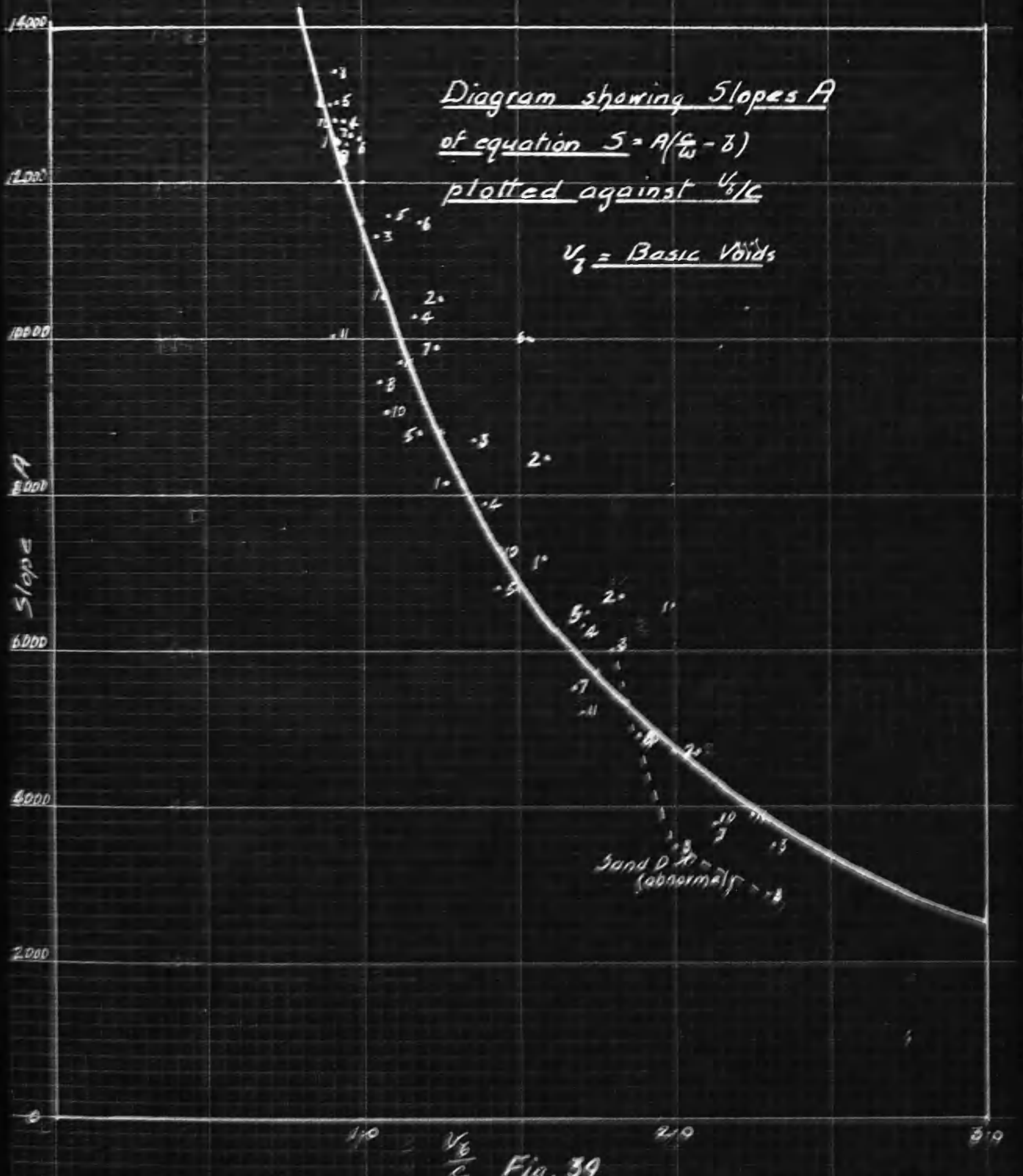


Fig. 38



$\frac{V_b}{c}$ Fig. 39.

Diagram showing volumetric composition of Mortar.

Sand A - 3 to 1 by weight

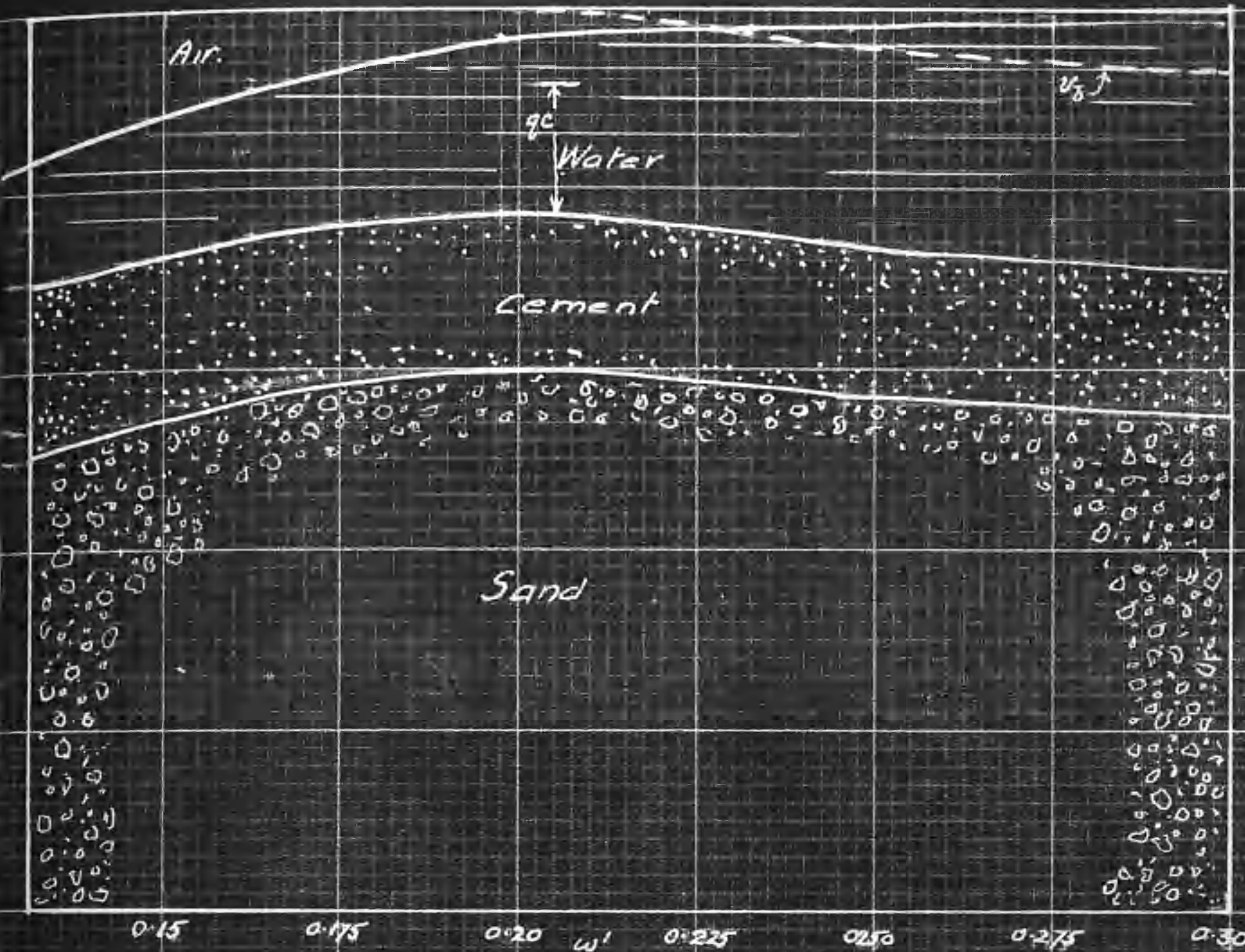


Fig. 40.

Diagram showing averaging curve for $(A - A')\frac{v_3}{c}$ plotted against $\frac{v_3}{c}$

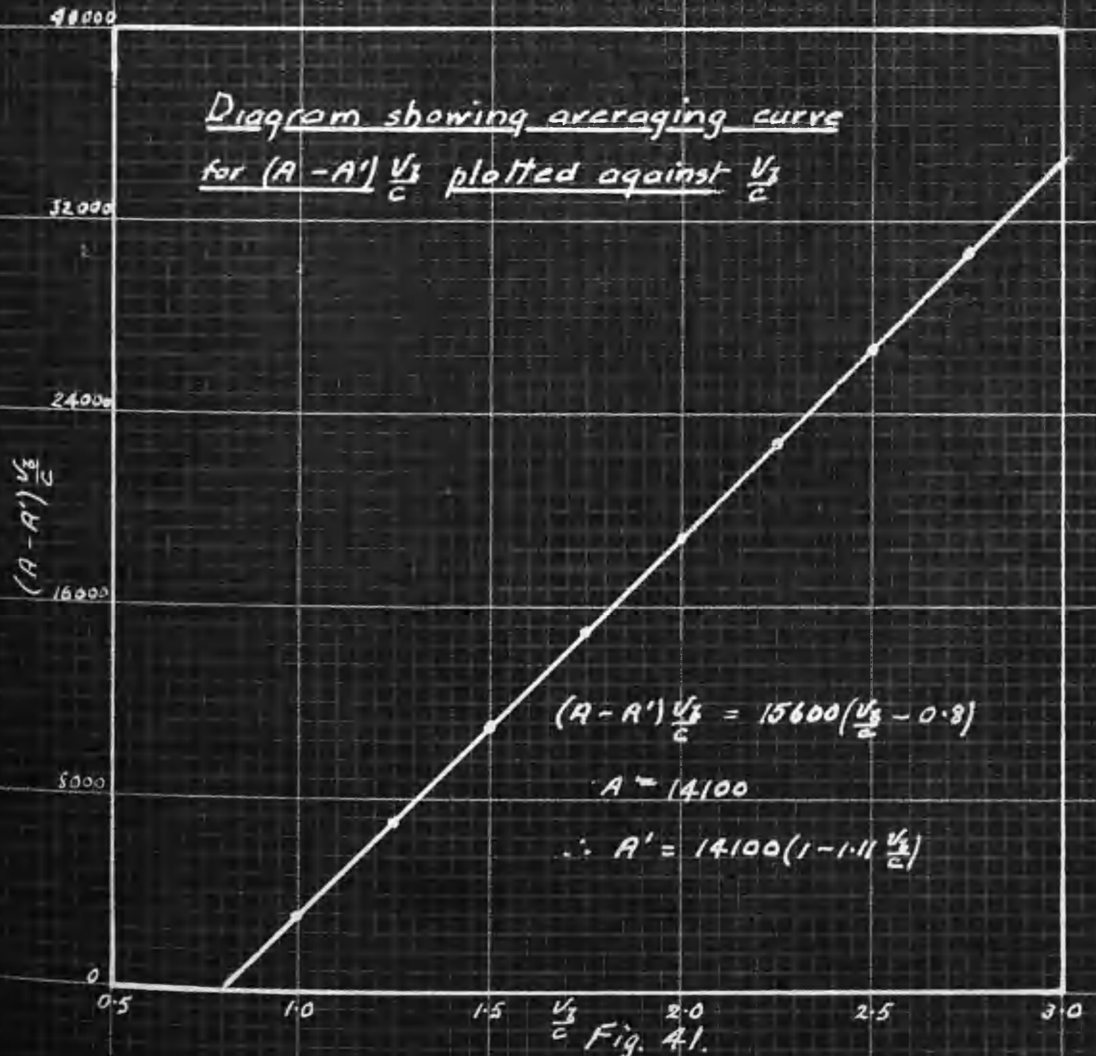


Fig. 41.

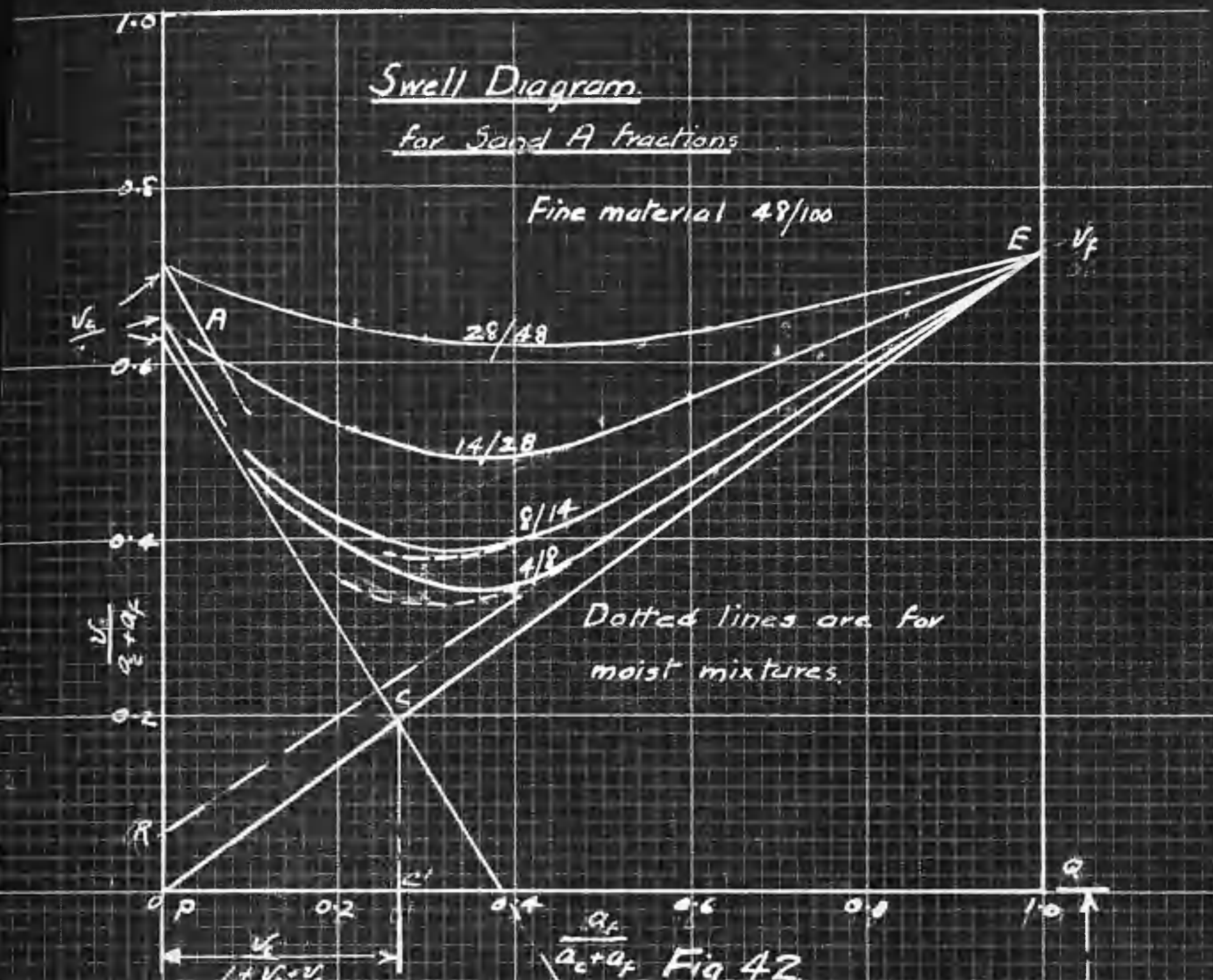

Swell Diagram.
for Sand A fractions
Fine material 48/100
28/48
14/28
8/14
4/8
Dotted lines are for
moist mixtures.
E
A
C
R
P
Q
0.2
0.4
0.6
0.8
1.0

Fig. 42

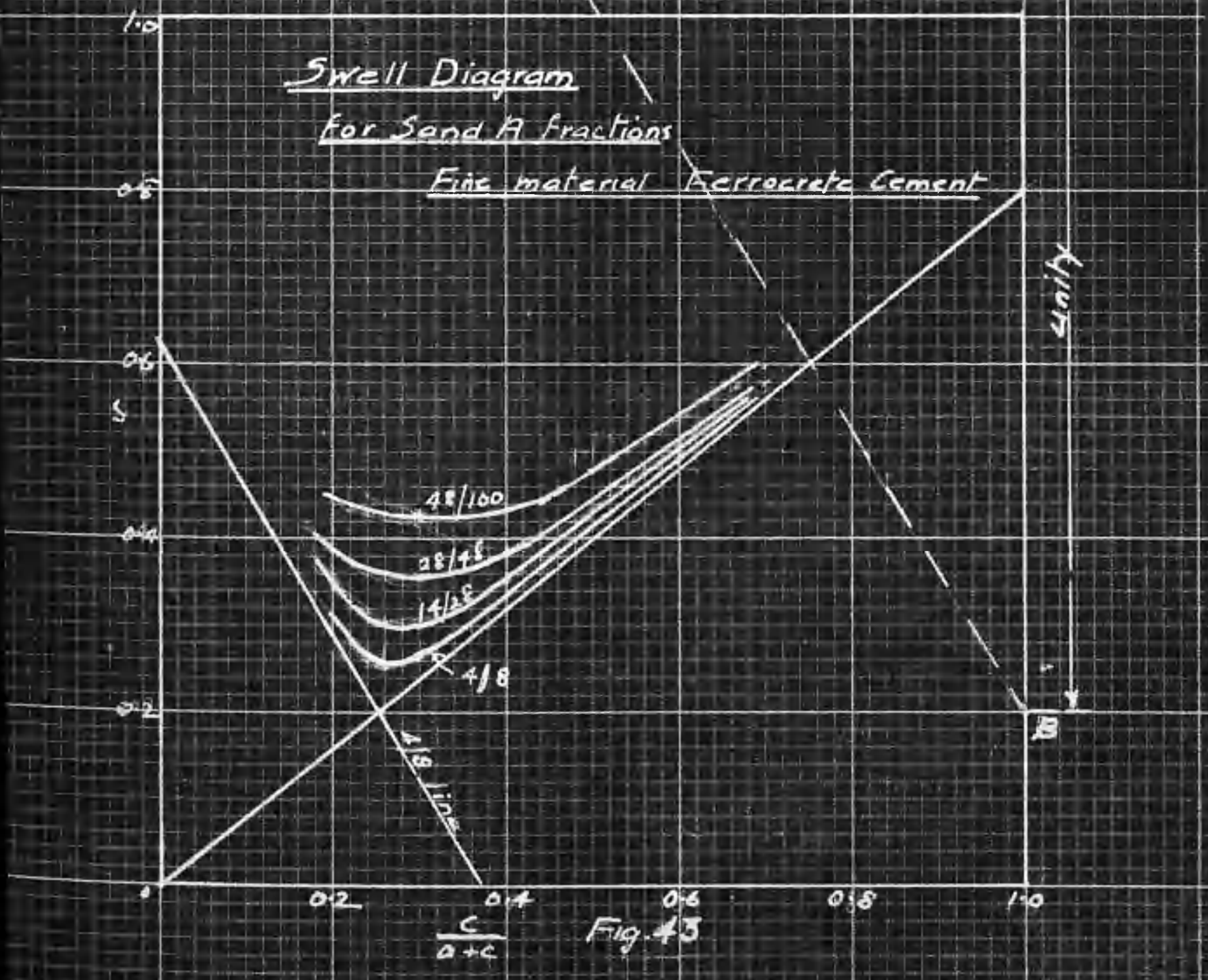

Swell Diagram
for Sand A fractions
Fine material Ferrocrete Cement
48/100
28/48
14/28
4/8
4/8 line
Unity
0.2
0.4
0.6
0.8
1.0

Fig. 43

Determination of Grading Constants for Cement and Sand A Fractions

Fig. 44

Mesh No. 100	48	28	14	8	4
Mean opening d	0·141"	0·071"	0·0351"	0·0174"	0·0088
A = ins² per ins³ = 6/d	42·6	85·8	171	346	684

$$t = mA\frac{d_c}{d_f + d_c}$$

$$\therefore\ 1 + \frac{d_f}{d_c} - m\frac{A}{v} = 0$$

$$\text{i.e.}\ 1 + a d_f - \bar{b} m = 0$$

Data for a = c = 0·5

Fraction	t	A	d_c	a	b
4/8	·006	21·3	·141	7·1	4260
14/28	·02	85·5	·035	28·5	4250
28/48	·04	173	·0174	57·6	4320
48/100	·07	342	·0088	114	4880

a^2	$a\bar{b}$	$\bar{b}^2$	$a \times 1$	$\bar{b} \times 1$
51·6	−30170	$18·1 \times 10^6$	7·1	−4260
813	−121200	$18·05 \times 10^6$	28·5	−4250
3320	−248300	$18·65 \times 10^6$	57·6	−4320
13000	−556700	$23·82 \times 10^6$	114	−4880
Σa^2 17184	$\Sigma a\bar{b}$ = −956,370	$\Sigma \bar{b}^2$ $78·62 \times 10^6$	Σa = 207·2	$\Sigma \bar{b}$ −17,710

Normal Equations

$$17184\, d_f - 956{,}370\, m + 207·2 = 0 \quad \text{---(1)}$$

$$956{,}370\, d_f - 78{,}620{,}000\, m - 17{,}710 = 0 \quad \text{---(2)}$$

$$956{,}370\, d_f + 53{,}200{,}000\, m + 11520 = 0 \quad \text{--(1)} \times \frac{956{,}370}{17{,}184}$$

$$\therefore\ 25{,}420{,}000\, m - 6210 = 0$$

$$m = ·000244$$

Substituting in (1), d_f = ·0017

Typical Voids Curve

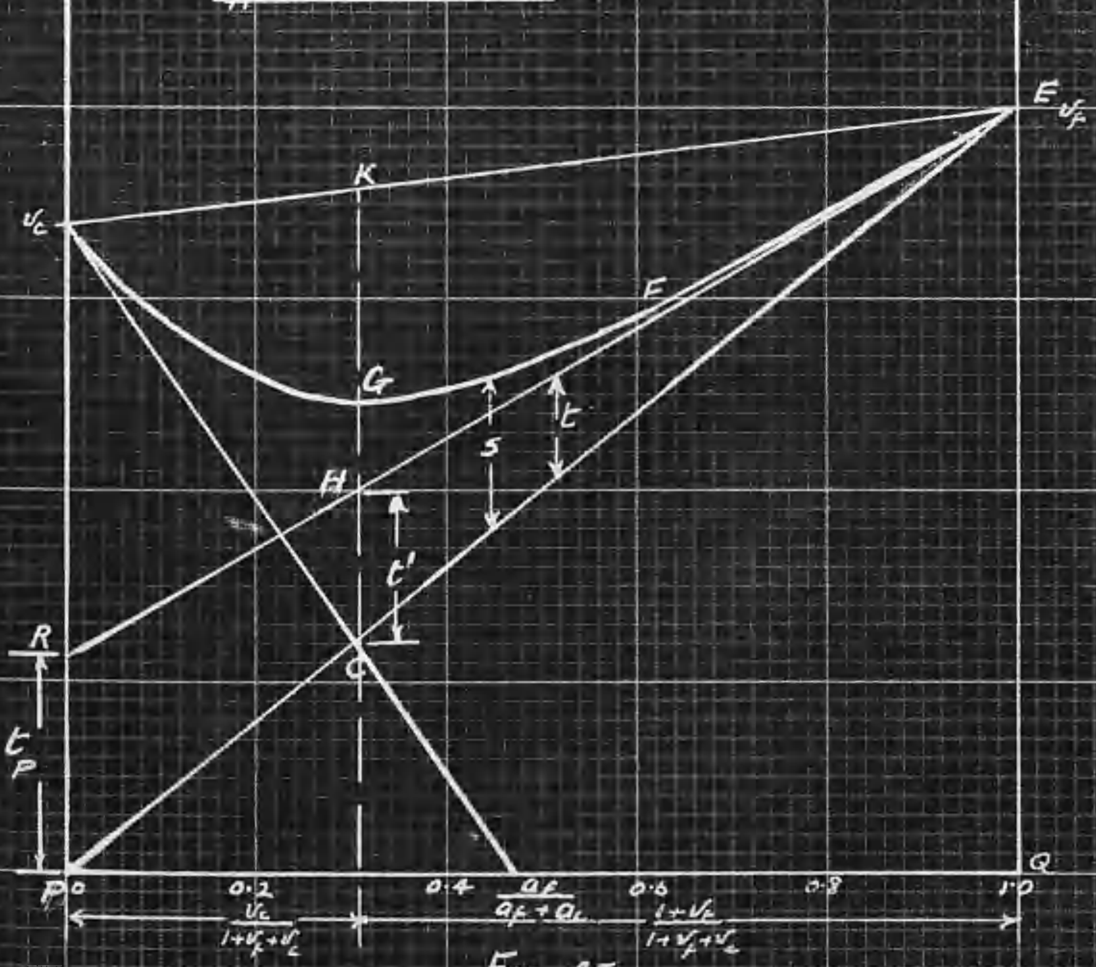


Fig. 45

Table of N values for Tyler Sieve Fractions and examples of estimation of V_b/c.

Sieve No.	N values	W lbs.	N×W	Diam. of Opening ins.	Mean Diam. d_c
$\frac{3}{4}$"				$\frac{3}{4}$ ins :	
	10·7	5·18	55		·56
$\frac{3}{8}$				·375	
	21	4·37	94		·281
4				·187	
	42	3·62	152		·141
8				·094	
	83·5	3·00	250		·0701
14				·047	
	83·5	2·50	404		·0351
28				·0232	
	310	2·08	644		·0174
48				·0117	
	556	1·31	727		·0088
100				·0059	
	950	0·44	417		·0044
		22·5	2743		

Sum of N×W col. will represent 2743 ins^2 of surface area per 22·5 ins^3 of agg. as Sp.Gr. is uniform and W values may be considered as abs. vols. N is (modified) units^2 per unit^3

$\therefore$ N for agg. $= \frac{2743}{22 \cdot 5} = 122$ units^2 per unit^3

Note:- Mean of sieve openings above and below have been taken as d_c for Fraction.

Examples:- Gravel Aggregate – Artificial Grading as given in table. Sp. Gr = 2·63. $V_a = 0{\cdot}316$.

Sp. Gr. of cement taken as 3·05, $V_c = 0{\cdot}8$

Critical agg. proportion $= \frac{1 \cdot 8}{\cdot 316} = 5 \cdot 7 = \frac{a'}{c}$

Mixture 1 – 5 lbs. Cem. to tabular wts. W

$\frac{a}{c} = \frac{22 \cdot 5 \times 3 \cdot 05}{2 \cdot 63 \times 5} = 5 \cdot 22$

$\therefore r = 0 \cdot 917$

$t_p = \cdot 00033 \times 122 = \cdot 043$

$(1 - \frac{\cdot 043}{\cdot 316}) = 0 \cdot 873$

$\frac{V_b}{c} = 0 \cdot 8 + \cdot 043 \times 5 \cdot 22 (1 + 0 \cdot 837 \times 0 \cdot 917^2)$

$= 1 \cdot 188$

$\frac{V_b}{c}$ was measured and found to be 1·10

Mixture 2. – 3 lbs Cem. to tabular wts W.

$\frac{a}{c} = \frac{22 \cdot 5 \times 3 \cdot 05}{2 \cdot 63 \times 3} = 8 \cdot 7$

$r' = \frac{5 \cdot 7}{8 \cdot 7} = 0 \cdot 655$

$\frac{V_b}{c} = 8 \cdot 7 \times \cdot 316 + \cdot 043 \times 5 \cdot 7 \times 1 \cdot 873 \times \cdot 655^2 - 1$

$= 1 \cdot 946.$

$\frac{V_b}{c}$ was measured and found to be 1·77

Fig. 46

Comparison of Estimated and Observed values of $\frac{V_b}{c}$ for Fine Aggregates Figs. 27 to 36

Agg. No.		1	2	3	4	5	7
V_a		0·48	0·60	0·66	0·42	0·38	0·60
N		237	418	461	175	131	423
1/1	$\frac{V_b}{c}$ (Est.)	0·90	0·98	1·04	0·87	0·85	0·98
	(Obs.)	1·00	0·98	1·08	0·84	0·80	0·98
1/2	$\frac{V_b}{c}$ (Est.)	1·04	1·26	1·34	0·96	0·92	1·27
	(Obs.)	1·14	1·25	1·40	0·98	0·91	1·24
1/3	$\frac{V_b}{c}$ (Est.)	1·27	1·63	1·75	1·11	1·02	1·64
	(Obs.)	1·42	1·58	1·84	1·09	1·09	1·58
1/4	$\frac{V_b}{c}$ (Est.)	1·60	2·09	2·35	1·34	1·12	2·09
	(Obs.)	1·75	2·03	2·32	1·30	1·16	2·08
1/5	$\frac{V_b}{c}$ (Est.)	2·10	2·67	–	1·87	1·44	–
	(Obs.)	2·13	2·63	–	1·60	1·42	–

Fig. 47.

Concrete Tests.

Artificially Graded Aggregates – Ferrocrete Cement.

8" × 4" Cylinders at 7 days age – Water cured.

All values means of 3 Tests.

General Grading, $r_g = \dfrac{\text{Vol of Fraction between Sieves Nos } n \text{ and } n+1}{\text{" " " " " } n-1 \text{ and } n}$

Exceptions:- Fractions below Sieve Nº 48 reduced in all cases.

"Calculated Strengths" are obtained from:-

$$S = 14100\,k\left(\frac{c}{w} - 0.42k\right)$$

$$k = 1 - 1.11\frac{e}{V_b} \quad , \quad V_b = \text{Basic voids}$$

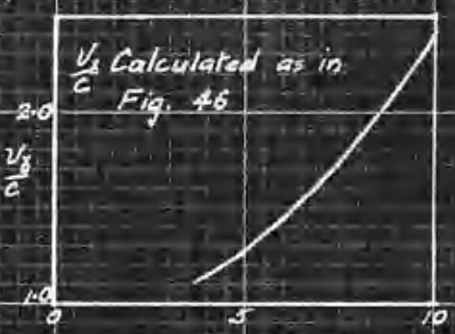
$$e = \frac{V_b}{c} - 0.8$$

w values are corrected for absorption, water in aggregates, and water rejected at the surfaces of the mixtures when placed.

Aggregate Nº 1. $r_g = 1$ $V_a = 0.320$

Sieve Nº	100	48	28	14	8	4	3/8"	3/4"
Fraction	·035	·107	·143	·143	·143	·143	·143	·143

Modified Surface Area Factor $N = 183 \ \frac{ins^2}{ins^3}$ (obtained on data of Fig. 46)



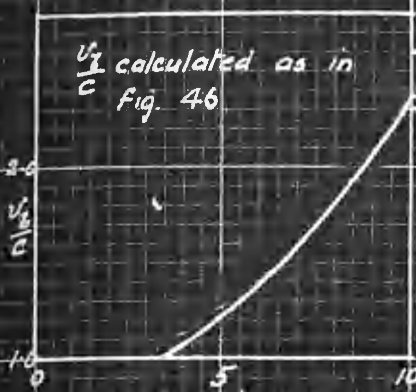
$\frac{a}{c} = \dfrac{\text{Abs. vol of Agg.}}{\text{" " " Cem.}}$

Mix No.	$\frac{\text{Wt. of Agg}}{\text{Wt. of Cem}}$	$\frac{a}{c}$	$\frac{c}{w}$	$\frac{V_b}{c}$	e	$\frac{e}{V_b}$	Calculated Strengths lbs/in²	Observed Strengths lbs/in²	Slump ins	Remarks
1	8·4	9·75	·425	2·30	1·50	0·65	1210	1290	2·0	Rodded - Plastic mix.
2	6·0	6·96	·431	1·66	0·86	0·52	1520	1630	5·0	" Fluid-plastic
3	4·66	5·4	·477	1·37	0·57	0·42	1900	1820	10·0	Poured - Fluid - did not show much evidence of separation
4	6·0	6·96	·575	1·66	0·86	0·52	2370	2530	0·5	Rodded - worked easily
5	4·66	5·4	·57	1·37	0·57	0·42	2620	2750	3·0	" "
6	3·82	4·45	·59	1·12	0·29	0·29	2920	2850	6·0	Lightly rodded - semi-fluid.

Fig. 48

Aggregate No. 2

$r_g = 1{\cdot}1$, $V_a = 0{\cdot}315$



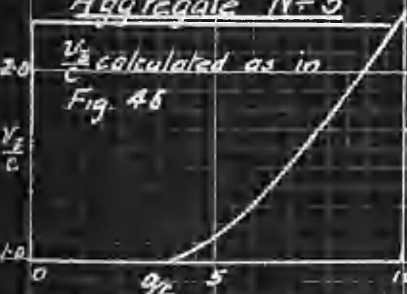
Sieve No.	100	48	24	14	8	4	3/8"	3/4"
Fraction	·024	·068	·118	·130	·142	·157	·172	·189

Modified Surface Area Factor $N = 145 \frac{ins^2}{ins^3}$

Mix No	Wt. of Agg / Wt. of Cem	$\frac{a}{c}$	$\frac{c}{w}$	$\frac{V_s}{c}$	k	Calculated Strength lbs/ins²	Observed Strength lbs/ins²	Slump ins.	Remarks
8	6·86	8·0	·435	1·75	·40	1500	1540	4·5	Rodded - placed well
9	5·87	6·8	·438	1·50	·482	1610	1650	6·0	Rodded lightly - no apparent separation
10	5·13	6·0	·443	1·37	·538	1650	1620	8·0	Poured
11	5·87	6·8	·567	1·50	·482	2470	2780	0·5	Rodded fairly easily
12	5·13	6·0	·570	1·37	·538	2620	2730	1·5	"
13	4·57	5·32	·576	1·27	·582	2720	2710	4·0	" - no separation
14	3·74	4·35	·59	1·11	·69	2920	3070	7½	Rodded lightly - fines showed tendency to rise
16	4·57	5·32	·66	1·27	·582	3300	3480	0·5	Rodded fairly easily
17	3·74	4·35	·67	1·11	·69	3640	3700	3·0	Rodded
7	9·12	10·6	·422	2·42	·26	1150	1480	0	Rammed - very stiff
15	5·13	6·0	·66	1·37	·538	3180	3500	0	" stiff

Aggregate No. 3

$r_g = 1{\cdot}2$ $V_a = 0{\cdot}316$



Sieve No.	100	48	24	14	8	4	3/8"	3/4"
Fraction	·019	·059	·092	·111	·134	·161	·194	·230

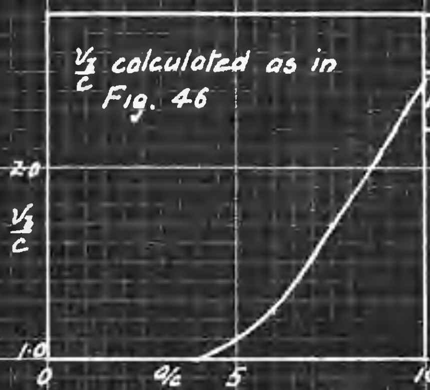
Modified Surface Area Factor $N = 122 \frac{ins^2}{ins^3}$

Mix No.	Wt. of Agg. / Wt. of Cem.	$\frac{a}{c}$	$\frac{c}{w}$	$\frac{V_s}{c}$	K	Calculated Strength lbs/ins²	Observed Strength lbs/ins²	Slump ins	Remarks.
18	9·0	10·4	·420	2·40	·26	1140	1505	0	Rammed - very stiff
19	7·5	8·81	·443	2·02	·328	1410	1465	0·25	Rodded - harsh mix.
20	6·42	7·47	·427	1·64	·43	1500	1260	6*	Rodded - sloppy mix. * collapse
22	5·62	6·54	·582	1·41	·52	2670	2530	2·5	Rodded - placed well
23	4·5	5·23	·582	1·16	·656	2840	2840	5½	Poured - tendency to collapse in slump mould
25	4·5	5·23	·697	1·16	·656	3820	3920	1¼	Rodded
26	3·75	4·35	·692	1·06	·73	3970	3940	3·5	Rodded - placed well
21	7·5	8·81	·55	2·02	·328	1900	2480	0	Rammed - very stiff
24	5·62	6·54	·667	1·41	·52	3300	4030	0	Rammed - stiff

Fig. 49

Aggregate No 4

$r_g = 1{\cdot}3$, $V_a = 0{\cdot}334$



Sieve No	100	48	25	14	8	4	3/8"	3/4"
Fraction	·014	·043	·074	·097	·125	·164	·210	·273

Modified Surface Area N = 100 $\frac{ins^2}{ins^3}$

Mix. No.	Wt. of Agg. / Wt. of Cem.	$\frac{a}{c}$	$\frac{c}{w}$	$\frac{V_a}{c}$	k	Calculated Strength lbs/ins²	Observed Strength lbs/ins²	Slump ins²	Remarks
27	5·48	6·36	·43	1·36	·548	1100	1110	6·0	Rodded - harsh
28	7·31	8·5	·42	2·00	·34	942	1020	·75	" - harsh
30	5·48	6·36	·567	1·36	·548	2610	2800	·25	" - harsh.
31	4·38	5·1	·58	1·10	·70	2820	2910	2·0	"
33	4·38	5·1	·68	1·10	·70	3820	4120	0·5	Rodded - placed easily
34	3·65	4·23	·71	1·00	·725	4150	4020	3·0	" "
29	7·31	8·5	·55	2·00	·34	1950	2700	0	Rammed in 1" layers. very stiff
32	5·48	6·36	·66	1·36	·548	3300	4340	0	Rammed in 1" layers very stiff

Aggregate No 5 Interrupted Grading

Sieve No	100	48	25	14	8	4	3/8"	3/4"
Fraction	·014	·043	·074	·097	·125	·164	·210	·273

Modified Surface Area N = 122

Mix. No	Wt of Agg. / Wt of Cem.	$\frac{a}{c}$	$\frac{c}{w}$	$\frac{V_a}{c}$	K	Calculated Strength lbs/ins²	Observed Strength lbs/ins²	Slump ins	Remarks
35	5·94	6·96	·567	1·19	·563	2620	3090	0	Rammed - stiff
36	4·74	5·5	·582	1·10	·665	2840	2820	4"	Rodded

Fig. 50

Granite – Sand A Concretes – Ferrocrete Cement.

8" × 4" Cylinders at 7 days – Water Cured. (each value mean of 3 tests)

Concretes of Water-ratios about 0·5 by weight.

First Group – No evidence of Particle Interference.

Mix Nº	Aggregate Fractions by Weights: I	II	Sand	Wt of Agg. / Wt of Cem.	$\frac{a}{c}$	$\frac{c}{w}$	$\frac{V_c}{c}$	k	Calculated Strengths lbs/ins²	Observed Strengths lbs/ins²	V_a	N	Remarks.
37	·27	·23	·50	5·2	6·02	·731	1·33	·555	3900	4030	·35	96	Rodded – stiff mix no slump
38	"	"	"	4·0	4·66	·73	1·06	·73	4460	4340	"	"	1½" Slump – Rodded
39	"	"	"	3·15	3·66	·733	·87	·81	4500	4320	"	"	2½" Slump "
40	"	"	"	2·5	2·92	·718	·92	·86	4310	4260	"	"	6½" " " no marked segreg.
41	·36	·24	·40	5·55	6·47	·735	1·75	·40	3160	4100	·41	81	No slump – Rammed in 1" layers
42	"	"	"	4·54	5·30	·727	1·32	·56	3900	4020	"	"	¼" slump – Rodded
43	"	"	"	3·85	4·48	·732	1·05	·73	4530	4700	"	"	¾" " "
44	"	"	"	3·33	3·88	·740	0·98	·80	4560	4540	"	"	2" " "
45	"	"	"	2·5	2·91	·723	0·91	·87	4430	4420	"	"	6" " "
46	"	"	"	4·6	5·36	·66	1·38	·53	3280	3400	"	"	1" " "

These mixes show in general good correspondence with formula

Nº 41 shows the usual high value at strength of stiff rammed mixes

Second Group – Showing evidence of Particle Interference.

47	·67	—	·33	4·8	5·6	·72	1·86	·56	2940	3540	·50	61	No slump Rammed in 1" layers
48	"		"	4·0	4·66	·71	1·41	·68	4060	3440	"	"	Harsh – Rodded Stuck in slump mould
49	"		"	3·55	4·13	·71	1·17	·65	4100	3500	"	"	5" Collapse Rodded
50	·42	·08	·5	4·8	5·6	·74	1·06	·73	4450	4700	·34	94	No slump – rodded with difficulty
51	"	"	"	4·0	4·67	·72	1·06	·73	4250	4060	"	"	1½" Slump – rodded
52	"	"	"	2·75	3·2	·71	·94	·84	4100	3340	"	"	6" collapse "
53	·44	·14	·42	5·56	6·47	·73	1·75	·40	3180	3866	·41	80	No slump – Rammed
54	"	"	"	4·54	5·3	·74	1·33	·56	4060	3920	"	"	¾" slump Rodded
55	"	"	"	3·75	4·37	·74	1·01	·77	4530	3750	"	"	1½" slump "
56	"	"	"	2·5	2·91	·73	·91	·87	4500	3300	"	"	6½" Collapse "

Rammed mixes show the usual high values.
Grading indicates particle interference and the results at the higher paste contents indicate that some additional factor, such as this, is operative.

Fig. 51.

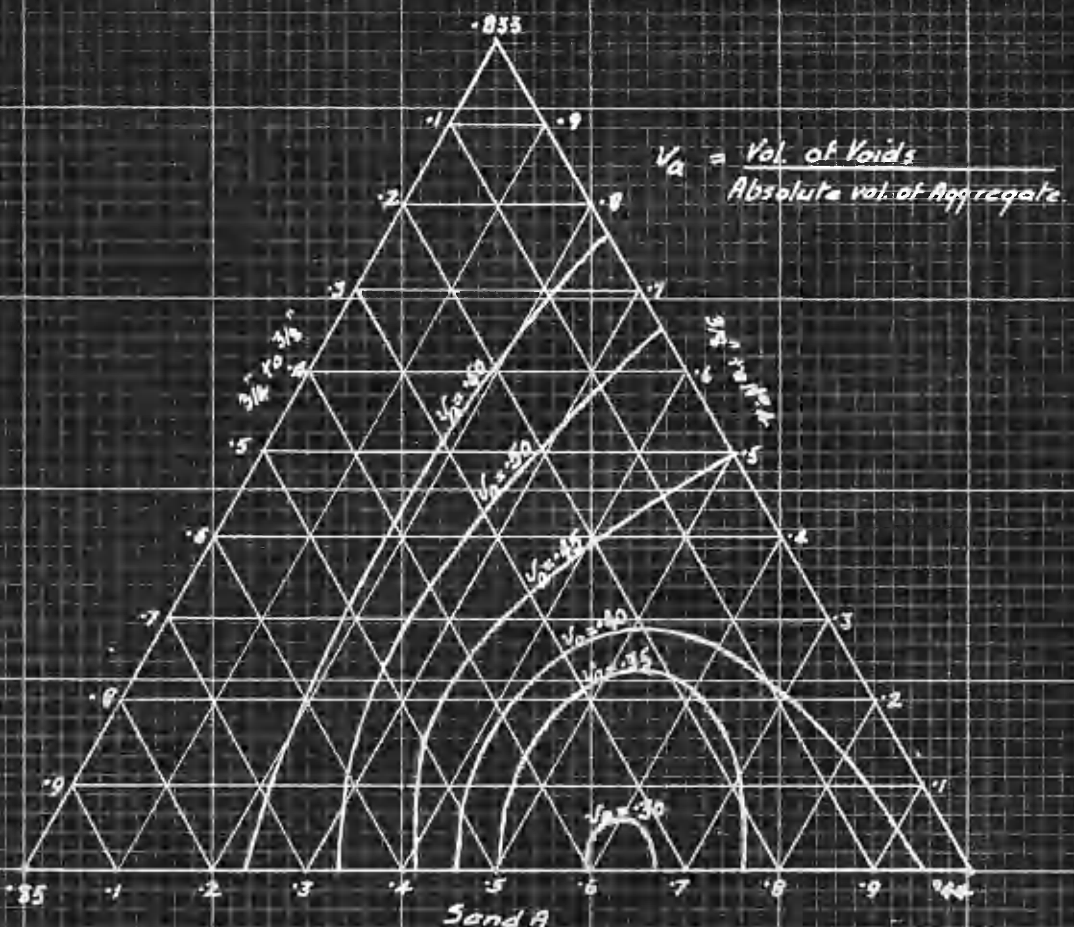
Details of Aggregates for Concretes No 37 to No 78

Materials.

1. – 3/4" to 3/8" Crushed Granite. Sp Gr 2·60, $N = 15 \frac{ins^2}{ins^3}$
2. – 3/8" to No 4 " " " " $N = 30 \frac{ins^2}{ins^3}$
3. – Sand A, Sp. Gr. 2·63, $N = 171 \frac{ins^2}{ins^3}$

(The sand was screened thro' No 4 Sieve)

Diagram showing Voids in Mixed Aggregates.



In the following tables Basic Voids V_b are calculated by the methods given in Fig. 46.

Calculated Strengths are obtained from the formula

$$S = 14100\,K\left(\frac{c}{w} - \cdot 42\,K\right)$$

Fig 51A

Granite – Sand A Concretes. Ferrocrete Cement.

8" × 4" Cylinders at 7 days – Water Cured (each value mean of 3 tests)

Concretes of Water-ratios about 0·6 by weight

First Group – No evidence of Particle Interference.

Mix. Nº	Aggregate Fractions by Weight 1	2	Sand	Wt. of Agg. / Wt. of Cem.	V_a	N	$\frac{a}{c}$	$\frac{c}{w}$	$\frac{V_f}{c}$	k	Calculated Strength lbs/ins²	Observed Strength	Remarks
57	·18	·20	·62	5·78	·35	1.14	6·75	·612	1·57	·46	2710	2760	No slump. Rodded
58	"	"	"	4·73	"	"	5·51	·612	1·25	·60	3040	2720	2" plastic slump – Rodded
59	"	"	"	4·0	"	"	4·67	·600	1·11	·70	3040	3130	5" slump "
60	·25	·25	·50	6·78	·35	97	6·73	·62	1·54	·47	2770	2630	No slump – roddable
61	"	"	"	4·53	"	"	5·29	·61	1·09	·70	3140	3200	4" slump – slow plastic collapse.
62	·31	·31	·38	4·8	·44	78	5·6	·59	1·57	·46	2610	2650	¼" slump – rodded.
63	"	"	"	4·0	"	"	4·67	·61	1·21	·624	3020	2750	5" collapse – poured with rodding
64	·32	·32	·36	5·55	·46	72	6·16	·40	1·90	·38	2260	2130	No slump – roddable.
	Second Group – evidences of Particle Interference.												
65	·50	—	·50	6·0	·35	93	7·0	·55	1·61	·44	2240	2040	2" slump
66	"		"	4·8	"	"	5·6	·55	1·22	·62	2540	2140	5" "
67	"		"	4·0	"	"	4·7	·57	1·05	·74	2710	2600	8" "
68	·33	·33	·34	6·0	·47	72	7·0	·55	2·43	·26	1600	1300	No slump – rodded
69	"	"	"	4·8	"	"	5·6	·57	1·85	·37	2160	1540	5" collapse
70	·67	—	·33	6·0	·50	61	7·0	·54	2·69	·22	1390	1430	No slump – harsh – wet mortar.
71	"		"	4·8	"	"	5·6	·56	1·86	·37	2100	1450	Collapse with escape of water

Concretes of Water-Ratios about 0·8 by weight.

Mix. Nº	Aggregate Fractions by Weight 1	2	Sand	Wt. of Agg / Wt. of Cem	V_a	N	$\frac{a}{c}$	$\frac{c}{w}$	$\frac{V_f}{c}$	k	Calculated Strength lbs/ins²	Observed Strength lbs/ins²	Remarks.
72	·5·0	–	·5·0	9·6	·35	93	11·2	·42	2·98	·19	910	1020	¼" slump – rodded
73	·38	–	·62	8·76	·31	111	10·1	·43	2·17	·30	1270	1110	¼" " "
74	"		"	6·5	"	"	7·57	·43	1·53	·47	1570	1010	4½" " sloppy
75	"		"	4·85	"	"	5·65	·44	1·11	·69	1450	1290	8" collapse – poured
76	·31	·31	·38	7·71	·43	80	9·00	·47	2·94	·19	1050	1150	5" slump – rodded
77	·25	·25	·50	8·0	·35	97	9·32	·46	2·36	·27	1290	1221	Harsh – no slump – placed ~~placed~~ with thorough rodding
78	·125	·125	·75	5·32	·38	134	6·2	·47	1·59	·45	1780	1830	6" Plastic collapse.

Sand A did not contain enough fine material to be suitable for water-ratio 0·8

Nº 78 was the only mixture which showed reasonably good working characteristics.

Fig. 52

Granite - Sands A + C Concretes. - Ferrocrete Cement.

8" × 4" Cylinders at 7 Days - Water Cured (all values means of 3 tests)

Additional Materials No 3 - No 4 to No 8 crushed Granite.

Sand C. Screened on No 4 Sieve (except mixture No 93)

Mix No	Aggregate Fractions by Weight 1	2	3	Sand A	Sand C	Wt of Agg / Wt of Cem	V_a	N	a/c	c/w	V_a/c	K	Calculated Strength lbs/ins²	Observed Strength lbs/ins²	Remarks.
79	·38	·19	·10	—	·33	4·2	·35	142	4·89	·73	1·21	·63	4100	4217	1/8" slump Rodded
80	"	"	"		"	3·23	"	"	3·76	·72	1·06	·73	4150	4120	3" " "
81	·67	–	—	—	·33	6·0	·41	135	7·00	·55	2·07	·32	1880	2020	1" slump.
82	"				"	4·8	"	"	6·32	·56	1·43	·51	2500	2110	5" collapse
83	·33	·33			·34	6·0	·35	140	7·0	·55	1·69	·42	2200	1890	1" slump
84	"	"			"	4·8	"	"	5·32	·55	1·28	·59	2510	2140	4" "
85	·25	·25		·31	·19	5·77	·32	136	6·72	·63	1·48	·49	2900	3430	No slump - rammed in 1" layers.
86	25	·17		·38	·20	5·33	·33	151	6·22	·61	1·20	·63	3050	2850	3/4" slump
87	"	"		"	"	4·8	"	"	5·6	·61	1·33	·56	2980	3340	2" "
88	"	"		"	"	3·7	"	"	4·31	·61	1·13	·68	3110	3000	7½" "
89	·25	·25		·33	·17	4·9	·33	129	5·7	·62	1·28	·58	3070	3183	1¾" "
90	·67				·33	6·4	·41	135	7·40	·43	2·10	·32	1880	2020	
91	"				"	8·0	·41	"	9·32	·43	2·90	·196	957	990	
92	"				"	9·6	"	"	11·2	·43	3·63	·135	706	980	No slump
93	·25	·25		·35	·17	8·0	·35	115	9·32	·47	2·37	·264	1330	1210	1" slump
94	·31	·30		·19	·20	6·93	·37	119	8·07	·45	1·97	·34	1530	1420	1/4" "
95	·23	·23		·27	·27	6·5	·31	158	7·58	·46	1·69	·42	1710	1870	1½" "
96	·11	·11	·11	·67	—	6·0	·34	123	7·0	·47	1·61	·44	1750	1810	1½" "
97	·19	·12	·08	·61	–	6·51	·28	116	7·6	·43	1·12	·69	1350	1240	1¼" "
98	"	"	"	"	–	8·76	"	"	10·1	·42	1·98	·34	1320	1310	No slump
99	·25	–	·25	·50	–	9·61	·33	104	11·2	·44	2·78	·21	1050	1010	1" "
100	"		"	"	–	8·00	"	"	9·33	·42	2·19	·30	1230	1150	No slump.

Fig. 53.

Consistence and Water

Continuous Gradings

$r_g = 1{\cdot}0$			$r_g = 1{\cdot}1$			$r_g = 1{\cdot}2$			$r_g = 1{\cdot}3$		
Mix.	w/v_g	Slump ins.	Mix	w/v_g	Slump ins.	Mix	w/v_g	Slump ins.	Mix	w/v_g	Slump ins.
1	1·00	2·0	8	1·32	4·5	18	0·91	0	27	1·7	6·0
2	1·39	5·0	9	1·52	6·0	19	1·11	0·25	28	1·19	0·7
3	1·53	10·0 coll.	10	1·65	8·0	20	1·43	6·0	30	1·30	0·3
4	1·05	0·5	11	1·17	0·5	22	1·22	2·5	31	1·57	4·0
5	1·28	3·0	12	1·28	1·5	23	1·48	5·5	33	1·35	1·5
6	1·53	6·0	13	1·37	4·0	24	1·23	7·3	34	1·41	3·0
			14	1·53	7·5	25	1·36	3·5	29	0·9	0
			15	1·10	0	21	0·89	0	32	1·1	0
			16	1·19	0·5	22	1·05	0			
			17	1·32	3·0						
			7	0·98	8						

Miscellaneous Gradings

Mix	w/v_g	Slump ins.	Mix.	w/v_g	Slump ins.	Mix.	w/v_g	Slump ins.	Mix.	w/v_g	Slump ins.
37	1·03	0	51	1·31	1·5	65	1·13	2·0	79	1·15	0·2
38	1·29	1·5	52	1·50	6·0	66	1·49	5·0	80	1·31	3·0
39	1·40	2·5	53	0·78	0	67	1·67	8·0	81	0·88	1·0
40	1·51	6·5	54	1·01	0·7	68	0·75	0	82	1·22	5·0
41	·78	0	55	1·34	1·5	69	0·95	coll.	83	1·07	1·0
42	1·04	0·3	56	1·50	6·5	70	0·69	0	84	1·42	4·0
43	1·30	0·8	57	1·04	0	71	0·96	coll.	85	1·07	0
44	1·38	2·0	58	1·32	2·0	72	0·8	0·2	86	1·37	0·8
45	1·52	6·0	59	1·50	5·0	73	1·07	0·2	87	1·23	2·0
46	1·10	1·0	60	1·05	0	74	1·51	4·5	88	1·45	7·5
47	0·75	0	61	1·50	4·0	75	2·05	8·0	89	1·26	1·7
48	1·0	0	62	1·08	0·2	76	0·73	5·0	92	0·64	0
49	1·20	5·0	63	1·35	5·0	77	0·95	0	93	0·91	1·0
50	1·27	0	64	0·88	0	78	1·34	6·0	94	1·10	0·2

Fig. 54.