UNIVERSITY OF CAPE TOWN.

THE WORKABILITY AND PROPORTIONING OF CONCRETE.

A THESIS

BY

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SUMMARY.

PART I.

Chapters 1 and 2: The thesis commences, after a brief introduction, with a review of progress in concrete technology from about the end of the first half of the 19th century to date. The trend of practice is indicated as a background to the present work.

PART II.

Chapter 3: Working definitions for the terms workability, consistency, plasticity, cohesion, segregation, placeability, are developed from a full discussion of many controversial points. The lack of uniformity of definition of some terms, notably "workability", is stressed.

Chapter 4: The difficulties of assessing quantitatively the various properties of concrete are discussed and this chapter is devoted to the measurement of these characteristics. A list of nearly 40 different tests is given and many of them are described and discussed.

A device evolved by the Author, termed the "Pressure Test Apparatus" or "PTA" is introduced. With this machine, the pressures required to deflect a concrete disc under certain conditions are observed. The apparatus can be used throughout the entire range of mixtures, no matter how wet or dry, and aggregate up to about 2½ins. has been found to have little effect on the reliability of the results. The apparatus is simple and portable and can readily be used for field design and control.

The Author experimented with the following apparatus:-
Standard Slump Test, ASTM flow test, Powers' remoulding test, Burmister's flow trough, Standard compacting factor test, pressure test.

The tests are compared, where applicable, in the light of experimental results and an attempt is made to describe the

properties/...

properties actually measured in each case.

<u>Chapter 5:</u> The flow characteristics of pastes, mortars and concretes and the concepts of viscous and plastic flow are discussed, bringing out the significance of the yield value possessed by plastic materials.

The theories of the structure of suspensions, and of mortars and concretes in particular are set forth, to provide the basis for an exposition on plastic flow. The theory includes ideas on the interaction of forces, yield value, plastic limit, dilatancy. Certain ~~characteristics~~ characteristic pressure test curves are interpreted in terms of the theory.

To sum up, plastic concrete contains various sized particles of solid phase, each size group forming a system containing voids enclosing smaller particles, the whole being dispersed in the continuous body of water and all solid particles or groups of particles having a certain freedom of movement. An unworkable concrete, on the other hand, has a rigid structure of solid particles, locked together.

<u>Chapter 6:</u> The factors influencing workability are considered in a more practical light, bearing in mind that the study of workability involves far more than plasticity. The interplay of the effects of quantity, consistency and plasticity of the cement paste and maximum size, gradation, type and angularity of aggregate particles is treated. The effects of various powdered admixtures are considered and the uses of air entraining and dispersing agents are mentioned.

The remainder of the chapter is devoted to consideration of the aggregates in view of their bearing on economy and influence on the properties of the concrete both before and after setting. It is shown how adequate workability can be assured by scientific design where an arbitrary mix may be harsh and unworkable with the particular aggregates available. The selection of the best overall grading for the materials available is explained in terms of separate coarse and fine aggregate gradings and the

best/...

best proportion in which to combine them for a particular cement and water content.

PART 111.

Chapter 7: The practical application of the foregoing research gives purpose to design. The properties desired, workability in the freshly mixed mass, homogeneity in the placed concrete, water-tightness, durability, low volume change and necessary strength in the hardened state, can be achieved by scientific design and control.

The selection of a suitable water-cement ratio, as required for strength and durability, is the first consideration. Design procedures for both laboratory and field are outlined, which depend on the systematic variation of materials. The pressure test is used to provide quantitative assessments of plastic properties which are used in conjunction with the operator's systematic visual observation in deciding the mix.

The importance of control is stressed.

The design of a typical concrete is given as an illustration.

Chapter 8: The problem of specifying concrete to ensure that it will possess the desired properties is tackled. The specification of strength, testing, rigid control and workability is discussed and suggestions made.

There are two courses open in draftinga specification:-

(1) The contractor may be required to adopt the concrete mix designed by the engineer, or

(11) The onus may be placed on the contractor to design a concrete complying with certain requirements, such as strength and workability.

The implications of the two types and the circumstances favouring their use are stated.

The draft of a full specification for structural concrete completes the chapter.

Appendices deal with aspects of moisture control, laboratory procedure and aconomy. Experimental data and results have also been grouped in an appendix.

There are illustrations, tables and diagrams.

P R E F A C E.

The work embodied in this thesis was begun in July, 1946 on a part-time basis. It was undertaken in the first instance in an attempt to correlate and apply some of the many theories reported in current literature.

The Author, a practising municipal engineer was anxious to find a rapid and simple means of designing a concrete and controlling its manufacture.

In South Africa it is still the usual practice, even on large works, to specify concrete by arbitrary proportions, with a complete disregard for local conditions, resources and economy. In general no control is exercised in the manufacture of the concrete. To combat this state of affairs, the practising engineer needs a simple easily understandable and readily applied system of specification, design and control.

The experimental work was carried out in the Concrete Testing Laboratory, Civil Engineering Dept, University of Cape Town.

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A brief illustration using a particular case.

PART I.

CHAPTER I. INTRODUCTION.

Much research has been devoted to the problems involved in the economical design of concrete for various types of structures; but it is not always easy to apply the theories and philosophies which have been evolved.

The study of the behaviour of fresh concrete, which covers a large field, has provided much controversial matter because of the difficulty of testing and the lack of uniform definition. There is at present no uniformity of definition regarding the various properties exhibited by fresh concrete and it must be inferred from certain writings that some investigators are not quite sure what physical properties they are trying to assess.

Arising in large measure out of this uncertainty, there are conflicting theories concerning the effects of aggregate grading, particle size and shape, the behaviour of fine particles, etc, on the observed characteristics of the concrete. Various mathematical methods have been adopted with the object of calculating the best proportions in any particular case. These schemes have included attempts to obtain the least cement content, minimum voids, maximum density, minimum surface area, maximum workability. Any method of design which entails a theoretical consideration of the component materials, will suffer from the disadvantage that even though the reasoning may be fundamentally sound, ideal conditions rarely pertain in practice. The service qualities required of the concrete will usually govern the water-cement ratio and this alone will upset many of these methods. Again, in order to make economical use of local materials and maintain the necessary workability for the particular job, proportions may be required which vary considerably from the theoretical. It can be demonstrated too, that high quality concrete can be produced of proportions which do not satisfy many

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of the theoretical requirements of grading, density, etc, so long as the water cement ratio is within the limits required and the concrete possesses adequate workability.

Investigations have always been hampered by the lack of adequate devices for measuring the properties of fresh concrete. The gauging of a property, whether consistency, plasticity, segregation or any other, is a complex problem due to the extremely wide variety of types of the materials used and to the endless variations in the characteristics and proportions of these materials.

Whilst it is possible to assess one or other of the properties, such as consistency, by a single test procedure, it is not possible to gauge workability by a single observation or by any single test whatever and no method has been devised for determining a "workability index" or measurement of relative workability which works equally well throughout the entire range of concrete mixtures.

There has been a need for a device capable of assessing quantitatively the placing characteristics of a concrete and which can be used in the laboratory or in the field. In an attempt to design such a device the author has evolved the "PRESSURE TEST APPARATUS", in which the pressures required to deflect a concrete disc under certain conditions are observed. Features of this machine are that it can be used throughout the entire range of mixtures, no matter how wet or dry and that aggregate up to 2½ ins. has been found to have little effect on the reliability of the results. The apparatus is simple and portable and can readily be used for field design and control. If standardised, it can afford the means of accurately specifying concrete possessing a particular mobility and plasticity. The Pressure Test Apparatus is felt to be a distinct advance and because of its importance it is given prominence in this thesis.

The results of experiments on concrete, using several

types/...

types of "workability" and consistency tests are reported and discussed herein, and compared where applicable, with the Pressure Test results. Other less important methods are also listed and discussed.

One of the most trying problems to be overcome in the making of uniform concrete, either in the field or in the laboratory, is the difficulty of assessing and/or controlling the amount of water entering the batch with the aggregates, or the amount of added water absorbed by the aggregates. In the field this problem has been very largely insuperable because free moisture content may vary from batch to batch and because of the difficulty of obtaining a representative sample. In an appendix testing methods are discussed and certain recommendations for laboratory and field use are made.

This thesis, then, embodies a study of the workability of concrete and sets out :-

(1) to develop working definitions for the properties embraced by the term workability;

(2) to discuss the characteristics of fresh concrete, largely in the light of experimental results, and to note the effects of grading of aggregates, particle size and shape, richness of mix, water-cement ratio etc.;

(3) to introduce a new method of test called The Pressure Test;

(4) to compare this machine with other testing apparatus and to correlate in some measure the work done in different countries;

(5) to set forth the practical aspects of the work done on workability.

Throughout the work theories and philosophies which are not easily applied to practice have, as far as possible, been avoided. This work was undertaken in an endeavour to combat the unscientific practice which is still so prevalent. The lack of a simple and reliable system of testing and control has perhaps been responsible for this state of affairs.

CHAPTER 2. HISTORICAL.

This brief review of the progress made towards a better understanding of the factors governing the properties of concrete has been compiled as a background to the theoretical considerations which follow, and to indicate the trend of practice.

Many investigations have had to be omitted from this summary.

VOIDS: One of the earliest attempts to rationalise design must have been that of W.H.Wright[1] about 1845, who advocated a voids method of proportioning, using sands of different sizes mixed together so that the interstices of the coarser were filled by the finer kinds. He obtained greater density in this way. A slight excess of mortar was allowed for proper workability. [2] "Wright made size analyses of sands to determine their relative value as an aggregate and recognised the superiority of weighing the ingredients over loose volume measurements".

How far has current South African practice progressed beyond this precept?

Dry and Wet Concretes: As early as 1868, one Henry Reed recommended[3] that cement, sand and coarse aggregate be properly mixed with the least amount of water for best results. He recommended that the concrete be placed in as dry a state as possible but made the reservation that too little moisture is as injurious as too much.

The use of dry concrete and rammed placing remained popular for over fifty years until the use of reinforcement made wetter consistencies essential.

At the turn of the century vigorous controversy raged over the question of wet versus dry concrete, little notice being taken of the remarkable contributions of Feret in France published as early as 1890.[2] " Feret's classical papers, published between 1890 and 1900 are surprisingly modern even in the light

of/...

of present day knowledge". Feret recognised the importance of plastic mixes and derived a relationship, from his work on such mixes, governing cement, water and strength, not very different from the present day cement-water ratio law[4]:

"For all series of plastic mortars made with the same cement and inert sands, the resistance to compression after the same time of set under identical conditions is solely a function of the ratio $\frac{C}{E+V}$, whatever may be the nature and size of the sand, the properties of the elements, - sand, cement and water - of which each is composed." In the above law E and V represent the volume of the water and air voids and C the volume of the cement.

Practical engineers paid scant attention to Gunnar Dillner[5] who by 1900 realised the importance of thorough compaction moist curing and the control of the water content.

A.Martens[6] (also in 1900) averred that the specifying of the proportions of the various materials without reference to the qualities of all of them is not a rational proceeding. If it were decided what strength and weight are to be required of the concrete at a certain age, the materials and method of mixing should be specified.

In 1903 Thomas Johnstone Bourne wrote[7]; "Whatever the relative value under laboratory tests of a 'driest possible' and a wet mixture may be - and this is sufficiently clear from tension tests of both neat cements and mixtures - in actual work, when concrete must be rapidly mixed by hand and placed in large quantities, there is practically no great variation possible in the amount of water used. Enough must be used to make the labour required in turning moderate, to make the mixture thoroughly plastic, and to ensure the mortar getting in freely between the stones ....; but so much must not be used that water and slurry collect on top of the work, or that fluid mortar carries the cement away through spaces in the shuttering, etc....."

Bourne recognized the importance of thorough curing and protection from freezing.

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By 1910 practice had become fairly standardised, Matthews and Cunningham[8] declaring that it was usual in the U.S.A. to place concrete fairly wet because "more dense and homogeneous concrete is obtained and reinforcing becomes better embedded". Cunningham boldly averred that, "in America concrete had passed the experimental stage, and it had been found in practice that concrete of a wet consistency was much superior to that of a dry, both in strength and in economy ...... in spite of laboratory tests on small quantities, well tamped, ... concrete structures built when the dry method was in vogue could not compare in looks and strength with later structures built with a wet mixture".

No mention is made of course of the amount of water in relation to the cement content.

<u>Empirical Formulae:</u> Empirical formulae of the type 1 : n : 2n, gained favour in the latter years of the nineteenth century and were almost universal in the first part of this century. They are used by numbers of engineers even today. Such practices, together with others implied by similar arbitrary specifications, reflect a lack of understanding of fundamental laws and relationships governing the behaviour of concrete.

Common British practice was to specify concrete in terms of proportions of cement to total combined aggregate, regardless of grading. Discussing a paper on Burntisland Harbour, J.M.Moncrieff wrote[9] (in 1904): "It was to be regretted that the author had given particulars of concrete used in the work in the vague and unsatisfactory manner which was in use many years ago... The statement that it (the concrete) was composed of 1 part of cement to 7 parts of sand, gravel, and broken stone, would apply with equal indefiniteness to a number of concretes in which the mortar was of widely different strengths.... Further, the .. method ... gave no information as to whether the sand and stones were measured separately, or when mixed together..... It would be just as definite to specify brickwork as composed of 1 of cement to 10 of bricks and sand".

Another/...

Another author was taken to task in the same year for using the term " 6 to 1 concrete". Two correspondents, Colson[10] and Robertson,[10] both condemning this practice as being too vague.

In 1906, Edwin Duryea, Jun. gave this account of common American usage:[11] "In general the practice on first class concrete work was 1 part cement, 3 parts sand and 5 parts broken stone or 6 parts gravel (packed volumes) - the richest perhaps 1 : 2 : 4, and the poorest perhaps 1 : 3 : 7. Machine mixing was now almost universally used in America, and was believed to be in England...."

Note that here, to some extent, allowance is made for particle shape - the angular material requiring relatively more sand for workability.

<u>Grading and Density:</u> In New Jersey about 1901, W.B.Fuller[12] conducted experiments which served to indicate that strength varied with the percentage of cement contained in a unit volume of the set concrete, and also with the density of the specimen. With a fixed percentage of cement in a given volume, the densest mixture, irrespective of the relative proportions of sand and stone, was in general the strongest. For the materials used it was stated that there was a certain aggregate grading which gave the highest breaking strength (other factors being equal), and greatest ease of working. This grading curve approached a parabolic form.

In 1907 W.B.Fuller and S.E.Thompson,[12] after further experiments, concluded that the larger the maximum size of the stone the stronger, less permeable and denser the concrete; that rounded material gives a denser and less permeable concrete than broken stone; that an angular coarse aggregate will form a stronger concrete than a rounded coarse aggregate, although less dense, provided that the fine aggregate is not also angular; that aggregates properly graded for maximum density give the greatest strength (grading to include the cement). They found, too, that the best mixture of cement and aggregate had a mechanical analysis curve resembling a parabola, but strictly an ellipse at the lower

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end running into a straight line above this to the maximum size stone; that the sand grading had more effect on the density and strength of the concrete than the coarse aggregate grading and that medium sizes of coarse aggregate could be varied without affecting the strength of the concrete; also that the larger the percentage of cement the fewer very fine sand grains required. Fuller and Thompson designed their mixes on an absolute volume basis and gauged them by weight.

In 1916, Wig, Williams and Gates[13] wrote: "There is no definite relation between the gradation of the aggregate and the compressive strength which is applicable to any considerable number of different aggregates... The so-called maximum density curve, (Fuller's Curve), does not represent the curve for maximum density excepting for the particular materials used in the tests from which it was derived, or very similar materials... Concrete having a desired compressive strength is not necessarily guaranteed by specifications requiring only the use of certain types of materials in stated proportions... Strength is just as much dependent on other factors, such as careful workmanship and the use of the proper quantity of water in mixing as it is upon the use of the proper quantity of cement... Too much emphasis cannot be placed upon the injurious effect of the use of excessive quantities of water in concrete".

<u>Surface-Area:</u> L.N.Edwards' surface area theory,[14] first published in 1918, and elaborated by R.B.Young[15] in 1919, was founded on the assumption that: "The amount of water required to produce a normal, uniform consistency of mortar is a function of the cement and of the surface area of the sand aggregate to be wetted." According to Young, for a given cement content and consistency, concrete made from aggregate having the least surface area will require the least water in excess of that needed to wet the cement and will be the strongest.

Abrams[16] found that: "There is the widest variation in the surface area of the aggregate without any appreciable difference in concrete strength..... Our studies have clearly shewn that

surface/...

surface area is not a satisfactory basis for proportioning aggregate... The sieve analysis curve of the aggregate may be widely different in form without exerting any influence on the concrete strength."

It has also been found that the amount of water necessary to produce "normal" consistency is dependent not only on the quantity of the cement and surface area of the aggregate but to a large extent upon the proportion of voids and character of the aggregate.

Water - Cement Ratio and Fineness Modulus: In 1918, Abrams[16] proposed the "fineness modulus" for designating the grading of aggregates and showed that for a workable concrete the Water-Cement ratio relationship was by far the most significant factor controlling strength. Abrams showed that the water requirements and workability of a concrete were dependent upon the fineness modulus of the particular aggregate, and stated: "Any sieve analysis curve of aggregate which will give the same fineness modulus will require the same quantity of water to produce a mix of the same plasticity and gives concrete of the same strength, so long as it is not too coarse for the quantity of cement used".

Abrams' water-cement ratio relationship is the basis of most modern methods of design, whether they be mathematical or trial methods, as it has been found that the water-cement ratio not only determines strength but also durability, impermeability, volume change and other properties and indirectly affects the economy of the mix. Cement content and water-cement ratio are complementory, for the amount of water present in the concrete determines its consistency.

The Abrams' method of mix design became the most important weapon in the fight against arbitrary proportioning, because of its simplicity and ease of application. The Abrams' water formula, used to predetermine the quantity of water which will be required in the concrete being designed, is the key to concrete mix design. The fineness modulus method has been attacked because there can be an infinite number of gradings having the same

fineness/...

fineness modulus and because no account is taken of the effect of particle shape in proportioning.

The Abrams' regular have been adapted by many workers and many variations have been published.[17,18,19] Some of these are discussed in this thesis.

1919 was an important year. Abrams published another outstanding contribution,[20] "The effect of the Fineness of Cement", in which the water-cement ratio law was substantiated. Most of the findings enunciated then still hold - all the more remarkable because the work was done before the turbidimeter for measuring the fineness of cements was known. Abrams concluded, inter alia, that there is no necessary relation between the strength of concrete and the fineness of cement, if different cements are considered; that, in general, the strength of concrete increases with the fineness of a given lot of cement, for all mixes, consistencies, gradings of aggregate and ages of concrete; that fine grinding of cement is more effective in increasing the strength of lean mixtures than rich, at seven days than at ages of 28 days to 1 year; that the fineness of cement had little effect on the workability of the concrete (as evidenced by slump test behaviour) except, possibly in the leaner mixtures; that a slight increase in cement content is more effective in increasing the strength of lean than rich concrete.

Mortar Voids: In a paper published in 1921, A.N.Talbot[21] elaborated the principles of Feret, giving relations between the strength of concrete and the cement and voids contained therein. Talbot proposed the study of fine aggregate through a determination of the voids in mortars made up with different proportions of cement and varying amounts of mixing water.

The theory may be stated:

" 1. (Other things being equal)... the greater strength is found in a concrete that has the smaller amount of voids and a lesser strength in one having the larger amount of voids (voids being the space occupied by air and water). A definite relation exists between the amount of voids and

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the strength of concrete... The percentage voids may therefore be taken as an index of the strength of the concrete.

"2... Strength may be taken as a function of the cement-voids ratio. A relation which is found to be still better is that between the strength and the ratio found by dividing the absolute volume of the cement by the sum of the voids in the concrete and the absolute volume of the cement.. (.. the cement-space ratio.)

"4. For the usual concrete mixtures, the bulk of the coarse aggregate is less than the bulk of the concrete, i.e. the bulk of the mortar in a given volume of concrete is greater than the voids in the coarse aggregate alone. For such mixtures the voids in the concrete may be considered to be made up of water and air voids in the mortar. The density of the mortar for the consistency used in the concrete is therefore an important fact or in determining strength."

F.E.Richart and E.E.Bauer,[12] studying the mortar-voids theory, found that "Water producing the minimum voids (basic water content) appears to coincide quite closely with the water required by the Standard Vicat test for Normal Consistency", and averred that "...this agreement for neat mixtures may throw light upon the suitability of the voids test as a measure of the normal plasticity or workability of mortar and concrete."

As an aid to the testing of cement and fine aggregate the basic water content is useful.

Talbot and Richart[13] found that "aggregate graded to produce maximum density gave a harsh mixture that is very difficult to place, and these minimum voids gradings of aggregate and even the next finer ones, cannot be considered useable gradings for ordinary concrete operations."

There is, of course, a close similarity between the water-cement ratio - strength, and the cement-voids - strength relationships. In workable concrete of normal consistency air

voids/...

voids may be neglected and therefore the two relationships will, for all practical purposes, give the same results for strength determinations.

General: Many methods and formulae have been put forward, derived both empirically and mathematically, for the best grading of the aggregate. Most of these have the disadvantage that they are not applicable over the full range of materials and give reliable results only with aggregates having shape and surface characteristics similar to those used in developing the criteria.

F.R.McMillan published a well-planned and understandable philosophy of concrete mixtures in 1929.[24] He stressed the fact that handling, placing, and curing of the concrete may have much greater effects on the useful life and appearance of the structure than small variations in cement, water-cement ratio, and type, size and grading of aggregate. These "basic principles" are as important and true today as when McMillan wrote his book.

Constant Water Content and Consistency: Inge Lyse,[15] in 1932, showed that the consistency of concrete remains nearly constant regardless of the richness of the mix, if the type and gradation of the aggregates and the water content per unit of fresh concrete remain constant. Type and gradation of aggregates had a great effect upon the water requirement for a given consistency of the concrete. "Above a given minimum number of cement particles necessary to give workability and binding strength to the concrete, strength increases in direct proportion to the increase in the number of cement particles in a unit of water." Lyse demonstrated that by means of the straight line relationship between the cement-water ratio and the strength of the concrete, the magnitude of the change in the cement content for a given change in the strength of the concrete may readily be determined.

The Inge Lyse law is extensively used in the design of mixtures, as the richness of the mix may be adjusted without

changing/...

changing consistency by suitably varying the fine aggregate content so as to maintain a constant absolute volume. i.e., say a decrease in cement content must be accompanied by an increase in sand content of equal absolute volume.

<u>Workability:</u> In a most noteworthy contribution to the study of workability, published in 1932, T.C. Powers[26] lucidly set forth the interplay of the factors governing the behaviour of fresh concrete mixtures. Workability, in general and for any specific materials, is determined by the combined effects of three factors namely, the quantity, and consistency of the cement-water paste and the gradation and type of the aggregate. A balance of opposing effects has to be sought in designing a mix. e.g. for a given water-cement ratio and richness of mix a coarse grading might be harsh and wet and a fine grading smooth but too stiff; a medium grading might strike a balance. The best, or "optimum" ~~grading~~ percentage of fine aggregate can be determined experimentally. At the optimum percentage of sand, the grading of the coarse aggregate was shewn to be relatively less important than for arbitrary mixes.

Weymouth's "Particle interference" theory was first published in 1933.[27] He determined mathematically the volume relationships between successive size groups of particles based upon the theory that the particles of each size group are distributed through the mass in such a way that the distance between them is equal to the mean diameter of the particles of the next smaller size group plus the thickness of the cement films between them. "Particle interference" occurs between two successive sizes when the distance between the particles is not sufficient to allow free passage of the smaller particles. Weymouth later presented in detail the basis for his theory of particle interference and linked the theory with the Talbot and Richart mortar-voids theory.[28,29]

<u>Modern Trends:</u> The present day practice is towards the rational specification of definite properties in the hardened concrete, suited to service in any specific structure, and the design of

mixtures/...

mixtures which will have adequate workability for the methods of mixing, transportation and conditions of placement . To ensure that the concrete shall attain the necessary strength, durability or impermeability, increased attention is being paid to methods of control, in both batching and curing.(eg. refs 30,31)

No new basic principles have been put forward recently; but greatly improved techniques are developing.

The selection of the Water-cement ratio(or the cement-water ratio)[32] has become the starting point for nearly all methods. The aggregates are proportioned to give the required consistency and workability either by trial[30,33,34,35] or by reference to grading curves[32,36] and/or tables[36,37] prepared from experimental data for similar types of materials, or by calculations based on adaptations of the Abrams ~~regular~~ or other theories.[17,18,19]

PART II.

CHAPTER 3:

Definitions: Terms Relating to Workability: In concrete literature there is an unfortunate lack of uniformity of definition of many terms. Some writers distinguish between the terms "Consistency", "Workability", Plasticity", "Mobility"; others frequently use them interchangeably.

It is important that the meanings should be defined so as to be generally acceptable. The need for standardisation of terms is international.

Various words will be examined with a view to establishing definitions which will be as informative as is necessary and give definite, or quantitative information if possible.

Workability: Many writers fail to distinguish between workability and some of the properties which affect it, such as consistency, and use the terms synonymously. It is shewn elsewhere that the consistency of the mix is mainly affected by changes in water content, whereas workability is largely affected by changes in the solid materials of the mix.

In an early definition, Pearson and Hitchcock[38] stated simply that one concrete is more workable than another when the process of mixing and placing is accomplished with less effort in the first case than in the other, admitting, however, that direct quantitative measurement is very difficult "because there is no definite condition that may be taken as a stop point in the placing operation".

They recognised the bearing that segregation has on workability, and qualified their definition by saying that those mixtures are most workable which tend to preserve their homogeneity in the greatest degree as they are being handled and placed.

Many writers have adopted similar concepts, for example Purrington and Loring[39] and Smith and Conahey,[40] the two main factors included being the effort required to place the concrete and the resistance to segregation.

Williams/...

Williams[41] adopted the standpoint of the practical worker, and gave a popular conception of workability as the ability of a mixture to remain homogeneous and free from segregation during the process of transportation and placement. Although no direct reference is made to ease of working, resistance to segregation is related thereto, as is cohesion.

Young[42] was rather more explicit in describing workability as "that combination of the properties of concrete which allow us to handle and place it with a minimum of labour and segregation".

Powers[26,43] looks upon workability as qualitative only; representing a complex quality that cannot be measured in fundamental units of M, L and T. He has defined it thus, "Workability is the combined effect of those properties of fresh concrete that determine the amount of internal work required for placement and compaction and that determine resistance to segregation". In this definition, workability embodies "the combined effects of mobility and cohesiveness", and several other definable physical properties.

According to Powers, "the severity of the placing conditions must also be taken into account in evaluating the workability of a given concrete mixture, for a concrete plastic and mobile for one set of conditions, may have these properties to an inadequate degree when used under conditions more severe".

In agreement with this, Blanks, Vidal, Price and Russell[2] defined workability as "the ease with which a given set of materials can be mixed into concrete and subsequently handled, transported and placed with minimum loss of homogeneity.

Facility of manipulation (mobility) and resistance to segregation (durable homogeneity) are, according to G.S.Lalin,[44] the most important factors relating to workability. A third property, "Smoothness", which is often mentioned, is complementary to mobility and reduces the liability to segregation. A.F. Samsioe[45] defined workability as "the facility with which the concrete mixture, by the aid of certain tools, may be worked into certain moulds so as to attain a mass free from cavities." Thus workability/...

bility may be considered as a function of two factors, viz, the properties of the concrete mixture and the method of working into the mould.

Herschel and Pisapia[46] and also Davis and Kelly[47] have adopted definitions which endeavour to place workability on a quantitative basis. Under their conception, workability is the inverse of the degree of effort required in handling and placing concrete in such a manner as to give a uniform and homogeneous finished product. On this basis segregation, in destroying homogeneity of the mix, necessarily contributes to a non-workable condition, requiring more work to bring about the desired compaction.

In a convincing hypothesis, Glanville[48] commences with the concept that workability is a physical property of concrete in some way connected with the amount of working necessary for full consolidation of the concrete, and develops a useful working definition. The idea of "working, or alternatively compacting or moulding, is the elimination of the air voids". The voids are maintained by surface friction between the constituent particles and the binding paste, and in all forms of working, consolidation is effected by overcoming this internal friction. Besides the "internal friction", another frictional resistance which has to be overcome is that between the concrete and the sides of the mould and surface of the reinforcement. This, called by Glanville "surface friction", may be considerable in the case of heavily reinforced structures and for a given concrete will be characteristic of the placing conditions. Working which overcomes surface friction does not compact the concrete.

The internal friction is a physical property of the mix and the surface friction is a combination of a physical property of the mix and a property of the mould and reinforcement.

Whatever the method of consolidation adopted a certain amount of the applied energy will be lost and will not help to overcome friction. Glanville introduced two terms: "The applied work is the energy actually expended and the useful work is the energy usefully employed."

"Considering/...

"Considering workability as a physical property of the concrete, it follows that useful work cannot be the absolute measure of workability since ... it includes surface friction... The fraction of useful work employed in overcoming the internal friction of the mix is the only term purely dependent on the physical characteristics of the mix. So if workability is to be both a physical characteristic of the concrete and in some way connected with applied work, it can only be connected with the useful work which overcomes the internal friction of the mix itself. We will call this the "useful internal work"."

Finally, Glanville defines workability as a physical property of concrete which determines the amount of useful internal work necessary to compact the concrete from the freshly mixed state to some specified final state corresponding with that of the placed concrete. (Or to increase its "compacting factor" from some initial value to some greater value specified... See "Standard Compacting Factor Test," page 45).

Most of the foregoing definitions agree that ease of placement and resistance to segregation are the essentials. The fundamental differences in the schools of thought are:-

1. Whether or not the property of workability can be assessed quantitatively - represented by a single numerical value.

2. Whether workability is solely a physical property of the concrete alone and independent of placing conditions.

Powers treats the degree of plasticity and cohesiveness as being inherent in the mixture; but the degree of mobility as depending on the placing conditions. He embraces all these properties in his concept of workability.

Glanville does not specifically mention segregation as a factor in assessing workability. He relates workability directly to the amount of useful internal work expended in placing. Segregation and cohesion will, of course, play their part in influencing this effort.

Under Glanville's definition, a segregating, sloppy concrete which/...

which may be almost fully compacted merely by pouring into a mould would be more workable than a well-proportioned, smooth working, non-segregating mixture of a slightly drier consistency. The former concrete, although of a pouring consistency, cannot be considered workable, except perhaps, under very special circumstances, as it will not remain homogeneous during the transporting and placing operations. See section on the Compacting Factor test for further discussion on the implications of this definition.

The method of mixing and the facilities for transporting the concrete to the work, the configuration of the mould, the presence of reinforcement, and the method of compaction, all influence the ease of placing quite without regard to the concrete itself. A concrete which is described as workable for one set of conditions - e.g. depositing in a large mass and compacting by vibrator - may be hopelessly unworkable when considered for another structure and method of consolidation, perhaps a thin wall with congested reinforcement and hand ramming.

In this thesis, workability will be regarded as a qualitative term used to describe the combined manifestation of several physical properties of concrete. It involves the question of the amount of work necessary in placing the concrete to accomplish a satisfactory finished product. This quality embraces ease of placement under a particular set of conditions and resistance to segregation and is thus a relative thing.

<u>Consistency:</u> In the Code of Practice[49] and also ASTM Designation C 143-39 reference is made to the "Consistence" (Code) or "Consistency" (ASTM) of concrete as measured in inches of slump. In other words consistency relates to the degree of wetness or dryness of the mix. The author inclines to this idea, although the property is more complex and is felt to be qualitative only in the strictest sense. It can only be visualised through a knowledge of the characteristic effects imparted by plasticity.

Consistency, as used in everyday speech, takes on many meanings according to context and is applied to a wide range of materials/...

materials. As defined in concrete literature, it has meant anything from "workability" to "fluidity".

Abrams[50] once described consistency as the "relative plasticity or workability of freshly mixed material" and again, "consistency is a fundamental requirement of concrete mixtures and....any variations in the proportions, characteristics of the aggregates, method of manipulation, etc, are reflected in the resulting consistency".

Pearson and Hitchcock,[38] on the other hand distinguished between consistency and workability, holding that the former term should only be used to describe the condition of the concrete as it is affected by changes in water content, whereas the latter term should be used to describe that condition of a given mixture which depends not only on the water content but upon any factor which affects the amount of work required to place and finish the concrete in a satisfactory manner.

Bingham[51] suggested that consistency is the reciprocal of mobility and defined it as "that property of a solid which causes it to resist continuous rapid deformation".

That consistency is a property of a granular plastic material which it possesses by virtue of the force-flow relationship is generally agreed. The difficulty has been to distinguish between the terms consistency and plasticity. Consistency should be used only in connection with materials possessing plasticity, a term which it embraces.

If consistency be defined by the force-flow relationship, as is plasticity, the curve would be in the typical form of fig.(1). The force-flow curve for concrete (or any other plastic) cannot be a straight line passing through the origin because of the yield value and it follows that consistency under this concept cannot be wholly defined by any single numerical value whatever, no matter by what method this value may be obtained. However, for some purposes, consistency may be adequately defined by some single quantitative value, even though not completely defined. Thus we look upon the "slump"

or/...

or"flow" of concrete as giving an index of consistency.

Useful descriptive terms which are used in connection with a visual assessment of consistency are "dry", "stiff", "medium", "wet" and "sloppy".

In this discussion, as in ASTM Designation E 24-42, consistency will be described as "that property of a body by virtue of which it tends to resist deformation".

<u>Plasticity:</u> ASTM Designation E 24-42: "That property of a body by virtue of which it tends to retain its deformation after reduction of the deforming stress to its yield stress".

The yield value of a mixture is the minimum force which must be exceeded before flow starts. If this yield value be greater than gravity the mixture will not flow except by the application of force greater than gravity. When a plastic material is stressed beyond this yield value it is distorted to an extent depending on the characteristics of the material. This distortion is inelastic, and may be considered as plastic flow.

Powers and Wiler[43] assert that plasticity cannot be defined by yield value and the characteristic response to forces greater than yield value alone. A third consideration is the plastic limit, which they refer to as "the capacity for plastic distortion" - in other words the point at which that material loses its plasticity and ceases to behave as a plastic. This is obviously important as it determines the amount of distortion which a concrete is capable of withstanding without rupture.

Thus, if "plastic" means "capable of being deformed continuously and permanently in any direction without rupture", the plasticity of a concrete cannot be fully defined in less than three terms:

(1) The yield value.

(2) The plastic stress-flow relationship, denoted by mobility.

(3) The plastic limit.

Although plasticity can only be completely defined by these factors, for the purpose of making a general assessment of the property it may be sufficient to observe characteristics such as cohesiveness, resistance to indentation or hardness, and smoothness of working with a trowel. If one mixture be more plastic than another it shears more easily and flows more readily when mixed or spread. Plasticity embodies many of the characteristics which determine workability.

Mobility: Mobility is applicable to plastic concrete and is used in the sense that "fluidity" is applied to liquids - the reciprocal of viscosity.

A "coefficient of mobility" analogous to viscosity has been suggested. This was the differential of flow rate with respect to force, under certain conditions of plastic flow, when this differential is a constant. The rate of flow plotted against force producing flow may be a straight line but it will not pass through the origin and cannot be considered a coefficient of viscosity (see fig. 1).

Cohesion: A property affecting the mobility of a concrete is cohesion, which is that force by virtue of which the particles tend to hold or stick together and resist being pulled apart.

A certain amount of cohesion is necessary in concrete so that it can be handled with a minimum tendency toward segregation. On the other hand too high a degree of cohesion produces a tacky mix with resulting loss of workability.

[52] "Cohesion is that form of attraction by which the particles of a body are united throughout the mass, whether such particles are alike or unlike".

Segregation: Segregation is a loose term which has been used to denote "bleeding" of water, separation of aggregate sizes, or departure in any way from the original composition during transportation, placing and compacting.

There is some relationship between workability and the tendency of a mixture to segregate. Cohesion and segregation are interrelated.

<u>Placeability:</u> This is a term which has been coined to replace workability where the latter term has a broader significance than is implied.

As an example, Hutchinson[53] reported that with his vibratory machine (see page 64) equal measurement could be obtained with concrete of poor design requiring excess water, as judged by bleeding and other indications of excess water; and a plastic mix containing no excess water. These mixes were said to have equal placeability under the conditions of the test.

CHAPTER 4 :

The Measurement of the Characteristics of Fresh Concrete:

Investigations of concrete mixtures have always been hampered by the lack of adequate devives for measuring workability and associated characteristics. With increased knowledge of the various factors influencing workability, came the demand for a gradation of this property and if possible a method of quantitative assessment.

The difficulty has been to distinguish fine differences between mixes as to their plastic properties. The engineer has had to depend for his information, regarding the workability of the concrete he is producing, upon the opinion of the workmen who are placing it, or that of the foreman. Until there is an accepted method of determining with some accuracy this quality which is called workability, its advantages will not be fully utilized.

The study of aggregate gradation, for instance, has provided fuel for controversy because there was no way of determining when two mixtures were exactly comparable. In the field, concrete of adequate workability has been produced for a variety of working conditions; but until recently there has been no measure of this property more precise than visual observation. There was, and still is, often doubt as to the relative economy of mixes differing only slightly in cement requirement.

Although no single test procedure for obtaining a "workability index" or measurement of relative workability has been devised which satisfies all the requirements of the definition and which works equally well throughout the entire range of mixes, the Pressure Test, the Remoulding Test and some of its developments, and the Standard Compacting Factor Test do provide a good practical indication of the amount of placing effort which the mix will require under certain conditions.

The measurement of any property, whether consistency, mobility, plasticity, segregation, etc, is a complex problem due to the extremely wide variety of types of materials used

and/...

and to the almost endless variations in the characteristics of these materials.

If reliable and reproduceable results are to be obtained in concrete testing it is essential to maintain the strictest control of conditions and to eliminate as many sources of variation as possible. All batching should be by weight, based, possibly, on the absolute volumes of the aggregates. The control of aggregate gradation (by suitably combining materials), water content, etc, should be very strict. Methods of performing the tests should be practised and standardised - usually results are to a greater or less extent dependent on the operator's skill and idiosyncracies. The control of the water content alone is a matter for careful thought and preparation in laboratory practice, and in the author's experience it is only by adopting the methods of control outlined later on that individual results will be reproduceable in any test.

As the various qualities which go to make up workability are all interdependent, the study of these properties enables a composite picture to be built up, and even if workability could be represented by a single numerical quantity it is also desirable to study and observe each independent factor that affects it.

There have been many attempts to measure the plastic propertie of concrete, and the list is steadily growing.

The more important of the published methods were summarised in Road Research Technical Paper No.5. This summary, with some additions, is reproduced here.

(i) <u>The Slump Test</u>[49,54]

(ii) <u>Flow Tests</u>

American Society for Testing Materials[55] (Flow table)

Graf[56]

Davey[67]

Yoshida[66]

German Committee for Reinforced Concrete[58]

Burmister[59]

Haegermann[60]

(iii) <u>Penetration Tests</u>[38]

Pearson and/...

Pearson and Hitchcock[38]

Smith and Conahey[40,61]

Yoshida[66]

Graf[62]

Humm[63]

Irribarren[64] Wigmore[78]

(iv) Drop Tests

Jackson and Werner[65]

Yoshida[66]

Gaber[67]

Road Research Laboratory (C.S.I.R.)[48] (Heap test)

(V) Mixer Tests

Pearson

Purrington and Loring[39]

Hagy[68]

Patch[69]

Miller[70]

Rayburn[71]

U.S.Bureau of Reclamation[30]

(vi) Deforming Tests

Smith and Conahey[40]

Powers[26] (Remoulding test)

Wuerpel[72,30,33] (Vibratory Remoulding Test)

Bahrner[73] ("Vebe" test)

Collier[74]

Nycander[75]

Granger (Pressure test)

(vii) Compacting Tests

Samsioe[45,76]

Humm[63]

Faury and Lamare[77]

Hutchinson[53]

Road Research Laboratory[48,36] (Standard Compacting Factor test and Slab test)

(viii) Viscometer Principle

Powers and Wiler[43]

Other/...

Other Properties: Tests have been designed for the measurement of such properties as harshness, segregation, stickiness or cohesion. Examples of these tests, using simple apparatus, are frequently met with; many operators improvise their own tests according to their needs. For example, a "Stickiness Test" is made by measuring the vertical force required to separate a horizontal steel plate from the surface of freshly made concrete.

The Author has carried out several series of experiments with the following apparatus:

Slump cone; ASTM flow table; Burmister's Flow Trough; Powers' Remoulding Apparatus; Standard Compacting Factor Apparatus; Pressure Test Apparatus. The methods of control, details of the mixtures and materials, etc, are given in Appendices A, B and C. The above methods of test are exhaustively discussed below and the properties they purport to measure are considered in the light of experimental results. Where possible, the relative merits of the tests are compared. The results of the workability tests are used and fully discussed in another section (on the properties of mixtures).

The Slump Test: This test, easily the best known and most popular of all, probably dates back to a device patented by Cloyd M.Chapman[54] primarily for studying the consistency of sand mortars. It was first successfully applied to the control of concrete consistency when rich, easily working mixes were being used in concrete ship construction. The slump mould in its present form (i.e. a truncated cone, 4 inches top diameter and 8 inches bottom diameter, 12 inches high) was developed by F.L. Roman, Illinois Bureau of Highways, about 1918, and has been called the "Roman Cone".

The Slump test has been standardised in America and has ASTM Designation C 143-39. It is included in the Code of Practice for Reinforced Concrete as a "Standard Method of Test for Consistance of Concrete".[49]

The test is not in itself a measure of workability and as Glanville has put it:[48]

(1) There is no obvious connection between the test and the definition of workability, and

(2) With all except very workable mixes, it is liable to random variations of such magnitude as to render it impossible to distinguish between the slumps of mixes of different observed workabilities.

The photographs, figures 2 to 25 were taken by the author. They are representative of a series of slump tests made with varying mixes and W/C's under strictly controlled conditions. The camera was positioned before each test by means of a wooden template so that it was a fixed distance from the axis of the slump cone. The photographs have been enlarged to a fixed scale and the horizontal lines indicate inches of slump. Besides giving a permanent record of the slumps, these photographs have provided a means of studying at leisure the form of the slump and the texture of the concrete. The figures have been suitably annotated to illustrate this.

During the making of the tests, four characteristic types of slump were observed:

(1) The specimen slumped slightly, and did not show any appreciable change in shape from that of the mould. This is illustrated by figs. 3 to 36

(2) An even settlement of several inches occurred and the specimen bulged outwards but held together. See figs. 11 to 15

(3) As the specimen slumped shear took place. A portion remained standing on one side and the remainder fell away. This type represents some uncertainty of measurement, and it is as well to perform the test a second time if it occur, when (2) will probably result. (Figs. 16 and 17)

(4) On removal of the cone the moulded concrete slushed down and flowed outward leaving a mound, generally of compacted aggregates, in the centre. (Figs. 23 to 25)

Types (1) and (4) represent the behaviour of dry and sloppy mixes respectively. The normal mix tends to combine various effects, according to the consistency. The fact that it is physically almost impossible to remove the mould without more or less

distortion/..

distortion, is manifest in the tendency of the slumped specimen to lean over slightly. (figs. 7 to 10.) An improvement might be brought about by mechanising the test, e.g. raising the mould in vertical guides.

The author has experimented with a simple modification, illustrated in figs. 31 and 32. A ¼inch diam. welding rod is screwed into a metal base piece attached to the underside of the 2ft X 2ft sheet steel covered wooden base, so that the height from the top of the rod to the base is 12 inches. In performing the test, the slump cone is accurately centred on the base board and filled with concrete in the standard manner. Experiments have shown that the central rod does not affect the slump measureably; but has the effect of preventing the cone from leaning and reduces the tendency for "shear" slump to take place. Incidentally, the rod is a very convenient aid in measuring the slump.

The decrease in height of the specimen as it slumps involves motion, so that momentum must tend to carry it past the theoretical equilibrium. The active hydraulic head depends not only on height but also on the density of the concrete - another possible reason for variation.

One great failing of the slump test has been brought out in all these experiments. Especially in the range of intermediate slumps, very large individual and random variations occur with precisely similar mixes so far as can be judged in the laboratory. This tendency to variation has been noted by many experimenters, notably Smith and Benham[79] and Glanville.[48]

If these variations occur under laboratory conditions, it would be expected that in the field still greater variations will occur. In specifying slump, therefofe, it would be as well to specify a maximum and minimum, or an average, instead of a fixed value.

In the region of 1-2 inch slump (condition (1) above) the variation of slump for a given water content is relatively less than in the other regions and in this range, the slump gives a more reliable indication of wetness.

For type (4) in the range of 7-8 inch slumps, after a definite

quantity/...

quantity of water had been used, no change in slump occurred by increasing the water, or the paste content at a fixed W/C. Due to the segregation and compaction of the coarse aggregate a cone of approximately constant height was left as the upper part of the sample poured down on all sides.

The graphs of slump versus water content (figs.26 to 29...) are all of the reversed curve type with points of inflection in the 4 - 5 inch slump range, and limiting tangents at zero and in the region of 8 inches.

Figs.26 to 29 illustrate the behaviour of four arbitrary classes of concrete having increasing water-cement ratios. These mixes were used in the early part of the work, more or less as exploratory or trial batches on which to plan the systematic mixtures used in the later work on the "workability" apparatus. Fig. 30 has been drawn for concretes having one coarse aggregate grading and a fixed water-cement ratio. (See appendix C.) This is illustrative of the later work.

In Fig.30, slump is plotted vs water-cement paste content (fixed W/C). It will be seen that the curves keep to the same general shape as the slump vs W/C types. The main point to note is that the various concretes of different fine aggregate proportions (finer or coarser gradings) require different amounts of water-cement paste for a given slump. These differences are, however, not necessarily indicative of the different characters of the concretes. For example, the concretes having 33.3% sand are harsh and stony in appearance. They tend to segregate badly when wet. A glance at fig.80A supports the supposition that this series (33.3%) requires a much higher paste content than the others to produce comparable workability. In fig.30 there is nothing to support this — nothing to distinguish the undersanded concrete as the curve lies in a group with the slightly under - and slightly over - sanded concretes. The curve for the 45% sand concretes does however, indicate higher slumps for a given paste content, which one would expect owing to the plastic well-lubricated nature of this series.

At both low and high limits the test is less sensitive to change in water or paste content than it is in the central range, if the condition indicated in the curves is taken as the criterion of sensitivity.

The slump test exhibited much more reliability for the richer mixes than for the leaner ones. The leanest, harsh mix gave particularly bad results. In the intermediate region the richest mixes gave fairly good results. This is unfortunate as water control is more important with the wetter pastes (higher water-cement ratios) and leaner mixes. For obvious reasons, the test is unsuited to dry mixes or concrete in which large sized (especially crushed) aggregate is used.

The slump test can give a measure of relative plasticity when true slump (conditions (1) and (2)) occurs. The plastic mass when well lubricated will slump more than a harsh mix for the same wetness. The U.S.Bureau of Reclamation Manual[30] recommends that; "After the slump measurement is completed, the side of the concrete frustrum should be tapped gently with the tamping rod. The behaviour of the concrete under this treatment is a valuable indication of its cohesiveness, workability, and placeability. A well proportioned, workable mix will slump gradually to lower elevations and retain its original identity, while a poor mix will crumble, segregate and fall apart".

In type (4), a breakdown in the binding property of the mortar due to excess of water is evident. There is therefore a greater tendency for segregation and for leaking of liquid from the concrete.

Concl The slump test should not be relied upon by itself as a gauge of wetness or any other property. The test is a measure of the wetness or consistency of the concrete and individually, with a certain class of concrete and for a given mix, may be a measure of the relative ease with which the concrete can be worked. That is to say, with fixed materials and fixed combinations of those materials the placeability can be represented by some slump; but if the conditions be changed, possibly by using

Concl

other/...

other materials, it will take another slump to represent the same degree of placeability. As a control test, this is not important.

Changes in aggregate proportions affect slump in much the same way as changes in water content. If too large a slump may be due to too much water, or too little aggregate, it is apparent that its function would be merely to indicate that a checking up of the measurement of materials is necessary.

Finally, it should be remembered that the value of the slump of the concrete should accompany any works cubes submitted for test, in order to comply with the requirement of appendix VIII, the Code of Practice for Reinforced Concrete.

The Flow Test. The Flow Test was first used in 1912 and is another invention of C.M.Chapman[80] who was granted a U.S.Patent in 1917. It was first used for the measurement of the consistency of sand mortars and was developed largely by the U.S. Bureau of Standards.[50]

The flow test has been standardised and given ASTM Designation C124-39.

Scope: 1. This method is intended for determining the flow of concrete.

Apparatus: See photographs, Figs. 33 A,B,C.

2. (a) Mould-Smooth metal in the form of a frustrum of a cone, base 10" diam, upper surface $6\frac{3}{4}$" diameter, altitude 5". The base and the top shall be open and at right angles to the axis of the cone.

(b) Flow Table: As illustrated. Table top 30" diam. (Stainless steel in this case; brass specified in ASTM). Cam mechanism allows the table to be raised and dropped $\frac{1}{2}$". The concrete base to weigh not less than 300 lbs.

Sample: 3. Sampling methods to be as for the Slump test.

Procedure: 4. "Immediately preceding the test, the table top shall be wetted and cleaned of all guilty material and the excess water removed". The mould is centred on the table and firmly held in place; the procedure for filling is the same as for the slump cone, except that it is filled in two layers, each approximately half the volume of the mould. After ramming as for the slump test the surface of the concrete is struck off with a trowel so that the mould is exactly filled. "The excess concrete which has overflowed the mould shall be removed and the area of the table outside the mould again cleaned. The mould shall be immediately removed from the

concrete/...

concrete by a steady, upward pull. The table shall then be raised and dropped $\frac{1}{2}$", 15 times in about 15 seconds. The diameter of the spread concrete shall be the average of six symmetrically distributed Caliper measurements read to the nearest $\frac{1}{4}$ in.

Flow: 5. "The flow of the concrete shall be recorded as the percentage increase in diameter of the spread concrete over the base diameter of the moulded concrete, calculated from the following formula:

$$\text{Flow, percent} = \frac{\text{spread diameter} - 10 \text{ ins}}{10} \times 100."$$

The flow test is, by its nature, intended as a laboratory test and is not subject to many of the faults of the slump test. It is useable over a greater range of mixtures. Although flow is not an index of workability or placeability it may be an indication of improvement in workability with any given set of conditions, just as was described in the case of the slump test. Workability may improve for a given mix and with given materials as the water is increased within certain limits. However, with thin pastes, increasing the paste content will probably decrease the workability, whilst increasing segregation, slump and flow. It is, of course, possible to obtain the same flow for two different mixes of vastly different workability.

Yoshida[66] states that the flow table measurement is open to the criticism that "it is concerned with the workability of concrete in a segregated condition", and adds that "with the flow table reliable results may be obtained only with concrete in which practically no segregation occurs during the test". The tendency to segregate is very noticeable in the leaner and drier mixes. As flow is unrestricted, some of the aggregate rides along only partially embedded in the mortar and at the end of the test the mass is scattered instead of being homogeneous .(See fig. 33C)

In order that the wetness of concrete may be visualised from the flow table data, it is imperative that the data be obtained

under/...

under fixed conditions. For a given condition of wetness as determined by the flow table those mixes which contain larger amounts of cement, and which are the more workable, quite consistently give the greater slumps.

Unlike the usual slump test results, individual flow test readings show consistent conformity with average curves, except in the case of the very lean mixes, which segregate readily. Even for lean concretes, flow results obtained by the author were better than the parallel slump readings.

This seems to be the concensus, and similar opinions have been voiced by Smith and Benham[79] and Schwalbe.[80]

Within the range of plastic concretes, flow is seen to be practically a straight line function of the quantity of water used.(Figs. 34 to 37). This holds generally, regardless of the mix. It is noticeable in the richer mixes that there is a tendency for the test to be less sensitive to change in water content at the wetter consistencies. (Figs. 34, 35b and 36b)

For a given wetness or consistency as measured by flow, slump changed considerably and quite consistently with change in richness of mix, increasing as the quantity of cement increased. Lyse and Johnson[81] claimed that this supported the conclusion that slump was superior to flow as an indication of workability. However, although difference in slump, flow being constant, does parallel improvement in workability, it is far from logical to conclude that because of this, slump is superior to flow as a measure of workability. Neither test can be used by itself as a reliable criterion. Note that although an increase in richness of mix may make the concrete more plastic, it will not necessarily make it more workable.

Where a reliable indication of consistency or wetness is desired, the flow test is preferable to the slump test because of its more uniform functioning.

Pearson[82] says of the slump and flow tests: "Their real significance is that they respond primarily to variations in water content ... and serve to indicate under given job or test conditions the proper amount of water to be used for optimum workability. Whether that optimum be relatively good or poor these tests do not alone tell ..."

<u>The Flow Trough:</u>[59] Donald M.Burmister developed the flow trough apparatus as a variation to the Standard flow table - to confine the flow in one direction along the axis of a semi-cylindrical trough, 6ins in diam, 3 ins deep and 24 ins long. The apparatus made for the author's use, illustrated in figs. 38 to 41 , is of 16 gauge stainless steel. Besides furnishing a measure of wetness, the flow trough results can give a good indication of relative plasticity and tendency to segregate. The apparatus is easily portable and two determinations can be made in about the time required for one slump test. The results are reproduceable, individual readings checking very well.

The method of operation is briefly as follows; (a full description may be found in Burmister's paper)[59]:-

The trough having been moistened and the gate inserted, the apparatus is placed on the level base so that the open end lies under the hook, which has a clearance of 1 inch. The trough is filled in a standard manner, by means of a mason's trowel, and rocked sufficiently to form the concrete into a homogeneous mass. The top is trowelled level with the side rails with as few smoothing motions as possible. The finishing properties of the concrete are brought out in this operation.

Just before pulling the gate, any mortar that may have worked thereunder is wiped away with a piece of damp waste. The gate is pulled by first rotating it out of one slot, when the appearance of the toe of the concrete mass may be noted, honeycombing indicating that the mix is too dry and there is a deficiency of mortar. If, however, mortar drain or leak from the face of the concrete, it indicates that the concrete bleeds readily with very little working or standing. It is important that any leakage flow be noted, as it indicates that the mix is not workable.

The test is made as soon as any leakage flow has come to rest and been noted. The front end of the trough is raised until it strikes the hook, allowing it to drop under its own weight. This is repeated ten times in ten seconds, causing the con-

crete/.

concrete to slump and at the same time to flow outward along the trough. The number of inches the concrete has flowed along the trough is a measure of the wetness, and is estimated to the nearest ¼ in. The average of two or more tests is desirable.

The test is primarily a measure of the work required to cause flow in concrete, and as flow is confined to one direction, a large, measureable flow is obtained.

__Plasticity Coefficient:__ Of two concretes, one may exhibit greater plasticity than the other, and yet be less wet. Burmister, having noticed that the trough appeared to function differently with different numbers of drops, divided the test into two halves and determined flows for 5 and 10 drops. He found that if he plotted twice the flow at 5 drops and slump on the same axes the two sets of curves were very similar in shape and could be made practically coincident by subtracting a constant from the flow values, indicating that flow at 5 drops and the slump test measure the same property. (See Fig 43)

When flows at 5 and 10 drops were compared, a consistent variation; not only with richness of mix but also with increased water content, developed. Burmister suggested the ratio:-

$$\frac{\text{Twice the flow at 5 drops}}{\text{Flow at 10 drops}}$$

as a measure of the relative qualities of concrete. He has termed this ratio the "Plasticity Coefficient", or P.C.

The P.C. increases both with the richness of the mixture and with the increase in water content, paralleling the order of workability for most mixes. According to Burmister: "Judging from the handling and placing conditions a mix cannot be called workable unless the P.C. is greater than 1.10, with a flow greater than 2 inches; but with no evidence of any leakage".

It is evident from the author's experiments, that different aggregates and mixes require different individual minimum flows and P.C.'s. A certain specification is applicable only to concrete for a certain use and composed of a certain type and grading of aggregate. The method does not seem to be applicable for/...

for general specification unless values are predetermined by experiment.

Application to Design: Plasticity Coefficient and flow (at 10 drops) are held to define a concrete and, when taken together are an indication of the relative ease with which a concrete may be handled and placed. A high P.C. is indicative of a uniform and homogeneous product with little tendency towards segregation. A low P.C. indicates either a lean, watery concrete which is harsh working and segregates readily, or one which is very dry and harsh. In either event, a concrete with a low p.c. will prove difficult to place without vibration and will result in honeycombing and, in the case of a wet mix, laitance.

Three requirements for a good concrete are:

(1) No evidence of leakage flow.

(2) Minimum P.C. consistent with the class of concrete and field conditions.

(3) Maximum flow suitable for given field conditions.

The author has found the flow trough to be a useful adjunct in designing mixes in the field. Its portability and the rapidity with which determinations may be made count very much in its favour. In handling and trowelling the concrete during the test and systematically recording the properties observed, a good idea of workability is formed and any desirable adjustments are readily indicated. The reservation should be made that the quantitative results are probably not reproduceable under other circumstances. The friction between the trough and the concrete must influence the results greatly and there must be wide fluctuations in the coefficient of friction. Whether the trough is wet or dry, the type of material used, the surface condition, all play some part. These things are difficult to standardise.

Comparison with Slump and Flow Tests: The flow trough is very much more sensitive than the slump test for the drier consistencies, but the slump test scores at the other end of the scale. See figs. 42 and 43. Flow test operates for zero slumps.

The test suffers with the flow table in that forces tending

to/...

to cause flow or deformation diminish with each drop due to the decrease in head, and the amount of decfease in force with each drop is different with each change in consistency. Therefore it is difficult to standardise the amount of work done on the concrete.

In pursuance of Burmister's suggestion that (twice flow at 5 drops — 2) was approximately equal to the slump, fig 43 was plotted. It was found that (2 X Flow at 5 drops — 1) gave a closer agreement in these examples.

Figs. 42 and 43 both show fair agreement with slump curves and in fig.43 the similarity in the case of the 1: 1.5: 2.25 and especially the 1; 2.5: 2.25 concretes is remarkably good.

These few arbitrary mixtures, which constitute the exploratory work on the various tests, were made during the period when the author was developing the technique outlined in Appendices A and B. Each adopted result is the average of about three good test readings. In the later work, using systematic variations of mixtures, the flow trough was not used. It was, however, used as a control test on certain Cape Town City Council Works over a period of some 8 months.

<u>The Remoulding Test:</u> 26 The Remoulding Test invented and developed by T.C.Powers, measures the relative effort required to change a mass of concrete from one definite shape to another by means of jigging. The change in shape involves flow under conditions which can be varied at will. The amount of effort, called the Remoulding Effort, is taken as the number of jigs required to complete the change.

Although the test does not offer a complete measure of workability it provides a good basis for comparison of the amount of placing effort which the mix will require under certain conditions. The test makes distinctions between mixes to a degree unobtained by any form of "consistency" apparatus such as the slump test or the flow test.

Figs. 44 to 49 show the Remoulding Apparatus as used by the author at the University of Cape Town. The device consists of a sheet steel container 12 ins in diameter carrying an internal ring $8\frac{1}{2}$ ins in diam, which can be set at varying heights. A standard slump cone fits inside the ring. A rider assembly for measuring the height of the concrete completes the apparatus. The container can be clamped to a flow table.

With the apparatus assembled as in fig. 44, the slump cone is filled in the standard manner. The cone is then unclamped and withdrawn. Then, as in fig. 47, the rider assembly is put into place. The device, clamped to the flow table, is then jigged and the remoulding effort in terms of the number of drops of the flow table required to complete the change from truncated cone to disc form is observed.

The inner ring tends to restrict movement which, without the ring, would take place in part by means of a crumbling, semi-plastic flow. The closer the lower edge of the ring to the bottom edge of the container, the more must movement be accomplished by plastic flow. Thus by changing the clearance of the ring the severity of the test can be varied at will.

While in general, the greater the slump, the less the remoulding effort, the relation between slump 27 and remoulding effort

varies/...

varies with richness of mix, gradation of aggregate and other factors. The test distinguishes readily between the plastic characteristics of different concretes, having the same slump (consistency), and was used in conjunction with the pressure test in the studies of the optimum percentage of sand, referred to elsewhere.

The test is a valuable aid in the laboratory design of concrete mixtures and since it was first developed, it has been acclaimed as possibly one of the best types for measuring relative workability or mobility. It has been improved and modified by different research bodies. Vibration has been introduced instead of jigging on the flow table. (See p. 62)

It has been suggested that the vertical jigs used in the test do not occur in practical concrete operations and that the jigging causes the heavy particles to become unduly concentrated within the ring clearance at the bottom of the apparatus and that this may cloud the interpretation of test data. The author has found that the apparatus exaggerates any tendency for segregation and thus favours rich, plastic highly sanded mixtures. When the mix segregates the mortar flows away, leaving a compacted mass of coarse aggregate within the ring, which prevents the rider from sinking to the zero mark even after large numbers of jigs. Fig.49 illustrates this tendency in a concrete which has segregated under the action of the test but which would normally be considered workable. Figs. 50 to 55 are typical of the results obtained by the remoulding test. As can be seen, concretes which have any tendency to undersanding or coarse grading with angular aggregates are extremely difficult to remould.

The machine is especially suited to the range of concretes from about 0 to 4½ inches slump. Wetter concrete segregates badly. With very dry concretes the test becomes tedious and the vibratory remoulding test would be more suitable. A useful adjunct on the flow table operated machine would be a "jig" counter.

Like most tests, the remoulding test works best with aggregates having a maximum size of ¾ inch or less. The author found that, as with the slump test, concrete having $1\frac{1}{2}$ inch aggregate could not be satisfactorily tested, except with the very highly sanded mixtures.

It has been demonstrated that the slump test is sensitive to changes in moisture content but not to variations in aggregate gradation. (Fig. 30).

The remoulding test is very sensitive to changes in gradation, to particle shape and in fact to any factor which affects the mobility such as changes in the inherent plasticity of the water-cement paste.

Figures 50 to 55 are discussed in another section.

<u>The Standard Compacting Factor Test:</u> In Road Research Technical Paper No.5 [26] a full description of the Standard Compacting Factor Apparatus and the method of performing the test were given.

The apparatus was designed by the Department of Scientific and Industrial Research to measure workability directly, the idea being that the nearest approximation would be to measure the applied work necessary to produce a certain required increase in the degree of compaction. If the work done on the concrete were standardised, the degree of compaction would be a measure of workability.

To appreciate the significance of the test, it must be clearly understood that workability is measured, under Glanville's definition, by the amount of useful internal work necessary to compact the concrete from the freshly mixed state to a specified final state. (see p 20).

The compacting factor is defined as "the ratio of the absolute volume of a partially compacted mix to the volume which it occupies; i.e. the ratio of the absolute volume to the absolute volume + the volume occupied by the air voids. The compacting factor is also equal to the ratio of the density when fully compacted, if the weight of the air voids be neglected."

The compacting factor is simply a measure of the degree of compactness in a partially compacted state. A compacting factor of unity means that the concrete is fully compacted. A compacting factor of 0.78 is described as "very low", 0.85 as "low", 0.92 as "medium" and 0.95 as "high".

In the test, illustrated in figures 56 to 59 , concrete is allowed to fall under standard conditions from a fixed height into a mould and compaction is produced by the kinetic energy of fall.

The Standard Compacting Factor Apparatus has been designed in two sizes. The smaller one being suitable for use with concrete containing aggregates up to a maximum size of ¾ in. and the larger one for aggregates up to 1½in.maximum size. Compacting/...

Compacting factors obtained by the large apparatus are, in general, higher than similar results for the small apparatus; but the results are related.

The small apparatus is illustrated in fig. 56

Hopper A is filled by hand and the degree of compaction at this stage will depend not only on the characteristics of the concrete but also on the method of filling. The concrete is deposited into hopper B by dropping a hinged door at the bottom. Hopper B has a smaller volume than A. The personal effect is greatly reduced when the concrete enters B, because its condition there is largely determined by the drop A B. Hopper B is always filled to overflowing and for a given mix and consistency will contain an approximately constant volume of concrete. Finally the concrete is released from B into C, which is a cylinder 12" high X 6" internal diameter. C is filled to overflowing and the surplus struck off by simultaneously working two trowels from outside to centre.

The concrete in B approaches a standard state and a standard amount of work is done on it for a given condition of fall into Hopper C.

An examination of the behaviour of the concrete in falling from the upper hopper, through the lower hopper, into the container below reveals that the ratio of the total applied work done in falling, to the useful work induced for the compaction of the concrete cannot be constant for all concretes. Indeed, it is far from constant, and the apparatus tends to favour well lubricated, wet, smooth concretes - i.e. the more plastic mixes.

Consider two concretes of different characteristics, one a stiff, sticky, cohesive concrete and the other wet to sloppy but smooth and rich. The former, deforming reluctantly, will slide very slowly from the hoppers and, indeed, in an extreme case may need assistance. Concrete will fall from the hopper in a loose, dispersed manner induced by the restraint of the sides of the hopper. In the case of a cohesive mix, concrete which has left the hopper on its "free" fall is restrained for a certain part

of/...

of the fall by its attachment to that part of the concrete still moving slowly downward in the hopper. The restraint ceases when the falling concrete breaks away from the upper mass. It is no longer in the compacted state prevailing in hopper B before the gate was released. The falling mixture is in an uncompacted, ruptured state. The latter type of concrete, on the other hand, will pour very rapidly from the hopper and will attain a greater velocity on the downward trip. Between the two extremes there is a varying range of behaviour which will determine:-

a) the state and amount of the concrete in the lower hopper B;

b) the amount of rupture or dispersal on leaving the hopper B;

c) the amount of useful work available for compacting the concrete in C.

Different concretes will not attain the same "standard" state in hopper B because, for equal work done on them, the more workable will be the more densely compacted. When the test is used for the control of a particular mixture, rather than for the comparison of concretes of different workabilities, the concrete in B can be considered to be in a standard state.

Segregation, especially in concretes of wetter consistencies, causes false values of compacting factor to be obtained, and the greater the segregation, the larger the error in the calculated compacting factor. This is because the heavier particles (of coarse aggregate) displace the mortar and /or cement water paste alone to an extent depending on the degree of segregation. Thus, with concretes of a sloppy consistency, compacting factors greater than unity can be obtained. (See tabulated test results.) Thus a wet concrete which requires a high remoulding effort or fairly high pressure test value, because of segregation, will have a high compacting factor. (Note this effect in figs. 61, 62, 64, 65) The author believes that mixtures with even a little tendency to segregation are slightly

favoured/...

favoured by the standard compacting factor test, and as segregation becomes more severe the bias increases.

Correct calculation of the compacting factor depends on a knowledge of the exact amount of each ingredient in the mould. It also requires accurate values of the various specific gravities on a saturated and surface dry basis. The specific gravity of the cement in an unhydrated condition is required. In assessing the workability of trial mixes, the calculation of the absolute volumes is tedious and in certain trial methods the proportions of each mix are not usually worked out.

Difficulty was experienced by the author in testing certain cohesive, sticky, dry to stiff concretes. The concrete would not flow unassisted from the hoppers and had to be given an impetus. This did not occur with dry, crumbly non cohesive concretes, nor with any of the more plastic mixtures.

The apparatus cannot be used for testing concretes containing large aggregate of, say, 3" maximum size, which detracts from its usefulness in a concrete laboratory. Concretes containing aggregate over 1½ins. could be wet - screened, although the behaviour of the screened concrete may be different from that of the original batch.

The standard compacting factor test does not distinguish sufficiently between workable (or wet) mixes in the range c.f. 0.92 to 0.95 or greater. It is difficult to decide on the relative merits of concretes having similar compacting factors within this less sensitive range. This is a pity because mixtures in this region are very extensively used in reinforced concrete work, especially in thin sections.

The above remarks are illustrated in figs. 60 to 65

Harsh or wet, undersanded concretes, including those which tend to segregate are not penalised to the same extent as in the remoulding test.

The different interpretations given by the two tests are strikingly illustrated in figs.52A and 62A which have been plotted from test results on the same series of mixtures. In

fig./...

FIG.62A, the differences between the most workable and least workable series are small. The segregation has not been illustrated. The compacting factor interprets the series containing 40% sand (by weight of total aggregate) as being more workable than the 50% sand series. On the other hand, according to the remoulding efforts the 40% sand series is undersanded for this W/C (0.70) and is shown to be less workable than the 50% sand series. It is probable that both interpretations are biased - each in the opposite manner.

Segregation tends to increase both remoulding effort and compacting factor.

The Pressure Test Apparatus:

This test was evolved by the author in the Civil Engineering Laboratories of the University of Cape Town. The study of the effects of internal resistance to deformation of concrete led to the conclusion that an effective method of measuring the force necessary to change the shape of a mass of concrete would be valuable in assessing workability. In the test, a flat cylinder or disc of concrete is deflected and the pressure necessary to cause a particular deflection is recorded.

Description of Apparatus: The Pressure Test Apparatus (P.T.A.) is illustrated in figs. 66 to 75 . It consists of a $^3/_{16}$" steel disc (A), 16 ins in diameter, which is pierced near its centre by three holes. Welded to the holes are three motor tyre valve tubes, a, b, c, being air inlet, manometer and outlet valve attachments, respectively. "b" has no internal valve fitting.

Sandwiched between the plate or disc (A) and the ring (B) is a diaphragm (C), cut from rubber sheeting $^3/_{16}$" thick. The ring (B) has an internal diameter of $12^3/_{32}$ ins. The lower assembly is supported on 3 legs, consisting of ½"x 5" carriage bolts.

The container (D), made of 18 gauge sheet metal, has an internal diameter of 12 ins. and is 3½ins. deep. It is provided with two handles. It may be fitted in position within the ring (B) and rests on the diaphragm.

The upper portion of the apparatus is made up of two rings (E) and (F) which hold the upper diaphragm (G). The lower ring (E) has an internal diameter of $12^{13}/_{32}$ ins. and can fit over the rim of the container. The upper ring has an internal diameter of 8 ins. The significance of this dimension is discussed later on. The upper diaphragm is made of ⅛" sheet rubber. Mounted in a central position above the upper diaphragm is a large deflectometer (H) which reads to $\frac{1}{100}$ inch and has a range of 0.60 in. The actuating arm of the deflectometer is attached as shewn to the centre of the diaphragm.

The/...

The Container is clamped in position between the upper and lower assemblies by means of four bolts and wing nuts.

Other Accessories: A small motor-tyre pump (a bicycle pump will also do; in which case the valve "a" must be a bicycle tube valve); a U tube manometer containing mercury, with as big a range as possible. (This may be replaced for field use by a sensitive large dial pressure gauge, range, say 0-15 P.S.I. For concretes of the wetter consistencies the manometer is essential;) standard $\frac{5}{8}$"d bar, 18 ins.long, bullet pointed; scoop and usual mixing utensils.

Preparing for Test: Figs 70 & 71 shows the apparatus ready for use. All metal parts are kept lightly oiled to assist cleaning and prevent rust. The motor pump is screwed onto valve a. The manometer is attached to tube b. All air is expelled from the apparatus through c. The diaphragms and container are moistened with a damp rag before each test.

Standard Methods of Filling the Container: With the container resting in position as shewn in fig. 72, the apparatus is loaded with concrete estimated to be sufficient to fill it. The concrete is rodded, giving 25 strokes of the standard bar. Then, by means of the rod placed across the upper rim of the container, the concrete is tamped as may be necessary and screeded off. It is important for the container to be exactly filled with concrete. An alternative method of compacting, for laboratory use, is to stand the apparatus on a flow table and, after filling the container as before, giving 5 half inch drops before screeding off the surface.

The rim of the Container having been wiped, the upper assembly is placed on top and secured in position by means of the 4 bolts and wing nuts. The nuts should be tightened evenly, diametrically opposite sides simultaneously. They should not be screwed too tight.

Performing the Test: (Figs. 73 & 75) Air is pumped in with

steady/...

steady strokes until the required deflection is indicated on the deflectometer. The pressure is immediately read on the manometer to 0.1 inch of mercury. Pressures can be recorded for each 0.1 inch deflection up to 0.6 ins. If an assistant work the pump the operator can record the pressures very rapidly, the whole test taking a matter of seconds. On the completion of the test the load is released by pressing the valve "c" until most of the air has been expelled. The stiffer concretes will retain some of their deformation on release of the pressure. The test may be repeated without disturbing the concrete and so the behaviour of the specimen for several deflections may be observed.

In this test, the effects of surface friction between mould and concrete are eliminated. There is no relative movement between container and concrete, and only very slight movement between concrete and diaphragm. The only measureable forces resisting deformation are caused by the internal stiffness, cohesion, friction and particle interference, etc, of the concrete itself. In almost all other tests, there is relative movement between a metal surface and the surface of the concrete, involving friction which is very difficult or impossible to measure or standardise. The readings obtained in this test are characteristic of the concrete and the severity of the test alone and are independent of the meterials of which the apparatus is made and of their surface condition.

The severity of the flow induced within the concrete can be varied at will by changing the internal diameter of the upper ring (F). For general purposes it has been fixed at 8 ins. For a more severe test, useful for wet consistencies, the internal diameter of the ring (F) can be reduced. A ring having an internal diameter of 9 ins. has been found to be useful for concretes of dry consistency (zero slump). With the internal diameter of 8 ins, all but the very dry and harsh concretes can be tested to full deflection and these latter concretes can be tested to some intermediate deflection.

In figs. 76 to 112 are plotted the results of several series of tests. Details of the tests are given in appendix (C). The implications of the results are fully treated in another chapter. Here the test method only is discussed.

Figs.108 - 112 show the characteristic relationships between pressure and deflection. In performing each test, the pressure was noted for each 0.1 inch deflection up to 0.6 inch. The yield value can readily be computed for each concrete after plotting the curve.

The value of the pressure in inches of mercury corresponding to a deflection of 0.6 inch has been chosen as a convenient figure on which to compare concretes. This pressure has been called the PRESSURE TEST VALUE and abbreviated PTV. It has been selected because it is a direct measure of the relative work expended in distorting the concrete and can be read off directly. Values based on, say, the slope of the characteristic curve are valuable in assessing mobility but are not so convenient in the field. The PTV does not completely describe a concrete. For example, there may be two concretes having the same PTV, one with a low yield value and a flatter curve and the other with a higher yield value and steeper curve. Compare the curve for Batch No. A16, fig.108, with that of Batch No.C123, fig.109. Again, the slope of the curve is not constant. There are two main types of normal curve.

a) A curve roughly parabolic throughout its whole range. This type is usual for the more plastic concretes having PTV's up to about 6 or 7 inches.

b) The curve starts rather steeply and curves to a fixed slope within a deflection of about 0.2 inches. It then follows a straight line to the maximum deflection. This type is characteristic of the harsher and dryer concretes.

The characteristic flow curve does define a concrete completely with regard to plastic properties within the range of test. It would be possible to devise an apparatus such that sufficiently severe flow could be introduced to cause rupture in any concrete, thus completely defining plasticity.

However, for the purpose of designing a concrete, it is sufficient to know that rupture does not occur at a deflection of 0.6 ins. or less.

Note/...

Note the very close conformity of the plotted points to the curves in figs.108 and 109. This is a feature of the test. Unless one of the phenomena indicated in figs.110 or 111 occur, the plotted PTV's will always be found to agree very closely with the curves, for any single test. If the concrete is retested after remixing, or a similar concrete be tested, it will be found that another smooth curve will be obtained. However, these two curves may not in every case be absolutely coincident. This is because, apart from unavoidable differences in moisture content, grading, etc, the actual arrangement of the particles plays a part in deciding the internal resistance. The ease of deformation depends to a certain extent on the amount of working the concrete has received in the same direction.

Fig.112 has been drawn to show this effect.

The test was performed in the usual way and immediately the maximum deflection was reached the air valve was opened and all air expelled. Then, without removing the concrete from the container, the test was repeated to full deflection. This was repeated until a constant PTV was obtained. It was found that the effect reported by Powers & Wiler was strikingly demonstrated.

The second deflection gave a greatly reduced PTV, whilst subsequent deflections produced smaller reductions in PTV., very little change being evident after the third test. When this stage has been reached the particles have taken up the configuration which offers the least resistance possible to flow in the vertical direction and in this stage the ~~vertical~~ PTV's will be independent of the previous history of the sample. Repeat tests show better agreement between PTV's for the 3rd deflection than for the 1st deflection.

Slight discrepancies in the PTV's for repeat batches are only evident because the test is so sensitive. If a pressure gauge be used instead of the manometer as described earlier, these differences are not evident and sufficient accuracy may be obtained for field use.

Figs.110 and 111 illustrate phenomena encountered in the tests/...

tests. The implications of these effects are discussed in Chapter 5. Slip flow is characterised by a sudden increase in deflection, with corresponding slight drop in pressure, as the normal test is proceeding. Or there may be a small steady rise in deflection, with slight drop in pressure, after every increment of pressure throughout the test. In this case the PTV can be estimated by plotting the probable normal curve.

Discontinuous flow and failure occur only in concretes which offer high resistance to flow. Due to severe particle interference there may be a period of increase in pressure with no corresponding increase in deflection. A point is reached at which there is a sudden failure or rupture of the specimen and large deflection increment.

Experiments with different ring clearances and several diameters of ring "F", of the remoulding apparatus and the PTA respectively have revealed a useful empirical relationship between results. With a ring clearance of 3 inches on the author's remoulding apparatus and ring "F" diameter, 8 inches, ten times the pressure in inches of mercury (for a deflection of 0.6 inches) is very roughly equal to the remoulding effort. Figs.104 - 107 show this relationship. Agreement is fairly good, indicating that the two tests measure the same property.

Points plotted above the straight line graph indicate either that the corresponding concretes are penalised by the remoulding test or that the pressure test tends to favour them. It is well known that concretes which tend to segregate are penalised by the remoulding test, any such tendency being accentuated by the action of vertical jigs and lateral flow. The mortar flows outwards in the container, leaving a compacted, harsh, less plastic mass within the inner ring (see fig.49). In an extreme case the plunger may be prevented from settling to zero even for very large remoulding efforts, indeed. This bias is especially evident in figs. 50 to 55 for mixtures having 33.3% sand by wt of total aggregate.

It should be noted that the points which in general fall

above/...

above the line (fig.49) represent undersanded mixtures. The medium - and slightly oversanded concretes conform closely with the empirical relationship, except for very low PTV's. The explanation for this is that for plastic concretes the yield point gives a pressure of at least 0.4 ins. of mercury (a very wet and mobile mixture) and corresponding PTV not less than about 1. Even concrete having a pouring consistency offers a certain internal resistance to deformation. The pressure test is thus able to indicate very small differences in seemingly similar concretes of this nature. In the remoulding test, such concretes will flow of their own volition on removal of the slump cone and, if well graded, will require very few jigs (less than five) to bring the plunger down to the zero mark. The Standard Compacting Factor test, too, will not bring out small differences between such concretes, as has been explained on page 48.

Other attempts to Measure the Properties of Fresh Concrete:

There are many other forms of "workability" apparatus; most suffer in that they are not related to a generally accepted definition of workability, and/or cannot readily be standardised, or are not sensitive to small changes in characteristics.

Some test methods of each of the types classified on page 27 are briefly discussed below.

The Method of Penetration: The early apparatus of Pearson and Hitchcock[38] consisted of a cylindrical steel mould clamped to the flow table. A $\frac{5}{8}$" steel bar was held over the concrete in the mould by a rider and allowed to settle under the action of the flow table drops. The number of drops required to make the rod settle 11 inches was taken to be a measure of workability.

A much later apparatus on the same principle was that of Humm[43], in which the cylindrical container $6\frac{1}{2}$" in diam X 12" deep was loosely filled with concrete. A smaller cylinder with a rounded or pointed end was placed on the concrete. Penetration and consolidation occurred when the apparatus was bumped or jigged on a flow table. Resistance to penetration was taken as a measure of workability. The degree of workability was, therefore, obtained from the curve for the relation between depth of penetration and the number of jigs. The cylinder penetrated comparatively easily into the loose concrete to a depth of a few inches and at the same time compacted it.

In both the above tests it was found that when a certain degree of compaction was reached and the mobility of the concrete no longer depended on consistence only but also on plasticity, compaction seemed to be replaced by better plastic flow. The more plastic mixes allowed the rod to settle more easily; the harsher mixes offered higher resistance. The property measured was actually the tendency of the mixture to pack under a definite amount of settling or compacting. A more complete interpretation seems to be lacking.

As the Pearson and Hitchcock apparatus seemed to lack precision, George A. Smith[61] developed an "improved penetration apparatus"

based/...

based on the earlier method. The concrete container was twice as large in cross-section and three hollow rods ½" in diam were used. In the other tests, the rod was allowed to settle under its own weight during the jolting of the flow table. This produced a consolidation of the concrete which penalised the leaner and harsh mixes. In the "improved" apparatus a hammer dropping from a fixed height was used to cause the penetration. The rods and driving mechanism were mounted on a moveable head which fitted on top of the container. The concrete was compacted by jigging on the flow table before the driving mechanism was fitted.

The energy expended in driving the rods through the concrete to the desired depth was computed as the "workability index".

Since resistance to penetration decreases as workability increases, the workability of two concretes will be inversely proportional to the indices obtained.

In the Graf[62] penetration test the concrete was placed into a standard container under specified conditions. A cylindrical plunger, having a certain diameter and weight and hemispherical at the lower end, was allowed to fall from a fixed height on to the sample. The depth of penetration was taken as a measure of workability.

Yoshida[66] reversed the procedure and measured the resistance offered by the concrete in pulling a wooden cone vertically upward from the concrete. He found that the test had all the disadvantages of Pearson and Hitchcock's apparatus.

The apparatus developed by Irribarren, described by Boeuf,[64] known as the "Docilimeter" is of inverted truncated conical form with a segmental lower portion. It weighs 22 kgs. The concrete to be tested is filled into a watertight box and the surface smoothed and tamped until the concrete begins to flow. The apparatus is then placed on the surface, held steady and then allowed to sink freely. On removal of the apparatus the diameter of the section to which it was submerged is taken as a measure of consistency.

The application of the penetration apparatus is mostly

limited/...

limited to concretes of consistencies met with in reinforced concrete practice.

<u>Drop Tests:</u> In these tests use is made of the differences in behaviour of concretes in dropping from a container through a certain height. Concrete of wetter consistencies, on striking a surface, will spread out more than the stiffer types. The most workable concrete assumes a more or less hemispherical shape, whilst heaps of a flat shape are formed by harsh or segregating concrete. An irregular shape is associated with cohesiveness.[36]

In an apparatus,[65] developed by the U.S.Bureau of Public Roads, called the "Plate Tester", the principle is applied by weighing the amount of concrete retained on a circular plate after being deposited thereon in a standard manner.

An interesting point claimed was that the test results showed that for any given mix the relation between consistency, as determined by this method, and water-cement ratio is essentially the same as the strength - water-cement ratio relationship, indicating that it would be possible to use the test as a direct measure of the probable strength of the concrete. "The test results likewise indicate that variations in size and type of aggregate do not affect results to the same extent as in the slump or flow tests."[65]

The test was used as a practical method of controlling the water in the mix. It was designed as a substitute for the slump test.

In Yoshida's test[66] concrete is dropped in a standard manner from a mould, similar to a flow table cone, onto a wooden plate and the mean diameter of the spread concrete is measured. This reading divided by the lower (larger) diameter of the cone was proposed to express the value of "workability".

In Gaber's test[67] the concrete is deposited from a container in the form of an inverted truncated cone with a hinged bottom - similar to the hoppers of the Standard Compacting Factor apparatus - into a shallow plate of conical shape. A mound of concrete is formed of a height depending on the consistence and

workability/...

workability. Several tests having been made, the height for the particular concrete tested is marked on a scale attached to the apparatus and serves as a guide for control. For different ranges of consistency different dimensions were proposed for the apparatus. A sufficient degree of accuracy in determining differences in water content of both pourable and earth damp concrete was claimed.

The heap test,[36] in which a mass of concrete is allowed to fall from a conical hopper onto a flat steel plate, furnishes visual and qualitative results. The deposited concrete is left undisturbed and, after setting, is photographed, thus providing a permanent record for future study.

An idea behind the action of all these drop tests is that the concrete is subjected to treatment similar to that in depositing it by shovelling or chuting.

As the shape assumed by the concrete deposited in a drop test is a complex function of workability and consistency, any quantitative results can be used only as a means of control and not as a direct measurement of workability.

<u>Mixer Tests:</u> Pearson used a horizontal axis mixer to plot the flow-pressure curves of cement pastes.

Purrington and Loring[39] conducted experiments on workability by measuring the power consumed in mixing the concrete in a tub type mixer with paddles and a moveable centre post. They found that:-

(1) Power consumption increased with the richer mixes.
(2) The time required uniformly to mix concrete may be determined by the power curve.
(3) The rate of absorption of water by cement particles varied greatly with different brands of cement; the more the hydration the greater the power consumption; and vice versa.

The apparatus did not, however, show very big differences between different concretes and there was a large element of friction in the machine.

More recently, some contractors on Bureau of Reclamation works in the U.S.A., have used electrical torque measuring meters that indicate variations in the power consumption of the mixer motor. However, this type, like the early model, has been found to lack sensitivity, especially with lean stiff concrete.

The principle on which many of the practical consistency indicators or meters work is that concrete falling from the blades of the mixer strikes a reaction cone, plate or bar and actuates the indicating mechanism. This type of meter is suited to non-tilting mixers; but is mechanically difficult to apply to tilting mixers and a new type of meter was developed for use at Grand Coulee Dam.[30] This consistency meter indicates relative differences in the overbalancing effect of the concrete in a tilting mixer of the bowl type. In the mixer's normal operating position the axis of rotation is inclined and any building up of the depth of the concrete in the rear of the drum tends to upset the balance of the mixer on its trunnions and increase the inclination of the axis. The drier the mix, the higher the concrete builds up in the drum and the greater the overturning moment.

These types ofconsistency meter can be coupled to give a continuous record on a chart and, if reliable, they have obvious advantages over any form of apparatus which measures the condition of concrete which has already been discharged from the mixer. Variations in consistency can be detected quickly and steps taken for immediate correction. These variations may, of course, be due to changes in grading or proportions as well as water content. The U.S.Bureau of Reclamation insists on regular slump tests to supplement the meter record, as the machine is not considered to be a sufficiently reliable guide.

Deforming Tests: An apparatus developed by Smith and Conahey[40] measured the resistance of a mass of wet concrete to deformation under a laterally applied load. A flexible metal mould 10" diam X 6" high had its bottom edge fitted with a rubber rim to reduce friction when the cylinder was deformed. The base plate, on which the cylinder rested, was of plate-glass, placed on top of a small

flow/...

flow table. The mould was filled by jolting on the flow table. The load was applied by squeezing the sides of the mould through a system of levers actuated by shot running into a bucket. Individual tests showed wide variation (for the same batch of concrete). There were very small observed differences for large differences in workability and the apparatus could not be made sensitive enough.

There are several developments of the Powers' Remoulding Test. Wuerpel[72] and Bährner[73] (the "Vebe" test) retained the fundamentals of the Powers Apparatus but accomplish remoulding effort by means of vibration because vibratory impulses are more akin to field conditions than the vertical drops of the flow table. Both of these vibratory remoulding tests are claimed to be very sensitive to small changes in gradation, paste content, etc.

Wuerpel expresses the remoulding effort in terms of the number of seconds required to remould the specimen. In the "Vebe" test the adjustable inner ring of the Powers' remoulding apparatus under which the concrete has to flow, is omitted. A glass disc which exactly fits the container takes the place of the rider assembly and weights the concrete specimen. The consistence is expressed in "degrees" which are obtained by multiplying the ratio of the volume of the specimen after vibration to the volume before vibration by the number of vibrations required to cause the specimen to settle until the upper surface is quite level.

As concrete which has a wetter consistency than about 2½ inches slump segregates badly and clouds the results, such mixes are unsuitable for testing in these vibratory machines. A parallel is that concrete for vibration in the field would be expected to segregate if it were of a consistency wetter than 2½ to 3 ins. of slump. The vibratory remoulding tests are therefore confined to the drier concretes, especially those suitable for vibration and for heavy sections.

A recently developed test of the remoulding type is the portable "mobility tester" (Mo-mätaren) of the Swedish State Testing Institute.[75] The apparatus, made of sheet metal, consists of a vertical cylinder to the bottom of which a semi-cylindrical

trough/...

trough is attached so that concrete can flow down from the cylinder into the trough. The tester can be hooked to a steel base so that it can be repeatedly raised and dropped two inches. To perform the test, the apparatus is held vertically and the cylinder completely filled with concrete. Workability is denoted by the number of drops required to cause the concrete to flow along the trough until its upper surface reaches the lower edge of the cylinder. The simplicity and portability of this test should ensure its use as a control test if the results prove to be reliable.

Compacting Tests: The Standard Compacting Factor test is the best known, least empirical and most reliable of this type of test and has been treated separately (p.p. 45 to 49)

The compacting tests measure the facility with which the concrete can be worked into certain moulds under certain conditions so as to obtain a mass free from cavities.

Samsioe[45,76] considered workability as a function of the innate properties of the concrete and the method of working this concrete into the mould (see p. 18). His test, developed at the Swedish Government Testing Institute, entails the packing of freshly mixed concrete into a cast iron box in a standard manner. In order to imitate reinforcement, the box is provided with ½" round steel bars fitted to its sides. The exactly filled box is weighed to determine the voids factor. Samsioe also determined segregation and surface characteristics of the concrete, the latter by allowing the concrete to set in the moulds.

The method of Faury and Lamare[77] is very similar. The apparatus consists of two moulds, of similar dimensions, one of which contains reinforcement bars. The concrete to be tested is filled into each mould in a standard manner, being compacted by a special prodder. When filled, the moulds are struck off and weighed. Thus the ability of the concrete to fill moulds or shuttering unde different conditions can be gauged.

Humm[63] used the steel container described for the penetration test (p. 57), fitted with a stamper. To perform the test, the

cylinder/...

cylinder is filled with 10 kgs of loose concrete, placed on the flow table and jigged until a predetermined weight per unit volume is approximately reached, the concrete being compacted by the stamper during the process. The idea is that the gradual process of consolidation can be watched and the energy represented by jigs related to unit weight. It was found that compaction occurs rapidly at first and until all open voids have been closed; further compaction can only be effected by eliminating the closed air voids. An "end point", however, was not observed. The determination of unit weight is held to be a reliable means of judging workability. The amount of energy required to compact the mix cannot be determined by this method because of the absence of an "end point" and also because the same degree of working cannot be produced throughout the mix at the same time. Energy is inevitably dissipated on concrete already fully compacted.

Another empirical compaction test is that of Hutchinson,[53] developed for the Claytor Dam Project, as a portable device for measuring the placeability of very lean, stiff mixes. The device consists of a vibrator having its point of greatest vibration attached rigidly to a hopper which is fixed to a base plate. Mounted on top of the hopper is a cylinder provided with a sliding gate at the bottom. A plunger slides freely within the cylinder and is equipped with a handle wider than the diameter of the cylinder. In performing the test, concrete is placed in the cylinder with the gate closed. The gate is then pulled and a certain amount of concrete drops into the lower hopper. The plunger is placed in the cylinder and comes to rest on top of the concrete. The time to vibrate the concrete into a compacted condition in the hopper is taken as a measure of placeability. The concrete is taken as fully compacted when the plunger handle settles onto the top of the cylinder.

Judging by published results, this test, which would be difficult to standardise, does not appear to be as sensitive as the vibratory remoulding test which it resembles in some respects. It is suited only to very dry, stiff concretes.

<u>Viscometer Principle:</u> Powers and Wiler[43] have developed a mechanism which should prove to be a useful tool in research on plasticity. The machine utilises the principle employed in certain types of viscometer. It consists of a vertical drum and container, with an automatic recorder which measures the torque on the specimen.

The sample may be tested in several ways. The container is caused to turn round its vertical axis and the rotation reacts on the drum through the material filling the space round the drum, producing a torque which is resisted by a stay bar acting through a lever and spring arrangement. Rotation of the drum is opposed by the spring. Any displacement of the spring is registered on graph paper moving 1 inch per second. Distortion of the material in the annulus is also recorded on the same graph paper.

With the ordinary rotating type of viscometer, rotation is continued throughout the test. If this procedure be followed using pastes or mortars, after a fraction of a revolution the sample fails in shear near the surface of the drum. The machine was so constructed that distortion can be stopped at any point, or the container can be caused to ascillate automatically through any desired arc.

In the early stages of their work on this machine, Powers and Wiler contributed much to the theory of the plastic behaviour of mortars and concretes.

<u>Rating the Qualities of Concrete by Systematic Observations:</u>

H.E.Davis and J.W.Kelly[47] introduced this method in a most instructive paper. They stated " that information regarding the characteristics of fresh concrete, based upon a systematic method of visual inspection, should occupy a more definite place in the record of fresh concrete tests than is now customary. Such information, as a supplement to the results of the commonly made tests provides a uniform basis for comparing the qualities of various concretes, particularly in ... trial mix tests, and serves as a guide to correct faulty mixes or to explain irregularities in the results of subsequent tests..."

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"An estimate of the quality of fresh concrete by visual inspection is necessarily based upon characteristics that are readily observable. Although some observable characteristics are partly or entirely the effect of others, causing some apparent duplication, each angle of approach is of value as evidence regarding quality."

The two forms, reproduced as figs. 113 and 114 were adapted by the author for use in experiments at the University and to aid in the adjustment and control of mixes in the field. The check list tends to ensure a more adequate record than when the observer merely comments on some factor which strikes him. In the laboratory, this system of recording results saves a deal of writing and helps to prevent the omission of readings. It also serves as an aid to the inexperienced observer.

Fig. 114 lists more characteristics than need normally be considered in the field and the observer is free to check only those items which he may deem necessary.

The lists are self-explanatory; but the following hints may help to achieve good results.

Items 1 and 2. Observations of consistency should be made at known and controlled times after mixing. If stiffening appear to be abnormally rapid, effort should be made to determine the cause.

Item 3. Although the complete definition of plasticity involves yield value, mobility and the plastic limit, for the purpose of visual inspection the observable characteristics are cohesiveness, resistance to indentation or hardness, and smoothness or the degree to which the plasticising component is present.

a. Cohesiveness. Some cohesion is desirable in order to handle with a minimum tendency towards segregation; too high a degree of cohesiveness produces tacky concrete with a resulting loss of workability. One indication of cohesiveness is the force required to lift a flat implement, such as a trowel, from the surface.

b. Resistance to indentation may be judged by trowelling or ramming the surface of the partly compacted concrete.

c. Presence/

c. Presence of Plasticising Component. The apparent sufficiency of paste or mortar, which imparts a lubricating quality, is called smoothness and lack of such an element is called harshness.

Item 4. The appearance or "feel" of the mix while it is being worked frequently indicates whether the properties are satisfactory. It is usually best to look for abnormalities in the mix; otherwise it should be classified as "satisfactory".

Item 5. In wet or undersanded mixes of low cohesiveness the tendency for coarse aggregate and mortar to separate during the period of handling and compacting. Bleeding is evidenced by the formation of small pools of clear water on the surface of the concrete which has been left undisturbed for ½ hour or so.

Item 6. Herein the qualities rated go to describe the inverse of the effort required to mould or form or finish the concrete. This rating will be influenced by the other factors which go to make up workability and should be based on a general consideration of those factors together with an estimate of the readiness with which the material can be consolidated into place.

Rating of Quality: Experience and judgment play a large part in filling in the form. The operator must bear in mind exactly what sort of concrete he needs for his particular purpose and must try to visualise its behaviour under field conditions. He will give weight to the consideration of the suitability of the concrete to the given type of construction.

"In judging the relative quality of concretes there appear to be some advantages in building up a composite rating or index from a consideration of the several individual characteristics. Not only are mixes of high all-round quality distinguished from those of low quality by such an index; but also in the attempt to secure a composite rating, the observer may detect defects..."

Numerical Rating Scale. For many purposes, it is desirable to express the degree of quality in a quantitative manner. The following rating scale has been suggested by Davis and Kelly:

10, perfect;/..

10, perfect; 9, excellent; 7, good; 5, fair, average;
3, poor; 1, very poor; 0, hopeless.

10 and 0 would only very rarely be used. Normally the major characteristics only would be considered but if desired some or all of the subordinate ones may be rated.

A composite-rating number can be built up, which includes all the properties considered. This has been called the "Quality Index".

Care and judgment must be exercised in the choice of significant properties and characteristics. These can be weighted if desired. It is important to have standards of reference which should be clearly defined and which should remain constant over a period of time. Photographs are of great assistance in showing ranges of quality and preventing "drift" in the observer's standard for rating.

CHAPTER 5: PLASTIC FLOW.

Fluid and Solid States: For the purposes of simplification, certain "ideal" properties are often ascribed to materials. e.g., definitions of rigid bodies, isotropic elastic bodies, perfect and viscous fluids, etc.

The classification of suspensions such as pastes or mortars as to a physical state, solid or liquid, is unsatisfactory and may be misleading. Rheologically they are liquids; but they possess many of the properties of solids.

In the perfect fluid the pressure at any internal section at rest is always perpendicular to that section. No shearing stresses can be developed in the liquid. On the contrary, the elements of a solid may carry shearing stresses which act tangential to the plane of the section.

Viscous fluids at rest behave as perfect fluids. Whilst in motion, however, they exhibit some properties akin to those of a solid. During flow, tangential forces are produced by the action of layers of fluid sliding over one another, continuous flow being a process of continuous shearing of liquid. Observed resistance to flow is the effect of this resistance to laminar shear. In viscous, or linear flow the rate of flow is, in general, directly proportional to the deforming force and the ratio of the latter to the former gives a measure of the viscosity. When the deforming force becomes sufficiently large, this ratio may suddenly drop, indicating that the regime of turbulent flow has begun.

Suspensions or Dispersions: The observed viscosity of a fluid gradually increases as the amount of suspended matter is increased, until resistance to shear approaches that of the solid particles themselves. Small amounts of suspended matter affect viscosity but little in spite of the fact that for mixtures of liquids viscosities are additive. As the concentration of suspended matter increases, viscosity is altered in a very definite manner. At higher concentrations the viscosity of a mixture is noticeably greater than that of the liquid alone and resistance to shear (i.e. to flow)

increases/...

increases very rapidly with concentrations approaching the order of pastes. As the proportion of solid phase increases, a point is reached where the viscosity (observed by, say, a capillary tube viscometer) becomes infinitely large for small forces.[83] That is to say, the fluidity, which is the reciprocal of the viscosity, has become zero.

If the solids in suspension be widely dispersed, the paste is likely to behave much like a fluid, although the force-flow curve will not be linear.[84] Pastes of high percentage of solid phase, such as cement pastes, exhibit some of the properties of a solid. In cement pastes even of a pouring consistency the forces of attraction between solid particles predominate over the forces of repulsion. For small forces such concentrations will display elasticity. Some minimum force, called the yield value,[43] must be exerted before flow starts, and this minimum force may be very small - the mortar, for example, will slump under its own weight to some extent unless extremely stiff.

Zero fluidity may be apparent immediately after mixing or it may be exhibited only after a lapse of time. In the latter case, the solidity is said to be the result of "thixotropic set". When the material is of this nature the yield value is not a fixed property of the suspension but depends to a larger degree on the history of the sample than with non-thixotropic suspensions.

<u>The Structure of Mortars and Concretes:</u> In a stiff cement paste the finest solids are so closely spaced and the water films so thin that polarised water, solvated layers, molecular cohesion combined with molecular adhesion, all play a part in the cohesion of the aggregation of solids; but such a paste cannot be classed as a true suspension of solids in water since the solids predominate. Powers, admitting that he lacks direct proof, nevertheless regards a cement paste "as a continuous network of particles in water, the bonds of the network being the forces of flocculation acting across small distances at points of near contact. In other words, a cement paste may be considered as one large floc; hence, all the water in a paste is within the floc".[85] On the other hand,

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in a paste made soft enough by adding water until it slumps appreciably, these finest particles are separated by water films too thick for molecular attractions to be transmitted across them from solid particle to solid particle. Such a paste, if plastic, can be classed as a suspension since the liquid phase predominates. Rhodes[86] divides the plastic state of soils into two parts when highly plastic clays are tested. A cohesive, but non-sticky, plastic state, and a sticky, adhesive, plastic state. Practical concrete mixtures that may be transported and placed principally by gravitation are in the adhesive plastic state.

This distinction is important because concrete mixtures have plasticity by virtue of the state of suspension of the solid phase. The solids are dispersed, separated and held apart in opposition to the gravitational and cohesive forces tending to agglomerate them.

The plastic suspension of solids by water, a lighter medium, implies, (1) maintenance for a sufficient placing time of enough clearance between the solids to permit free movement along planes of shear and a sluggish interchange of portions of the mass while being moulded, and (2) a vigorous retention of the water within the structure of the mix. Not only must clear water be kept from leaking from the cement paste, but cement paste must be retained within the voids of sand in mortars, and mortar within the voids of stone in concrete. Powers[87] has shown that bleeding of clear water begins immediately by a process of sedimentation when fresh concrete of high quality is placed and agitation has ceased. The forces causing flocculation of cement particles are responsible for the simultaneous settlement of large and small particles, until "arch action", or interlocking, of large particles causes them to segregate from smaller, settling particles.

<u>Coarse Structure:</u> Weymouth has considered the complex structure of solids varying from fine cement to coarse stone as an aggregation of size groups of solids.[27,28,29,43] Each size group, whatever the diameter of the particles, possesses an elementary structure in which the total voids are subdivided into a series of void spaces, called "void pockets". If the particles be large enough, of uniform size

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and piled up in close packing, each pocket would have a bulky volume outlined by the surfaces of surrounding stones with openings leading into adjacent pockets on all sides. A smaller particle just circumscribed in such a pocket would be much too large to pass through any of these openings. A size group of particles is, however, never "close-packed" in a mixture with finer particles, such as in concrete. Particles of the group are held apart from each other but are still capable of forming typical void pockets with bulky volumes and interconnecting openings, provided that their average clearance is not too much for them to have a definite structure.

The void pockets defined by the particles of any size-group are important because each contains its proportion of all the finer elements of the mixture of concrete. Freedom of movement of each such portion of the matrix is held in check by the surfaces outlining the pocket and by the size of the orifices leading from it. Conversely, the spacing of the particles of each size group is determined by the confinement of its matrix. This structure of size groups persists, according to Weymouth, even down to the microscopic cement solids.

<u>Structure at the Finest Range of Solids:</u> The matrix filling the finest void pockets of the paste consists of water with its concentration of colloidal cement solids and hydration flocs. The rate of hydration of the finest, and therefore the softest, cement particles is believed to be very rapid. Cement is usually strongly hydrophilic.[86] The whole surface area rapidly wets and hydrates, even in the flocculated condition, as there is no particle to particle contact, the flocs being held together by forces acting across a thin film of water. The concentration of hydrous material in the water films is undoubtedly increased by that rubbed off the larger solids during the mixing period.

Any structural air present would be in the form of microscopic bubbles and would be found within the smallest void pockets, tending to impede free movement of flocculent elements into adjacent pockets. While clear water leaks, or "bleeds", through the orifices of these primary pockets when agitation has stopped in a concrete mass, the system of void pockets traps all fine elements during sedimentation and prevents free settling. Powers[47] has stated that "in spite of the fact that the largest particles present may be a thousand times the size of the smallest ... the particles of various sizes and densities do not settle independently, but all move in unison, the finer particles being carried down by the coarser ones". This process of sedimentation causes a progressive compaction from the bottom stratum upward.

Plastic Flow of Suspensions: Consider a dispersion consisting of discrete solid particles. Fig. 115 represents particles of the solid phase, set in motion by distortion of the specimen. Disregarding the forces of suspension, consider particles in strata which are moving relatively to one another.

The shearing of the liquid phase which causes any cubical figure of fluid to assume the form of a rhombohedron, will cause solid particles to rotate, thereby assisting flow.

Stream lines are curved owing to the presence of the solid particles; but the particles themselves move in linear directions, each with the velocity of the stratum of fluid which would, if continuous, pass through the centre of the particle. Particles in the same stratum do not approach each other since they have equal velocity. Solid bodies in different strata will have unequal velocities and collisions will result with a frequency depending on the proportion of the solid phase, the sizes of the particles, and the mutual attraction or repulsion.

Surfaces of two solid particles which are approaching each other must be moving in opposite directions, which are at right angles to the line joining their centres. Viscous resistance to this induced shearing action as the gap diminishes will rapidly dissipate as heat the energy of rotation.

The near contact of two particles, which are large in comparison with molecular dimensions, brings the laws of ordinary friction into play. The bodies cannot rotate unless the torque exceeds a certain value depending on the pressure at the point

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of contact. This pressure, in turn, depends on the rate of shear and the attraction or repulsion which may exist between the particles.

During the period of contact, the group of particles begins to rotate as a whole, whilst the liquid phase flows around and between them, and some of them pass out of the strata to which they formerly belonged and into layers of different velocities. Fig. 15 illustrates this. Thus other spheres tend to collide with the groups and the combined mass tends to rotate as a whole. When equilibrium has been reached, these agglomerations will have a certain average size, depending on the size, number and specific attraction of the particles.

In pastes and mortars exhibiting plasticity all these groups are in contact with each other and there can be no viscous flow. That is to say, the concentration in which the fluidity becomes zero under a very small shearing force serves to demarcate the viscous and the plastic states of matter. As has been stated earlier, concentrations of the order represented by the usual cement pastes and mortars have zero fluidity or infinite viscosity and will not be permanently deformed by very small shearing forces. These suspensions possess plasticity and any attempt to measure their "viscosity" is obviously futile.

In the adhesive, plastic state, the structure is held together by forces of attraction between the particles of the solid phase, and these forces of attraction are responsible for the rigidity of the concentration. The initial rigidity, or yield value, is determined by the sum total force of attraction between the particles at the initial mean distance between particles corresponding to the arbitrary proportion of liquid. When the proportion of water in a cement paste is increased, the distance of separation is increased, resulting in a decrease in the total force of attraction and hence a decrease in yield value, as observed.

When plastic distortion takes place, the solid particles are forced relatively closer together in the direction of the unilateral stress. This is indicated in the case of coarse suspensions

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by the well-known laminated structure of impurities and of air bubbles in plastically compressed pastes. Another effect is that elongated or flat particles, owing to their flow, and by slipping rolling and rotating, contact each other more and more at their faces, rather than at corners and edges, and therefore over a greater surface.

Plastic flow implies excess free space between particles. If the void pockets of each size group were densely packed with solid particles so that there were no freedom of movement, there would be no plastic flow. Permanence of deformation implies that bonds are broken completely during plastic flow and new ones are formed. If bonds were merely stretched without yielding, elastic flow or elastic after effect would be evident.

Increasing resistance to plastic flow derives from the approach to a closer configuration of particles of the disperse phase. The greater the specific force of attraction, the more stable the structure is and the more it retains its original shape during plastic flow.

Effect of Rate of Deformation: The effect of the rate of deformation of a plastic suspension is twofold. A change in rate may affect plastic resistance. Secondly, a finite rate of deformation introduces an independent viscous resistance which is to be added to the plastic resistance to obtain the actual total resistance. At moderate rates of deformation the viscous component of resistance is so small that it can be neglected when considering the plasticity of cement pastes, mortars and concretes. Whatever its value, the viscous component may be reduced to an indefinitely small value by a sufficient decrease in the rate of deformation. The plastic resistance can then be gauged.

The effect of rate of deformation on the constants of plastic flow should be a second order one since plastic resistance depends only on the static configuration of a plastic mass. This has been demonstrated by Roller.[88]

The Plastic Limit: It has been demonstrated that the characteristics of plasticity are the yield value and the manner in which the material responds to forces greater than the yield value.

Powers/...

Powers and Wiler[43] pointed out that it does not follow that these two factors are sufficient to descfibe fully the degree of plasticity possessed by a given material. An essential factor in defining a plastic is the amount of distortion which it can continuously and permanently sustain in any direction <u>without rupture</u>. "Without rupture" implies not only that any given solid is plastic while it is deforming continuously, inelastically and without rupture under stresses greater than the yield value; but also it implies that when the same material ceases to deform in this manner it likewise ceases to behave as a plastic. Thus, a "limit on the inherent capacity for plastic deformation is an essential part of this concept".

<u>Dilatancy:</u> As a plastic suspension distorts, solid particles are being forced into a closer configuration in the direction of the unilateral deforming stress. The limit of plastic distortion is finally reached and is marked by the beginning of structural failure, rupture, or by the phenomenon known as dilatation.

Dilatancy may be defined as "having the property of increasing in volume when changed in shape, owing to an increase of space between the particles."

When the range of free movement of the solid particles has become sufficiently restricted, grains in adjacent planes of shear interlock as they attempt to slide past each other. If the distortion is forced beyond this limit, particle interference causes the mass to expand. Dilatation takes place.

An example of dilatancy, quoted by Powers and Wiler, was given by the originator of the term, Osborne Reynolds,[89] in 1885. Wave-beaten beach sand whitensand appears to become dry with each footfall; but takes on its original appearance when the pressure is released. This phenomenon is caused by the displacement of closely-packed grains which have assumed such an arrangement that only slight deformation can occur without dilatation.

That dilatancy may, under certain circumstances, involve the element of time, was demonstrated by Freundlich and Röder[90] using certain fine powders mixed with water.

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A mass, which may be capable of a given amount of plastic deformation at a low rate of flow, may, at a sufficiently high rate, exhibit marked dilatancy, apparently because the particles do not have time to find paths in which free movement might have taken place.

In general, in any mass so constituted that the particles are restricted in their movements, dilatancy will occur at some degree of distortion. Futhermore, even if it be geometrically possible for any particle of a dispersion to find a free path through the mass, the system may become dilatant at a sufficiently high rate of distortion.

Effect of Working on Workability. It is well known that the workability of a concrete depends not only on the constituent materials but also to some considerable extent on the history of the mixture with regard to the amount of mixing or puddling which it has received.

Powers and Wiler demonstrated, with their viscometer type apparatus, the effects of repeated cycles of a unilateral motion and showed that a concrete offers less resistance to subsequent distortions than to the first.

The Pressure Test provides a useful tool for the study of this effect. Consider the curves in Fig. 112 which were prepared as described on page 54. The curve for the first deflection lies to the right of the curves for repeated deflections in each case, higher pressures being needed. There is a big drop in the energy expended on the second distortion compared with that for the first. The concrete offers still less resistance to the third deflection cycle; but the reduction is less than between the first and second. The fourth deflection may see a slight further reduction in resistance to movement. Subsequent deflection cycles will produce a single curve. It is usually sufficient to perform three deflections, there being very difference between the third and fourth.

When concrete is loaded into the container the arrangement of solid particles is a random one which offers a maximum of particle interference. When flow takes place a certain amount of energy is expended in rearranging the solid particles so that in their new configuration they offer less resistance to movement in the same or opposite direction; when the particles are in the configuration which offers the least resistance to flow, more working will not produce improvement in workability. In Fig.112 it is seen that the left hand curve in each case describes this state which is independent of the method of filling the mould. It is suggested that the relationship between the 1st. and 3rd. deflections would provide a plasticity index and help to define a concrete. The author has found that for harsh lean concretes (such as D.165 in Fig. 112) the proportional reduction in pressure on repeated deflections is far greater than for plastic, rich mixtures (see D.158) in which particle interference plays a smaller part. In the field, the PTV's for the 1st. and 3rd. deflections could define the behaviour of a concrete. The author has as yet insufficient data to put this proposal in more specific terms.

<u>Special Types of Flow.</u> Fig. 110 shows a type of flow in which slips occur. As explained on page 55, there may be a sudden in deflecting with corresponding slight drop in pressure, as the normal test is proceeding. Or there may be a small steady rise in deflection with slight drop in pressure after every increment of pressure throughout the test. It is probable that the effect is caused by the difference between limiting friction and a reduced coefficient of friction during flow. Discontinuous flow and failuee or rupture of the specimen, as in Fig.111, occur in concretes which offer hogher resistance to movement, as for harsh, lean and stiff or sloppy, segregating types. This mechanical failure takes place when the force inducing flow exceeds the frictional forces of resistance caused by the mechanical interlocking of particles. Particle interference may be so high that periods of no deflection occur, whilst pressure builds up. In extreme cases this may continue beyond the limit of the apparatus In other cases, periods of no deflection may be followed by failure of the specimen, which may regain its homogeneity after a small slip or may rupture completely.

CHAPTER 6 : FACTORS INFLUENCING WORKABILITY.

General Considerations: In the foregoing discussion, some of the factors influencing plasticity have been set forth and illustrated. Plastic concrete was described as containing various sized particles of solid phase, each size group forming a system containing voids enclosing smaller particles, the whole being dispersed in the continuous body of water and all solid particles or groups of particles having a certain freedom of movement.

An unworkable concrete on the other hand, has a rigid structure of solid particles, locked together.

Consider, now, some of the more practical aspects of the problem.

T.C.Powers in a very important paper[26] reporting his earlier studies of workability and his development of the "Remoulding Apparatus" stated, "One phase .... of the study of workability is that of finding those combinations of particle sizes which, when combined with a definite quantity of water, will be held in suspension by the water, forming a plastic mass of the desired mobility."

It has not been easy to establish all the forces governing workability, as defined in Chapter 3, see page 21 . The study of workability involves far more than plasticity and in practice, under many placing conditions, the concrete may find its final shape not entirely by plastic flow. The process of placing concrete was taken by Powers to be one of "remoulding", i.e. changing the shape of a mass of concrete from one form to another. In the field such a process is easily recognised. When a mass of concrete is dumped in a heap and worked into place in the form it undergoes distortion which may be less than or greater than the plastic limit. In the latter case, the continuity of the mass will be temporarily ruptured, as was explained above.

The ease, under a given condition of placement, with which movements within the mass are accomplished is dependent on the size, shape and surface characteristic of the aggregate particles and the quality, quantity and character of the medium in which they

are/...

are distributed. It also depends on the history of the sample with respect to mixing, working, etc., and the time factor. Cohesion or lack of segregation depends on the same factors as those which influence ease of movement but do not always function in the same direction to affect the amount of work necessary to place the concrete. e.g., increasing the quantity of cement, consistency and other conditions remaining constant, increases both mobility and cohesion within the mass. On the other hand, increasing the quantity of mixing water increases ease of movement under a condition of uniform distribution but decreases cohesion. Each of the various items has a definite effect; but water used as an admixture to increase mobility is most unreliable.

The total number of factors building up the quality of workability is uncertain; but, besides plasticity, segregation, stickiness and shear resistance are important. The appearance and "feel" of the mix while it is being worked frequently indicate whether the properties are satisfactory.

Powers found that in general, for any specific materials, workability appeared to be determined by the combined effects of three factors:[26]

(a) Quantity of cement-water paste per unit volume of concrete (lubricant)

(b) Consistency of paste - dependent on relative proportions and kinds of materials of which it is composed.

(c) Gradation, type and angularity of aggregate particles.

In addition, it must be borne in mind that proper mixing is prerequisite to achieving workability.

The general study of workability, therefore, resolves itself largely to a consideration of the conditions necessary to plasticity and of those factors which affect the degree of plasticity and mobility. The cohesiveness of a mixture, which is closely associated with the degree of plasticity, is also an important factor.

In addition, the severity of the placing conditions must be taken into account in evaluating the workability of a given concrete mixture, for a mixture plastic and mobile for one set of

conditions/...

conditions may have these properties to an inadequate degree when used under conditions more severe. The degree of plasticity and cohesiveness are inherent in the mixture; but the degree of mobility or placeability depends on the placing conditions.

Consideration of Cement Paste: It is strictly correct to consider the water as the suspending medium in concrete, and cement and aggregate as being dispersed therein. It is simpler, however, and in accordance with modern ideas to treat the paste of water, cement and other fine material, such as an admixture, as the matrix. The carrying capacity of the cement-water paste will determine the amount of aggregate to be used, as well as its grading. The first step in design is the selection of the water-cement ratio, which for any given cement, will determine the characteristics of the paste. The design problem, then, is to select a suitable type and grading of aggregates in the best proportion to the chosen paste, for the particular conditions of placement.

Paste Content: Reference to figures 76-91 shows that for any given aggregate gradation and water-cement ratio, increasing the paste content increases the mobility of the concrete, except for very fluid pastes or the coarser gradations, in which case the maximum mobility of the concrete may be found at some indeterminate paste content. Under the severity of the test, in this latter case, the point of segregation has been reached. If mobility be determined by the remoulding test the tendency to segregation will be accentuated. It will be noticeable in the pressure test; but compacting factors will increase steadily with increase in paste content, regardless of segregation. (figs. 54,55; 64,65).

Consistency of Paste: With both aggregate gradation and paste content fixed, stiffening the consistency of the paste may either increase or decrease the stability of the concrete, depending on the gradation and initial consistency of the paste. For example, a concrete which is dry and crumbling, lacking in necessary cohesion, may with increased water content, become of medium

consistency/...

has a twofold effect. Firstly, the greater total surface area causes the water film to become further attenuated, thus increasing the surface tension. Secondly, the particles, being further agglomerated, have less freedom of movement. Particle interference is increased during flow, to an extent depending on the concentration. A concentration is reached where the continuity of the suspending body of water has been destroyed and the mixture becomes crumbly and loses cohesion.

Kinds of Materials Composing the Paste:

From tests reported by Powers it appeared that when paste content, paste consistency and aggregate gradation were constant the kinds of materials of which the paste was made were of secondary importance to mobility. Fineness of grinding of the solid particles was of prime importance in determining the characteristics of a paste.

The above must be qualified, however, in the light of the behaviour of certain substances in the presence of water. A suspension containing a lyophilic substance would be expected to behave differently from a physically similar dispersion of lyophobic material.

Roller found that portland cement paste has a plasticity far greater than would be predicted, considering its fineness alone. The reason for this higher plasticity is the presence of a film of freshly formed gel around each particle. The gel arises from hydrolitic decomposition of cement. It may increase the total force of attraction, either by an increase in the effective area of contact owing to unequal growth or deformation of the

enveloping/...

enveloping film, or by an increase in specific attractive force due to unsaturated bonds at the surface.

Roller also suggested a possible material repulsion between cement particles when brought into too close a configuration. This of course, implies repellent forces greater than the ever-present forces of attraction (Van der Waal's forces). Powers suggested that there is an electrostatic force of repulsion, strongly dependent on the environment of the particles.

<u>Powdered Admixtures:</u> It has been claimed that the addition of certain finely ground materials to normal concrete, in addition to the cement content, improves strength, watertightness and workability. Typical admixtures are hydrated lime, diatomaceous earth, powdered sand, etc.

Notwithstanding the possible effects of certain substances on the suspension, the consistency (which for a given paste will determine its plasticity) and quantity of the paste are probably the primary factors determining workability, when the aggregate factor is constant. It would be logical to expect that the fineness and structure of the admixture would have a greater influence than its nature.

Non-workability or segregation may be due to low mortar content excessively wet mortar, excess of coarse aggregate or a comination of the above factors. Low mortar content may be due to low cement content (lean mix) with an aggregate which may be well-balanced with respect to the relative fine and coarse particles. The use of additional mixing water to obtain placeability results, in turn, in an excessively wet, segregating mortar which flows away from the coarse aggregate or which permits the coarse particles to settle out.

Fairly rich mixtures of low sand- coarse aggregate ratio (i.e. coarse grading) may also lack a sufficient volume of mortar to prevent particle interference in the larger size-groups and the addition of water in an attempt to gain mobility will result in segregation.

A non-segregating, homogeneous mix must have a sufficient volume of mortar to float and hold in suspension the coarser

aggregate/...

aggregate particles. This implies not only a relatively large mortar volume but a sticky, adhesive plastic mortar which will carry and hold the heavy particles in opposition to the agglomerating forces when the mass is set in motion.

The practical aspects are quite simple. The addition of fine materials to concrete affects primarily the properties of the paste. For example when cement is added to a mixture, without any increase in moisture content, it reduces the mobility of the paste. It also increases the volume of the paste by its own displacement, usually a very small amount. The increase in volume will, of course, generally benefit workability; but the effect of reducing mobility depends on other factors, such as the character and grading of the aggregates and the initial consistency of the paste.

Reduction in mobility of the paste may either increase or decrease the mobility of the concrete. This can be explained by considering the opposing effects of (a) the increase in volume of paste, which serves to reduce particle interference, and (b) the stiffening caused by increased surface tension due to the dispersal of the water over the surfaces of the added fines. Under certain conditions, a balance would be obtained at some optimum admixture content.

Mobility is not the only factor in workability and mixes lacking in mobility may have desirable cohesiveness; but a certain degree of mobility is indispensable and cannot be sacrificed for cohesiveness.

The rate of bleeding of water from cement paste can be slowed down by an increase in the surface area of the solid particles. Particles passing the No.200 sieve are of far more value in this respect than all except the finest fractions of the sand. The average fine aggregate contains only about 2 to 4 per cent finer than the No.100 sieve.

Powers[27] has shown that the rate of bleeding is inversely proportional to the square of the surface area of the solid particles, and the surface area contributed by even a small quantity of material of the order of fineness of portland cement (specific

surface/...

surface about 5,000 square cm.per c.c. or 1600 sq.cm per gm) is a hundred-fold more effective in reducing bleeding rate than the finest possible aggregate grading. It does not, however, follow that the addition of a quantity of very fine (perhaps inert) material to the concrete will impart other desirable properties. The bleeding rate can be controlled by reduction in the amount of water in the mix. This matter is more fully dealt with on page

Users of concrete who have habitually worked with lean mixes or with high water-cement ratios, or low percentages of sand, or sand deficient in fines, are certain to be convinced of the worth of whatever admixtures they happen to be using.

Almost any of the admixtures, including portland cement, can be made to serve the purpose of improving placeability under certain conditions. However, it is fundamentally wrong to choose an arbitrary mix (with probably too coarse a grading) and endeavour to improve its workability by the addition of a powdered admixture. Greater, or at least equal, improvement could be brought about by the selection of a grading suitable to the aggregates and conditions of placement. Powdered admixtures, injudiciously used, may be harmful.

<u>Air Entraining Agents and Dispersing Agents:</u> The study of the effects of products sold as air entraining agents and dispersing agents (most of which also entrain air to some extent) covers a wide field. There is no doubt that certain beneficial effects, (such as increased plasticity, reduced permeability and bleeding, etc) result from the intelligent use of entrained air. Whether portland cement should be dispersed artificially is a controversial matter. The use of certain dispersing agents which are also air entraining agents may be beneficial.

The treatment of this aspect of workability, a big study in itself, has been kept beyond the scope of the present work.

<u>Consideration of Aggregates.</u>

1. <u>Aggregate Selection:</u> In view of the aggregate's bearing on economy and its influence on the properties of the concrete

both/...

both before and after setting, it is well to give thought to its selection.

The utilisation of local material is of course a most important factor, and it may be that by suitably arranging the cement dosage and controlling the fine aggregate an otherwise unuseable, badly and even irregularly graded coarse aggregate might be acceptable.

Adequate workability can be assured by scientific design where an arbitrary mix - such as 1:n:2n - may be harsh and unworkable with the particular aggregate available. It will be shown that, on the basis of an arbitrary percentage of sand, the gradation of the coarse aggregate has an important bearing on the cement requirement for a fixed water-cement ratio and degree of mobility. However, when the coarse aggregate is combined with the optimum sand content, the gradation of the coarse aggregate is much less important. One cannot guess at this optimum percentage of fine aggregate, which has to be determined experimentally.

The methods of sampling and testing should be in accordance with B.S.S.882/1944, "Coarse and Fine Aggregates from Natural Sources for Concrete", and Appendices thereto, which supercede BSS 812/1943. If the sieve analysis be plotted on the Standard form, see figs. 118 to 121, the grading can be adjusted to conform with any desired curve. This log plot is very convenient, since the regular sieve analysis is represented by equal spacing.

Petrographic examination of the aggregates is highly desirable, as the normal acceptance tests do not yield information sufficient to decide the serviceability of a stone in concrete. Advance information should be acquired concerning the strength and permanence of the bond with portland cement and the behaviour of the aggregate embedded in concrete (chemical reactivity), which are functions of pore characteristics and chemical stability

2. Grading and Type: Aggregates graded to contain many sizes are said to be more economical than aggregates in which one or two sizes predominate, because they contain fewer voids. On the other hand, it is known that gradings in which the inter-

mediate/...

intermediate sizes are omitted generally have the least voids and should therefore require less suspending paste than continuous gradings. "Gap" gradings and "sized" materials have found favour especially in crushed aggregates, and are used to lessen segregation in stock piles. The cement requirements under different conditions and various types of gradings are discussed further on.

Glanville has stated that, from the standpoint of its effect on workability, for a rich mix the grading of the aggregate is of very small importance. The influence of grading increases progressively both with a reduction in cement content and with the requirement of a higher workability.

That this is true on the basis of an arbitrary percentage of sand has been fully demonstrated by Powers, who reported that "gradation of the coarse aggregate has an important bearing on the cement requirement for a fixed water-cement ratio and degree of mobility. But when compared on the basis of optimum sand percentages, gradation of coarse aggregate is much less important, permitting considerable range of proportions to accommodate a shortage or excess of any particular size. This emphasises the importance of designing mixes to suit available materials."

Figs. 92-96 clearly demonstrate the truth of this statement. Figs 92-95 represent paste contents for certain pressure test values versus the ratio of largest to intermediate size aggregate (expressed by Group Letter) for mixes identical except for the gradation of the coarse aggregate. In fig. 96 on the other hand, PTV's were plotted, at each gradation of the coarse aggregate, for mixes containing the optimum percentage of sand at the particular gradation.

On the basis of an arbitrary percentage of sand, lack of intermediate sizes had a marked effect on mobility; but when considered at the optimum percentage of sand, there was no appreciabl difference in observed workability for different percentages of the "pea gravel" size~~s~~.

Gradations requiring the least cement at constant water-cement ratio are not necessarily those having the least voids in the mixed aggregates (See figs 100-103). Proper proportioning promotes the use of various gradings. There is no need to strive

after/...

after a difficult and perhaps expensive grading. For example the Fuller and Thompson "best mix" curves give gradings which are often difficult to achieve, and , especially with commercial crushed aggregates, entail considerable extra expense. With crushed, angular aggregates this method results in an undersanded, harsh mix. It is seen from figs 97-99 that crushed coarse aggregate requires a higher percentage of sand and more cement for a given PTV than rounded gravel of the same gradation. The surface characteristics of the aggregates concerned are described in appendix C . The shape alone of the aggregates, as well as the texture of the particle surfaces, has a profound effect on the plastic property of the concrete. The differences in the behaviour of the aggregates in different mixes may not be as striking as in figs 97-99, which illustrate the futility of endeavouring to make use of any method of design which does not take into account the physical characteristics of the aggregate.

High proportions of flat or elongated particles decrease workability and hence necessitate the use of more sand, cement and water. In addition, they pack poorly, giving reduced bulk weight and decreased compressive strength. A large percentage of flat particles will tend to lie horizontally and collect segregated water on their under-surfaces, thus reducing bond.

In design, grading curves worked out for particular aggregates, richness of mix and water-cement ratios should not be applied to aggregates of a similar nature, differing perhaps only very slightly, except as a first approximation. It is far better to make a series of tests to arrive at the best grading for the particular conditions as there are so many variables.

The use of the pressure test provides a rapid means of designing the mix for maximum mobility under selected conditions.

It is not intended to convey the idea that good grading of the coarse aggregate is unimportant. On the contrary, if good grading can be achieved it is highly desirable; but other factors must also be taken into account. Whilst it is possible to design for a poor grading, there is no way of providing for a grading

which/...

which varies at random beyond certain limits, although the provision of a high percentage of sand will help. It is far more important that the fine aggregate grading be constant than that of the coarse aggregate. Especially does this apply to the fines in the fine aggregate - small variations in the -100 sieve material entail large variations in wetted surface area.

Percentage of Sand: The fine material in a concrete, when present in sufficient quantities, acts as a lubricant and tends, through its effect on surface tension or capillarity, to retain the mixing water within the mass. The plasticity produced will vary with the amount and kind of fine material and also with the amount of water.

Either very fine or very coarse sand should be avoided and the sand selected should have a smooth grading curve for best results. The particle shape and surface characteristics of the fine aggregate particles will affect their freedom of movement within the mass. Angular particles tend to interlock, whilst smooth, rounded particles, by contrast, do not offer the same particle interference. The relative roughness or smoothness of the surface of the grains has a marked effect on the internal friction of plastic flow. The effect of the grading and character of the sand is more marked at a constant sand content than at the best ratio of sand to coarse aggregate which can be found for the particular materials.

From the standpoint of economy, volume change and other properties enhanced by low cement content, the most desirable mixture is that which produces the desired workability with the least quantity of a given paste per unit volume of the concrete. Increasing the proportion of coarse aggregate up to a certain point reduces the cement requirement per cubic yard. Beyond this point the saving is very slight, while the deficiency in mortar increases the cost of placing the concrete. Because coarser gradings are more economical in cement requirement, there has been a tendency to use undersanded, harsh mixes. Harshness is the principal cause of overwet mixes. Whilst increasing the

proportion/...

The more heavily sanded mixes have at least two other important advantages:

(a) If the voids in the coarse aggregate are more than filled by cement and sand mortar, the internal grading of the coarse aggregate has little effect on the concrete, as demonstrated above. This makes possible the use of aggregates which might otherwise not be suitable.

(b) In proportioning mixes, the amount of cement is based on the maximum amount of sand. If the sand become less, for any reason, e.g. due to bulking when batching is by volume, the high ratio of cement to sand will compensate for the variation.

The practical significance of the above must be tempered by the necessity for avoiding excessive sandiness, with its attendant greater cement-water paste demand and higher shrinkage effects. The experimental determination of the best fine to coarse aggregate ratio is therefore all the more justified.

<u>Maximum Size of Aggregate:</u> The amount of solid material that can be suspended by water is not only dependent on particle shape and grading, but also on the total surface area to be wetted. Particle size is therfore a major consideration. For aggregate graded to a given maximum size there is a fineness modulus or average particle size which cannot be exceeded if the concrete is to remain plastic. However, the fineness modulus may be raised by increasing the maximum size to which the aggregate is graded, thereby enabling the solid phase to be increased.

Aggregate should be graded, then, from the finest particles to a size as large as the work permits. The larger the maximum size of the aggregate, the less the voids and surface area and therefore the less the quantity of cement paste required. The maximum size of the coarse aggregate influences the grading and therefore the best ratio of fine to coarse aggregate, for a given workability requirement. It also affects the amount of water required for a given consistency. These factors also have a marked influence on the cement requirement of the concrete.

Figures ——— have been ~~adopted from~~ published in the U.S.Bureau of Reclamation/...

Reclamation Concrete Manual. They show the advantages of using the maximum possible size of aggregate. The reduction in the amount of cement required is seen to decrease very rapidly in the range up to a maximum size of about 3 inches. The use of larger aggregate is usually not justifiable owing to the difficulty of mixing and transporting without heavy plant.

PART III. PRACTICAL APPLICATIONS.

CHAPTER 7: DESIGN METHODS.

General Considerations: The purpose behind the scientific design of a concrete is to achieve a satisfactory product, possessing specific qualities, at the least cost. Workability in the freshly mixed mass, homogeneity in the placed concrete, watertightness, durability, low volume change and necessary strength in the hardened state are desired in all concretes, / different conditions requiring different treatment.

Fresh concrete should be relatively easy to mix, convey, deposit and compact and should work to a good finish. It should remain homogeneous throughout the period of transporting and placing. In other words the concrete should be workable. A mixture too dry and harsh for the conditions will not be fully compacted and will exhibit hollow pockets. A concrete too wet and sloppy will segregate and show honeycomb; there will be excessive bleeding and the formation of scum.

Economically and structurally, the most desirable combination of particles is that which produces the desired workability with the least quantity of the particular water-cement paste selected, per unit volume of the concrete. Cement is the binding medium and is necessary to the integrity of the member. It is also unstable and is the weakest of the solid ingredients. It should therefore be kept at a practical minimum under normal conditions. In Chapter 6, the factors governing workability were set forth and the interplay of effects were illustrated. The consistency of the concrete is greatly influenced by the quantity of water-cement paste, a reduction in the quantity giving a drier consistency and vice versa. The consistency of the paste itself and the kinds of particles therein determine the amount of solids which can be supported in a plastic mix. The supporting power of the paste, together with the maximum size and gradation of the aggregate, controls the quantity of a given aggregate that can be carried in suspension. It was

shown/...

shown in Chapter 6 that the proper proportion of sand is dependent on the water content of the paste (water-cement ratio) and the degree of workability desired; but is not usually that proportion giving maximum density of the mixed aggregate. For any fine and coarse aggregate used in combination with a given water-cement paste there is a definite percentage of sand which for a given degree of workability will require the least amount of paste. Smaller or greater amounts of sand will necessitate the use of more cement and water for equal workability. Refer to Figs. 76 - 91 where paste contents vs. fine aggregate proportion are plotted for different PTV's. The curves show a definite minimum paste content, at the optimum percentage of sand, for each degree of mobility. Points to the left of the "optimum" values represent concretes which are undersanded - too coarse a grading for the size and type of coarse aggregate - and points to the right indicate mixes which are oversanded and have reduced mobility because of excess of fines.

Cement: The conditions under which it will be necessary to use a special cement are infrequently met with. It is general experience that Ordinary Portland Cement complying with BSS No. 12/1947, intelligently used, will fulfil most requirements. "Where there is a possibility of excessive temperature rise, use a minimum of cement and provide a maximum provision for the dissipation of heat. If durability, watertightness and sightliness are paramount strive for maximum density and efficiency of placement and curing. Intelligent design and good workmanship are of paramount importance in achieving the desired result".[33]

Water-cement Ratio: The first step in the design of a concrete must be the choice of a suitable water-cement ratio. In each method of design recommended in this chapter, the water-cement ratio is the one fixed factor on which the proportions are determined. It forms the basis for both design and control.

The water-cement ratio will be decided by the type of structure to be built, the conditions of exposure for the particular climate and any special circumstances, and the compressive strength/...

strength required. Table 1 has been prepared as a guide to the selection of the appropriate water-cement ratio. It represents the recommendations of the Portland Cement Association[91] and the American Concrete Institute.[92]

If a water-cement ratio be selected from the table, it will be found in most cases to be lower than that required for most design strength requirements. The engineer should have available W/C - strength or C/W - strength curves for the particular cement used or published data such as is given in tables 1 and 2 and fig. 1, Road Note No.4.[37] He should choose the lower of the values suggested by Table 1 and the 28 day strength requirement. In choosing a W/C from the strength curve, consideration must be given to the methods of batching and control to be adopted on the job, which will determine the variations in strength to be expected. Weight must be given to the probability of a specified percentage of works cubes being weaker than a certain minimum strength. See page 104.

If the concrete be workable, carefully placed and properly cured, the water-cement ratio, besides controlling strength, has a profound effect on durability, through determining porosity, density and volumetric stability.

Applying the Inge Lyse rule of constant water content,[25] to maintain a particular consistency whilst water-cement ratio is reduced, the cement factor must be increased because more cement is required per unit volume of water. The water-cement ratio is thus an index to the relative economy of a mix since a certain amount of cement water paste is necessary for any particular aggregates and condition of placement.

Having regard to the foregoing considerations, the highest water-cement ratio which will fulfil all the requirements should be chosen.

Workability: The concrete must be workable under the particular job conditions. It need not possess greater workability than necessary for mixing, handling and placing with reasonable facility. Although no single test procedure can assess

workability/...

workability, this property can be gauged by means of the systematic recording of results described in Chapter 4, page 65, using form (113) or (114). However in comparing the relative merits of two similar mixes, a test such as the Pressure Test is a great help because it enables the comparison to be made on the basis of plasticity - the most important component of workability - which determines the ease of compaction.

The first consideration, then, is to design a mix with the given W/C having the requisite mobility as evidenced by the Pressure Test. Such a mix will be satisfactory provided it possesses the desired cohesiveness and there is no tendency towards segregation. The aim is to achieve a concrete having the minimum paste content (of given W/C) which possesses the desired plastic properties, which does not segregate and works to a good finish.

Table 2 shows the recommended PTV limits for each type of placing condition using a ring F having an internal diameter of 8". Values of slump and compacting factor <u>roughly</u> corresponding with these groups are given as a guide. It should be noted that the slumps are given to indicate a trend only. In the range of stiffer consistencies and non-segregating concretes the compacting factors parallel the PTV's; but concretes tending to segregate are favoured by the compacting factor test - see page .

<u>Aggregate Selection:</u> The choice of the aggregate has been dealt with in Chapter 6, p 86. It will, of course, be important to utilise local material as far as possible. The methods of sampling and testing should be in accordance with BSS 882/1944, "Coarse and Fine Aggregates from Natural Sources for Concrete", and appendices thereto, which supercede BSS 812/1943.

The maximum size to which the aggregate can be graded will be determined by the size of the member to be cast and the spacing of the steel in accordance with the Code of Practice or else by the difficulties of handling, mixing and placing. (See chapter 6.)

<u>Design:</u> The most practical way of arriving at the best proportions/...

proportions of the mix is by final adjustment of a trial mix on the job. A laboratory investigation is recommended and, adopting the methods outlined below, a mix can be designed which will require little or no alteration under conditions of full scale production.

The designer can arrive at his preliminary trial mix by any of the published methods he happens to favour, or by his experience with similar conditions and materials. As a starting point he can select a grading from, say, data given in Road Note No.4,[37] or H.N.Walsh's curves.[32] After this step, design is furthered by a systematic variation of the proportion of one ingredient at a time, until the observed properties are satisfactory and the concrete is the most economical.

<u>Laboratory Practice; Use of Pressure Test:</u> It is of little avail to design a mix in the laboratory for use in the field unless the samples submitted are representative of the materials to be used, and careful control is exercised.

The pressure test apparatus is a useful tool for designing mixes and, under conditions of reasonably uniform aggregates, can be used to proportion concrete in the laboratory which will prove to be satisfactory in the field.

The method of design recommended depends on the systematic variation of materials and the choice of arbitrary proportions should be avoided. The operator's visual observation, in conjunction with the quantitative results obtained, will help in deciding the mix.

Different ranges of placing conditions can, if desired, be simulated by changing the ring F (fig 66 and page 52) and so altering the severity of the test. The smaller the internal diameter of the ring F, the greater will be the plastic distortion of the sample necessary for a given deflection. The placing conditions affect the workability, as has been explained in a previous chapter through the plastic properties inherent in the mix. Under certain conditions a concrete may settle into the form entirely by plastic flow/...

flow as the distortion remains within the plastic limit; whereas with a more confined or intricate form, placing might necessitate flow which exceeds the plastic limit, flow then being impeded by the interlocking of particles.

With the apparatus, a complete investigation of the available materials may be undertaken, with varying water-cement ratio and material proportions, and data plotted so as to provide a guide for the practical design of concrete for any purpose. For example, for a municipality, obtaining its aggregates from certain fixed sources, it would be of great value to have complete data available from which to gauge the behaviour of concrete under different circumstances. The apparatus may also be employed to design a particular concrete possessing specific plastic properties, having chosen a suitable W/C. Any method of systematic trial may be used.

<u>Field Practice:</u> The pressure test apparatus (PTA) is well adapted for use on works. The method to be followed in designing a mix on the job may be exactly as outlined previously. The test can also be used in the design of a mix with full scale plant, following the method suggested by T.C.Powers[93] and recommended by the American Concrete Institute,[94] an adaptation of which is given below.

As a control test, the PT is most useful, being sufficiently sensitive to detect the smallest variation in the mix.

<u>Design using full scale plant:</u> A mix is selected so that

1) the W/C will be slightly smaller than required;
2) the mix will possess greater mobility than placing conditions demand;
3) the overall grading of the aggregates is finer than necessary - i.e. the concrete is definitely oversanded.

This, of course, implies a greater water-cement paste content than required finally.

From the known specific gravities of the ingredients, the batch weights are worked out to suit the particular mixer capacity. The normal concreting operation is then commenced,

using/...

using the minimum amount of water (estimated by the engineer on the job) which will permit placing at the desired rate. Having established this mix with satisfactory placeability, the average P.T.V. is obtained, concreting proceeding the while.

The next step is a slight reduction in the percentage of sand, with a complementory increase in the coarse aggregate. The grading of the coarse aggregate must be kept constant at this stage. Keeping the same cement content, mixing continues, still using the minimum amount of water to maintain a constant PTV as judged by eye and checked by test. It will be found that a reduced quantity of water, as compared with the first trial, is required. This procedure is now repeated until no further reduction in water content can be achieved by reduction in sand. At this point the mix will have a harsh, stony appearance, will tend to segregate and will have a greatly increased PTV, even with a wetter consistency. This is definite evidence of an undersanded mix.

A minimum water content has been reached. The water must be held at this minimum, whilst the percentage of sand is increased by stages to the maximum which can be used with this quantity of water and still have the required mobility. There should be a slight bias, 2 to 3% of total aggregate, towards the oversanded side; the check list will be useful here. In the series of trial mixes the minimum amount of water per cubic yard has been determined. Dividing this by the specified W/C gives the required amount of cement. Under the conditions described, the concrete which has been placed during the experimental stage will have a lower W/C and thus it will be found necessary to reduce the amount of cement, increasing the sand content to compensate for loss of fines. Making use of the Inge Lyse law, the absolute volume of decrease in cement content must be equal to the absolute volume of the increase in sand content, so that the unit water content will remain unchanged. That is, for constant consistency, the water content per cubic yard of concrete must be constant. This rule is only approximately true

for/...

for consistency (slump) and in so far as workability is concerned its application must result in a loss of plasticity and increased bleeding, for the specific surface of the cement is at least a hundred-fold greater than that of the fine aggregate. (refer to Chapter 6, p. 85). However, over a small range, the rule can be applied quite successfully to bring about the necessary cement adjustment. For the correction, the weights will be inversely proportional to the specific gravities of the respective materials; the fine aggregate will have to be increased by about 0.85lbs for each 1 lb decrease in cement.

Further small adjustment of fine aggregate content may be made as desired during concreting, keeping the total absolute volume of all the materials constant.

In the above description, the grading of the coarse aggregate has been kept constant. However, if two or more sizes of coarse aggregate are being combined by weight at the mixer, so that the coarse aggregate grading can be changed with facility, exactly the same procedure can be followed, holding the percentage of fine aggregate constant and varying the amount of a particular coarse aggregate size group. In this way the optimum coarse aggregate grading can be achieved. At the optimum overall grading for the particular paste content, the grading of the coarse aggregate is usually of secondary importance, as shown in Chapter 6. For this reason, there will be considerable allowable latitude in the coarse aggregate grading, which can very often be adjusted to suit the convenience of supply.

During the whole operation concrete has been placed which will have at least the desired strength and durability. The smooth routine of concreting should not have been interrupted in any way. The PTV or mobility adopted, which has been chosen from observation to ensure satisfactory workability, can now be the basis of control, the test being performed as often as may be deemed necessary by the engineer - certainly whenever works cubes are made.

As described above, this method of design appears to be somewhat long; but in practice the author has found that it works very well, especially when used as a method of final adjustment of a laboratory-designed mix where very little variation is required.

<u>Control:</u> This is an important aspect of concrete making which should not be neglected, either in the laboratory or in the field. In laboratory practice, the uniformity of the results is primarily dependent on the accuracy with which the aggregates and cement are batched and with which the nett water content of the mix is controlled. Other factors are the uniformity of the samples, the uniformity of methods of mixing, testing fresh concrete, making, curing and testing cubes, etc. For reliable and consistent results, the operator must standardise his methods and take precautions to eliminate as many variables as possible. Moisture control is dealt with in Appendix A.

Applied to field practice, "control" means the production of concrete in such a manner that there is deposited in place an adequate supply of uniform, workable concrete, which when properly cured will have the necessary service properties.

In this matter results are the primary concern; but as methods affect results the job must be organised to the best advantage with the plant and men available. All materials used should be tested, an economical mix should be designed and follow-up tests made as necessary for uniformity. Attention should be paid to inspection, which is very important and should not be treated with indifference. On a job where a large amount of concrete is being placed the resident engineer will probably not be able to give it the personal supervision necessary and it is advisable to employ a fully trained junior engineer to control the work, in accordance with the Engineer's instructions. This duty should not, on important works, be delegated to a foreman.

During the design stage, it is most important to correct for moisture contained in the aggregates. This means frequent testing of the fine and coarse aggregates - especially the fine aggregate- by some rapid and convenient method, and the computation of nett

batch/...

CHAPTER 8: THE SPECIFICATION OF CONCRETE.

The problem of specifying concrete to ensure that it will possess the properties desired by the engineer must be solved before the general standard of production can be raised.

The concrete specification must be clear, concise and adequate. It must be rigid enough to ensure that the concrete will have the desired qualities and yet be sufficiently flexible to enable economies to be effected in the use of local materials.

In compiling a specification there should be co-ordination between drawing office and field. The first step is a thorough investigation of

(1) the properties desired in the concrete in its plastic and its hardened state,

(2) the materials available for use on the particular job,

(3) the design of the concrete mixture and

(4) the assessment of the properties of this concrete and the computation of design data — permissable stresses (bending, direct, shear and bond), modular ratio.

These data should be available to the designer before he commences work and the field conditions should be borne in mind.

In this section the significance of the water-cement ratio to be specified is discussed in relation to strength and durability and suggestions as to the specification of that intangible factor, workability are made.

The Specification of Strength: Although strength, per se, may not be the most desirable property, it is the simplest to specify because it may be quantitatively assessed. The uniformity of routine compressive strength tests is an indication of the effectiveness of field control. In the previous chapter the selection of water-cement ratio's for durability and strength was discussed. It should be stressed that the nominal W/C should be decided having regard to the methods of control. That is to say, the weight that can be given to a certain nominal W/C depends on the overall control of quality. The specification of a W/C loses

significance/...

significance if the methods of control and the means of assessing quality be not also specified.

The bare specification of minimum strength should be avoided because it is certain that if no single test cube result is to be less than a certain minimum the nominal W/C chosen would have to be unnecessarily high. One plan is to adopt the method of Stanton Walker[99] and specify that not more than a certain percentage of test results shall be less than a certain minimum. Thus, by implication, the better the control adopted by the Contractor the higher can be his nominal W/C and the lower his cement factor.

If desired, an average strength can be specified as well, which would in effect decide the maximum allowable standard deviation (S D) of a single test. The average strength and a maximum coefficient of variation could be specified. The greater the coefficient of variation (V), the higher will have to be the nominal W/C and the more the cost of the concrete (for materials).

<u>Test Specimens:</u> The specification should provide for the making of some cubes or cylinders from concrete already deposited in different parts of the mould, or if this is not possible, from samples taken at the point of deposit, in accordance with the Code of Practice for Reinforced Concrete,[49] appendix 8, "Standard Method of Making Works Cube Tests of Concrete".

The test results are of significance only insofar as they reflect the properties of concrete doing service in the structure. This implies that the cubes be fully representative of the batch as placed, that there be sufficient to give a fair average, that some of the cubes are to be cured under the same conditions of and temperature as the structure (so far as possible). This question of the relationship between test cubes and structure is a most important one. Moist curing at 70°F is often specified (Standard Curing). Appendix 8 (ibid) specifies moist curing under site temperatures (not less than 40°F) for at least three quarters of the period before test except for tests at less than 7 days. Specimens can also be cured in sealed containers, in water tanks, in fog or in special apparatus for accelerated hardening or for adiabatic conditions.

It/...

It is advisable to take into consideration the special conditions of each job. The taking of cores from the hardened concrete would provide the most direct indication of strength and quality in place.

<u>Factors Affecting Test Results:</u> The coefficient of variation obtained from cube test results is compounded of several variables. The main classes into which these fall are broadly (1) proportioning, mixing and depositing the concrete and (2) sampling, curing and testing of the specimens. Clearly, the variations inherent in the second group are independent of the variations inherent in the first. The uniformity of the concrete will be better than the test results indicate.

The most obvious sources of random variation in strength test results with any given type of test specimen are

a) Moisture content of concrete at time of test,

b) Condition of bearing surfaces and

c) rate of load application.

The coefficient of variation of the test procedure, which should be standardised, can be found.

<u>Specification of Rigid Control:</u> Good control and detailed specification undoubtedly save money. (See Appendix D). Although gravimetric batching eliminates many of the errors which are attendant on volumetric batching, there is still the uncertainty of the amount of moisture brought into the mix with the aggregates, especially the fine aggregate. This uncertainty is costly. Available methods of test for moisture content do not enable a very strict check to be kept in all cases, although it is possible at present, under favourable circumstances, to achieve a good measure of uniformity. Effort is being directed toward the solution of this problem.

Many of the benefits obtained by careful control of the concrete as it comes from the mixing plant can be lost by:-

(1) Methods of transporting and placing which require extended periods of time, or which cause excessive segregation and reduction in consistency of the concrete;

(2) inefficient/...

(2) inefficient methods of compacting the concrete which result in a porous, honeycombed structure;

(3) inadequate or inefficient curing, resulting in greatly increased permeability and reduced strength.

<u>The Specification of Workability:</u> It is difficult to specify that a concrete shall have a certain workability because the conception of different degrees of workability has always been subject to individual judgment.

The specification of consistency (or slump) whilst fixing the water content of a concrete - a most desirable and important feature - does not fix the ease with which the concrete can be deposited in place, nor does it control the amount of segregation. However, where the particular aggregates, proportioning and grading necessary for a workable concrete are specified, fixing the allowable consistency range should ensure adequate control of workability.

The pressure test provides a ready means of specifying the plastic properties of concrete. It goes further, for intelligently used it will ensure that the concrete is workable under the specific conditions, since not only will it possess the desired mobility but any tendency to segregation will be reflected in higher PTV's. For any particular placing conditions, a PTV can be specified such that the concrete will fill the mould entirely by plastic flow.

The author is working on a more advanced application of the pressure test, towards determining the plastic constants mathematically from the log plots of the pressure-deflection curve. However, this work has not reached a conclusive stage. It should also be possible to specify workability in terms of the relationship between the PTV for the first deflection and the PTV for some subsequent deflection. (See page 54 and fig. 112). This could possibly be adopted as a plasticity coefficient, which would give a better idea than a value based on a single deflection. It would be a measure of the ability of the concrete to respond to puddling or to vibration or to repeated surges of motion. The workability of a concrete at any stage depends to a considerable extent on the previous history of the batch and the amount of working expended at

that/...

that stage. Thorough mixing is, of course, a prerequisite of workability and minimum time of mixing in an approved type of mixer should be specified.

General terms of a Specification: In broad terms there are two courses open in the drafting of a specification:

(i) The Contractor may be required to adopt the concrete mix designed by the Engineer, or

(ii) The onus may be placed on the Contractor to design a concrete complying with certain requirements, such as strength and workability, as discussed previously.

In the first category would conveniently fall the specification for works on which particular local aggregates, such as stone from a Municipal or Government quarry, must be used. The Engineer probably has extensive experience of the behaviour of the specified aggregates or mixtures. This type of specification is particularly useful in the form of standing instructions to a District or Resident Engineer, in which case a series of mixtures for different purposes would be laid down.

The second type has a more general application.

In either type it will be necessary to specify the general conditions of field control (including moisture content determination, etc and strength and workability testing) so that the W/C may be fixed.

In the first type of specification, it is necessary to cover each phase of the designed mix, to ensure that not only is the nominal proportioning carried out but also the required uniformity of grading, limits of accuracy of batching and overall methods of control are obtained. If desired the Contractor may be allowed the choice of alternative degrees of control and suitable corresponding mixtures of varying economy. The Engineer must, of course, reserve the right to adjust the proportions on the job as he may deem necessary. There are several reasons for this, one being for example, that different brands of cement, and even different batches of the same brand, complying with the same specification, will possess differing plastic properties and this may affect design requirements.

To/...

To cover all aspects of the designed concrete the following should be specified in addition to the degree of control: type of cement, quality of water, water-cement ratio, cement factor, particular fine and coarse aggregates (by name or type), size-groups of coarse aggregate to be batched and limits of grading within each size-group, grading and uniformity of fine aggregate.

The nominal proportions by weight or the actual nett batch weights for each ingredient may be specified.

The Specification: Relevent sections from a specification suggested by the Author for structural concrete are given to illustrate the foregoing remarks. Those portions of the specification dealing with standard terms of reference have been omitted.

5. MATERIALS:

Cement:

Aggregates: The Contractor shall purchase and transport to the site, at his own expense, the following aggregates:

Coarse Aggregate: The coarse aggregate shall be crusher run granite from the Council's quarry at Brackenfel. This stone is generally angular in shape, with a small proportion of flaky pieces. It has a coarse crystalline surface. It is supplied in nominal sizes. It is comparatively free from dust ..... The Contractor shall nevertheless wash all coarse aggregate in an approved plant on arrival at the site and prior to stockpiling. The maximum size to which the aggregate shall be graded is .... inch, nominal. (Approximate grading of each size group can be given).

Fine Aggregate: The fine aggregate shall be well-washed Malmesbury river sand with the following grading (Tyler sieves):

No.4	No 8.	No.14	No.28	No.50	No.100	No.200

(give % passing each sieve size (limits of values). Fineness modulus shall not vary more than plus or minus 0.20 from (give F M).

Water: All water to be used on the works must be taken from the Council's water mains and paid for at the usual rates.

(There/...

(There is a clause under "General Conditions of Contract" covering the use of Municipal Water, Waterworks regulations and responsibility for shortage of water.)

6. STORAGE OF MATERIALS:

7. CONCRETE: The concrete shall be classified as "High Grade" and shall conform to the following requirements:

Design: The nett proportions by weight, referred to saturated and surface dry aggregates, shall be as follows:

				Coarse Aggregate (Nominal Sizes)		
	Water	Cement	Sand	$1\frac{1}{2}$"	$\frac{3}{4}$"	$\frac{5}{8}$" – $\frac{3}{8}$"
Proportions by weight						
Batch weights per pocket of cement						

These proportions are such that the concrete will possess adequate workability.

(Two mixes (A and B) may be specified here; the first with a slightly lower W/C (slightly richer mix) and state, " The Contractor shall commence concreting operations with mix A. He may subsequently, at the Engineer's discretion, change to Mix B if test results indicate that the overall standard of uniformity is within that specified below.")

Strength Requirements: The concrete shall develop a strength such that not more than % of standard works cubes tested 28 days after moulding fail at less than p s i.

Workability: The workability of the mix shall be adequate for satisfactory placing in the forms and around the reinforcement without tangible segregation and other defects.

The pressure test shall be used as a control test and shall be performed on representative samples taken at the point of deposit of the concrete, as may be directed by the Engineer (or Resident Engineer, or Inspector, as relevant.)

(Assume that the test has been standardised or attach a full specification.)

The PTV shall be within the following limits:

1st Deflection: ...... and ...... (ins of mercury)

3rd Deflection: .... and .... (ins. of mercury)

Tests for consistency, water gain, segregation, shall be made at the discretion of the Engineer.

(The Inspector will be required to fill in a check list whenever test cubes are taken, for the information of the Engineer.

Mix Adjustment: The water content shall not be increased from the amount required by the mix design unless cement at the required water-cement ratio be added. The Engineer may, at his discretion, vary the mix as he may deem necessary. He may require additional cement without extra compensation to the contractor if tests indicate that the required uniformity is not being achieved.

8. MOISTURE CONTROL: The Contractor shall make determinations of free moisture contents and absorption capacities in respect of the aggregates, using an approved field method, sufficient to ensure adequate control. The water dosage and batch weights of the aggregates shall be adjusted in accordance with the test results.

The following information, which is not guaranteed, is supplied for the guidance of the Contractor, who shall check it independently.

	Coarse Aggregate	Fine aggregate.
Specific Gravity		
Absorption		

9. TRANSPORTING MATERIALS:

10. BATCHING OF CONCRETE: Aggregates and bulk cement shall be measured to within 1% by weight. Cement in Standard pockets need not be weighed. Water shall be measured by volume or by weight to within 1½%.

The complete plant assembly shall be approved by the Engineer and shall provide for the ready adjustment of aggregate weights for varying moisture-contents or any other reason.

11. MIXING CONCRETE: Intimation must be given to the Inspector before the mixing of concrete is begun, as no concrete which

has/...

has not been mixed under his supervision will be allowed to be placed in the Work.

Concrete shall be mixed in a standard type of batch mixer with a drum speed of 200 to 225 peripheral feet per minute. Mixing time shall be 1 min. for batches of 1 cu.yd or under, and shall be increased 15 sec. for each additional $\frac{1}{2}$ yd. or fraction thereof.

Retempered concrete shall not be allowed. The contents of the mixer shall be completely discharged before each new batch is loaded.

12. <u>CONTRACTOR RESPONSIBLE FOR PROPERTIES OF CONCRETE:</u> The Contractor shall be solely responsible for the workability, strength and other specified properties of the concrete at all stages of the construction and he shall take all necessary steps for this purpose.

Should the Resident Engineer or the Inspector assist or guide the Contractor at any time this shall be at the entire risk and responsibility of the Contractor and no error or alleged error, and no act, order or direction of the Resident Engineer or of the Inspector shall be admitted as a plea for the improper performance of the work, or used by the Contractor for any claim against the Council. Any faulty concrete, at whatever time it may be discovered, shall be rectified by the Contractor at his own expense, to the satisfaction of the Engineer.

13. <u>PLACING OF CONCRETE:</u> Concrete shall be deposited, when practicable, in its final position without segregation, rehandling, or flowing. When possible concreting shall be continuous until the section is complete.

Forms shall be clean before concrete is placed.

Concrete shall be spaded (or vibrated) to maximum subsidence, without segregation, and adjacent to forms and joints. (The usual conditions concerning reinforcement, slabs, beams,

construction/...

construction joints, stoppages, joining new to old work, watertight and dry forms, etc, to follow.)

14. CURING:

15. FORMS:

16. REINFORCING STEEL:

17. ? Structural requirements, finishes, protection, fixtures, etc.

APPENDIX A.

MOISTURE CONTROL.

1. Consideration of Moisture in the Aggregates. Aggregate may be in the following states with regard to moisture:

   a. Ovendry: All moisture, whether external or internal, has been driven off, usually by heating at 100-110°C.

   b. Airdry: There is no surface moisture on the particles; but there is some internal moisture. The particles are not saturated.

   c. Saturated and Surface dry. In this case there is no surface or free water; but all internal voids are full of water.

   d. Wet or damp. The particles are saturated and free or surface water exists in some degree.

2. Determining the "Saturated and Surface dry" Condition: As the saturated and surface dry condition is used as the basis for W/C calculations and in batching it is important to be able to determine it accurately. This is by no means easy and depends to some extent on individual judgment.

A coarse aggregate is considered surface dry when it has been wiped free of visible moisture films with a cloth or washleather. Aggregate particles glisten when surface water is present; are dull when the film has been removed. Care must be taken that internal moisture is not removed during the drying operation.

The saturated, surface dry condition of a fine aggregate is not so readily determined. The earliest method used was visional inspection. The sand was simply spread out on a smooth surface and permitted to dry, stirring frequently to ensure uniform drying, and the end point was determined by noting when the sand appeared to be surface dry and free flowing. This method has been adopted in BSS 882/1944, Appendix F.

Other methods were suggested by Rea,[95] Pearson,[96] and Chapman.[97] The method which seems to have found general acceptance in America because of its simplicity, ease of performance and accuracy, was suggested by D.O.Woolf.[98] The idea is based on the fact that moist sand (containing free water) can be formed into shapes by light

pressure/...

pressure and that dry sand cannot. A sheet metal cone with top and bottom diameters of $1\frac{1}{2}$ and $3\frac{1}{2}$ins. respectively, and a height of $2\frac{7}{8}$in. (fig/25) is filled with the previously prepared sand, which has been dried almost to the surface dry condition, and tamped 25 times with a standard 12 oz.metal rod having a flat face 1 inch in diameter. The cone is lifted vertically and if the sand does not slump, free moisture is present. Drying is then resumed. Trials with the cone are made at frequent intervals until the sand slumps on removal of the cone. This indicates that the sand has reached a surface dry condition. The weight of the sample is determined at this stage. As a check, the sand is moistened slightly (5 drops) to ensure that there is free moisture -- the cone should not slump. The cone test forms part of ASTM C 128-42. Fig./25 illustrates the appearance of sand having various moisture contents.

3. <u>Determining Moisture Content:</u> The internal moisture of an aggregate in the saturated, surface dry condition is termed the "absorption capacity" or simply the "absorption". The amount of water required to bring the aggregate from an air dry condition to the saturated and surface dry condition is the "effective absorption".

The absorption may be found by soaking a sample for 24 hours bringing it to the surface dry condition and weighing. After drying in an oven, the sample is again weighed. The difference in the weights, expressed as a percentage of the dry sample weight is the absorption. The absorption is a measure of the porosity of an aggregate and is also used as a correction factor in the determination of free moisture by the oven drying method.

The accurate and rapid determination of free moisture in the aggregates is of prime importance both in the laboratory and in the field. Laboratory methods are usually too slow for field use; but a rapid method is useless unless accurate. The practical aspects of the problem are discussed in Chapter 7.

The author uses a modification of the pycnometer method given in BSS 882. Other useful procedures are outlined in the

U.S. Bureau of Reclamation Concrete Manual.

4. Laboratory Moisture Control: In the laboratory, elaborate precautions must be taken to avoid small fluctuations in the nett moisture content of experimental mixtures. There are several ways of achieving a measure of uniformity.

Powers suggested that aggregates should be weighed dry and placed in containers together with the water required for nett water content + the water calculated from the absorption. The containers are sealed and weighed. After 24 hours they are re-weighed to determine whether any moisture has been lost, corrected if necessary and then used.

This method has the great advantage that the aggregates are initially in a uniform state - i.e. oven dry, making repeated moisture content determinations unnecessary. The author found, however, that in practice it was difficult to determine within fine limits the final nett water content (actually used in the test batch) because,

(i) a certain amount of water was retained in the container (a large steel bucket with lid), and

(ii) no facilities were available for weighing the aggregates water container more accurately than ± 1 oz. (Total weight about 40lbs).

In the batches used it was found that in the critical intermediate range the addition or subtraction of ½oz. of water made an appreciable difference to test readings - especially to sensitive PTVs.

Notwithstanding the above difficulties, the Powers' method yields more uniform results than can be obtained by another method used by the author, which is briefly outlined:

(i) The aggregates are soaked in water for 24 hours and allowed to drain off in aggregate bins.

(ii) Before commencing a series of tests, samples, as representative as possible, are taken and the free moisture contents determined. It was found that the moisture held by the coarse aggregate did not vary greatly for any set of conditions.

(iii) The/..

(111) The requisite amounts of fine and coarse aggregates for the test batches, corrected for moisture content, were weighed out, and the mixing water was corrected for the free-water in the aggregates.

(1V) When this method was used, a standard batch was made up prior to any other batches and tested (for slump and PTV or compacting factor, etc.) Variations were usually reasonably small; but if the control test varied considerably from the mean the moisture contents of the aggregates were re-checked. The test results of the control batches gave a good indication of the actual error in moisture content.

(V) The aggregates were kept well turned in the bins.

The disadvantages of this method are as follows:-

(1) The moisture content of any aggregate is not uniform, no matter how carefully sampled and batched. The moisture content was found to decrease upwards in the bin, especially with coarse aggregate.

(11) It is necessary to check frequently, as small variations in moisture content upset results. This checking becomes laborious.

One advantage of this method, compared with the former procedure, is that damp aggregates do not segregate so readily as dry ones. This is important in the case of the sand, as in drying an important amount of very fine material is easily lost. The coarse aggregates should be separated and combined according to the adopted grading, for research purposes. This may not be necessary in designing mixes, depending on the type of aggregate.

All things considered, the Powers method yields the more uniform results, especially if the containers be well sealed or stored under conditions of high relative humidity. The essential point, whatever method be adopted, is to standardise procedure and eliminate as many sources of error as possible. This is most importamt. Standard procedure should be followed slavishly so that conditions are comparable..In testing, trowels, rammers, mixing pan and any part of the apparatus which will come into contact with concrete should always be dampened in a standardised manner.

APPENDIX B.

LABORATORY PROCEDURE.

It is essential to standardise procedure in testing. That is to say, the work must be planned in advance and become a routine. This will help to make each operation identical for every batch. Many accidental errors are thus eliminated or at least rendered more uniform. Random fluctuations have to be guarded against.

The laboratory methods adopted by the author for batching and mixing are discussed below.

BATCHING: All quantities of cement, aggregates and water are determined by weight. A data sheet is prepared in respect of each batch, on which proportions, batch weights, moisture conditions of aggregates, humidity, temp, etc, are recorded (see fig. 113).

Procedure: (a) The aggregate is weighed on a platform scale accurate to 1 oz. A bucket large enough to hold the batch (say, 30 lbs. of aggregates) is placed on the scale platform and weighed. The cumulative aggregate weights are added to the weight of the bucket.

(b) All weights are checked before the next fraction of aggregate is added.

(c) Here there are two alternatives. See method given in Appendix A. Either (i) the aggregates are sealed with the requisite water for 24 hours or (ii) cement and water are weighed and kept separate. In either event cement and water are batched on a scale accurate to $\frac{1}{100}$ lb.

(d) Corrections in batch weights are made as described in Appendix A.

Mixing:

1. Machine Mixing: The author designed and constructed the electric laboratory Concrete Mixer illustrated in figs 116-118. It was hoped that use of the mixer, besides saving an enormous amount of labour and time, would produce more uniform results than hand mixing because the mixer does not show fatigue and the procedure

lends/...

lends itself to standardisation of action and time.

Research workers have avoided mechanical mixing on the ground that with small quantities a considerable percentage of the finer particles and water remains in the mixer. Another objection is that the concrete tends to segregate on discharge. With hand mixing, the pan can be scraped to avoid losses.

The author carried out many experiments with this machine and has found that it has two serious disadvantages:

a) A certain amount of mortar always remains behind in the drum on discharge of the batch. The quantity of mortar lost is, however, not constant. It varies with different types of mix.

b) Mixes of very dry (earth damp) consistency tend to stick in the drum. Aggregate and mortar ball up into tight-packed cakes.

The machine has proved to be a valuable time saver and is most useful where routine testing of wet or medium concretes is being undertaken. It gives sufficiently accurate results for design purposes. For research, however, hand mixing is undoubtedly preferable.

In use, the best procedure has been found to be as follows:-

a) A small batch is made up with a mortar content similar to the first test batch, rather wet consistency. This batch is mixed and discharged, leaving a coating in the drum.

b) The mixer is started and the aggregates (together with water in one method) are added first, using a special funnel-shaped loading chute. If the water was not added with the aggregates, about $\frac{3}{4}$ of the water required is now added, then the cement and finally the last of the water, slowly.

c) The mixing time allowed is $2\frac{1}{2}$ mins.

d) The concrete is dumped from the mixer into a large mixing pan and turned over by hand continuously whilst the apparatus is being filled. Testing is commenced immediately/...

immediately after discharge of the concrete.

Mixer efficiency tests, using no blades in the drum, different types of blades and different loading procedures have been carried out. The results are not reported in this thesis.

2. Hand Mixing: Concrete is mixed by hand in a large metal pan (2 "diam $4\frac{1}{2}$" deep), observing the following procedure:-

a) The aggregates are placed in the dampened pan and the cement added on top.

b) The ingredients are mixed either damp or wet depending on choice of methods (see Appendix A). If mixed damp, about $1\frac{1}{2}$ minutes suffices at this stage. Two trowels are used, employing a rythmic action.

c) The requisite water is slowly added.

d) Mixing continues until the concrete appears to be thoroughly homogeneous. As in the case of machine-mixed concrete, the mixture is turned over continuously during the loading of any apparatus.

A P P E N D I X C.

EXPERIMENTAL DATA.

I. THE AGGREGATES.

1. Coarse aggregates. At the Cape there are few natural gravels available for use as concrete aggregates and the usual practice is to make use of crusher-run stone. Most of the stone used in the experiments was granite from the Cape Town City Council's Quarry. A few experiments were carried out with a quarried laterite gravel and with a river gravel.

These aggregates are described below:

a) Brackenfel Granite. In bulk, the stone is clean and free from dust (after washing). The individual stones are generally angular in shape with a small proportion of flaky pieces. Surface characteristic: coarse crystalline (Group 4, Appx M.BSS 882). Fig.

b) Durbanville Laterite. The stone has been washed and is free from fines. As naturally occurring, contains undesirable mud and clay. The particle shape is mainly irregular with a few rounded particles and occasional fractured pieces. Surface texture is gfanular, pitted (3 and 5) Fig.

c) Liesbeek River Gravel. (Mixed Quartzites and sandstones). Stone has been washed free from fines which are a feature of the natural beds. Particle shape is in general rounded and angular pieces rarely occur. Many stones are almost spherical. Surface texture fine crystalline.

Sieve analyses of the artificially graded stone:

$\frac{3}{4}$" Brackenfel:

Tyler Sieve No.	Retained on: Weight gms.	%	Cumulative percent
$1\frac{1}{2}$	N I L	0	0
$\frac{3}{4}$	464.1	12	12
$\frac{3}{8}$	3268.0	84.3	96.3
4	108.6	2.8	99.1
8	(Passing, 36.3)	0.9	100.
etc		0	etc.

F.M. 7.07

$\frac{5}{8}$" - No.4/...

$\frac{3}{8}$"-No.4.Brackenfel:

Tyler Sieve No.	Retained on Weight gms.	%	Cumulative percent
$\frac{3}{4}$	0	0	0
$\frac{3}{8}$	628	26.4	26.4
4	678	28.5	54.9
8	540.6	22.8	77.7
14	530.4	22.3	100.0
28	0	0	100
48	0	0	100
100	0	0	100
	2377 gms	100.0	5.59 F.M.

Durbanville Laterite:

Tyler Sieve No.	Retained on Weight lbs.	%	Cumulative percent
$\frac{3}{4}$	18.31	14.9	14.9
$\frac{3}{8}$	69.20	56.3	71.2
4	33.31	27.1	98.3
8	2.125	1.7	100
14	0	0	100
28	0	0	etc
48	0	0	
100	0	0	
	122.95lbs	100.0 ✓	F.M. 6.84

This grading is similar to the combined grading of Brackenfel $\frac{3}{4}$" and $\frac{3}{8}$ - No.4 for Group C.

Liesbeek River Gravel:

Tyler Sieve No.	Retained on Weight lbs.	%	Cumulative percent
$\frac{3}{4}$	13.01	10.3	10.3.
$\frac{3}{8}$	82.47	65.3	75.6.
4	30.82	24.4	100
8	0	0	100
14	0	0	100
28	etc	0	etc
etc		etc	
	126.30 lbs	100.0 ✓	F.M., 6.86

2. Fine Aggregate. The sand used throughout all these tests was a red river sand from Malmesbury, C.P. Fig. 124

It is a well-washed sharp-grained sand of local quartzites having a very constant sieve analysis, as follows:-

Tyler Sieve No.	Retained on Weight in gms.	%	Cumulative % retained.
4	18.7	3.74	3.74
8	24.2	4.83	8.57
14	78.2	15.64	24.21
28	121.5	24.30	48.51
48	183.6	36.70	85.21
100	63.6	12.75	97.96
100 (passing)	10.2	2.09	100.00
	Total, 500 gms	100.00 ✓	

Fineness modulus 2.68.

3.Table/...

3. Table of Data for Aggregates

Material	Moisture Condition	Approx. Unit Wt lbs per cu. ft loose	compact	Specif. Gravity	% Absorption
(1)	(2)	(3)	(4)	(5)	(6)
¾" Brack-enfel.	Saturated, surface dry			2.63	0.56
	Bin dry	84.6	91		
⅜" Brack-enfel.	Saturated, surface dry			2.63	0.56
	Bin dry	84.5	93		
¾" Later-ite	Saturated, surface dry			2.59	0.58
¾" Lies-beek	do do			2.67	0.43
Malmesbury Sand	do do	90	102-104	2.53	1.12

II. THE CEMENT.

Ordinary Portland Cement, complying with B.S.S. No.12, supplied by Cape Cement Sales in 94 lb. bags. Each series of tests was performed on one consignment which was carefully stored to prevent deterioration. Cement was used as soon as possible after receipt.

Typical Standard Test Results.

Batch No.	2A1	5A1	5B1	6B1
Retained on 170 sieve, per cent	7.61	5.34	8.26	6.02
" " 72 " " "	0.12	0.07	0.11	0.07
Setting Time (Initial hr. mn.	1-30	0-55	1-25	1-35
(Final " "	2-10	2-05	3 -15	3-00
Soundness. Le chatelier (mm)	1.0	1.0	1.0	1.0
Vicat needle test; W/C for standard penetration..percent	31.0	32.0	29.5	32.5
Tensile strength, lbs./sq.ins. 1:3 Mortar by wt. (3 days	386	401	420	396
(7 days	441	456	506	492

III. EARLY TEST RESULTS. Prior to the carrying out of the systematic series of tests, which are reported in Tables 4 to 6, the tests given in Tables 3 and 3A were carried out, with results as shown.

Mixes were batched by weight. All results shown are averages of at least 3 tests.

TABLE 3.

Serial No. (1)	Proportions by weight (Nominal) (2)	Water Cement Ratio (3)	Slump in ins. (4)	Flow % (5)	Remarks. (6)
3.01	1:2.4:3.6	0.40	0		Dry, pebbly.
3.10	by weight	0.45	0⅛		Dry.
3.03		0.50	0⅜		Dry, cohesive.
3.08		0.55	0⅝	33	Stiff.
3.12		0.575	1¼		Stiff - medium.
3.06	1:2.4:3.6	0.60	3	52.5	Medium. Good concrete.
3.09		0.65	6	72	Medium to wet, segregating.
3.02		0.70	5¾	85	Medium to wet, segregating.
3.05		0.75	6¾	90	Wet.
3.04		0.80	7	110	Wet, segregating.
3.11	1:2.4:3.6	0.85	8½		Wet.
3.07		0.90	8¾		V.sloppy.
4.01	1: 2: 3	0.40	0		
4.03		0.45	1	20	Sticky.
4.02		0.50	0¾	42.5	Dry, cohesive.
4.04		0.55	5	67.5	
4.05		0.60	3	85	Cohesive, plastic.
4.07	1: 2: 3	0.65	8¼	103	
4.06		0.70	8½	120	
4.08		0.75	8½		Sloppy.
4.09		0.45	0⅜	20	Stiff.
4.10		0.50	1½	42.5	Medium, fatty.
4.11	1: 2: 3	0.55	3 ½	65	Medium, plastic.
4.12		0.60	7½	85	Wet, quaking.
5.01	1:1.5:2.25	0.35	0¾		Stiff, creamy and rich.
5.15		0.45	2¼	55	Stiff to medium
5.02		0.50	7¼	80	Sloppy.
5.03		0.55	9	92.5	Sloppy.
5.04		0.60	9	97.5	
5.05	1:1.5:2.25	0.65	9½		Sloppy.
5.06		0.40	1½	27.5	
6.03		0.35	1⅜		Stiff, creamy, sandy.
6.04		0.475	8¼		Wet.

Note: In the above concretes the aggregates are,

Coarse: Backenfel granite,
¾" Nominal, 60%) by weight of coarse
⅜" -4, 40%) aggregate.

Fine: Malmesbury River sand.

TABLE 3A :

Serial No.	Nominal Proportions by weight	Water Cement Ratio	Slump in ins	Flow Trough Leakage Flow	Flow @ 5	Flow @ 10	Plast. Coeft.	Remarks
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
7.01	1:1.5:2.25	0.40	1½	-	1⅛	3⅜	0.95	Stiff
7.02		0.45	3	-	2½	3½	1.42	Medium, plastic
7.03		0.475	7	-	3¼	4¾	1.37	Wet
7.04		0.50	7¼	-	4	6	1.33	S.sloppy
7.05		0.55	8¾	½	5½	8¼	1.33	Sloppy
7.06	1:2:3	0.475	0¾	-	1	1¾	1.14	Stiff
7.07		0.50	0¾	-	1¼	2	1.25	Rather stick
7.08		0.55	3½	-	2	3½	1.14	
7.09		0.60	6	v.small	3¼	5½	1.18	V.bad segregat
7.10		0.65	8¼	½	5	7¼	1.38	Sloppy
7.11	1:2.4:3.6	0.575	1¼	-	1⅛	1¾	1.29	Stiff-medium
7.12		0.60	2¼	-	1⅜	2¼	1.22	Medium
7.13		0.625	2¾	-	1⅝	2¾	1.18	do
7.14		0.65	4½	trace	2	3¾	1.07	Begng to segreg
7.15		0.70	5¾	¼	3½	6	1.17	(Medium-wet (slight segregn-
7.16	1:2.5:5	0.55	0	-	¼	0½	1.0	Dry
7.17		0.65	0½	-	0⅞	1⅝	1.07	V.stiff
7.18		0.70	1½	-	1¼	2⅝	0.95	
7.19		0.75	3	¾	2	4	1.0	Segregates badly
7.20		0.80	5	1	4	6½	1.23	Wet, segregating

Note: In the above concretes the aggregates are:

Coarse: Brackenfel granite,
¾" Nominal, 60%) by weight of coarse
⅜" - 4, 40%) aggregate

Fine: Malmesbury River sand,

TABLE 4 : Main Series of Tests using Brackenfel Granite and Malmesbury Sand. In the table, each result given is, except where otherwise noted, the average of three separate determinations at different times. Results marked - are the average of two tests.

Remoulding Test: Results are in terms of ½" drops of Flow Table. 3" Ring Clearance.

Pressure Test: PTV represents the pressure necessary for 0.6 ins. deflection.

Group	Serial No.	Coarse Aggte ¾"Nom	Coarse Aggte ¾"-4	Aggte Fine	Cement	Water cement ratio	Absolute Volumes water cement	Absolute Volumes all materls	Absolute Volumes Ratio 8/9	Slump ins	Flow %	Serial No.	Remouldg Effort ½"drops	Standard Compactg Factor	Pressure Test PTV	Remarks
		% by wt of total aggregate														
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(2)	(13)	(14)	(15)	(16)
A	1	66.6	0	33.3	27.5	0.45	0.1020	0.2873	0.355	4¾	50	1	114	.984	10.5	Rich, sticky, stony.
	2				25.0		.0927	.2780	.333	0⅜	40	2	200	.963	16.0	Harsh, rather wet.
	3				22.5		.0835	.2688	.311	0⅛	30	3		.881	23	Segregates badly in rem. test.
	4				20		.0742	.2595	.286	0	15	4		.830		Stiff and harsh very stony
	5				17.5		.0648	.25o1	.259	0	6	5		.782		undersanded too stiff for r.t.
A	6	66.6	0	33.3	25.0	0.575	.1077	.2930	.367	6½	77.5	6	73	.991	9.3	Sloppy-wet, segrtg, undersanded
	7				22.5		.0970	.2823	.343	3	62.5	7	120		11.0	RT, segregated very badly
	8				20		.0862	.2715	.317	2	60	8	160	.958	14.5	Stony, wet, segregating
	9				17.5		.0754	.2607	.289	1	50	9	240		23.1	
	10				15		.0647	.2500	.259	0	--	10		.834		Stony, lacks mortar.
A	11	66.6	0	33.3	22.5	0.70	.1106	.2959	.374	6	75	11	130 †	1.007 †	19.4	Very stony and sloppy
	12				20		.0982	.2835	.347	8¼	110	12	150		22.6	do.
	13				17.5		.0859	.2712	.317	7¾	92.5	13		.962	29	Segregating, sloppy.
	14				15		.0737	.2590	.285	6½	90	14				
	15				12.5		.0612	.2465	.248	--	--	15		.898		Seriously lacks mortar.
A	16	~~66.6~~ 60	0	~~33.3~~ 40	27.5	0.45	.1020	.2878	.355	6¾	82.5	16	49	.947 †	5.5	Rich, cohesive, smooth.
	17				25.0		.0927	.2785	.333	2½ †	37.5	17	88		7.0	Sticky, rich.
	18				22.5		.0835	.2693	.310	1	25	18	116	.843	10.0	Sticky, rather stiff.
	19				20		.0742	.2600	.285	0¼	17.5	19	176 †		17	Cohesive, stiff.
	20				17.5		.0648	.2506	.259	0	--	20		.72		Dry, pebbly.
A	21	60	0	40	25.0	0.575	.1077	.2935	.367	7¼	110 †	21	70	.998	3.8	Wet, smooth.
	22				22.5		.0970	.2828	.343	6¾	90	22	95		4.2	
	23				20		.0862	.2720	.317	3½	70	23	139	.973	6.0	Medium
	24				17.5		.0754	.2612	.289	1½	40	24	145	.	10	Wet, (apparently)
	25				15		.0647	.2505	.258	1¼	20 †	25	150	.852	20	Stiff
A	26	60	0	40	22.5	0.70	.1106	.2964	.373	7½	150	26	48	1.013 †	4.2	Very wet and sloppy.
	27				20		.0982	.2840	.346	7	130	27	74		5.3	Segregating
	28				17.5		.0859	.2717	.316	7	100	28	140	.995	7.9	Rem. Test segregated.
	29				15		.0737	.2595	.284	--	--	29			13.1	
	30				12.5		.0612	.2470	.247	--	--	30		.873	23.9	Stiff, lacks mortar.
A	31	55	0	45	27.5	0.45	.1020	.2881	.354	7	77.	31	27	.968	3.5	Cohesive, sticky.
	32				25		.0927	.2788	.333	2¼ †	42.5	32	45		4	stuck in compacting factor
	33				22.5		.0835	.2696	.310	0⅜	25	33	77	.898	6	hoppers.
	34				20		.0742	.2603	.285	0⅛	15	34	130		11.25	
	35				17.5		.0648	.2509	.259	0	--	35	200	.758	20	Dry, stony, gritty.
A	36	55	0	45	25	0.575	.1077	.2938	.367	7½	92.5	36	17	1.007	2.5	Rich, smooth, wet.
	37				22.5		.0970	.2831	.343	7	75 †	37	26		2.8	Sheer slump
	38				20		.0862	.2723	.316	2¼	37.5	38	51	.928 †	3.4	Medium, wet.
	39				17.5		.0754	.2615	.289	0½	22.5	39	99		5.5	Medium, well sanded.
	40				15		.0647	.2508	.258	1	20	40	137	.833	11.5	Stiff, sticky.
A	41	55	0	45	22.5	0.70	.1106	.2967	.373	8½	150	41	16	.755	2.4	Very wet, rich.
	42				20		.0982	.2843	.345	7¾	140	42	20		2.8	
	43				17.5		.0859	.2720	.315	4¾	95	43	80	1.000 †	3.9	Rather wet.
	44				15		.0737	.2598	.284	2	45 †	44	85	~~xx~~	6.7	Medium.
	45				12.5		.0612	.2473	.247	--	--	45		.848	13.5	Stiff, stony.

TABLE 4, Continued:

Group	Serial No.	Coarse Aggte $\frac{3}{4}$"Nom	Coarse Aggte $\frac{3}{8}$"-4	Fine Aggte	Cement	Water cement ratio	Absolute Volumes water cement	Absolute Volumes all matls	Absolute Volumes Ratio, 8/9	Slump ins	Serial No.	Flow %	Remouldg Effort $\frac{1}{4}$"drops	Standard Compactg Factor	Pressure Test PTV	Remarks
		% by wt of total aggte														
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(2)	(12)	(13)	(14)	(15)	(16)
A	226	50	0	50	27.5	0.45	0.1020	0.2883	.354	6	226		30	.928	3	(Medium - stiff. Sticky and
	227				25		.0927	.2790	.332	4	227		70		5.7	(cohesive.
	228				22.5		.0835	.2698	.310	1¼	228		120	.833	8.4	Smooth, stiffer.
	229				20		.0742	.2605	.285	0	229		200		18	
	230				17.5		.0648	.2511	.258	0	230			.755		Dry, crumbly and gritty.
A	231	50	0	50	25	0.575	.1077	.2940	.366	4½	231			1.000	1.3	Very smooth, sandy.
	232				22.5		.0970	.2833	.343	2¾	232				1.8	
	233				20		.0862	.2725	.316	1	233			.952	4	
	234				17.5		.0754	.2617	.288	¼ †	234				7.6	
	235				15		.0647	.2510	.257	0	235				22	
A	236	50	0	50	22.5	0.70	.1106	.2969	.372	8½	236			1.02	1.9	Sloppy, segregating.
	237				20		.0982	.2845	.345	7	237				2.2	
	238				17.5		.0859	.2722	.315	4	238			.989	4.0	Still very wet.
	239				15		.0737	.2600	.283	1	239				7.0	
	240				12.5		.0612	.2475	.247	-	240			.853	14.8	Medium-stiff, sandy.
B	46	50	16.7	33.3	27.5	0.45	.1020	.2873	.355	4¾	46	60	100	.926	12	Medium-rich, sticky, stony.
	47				25		.0927	.2780	.333	1¼	47	38	172		18	Rich appearance. Rather harsh.
	48				22.5		.0835	.2688	.311	0¾	48	20	290	.843	27	Medium-stiff.
	49				20		.0742	.2595	.286	0	49	8				Too stiff for Rem.Test.
	50				17.5		.0648	.2501	.259	0	50					No cohesion. Crumbled on testing
B	51	50	16.7	33.3	25	0.575	.1077	12930	.367	5¾	51	92	93	.977	7.3	Rich looking and sloppy
	52				22.5		.0970	.2823	.345	5½	52	80	120	.962	8.5	Appeared too wet.
	53				20		.0862	.2715	.317	3¼	53	57.5	170	.938	12.5	Stony, medium.
	54				17.5		.0754	.2607	.289	1½	54	40		.901	18	(R.T. not completed.
	55				15		.0647	.2500	.259	0	55	30		.817		(Very badly segregated.
B	56	50	16.7	33.3	22.5	0.70	.1106	.2959	.374	8½	56	175	144	1.002	13.8	Sloppy and stony
	57				20		.0982	.2835	.347	8	57	120	163	.999	16.6	Sloppy, segregating
	58 †				17.5		.0859	.2712	.317	4	58 †	100		.985	24	Mortar thin, segregates.
	59				15		.0737	.2590	.285	1	59			.937		Very stony and harsh
	60				12.5		.0612	.2465	.248	-	60			.849		do. lacks mortar.
B	61	45	15	40	27.5	0.45	.1020	.2878	.355	8¼	61		55	.968	5.5	Sticky, smooth, cohesive.
	62				25		.0927	.2785	.333	1½	62	25	75		9.2	Rich, sticky, stiff.
	63				22.5		.0835	.2693	.310	¾	63	20	108	.907	13.2	Good cohesion
	64				20		.0742	.2600	.285	0½	64	12.5	190		21.3	Dry.
	65 †				17.5		.0648	.2506	.259	0	65 †	5		.797	35 ?	Crumbling.
B	66	45	15	40	25	0.575	.1077	12935	.367	7½	66	92.5	40	1.000	2.8	Rather sloppy.
	67				22.5		.0970	.2828	.343	7	67	87.5	52	.997	3.3	Rich, wet.
	68				20		.0862	.2720	.317	3½	68	55	80	.983	4.6	S.wet to medium.
	69				17.5		.0754	.2612	.289	0¾	69	37.5	114	.951	7.6	Stiff to medium.
	70				15		.0647	.2505	.258	0¼	70	17.5	156	.876	15.1	do. Stiff.
B	71	45	15	40	22.5	0.70	.1106	.2964	.373	7¼	71	130	50	1.013	3.2	Segregated badly in R.T.
	72				20		.0982	.2840	.346	7	72		60	1.011	4.0	Sloppy, segregating.
	73				17.5		.0859	.2717	.316	5½	73	105	90	1.002	6.8	Wet, segregates.
	74				15		.0737	.2595	.284	3	74	73	132	.955	12	Medium, hungry for mortar.
	75				12.5		.0612	.2470	.247	-	75			.867 †	24 †	harsh, undersanded.
B	76	41.25	13.75	45	27.5	0.45	.1020	.2881	.354	4	76	52.5	24	.955	3.8	Rich, sticky, cohesive, smooth
	77				25		.0927	.2788	.332	1½	77	32.5	42		5.3	Medium-stiff, smooth.
	78				22.5		.0835	.2696	.310	1	78	25	80	.853	8.8	Stiff, cohesive.
	79				20		.0742	.2603	.285	0½	79	15	160		17	Vibration could compact well.
	80				17.5		.0648	.2509	.259	0 †	80			.774 †	30 ? †	Dry, crumbling on flow test.

TABLE 4, Continued:

Group	Serial No.	Coarse Aggte ¾"Nom, % by wt of total aggte	Coarse Aggte ⅜"-4, % by wt of total aggte	Fine Aggte, % by wt of total aggte	Cement	Water cement ratio	Absolute Volumes: water cement	Absolute Volumes: all matls	Absolute Volumes: Ratio, 8/9	Slump ins	Flow %	Remouldg Effort ¼"drops	Standard Compactg Factor	Pressure Test PTV	Remarks
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
B	81	41.25	13.75	45	25	0.575	0.1077	0.2938	0.367	8	85	17	1.006	1.9	Sloppy, well sanded.
	82				22.5		.0970	.2831	.343	6½	80	24	1.003	2.1	Adequate, rich, creamy mortar.
	83				20		.0862	.2723	.316	4½	50	32	.999	2.7	Smooth, medium-wet.
	84				17.5		.0754	.2615	.289	2	30	55	.966	4.0	Smooth, workable.
	85 †				15		.0647	.2508	.258	¼		144	.876	9.2	Stiffer
B	86	[illegible]	[illegible]	[illegible]	22.5	0.70	0.1106	.2967	.373	8	165	12	1.018	2.1	Sloppy.
	87	41.25	13.75	45	20		.0982	.2843	.345	7½	140	20	1.014	2.5	Medium consistency.
	88				17.5		.0859	.2720	.315	6	95	32	.994	3.3	
	89				15		.0737	.2598	.284	3	55	52	.960	7.0	Does not appear oversanded.
	90				12.5		.0612	.2473	.247	[illegible]		96	.869	16	
B	241	37.5	12.5	50	27.5	0.45	.1020	.2883	.354			38	.961	3.4	V. sticky.
	242				25		.0927	.2790	.332			68		7.5	
	243 †				22.5		.0835	.2698	.310			120	.883	13	
	244				20		.0742	.2605	.285					25	Oversanded.
	245				17.5		.0648	.2511	.258				.795		Dry, crumbly, gritty.
B	246	37.5	12.5	50	25	0.575	.1077	.2940	.366			10	.970	1.8	
	247				22.5		.0970	.2833	.343			20	.970	2.0	
	248				20		.0862	.2725	.316			46	.963	3.3	V. smooth
	249				17.5		.0754	.2617	.288			92	.941	6.6	
	250 †				15		.0647	.2510	.257				.832	16	
B	251	37.5	12.5	50	22.5	0.70	.1106	.2969	.372			7	1.018	1.8	Sloppy does not hold water.
	252				20		.0982	.2845	.345			11		2.0	
	253				17.5		.0859	.2722	.315			20	.987	2.6	V. Smooth, wet.
	254				15		.0737	.2600	.283			48		6.0	
	255				12.5		.0612	.2475	.247			120	.853	17	
C	91	33.3	33.3	33.3	27.5	0.45	.1020	.2875	.355	2	32.5	100	.963	4.8	Sticky, rich, rather wet.
	92				25		.0927	.2780	.333	1½	27.5	156		9	Medium, stony, stiff.
	93				22.5		.0835	.2688	.311	1	17.5		.854	15	
	94				20		.0742	.2595	.286	⅛	12.5			28.5	Stiff, stony
	95				15		.0648	.2501	.259	0			.757	41	Dry
C	96	33.3	33.3	33.3	25	0.575	.1077	.2930	.367	6	96	150	.998	2.9	Wet, segregation.
	97				22.5		.0970	.2823	.343	5½	85	134		3.3	do do.
	98				20		.0862	.2715	.317	4	55	125	.971	7	Medium, stony, rich mortar, under
	99				17.5		.0754	.2607	.289	0½	30	185	.917	17	Medium, stony, undersanded.
	100				15		.0647	.2500	.259	0					Tests inopperative.
C	101	33.3	33.3	33.3	22.5	0.70	.1106	.2959	.374	7¾	110	120	1.008	4.6	Mortar v. thin, sloppy, segregatin
	102				20		.0982	.2835	.347	6	95	75		8.8	Medium, s tony
	103				17.5		.0859	.2712	.317	3	77.5	80	.946	18.5	Definately undersanded
	104				15		.0737	.2590	.285	1				34	
	105				12.5		.0612	.2465	.248	-			.857		Very stony lacks mortar.
C	106	30	30	40	27.5	0.45	.1020	.2878	.355	4¼	67.5	32	.962	1.7	Smooth, rich, medium
	107				25		.0927	.2785	.333	1¾	30	49		4.0	Good cohesion,
	108				22.5		.0835	.2693	.310	1	20	25	.879	6.6	Medium-stiff
	109				20		.0742	.2600	.285	0	7.5	172		13	Smooth, workable.
	110				17.5		.0648	.2506	.259	0			.791	22	Crumbling, obscured flow test.
C	111	30	30	40	25	0.575	.1077	.2935	.367	8½	85	43	1.001	1.2	V. Wet but not segtg. too badly.
	112				22.5		.0970	.2828	.343	6¾	70	37		1.4	Wet do
	113				17.5		.0862	.2720	.317	4	47	61	.974	2.4	Medium, less water evident.
	114				15		.0754	.2612	.289	1¾	40	99	.928	6.0	Medium
	115				12.5		.0647	.2505	.259	0¼	30	172		14	Stiff and stony.

TABLE 4, Continued :

Group	Serial No.	Coarse Aggte ¾"Nom	Coarse Aggte ½"-4	Fine Aggte	Cement	Water cement ratio	Absolute Volumes water+cement	Absolute Volumes all matls	Absolute Volumes Ratio, 8/9	Slump ins	Serial No.	Flow %	Remouldg Effort ½"drops	Standard Compactg Factor	Pressure Test PTV	Remarks
		% by wt of total aggte														
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(2)	(12)	(13)	(14)	(15)	(16)
C	116	30	30	40	22.5	0.70	0.1106	0.2964	0.373	8	116	110	22	1.018	2.5	Sloppy,rich looking
	117				20		.0982	.2840	.346	7½	117	100	28		3.0	
	118				17.5		.0859	.2717	.316	5½	118	75	50	.995	4.8	Med.-sloppy. Segregates.
	119				15		.0737	.2595	.284	1½	119	60	90		11	Wet, segregating, stony.
	120				12.5		.0612	.2470	.247	0	120			.886	23.5	S.stiff-medium, undermortared.
C	121	27.5	27.5	45	27.5	0.45	.1020	.2881	.354	5	121	56	25	.966	1.6	Rich,heavily sanded,smooth,fat.
	122				25		.0927	.2788	.332	2¼	122	37.5	38		3.0	do, cohesive, medium.
	123				22.5		.0835	.2696	.310	0¼	123	15	72	.871	5.6	(Med-stiff.Had to be helped thru'
	124				20		.0742	.2603	.285	0	124		152		11	(both hoppers in comp.factor test
	125				17.5		.0648	.2509	.259	0	125			.798	18	Stiff,both hoppers O.K.
C	126	27.5	27.5	45	25	0.575	.1077	.2938	.367	7½	126	105	8	1.005	1.6	Wet but non-segregatg,v.smooth.
	127				22.5		.0970	.2831	.343	6	127	57.5	26		1.6	s.wet-med.,smooth.
	128				20		.0862	.2723	.316	2½	128	45	42	.992	1.7	do
	129				17.5		.0754	.2615	.289	0¼	129	17.5	72	.949	3.0	Medium-stiff.
	130				15		.0647	.2508	.258	0	130		132		8.7	
C	131	27.5	27.5	45	22.5	0.70	.1106	12967	.373	8¾	131	140	5	1.020	1.8	Sloppy, rich looking.
	132				20		.0982	.2843	.345	8½	132	105	20		2.5	
	133				17.5		.0859	.2720	.315	5¾	133	70	37	.989	3.5	Wet, well mortared.
	134				15		.0737	.2598	.284	-	134		73		6.8	
	135				12.5		.0612	.2473	.247	-	135			.858	18	Medium-stiff,lacks lubricating compt
C	256	25	25	50	27.5	0.45	.1020	.2883	.354		256		18	.965	2.7	Cohesive,oversanded.Stuck in c.f.hopper
	257				25		.0927	.2790	.332		257		46		4.3	
	258				22.5		.0835	.2698	.310		258		104	.841	7.2	do,also had to be helped thru "
	259				20		.0742	.2605	.285		259				14.6	
	260				17.5		.0648	.2511	.258		260			.714	25	Dry, crumbly.
C	261	25	25	50	25	0.575	.1077	.2940	.366		261		8	1.000	1.4	Wet, v.smooth, does not segregate
	262				22.5		.0970	.2833	.343		262		18		1.4	
	263				20		.0862	.2725	.316		263		46	.937	2,5	Med-stiff, cohesive, gritty
	264				17.5		.0754	.2617	.288		264		82		5.8	
	265				15		.0647	.2510	.257		265		160	.813	15	Dry,crumbling,sandy.
C	266	25	25	50	22.5	0.70	.1106	.2969	.372		266		4	1.014	1.7	Sloppy, well mortared
	267				20		.0982	.2845	.345		267		15		1.8	
	268				17.5		.0859	.2722	.315		268		43	.991	2.4	med-wet, do.
	269				15		.0737	.2600	.283		269		90		8	
	270				12.5		.0612	.2475	.247		270			.839	23	dry - stiff.
D	136	16.65	50	33.3	27.5	0.45	.1020	.2873	.355	2	136		80	.904	8	medium,sticky, cohesive.
	137				25		.0927	.2780	.333	1¼	137	25	110		11.5	rich looking, pebbly.
	138				22.5		.0835	.2688	.311	½	138	22.5	150	.843	17.3	intermediate sizes evident
	139				20		.0742	.2595	.286	0	139				32	dry - stiff
	140 †				17.5		.0648	.2501	.259	0	140 †			.774		stiff, harsh and pebbly.
D	141	16.65	50	33.3	25	0.575	.1077	.2930	.367	5½	141	77	56	.993	3.2	overwet, stony, segregating.
	142				22.5		.0970	.2823	.343	5⅛	142	70	62		5.9	seems less segregation
	143				20		.0862	.2715	.317	1	143	47.5	130	.905	11.5	harsh.
	144				17.5		.0754	.2607	.289	0¾	144	30		.863	24	medium - stiff, lacks mortar.
	145				15		.0647	.2500	.259	0	145					
D	146	16.65	50	33.3	22.5	0.70	.1106	.2959	.374	7	146	125	46	1.16	7.7	sloppy, segregating, stony.
	147				20		.0982	.2835	.347	3½	147	82.5	68		12.6	
	148				17.5		.0859	.2712	.317	-	148	82	126	.964	28	weak thin mortar bad segregation
	149				15		.0737	.2590	.285	-	149					
	150				12.5		.0612	.2465	.248	-	150			.853		as 148, very stony.

TABLE 4, Continued:

Group	Serial No.	Coarse Aggte ¾"Nom	Coarse Aggte [illegible]-4	Fine Aggte	Cement	Water cement ratio	Absolute Volumes water+ cement	Absolute Volumes all matls	Absolute Volumes Ratio, 8/9	Slump ins	Serial No.	Flow %	Remouldg Effort ½"drops	Standard Compactg Factor	Pressure Test PTF	Remarks
		% by wt of total aggte														
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(2)	(12)	(13)	(14)	(15)	(16)
D	151	15	45	40	27.5	0.45	0.1020	.2878	.355	7½	151		42	.860	3	Very plastic, cohesive.
	152				25		.0927	.2785	.333	6⅛	152	50	58		4.6	rich, smooth.
	153				22.5		.0835	.2693	.310	0⅛	153	12.5	85	.853	7	medium v.smooth, cohesive.
	154				20		.0742	.2600	.285	0	154	12.5	160		13	crumbling in flow test.
	155				17.5		.0648	.2506	.259	0	155			.811	22.5	stiff suitable for vibration onl
D	156	15	45	40	25	0.575	.1077	.2935	.367	7½	156	80	12	.999	1.4	wet, smooth.
	157				22.5		.0970	.2828	.343	4⅜	157	50	34		1.8	v.plastic
	158				20		.0862	.2720	.317	0⅞	158	20	80	.953	2.9	wet to medium
	159				17.5		.0754	.2612	.289	0	159	10	133	.953	8.0	medium, good mortar
	160				15		.0647	.2505	.258	0	160				17	
D	161 †	15	45	40	22.5	0.70	.1106	.2964	.373	8	161 †	130	25	.995	2.2	sloppy, segregating.
	162				20		.0982	.2840	.346	6½	162	82.5	38		3.7	sloppy.
	163				17.5		.0859	.2717	.316	0½	163	25	53	.960	7.8	wet, lean mortar.
	164				15		.0737	.2595	.284	0	164		92		18	
	165				12.5		.0612	.2470	.247	0	165		200	.856		lacks mortar, segregates, harsh.
D	166	13.75	41.25	45	27.5	0.45	.1020	.2881	.354	4	166		34	.957	2.3	cohesive, smooth.
	167				25		.0927	.2788	.333	0¼	167	17.5	52		3	stiff, good cohesion, sandy.
	168				22.5		.0835	.2696	.310	0	168	10	84	.908	5.8	(crumbles on flow test. Stuck in
	169				17.5		.0742	.2605	.285	-	169		136		11.5	(both hoppers; comp.factor test.
	170				15		.0648	.2509	.259	-	170			.852	18.5	medium - stiff, stony.
D	171 †	13.75	41.25	45	25	0.575	.1077	.2938	.367	6½	171 †	60	20	.996	1.1	smooth, rich, heavily sanded.
	172				22.5		.0970	.2831	.343	4	172	42.5	26		1.4	
	173				20		.0862	.2723	.316	1½	173	27.5	57	.972	1.8	
	174				17.5		.0754	.2615	.289	0	174	11	126	.939	3.6	starting to crumble on flow test.
	175				15		.0647	.2508	.258	0	175				9.8	
D	176	13.75	41.25	45	22.5	0.70	.1106	.2967	.373	8½	176	125	8	1.003	1.2	sloppy, smooth, not segregating bad
	177				20		.0982	.2843	.345	7	177	80	24		1.6	rich mortar
	178				17.5		.0859	.2720	.315	1½	178	42.5	42	.983	4.1	sloppy to wet, slightly ~~more cohesi~~
	179				15		.0737	.2598	.284	-	179		76		11	
	180				12.5		.0612	.2473	.247	-	180		138	.898		
D	271 †	12.5	37.5	50	27.5	0.45	.1020	.2883	.354		271 †		51		2.6	
	272 †				25		.0927	.2790	.332		272 †		70		6	
	273				22.5		.0835	.2698	.310		273		103		9.0	
	274 †				20		.0742	.2605	.285		274 †		175		16	
	275				17.5		.0648	.2511	.258		275				23.5	
D	276 †	12.5	37.5	50	25	0.575	.1077	.2940	.366		276 †		7		2.4	
	277				22.5		.0970	.2833	.343		277		25		3.0	
	278				20		.0862	.2725	.316		278		68		3.9	
	279 †				17.5		.0754	.2617	.288		279 †		160		6.2	
	280				15		.0647	.2510	.257		280				13.8	
D	281 †	12.5	37.5	50	22.5	0.70	.1106	.2969	.372		281 †		20		1.0	
	282				20		.0982	.2845	.345		282		28		2.2	
	283				17.5		.0859	.2722	.315		283		48		6.8	
	284				15		.0737	.2600	.283		284		82		17.5	
	285				12.5		.0612	.2475	.247		285					

TABLE 5 : Tests using Durbanville Laterite Gravel.

Group	Serial No.	Coarse Aggte %by wt of total	Fine Aggte aggte	Cement	Water Cement Ratio	Remouldg Test ½"drops	Pressure Test PTV	Remarks
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
F	501	66.7	33.3	22.5	0.575	28	3.0	Wet,inclined to/ segregate
	502			20		40	4.2	
	503			17.5		71	10.5	S.wet, pebbly
	504			15		120	35	(Inadequate mort-
	505			12.5		165	--	(v.pebbly
F	506	60	40	22.5	0.575	22	1.5	Wet,thin mortar
	507			20		25	2.0	
	508			17.5		47	3.8	Med.,good concr.
	509			15		80	8.0	Medium-stiff
	510			12.5		140	20	V.stiff
F	511	55	45	22.5	0.575	8	1.9	V.smooth,plastic non-segregatg
	512			20		20	2.1	
	513			17.5		36	3.9	Smooth, medium
	514			15		94	10.5	Appears oversand.
	515			12.5			28	Dry
F	516	50	50	22.5	0.575	5	1.1	Sloppy
	517			20		18	2.0	V.wet,sandy
	518			17.5		50	6.6	Medium-stiff
	519			15		105	20	Stiff,oversanded
	520			12.5		143	-	Dry, crumbling.

TABLE 6 : Tests using Liesbeek River Gravel.

Group	Serial No.	Coarse Aggte %by wt of total	Fine Aggte aggte	Cement	Water Cement Ratio	Remouldg Test ½"drops	Pressure Test PTV	Remarks
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
G	601	66.7	33.3	22.5	0.575	5		Sloppy,segregatg
	602			20		9	1.0	Undersanded
	603			17.5		30	3.1	Medium-wet
	604			15		100	9.8	do, v.unders.
	605			12.5		-	19.6	Stiff,harsh
G	606	60	40	22.5	0.575	6	-	Sloppy,rich
	607			20		9	0.9	do
	608			17.5		20	1.9	Wet, plastic
	609			15		60	5.3	v.good mixture
	610			12.5		150	14.8	Stiff,v. plastic
G	611	55	45	22.5	0.575	18	22.0	Sloppy,sandy
	612			20		25	2.1	Wet, v.sandy
	613			17.5		35	3.0	
	614			15		88	6.8	Med.,plastic,sa/-ndy
	615			12.5		160	-	Dry & sandy.
G	616	50	50	22.5	0.575	22	2.6	Wet, v.sandy
	617			20		30	3.0	do
	618			17.5		50	4.7	Medium, sandy
	619			15		120	11.0	V. Oversanded
	620			12.5				Dry and crumbly

Note : In the above tests the fine aggregate was Malmesbury River Sand.

APPENDIX D.

The Economy of Rigid Specification and Control.

(A brief illustration using a particular case.)

The savings possible are significant compared with the cost of controlled design and manufacture and may be considered from two aspects (aside from the wide subject of plant). Firstly, the saving in concrete possible by the use of higher allowable working stresses; secondly, in the use of less cement per cubic yard and the maximum utilization of the most suitable materials.

Consider briefly a specific case, the construction of a canal for the City of Cape Town. The figures quoted were obtained from a section of the Canal recently built by the Author. On a previously built portion of the same canal batching was by volume with a 7/5 tilting drum mixer. On the later portion, the same mixer was used but batching of aggregates was by weight using platform scales and barrows, cement in 94lb pockets, water by volume, accurately gauged. Frequent PTV's and 5 test cubes per day. General moisture control was visual.

(1) Saving by use of Higher Allowable Design.

Stress: To ensure durability and impermeability a nominal W/C of 0.60 by weight was adopted. This gave an average ultimate stress of 4,250 psi and a minm. of 3,800 psi on 6 inch laboratory cubes. (V = 6·6% and SD = 280 psi).

The basis for design was that not more than 10% of tested works cubes were to have an altimate strength less than 3,500 psi. (82.3% of average strength). This was easily achieved with the actual overall coefficient of variation of 14.8% obtained on the job. Note that this was with visual control of consistency. Two nominal sizes of crushed aggregate were combined by weight at the mixer. The fine aggregate, a Cape Flats sand, has a surprisingly constant grading.

According to the Code of Practice, permissable bending

stress/...

stress = X, where 3X = minim. crushing strength of works cubes. In this case a working stress of 1,000 psi was adopted for design as it was not known in advance how effective control would be. (An additional saving could have been effected by adopting a working stress of 1,150 psi.) Modular ratio was taken as

$\frac{40,000}{3,500}$ = 12.

C. of P. gives allowable working stress of 750 psi for Ordinary Grade 1 : 2 : 4 : Concrete (and n = 18)

These figures were used in the design of the first portion of the canal.

This lead to a saving of about 350 cu.yds in a total of 2,500 cu.yds, or 14%, representing (at 45/- per cu.yd) nearly £800.

Saving in cement at 5.6 pockets per cu.yd = 1,960 pockets = 82 tons (or £343).

(11) <u>Saving by Good Control:</u>

(a) <u>Design:</u> The mix was specially designed to enable as high a percentage as possible of a cheap, local pit sand to be used. There was a saving of 8d per cu.yd on materials in this case and, over 2,150 cu.yds, a total saving of approx. £70.

(b) <u>Control of Batching:</u> On a poorly controlled job, with volumetric batching, uncertain moisture content, etc, the minimum strength of works cubes would vary from 40% to 50% of the average strength of laboratory cubes, for the same nominal W/C.

Assuming a coefficient of variation of, say, 22%, and the requirement that not more than 10% of works cubes are to have an altimate stress less than 3500 psi, the nominal W/C needed would have to be at most 0.50 by weight, or 2.00 lbs of cement per pound of water. Design W/C = 0.60 by wt, or 1.67 lbs of cement per pound of water.

Difference,

Difference, 0.33 lbs of cement per pound of water. This difference, applied to 300 lbs of water, (roughly 300 lbs of water are required per cu.yd for workability) would be 99 lbs, or, say, 1 pocket of cement.

On 2,150 cu.yds, this represents a saving of about 90 tons of cement; @ 3/6d per 94 lb pocket delivered on site this means £376.

No mention has been made of the saving in labour in placing. Besides the above, the concrete is stronger, less permeable, more durable.

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T A B L E 1.

Water-Cement Ratio's for Different Conditions of Exposure.

Concrete will have the desired durability, other factors being favourable, if appreciable loss of moisture be prevented by effective curing for at least 7 days at a temperature of at least 70°F. Higher water-cement ratio's should be used for less favourable curing conditions. The data are based on the assumption that the concrete is of a suitable consistency and thoroughly compacted.

CLASS OF STRUCTURE EXPOSURE	WATER-CEMENT RATIO'S BY WEIGHT Thin reinfcd sections, piles, external columns and beams.	 Plain thin sectns, moderate reinfcd sections	 Heavy walls piers, foundations, dams of heavy sectn.
Extreme			
1. In severe climates, exposure to alternate wetting and drying, freezing and thawing, as at water-line in hydraulic structures.	0.44	0.45	0.50
	to	to	to
2. Exposure to sea and strong sulphate waters and other corrosive salts in both severe and moderate climates.	0.49	0.50	0.54
Severe			
3. In severe climates, exposure to rain and snow, freezing and thawing, but not continually in contact with water.	0.49	0.50	0.58
	to	to	to
4. In moderate climates, exposure to alternate wetting and drying as at water-level in hydraulic structures.	0.53	0.54	0.60
Moderate			
5. In temperate climates, exposure to ordinary weather but not continuously in contact with water.	0.54	0.56	0.63
	to	to	to
6. Completely submerged, but protected from freezing.	0.60	0.65	0.67
7. Concrete deposited through water	0.49	0.49	0.49
Protected:			
8. Ordinary enclosed structural members; concrete below ground and not subject to corrosive waters or freezing and thawing.	0.63 to 0.67	0.67	0.68

Note: In moderate or protected conditions strength requirement may decide water-cement ratio, which must not be greater than indicated in table.

TABLE 2.

RECOMMENDED PRESSURE TEST VALUES.

(Incorporating "Uses of Concrete of Different Degrees of Workability" as set out in Table 4, Road Note No.4.[37])

Degree of workability	Slump* in inches	COMPACTING FACTOR Small Apparatus	COMPACTING FACTOR Large Apparatus	P T V range	Use for which concrete is suitable.
"Very low"	0 to 1	0.78	0.80	25 to 35	Vibrated concrete in roads or other large sections
"Low"	1 to 2	0.85	0.87	15 to 20	Mass concrete foundations without vibration. Simple reinforced sections with vibration.
"Medium"	2 to 4	0.92	0.935	8 to 10	For normal reinforced work without vibration and heavily reinforced sections with vibration
"High"	4 to 7	0.95	0.96	3 to 5	For sections with congested reinforcement. Not normally suitable for vibration.

* The slump is not definitely related to workability or plasticity. The figures must, therefore, be regarded as providing a rough indication of the order of the slump and nothing more.

Note that the difference between "medium" and "high" workability involves a change in compacting factor of only 0.03, whereas the change in PTV is of the order of several inches of mercury.

Fig.2 Slump, 0 inch. Batch 3.01
1:2.4:3.6 W/C, 0.40
"Dry", pebbly appearance.

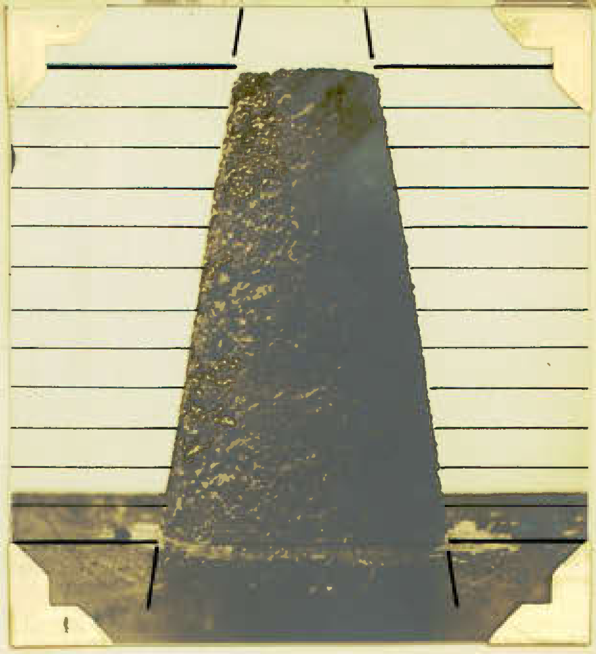


Fig.3 Slump $\frac{1}{8}$ inch. Batch 3.10
1:2.4:3.6 W/C, 0.45
"Dry", more workable than 3.01.

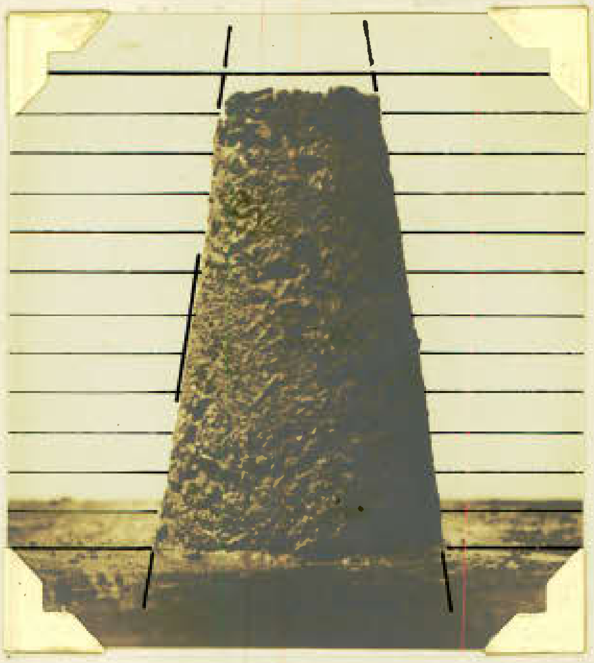


Fig.4 Slump, $\frac{3}{8}$ inch. Bach 3.03
1:2.4:3.6 W/C, 0.50
"Dry", wetter and more cohesive.

Fig.5 Slump, $\frac{5}{8}$ inch. Batch 3.08
1:2.4:3.6 W/C, 0.55
Note progressive change in surface texture.

Fig.6 Slump, $\frac{3}{4}$ inch. Batch 4.02
1:2:3 W/C, 0.50
Cohesive and dry, sticky.

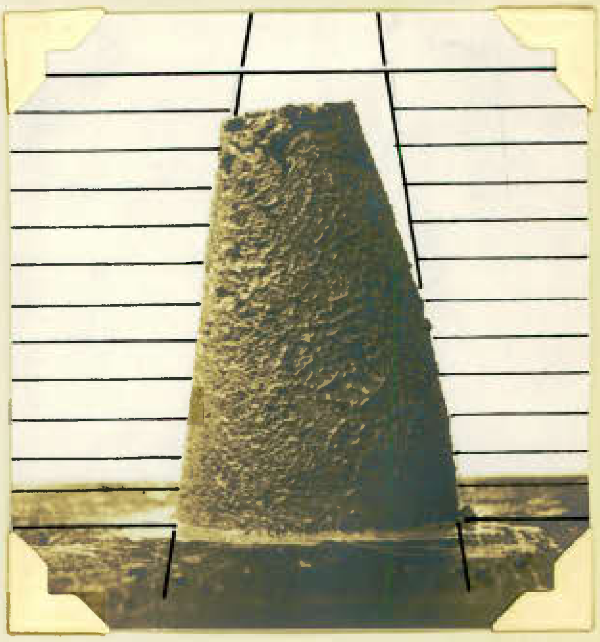


Fig.7 Slump, 1 inch. Batch 4.03
1:2:3 W/C, 0.45
4.02 is wetter than this.
"Sticky"

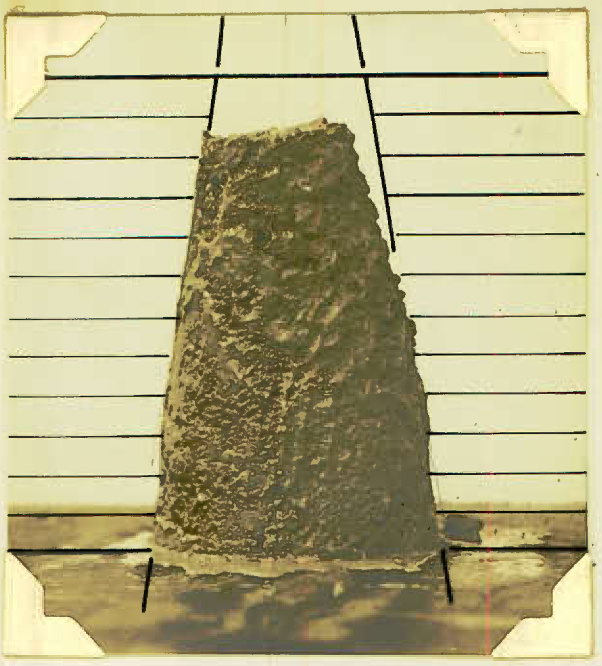


Fig.8. Slump, 1¼ inch. Batch 3.12
1:2.4:3.6 W/C, 0.575
Note bulging of specimen.
Desiginated "stiff."

Fig.9. Slump, 1½ inch. Batch 4.10
1:2:3 W/C, 0.50
Fatty concrete. "Stiff."

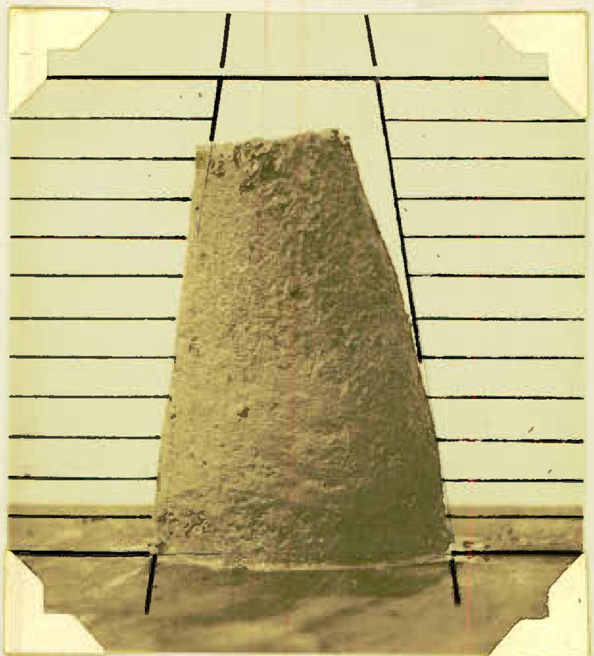


Fig.10. Slump, 1⅝ inch. Batch 6.03
1:1.5:2.25 W/C, 0.35
Sandy texture. Creamy and workable, yet "stiff."

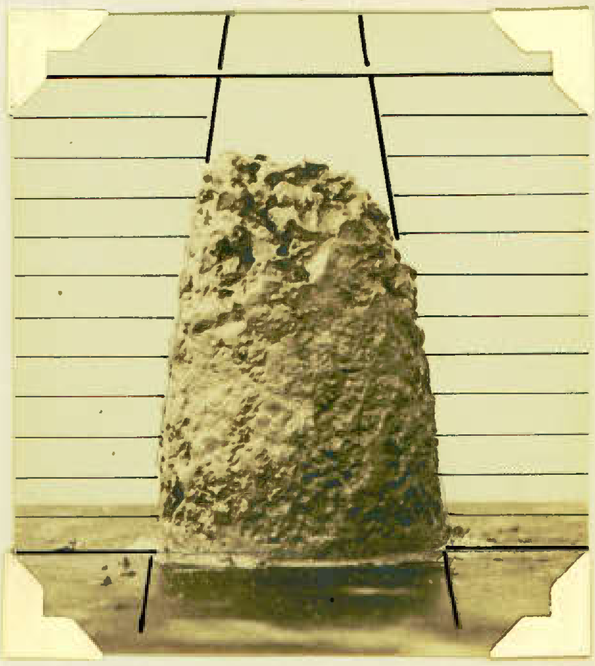


Fig.11. Slump, 2¼ inches. Batch 5.15
1:1.5:2.25 W/C, 0.45
Even slump with bulging.
Stiff to work.

Fig.12. Slump, 3 inches. Batch 3.06
1:2.4:3.6 W/C, 0.60
"Medium" consistency.
Decided outward bulging.

Fig.13. Slump 3 inches. Batch 4.05
1:2:3, W/C 0.60
Cohesive, plastic symmetrical slump.

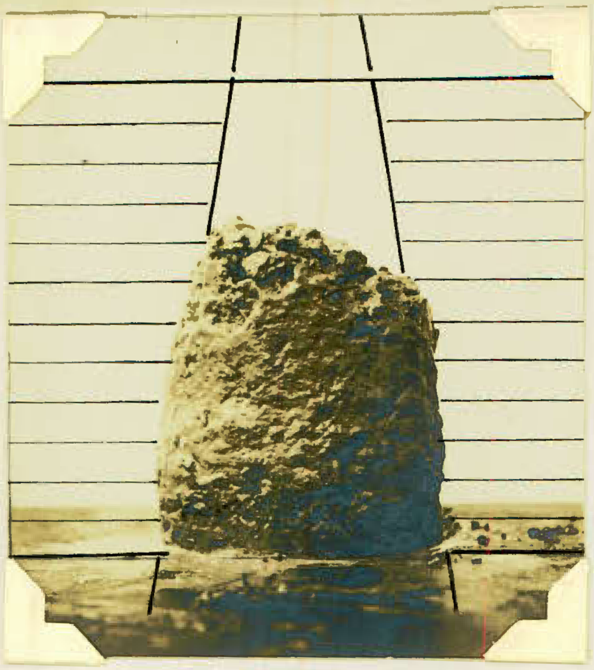


Fig.14. Slump 3½inches. Batch4.11
1:2:3. W/C,0.55
"Medium" consistency.
Plastic, easily workable.

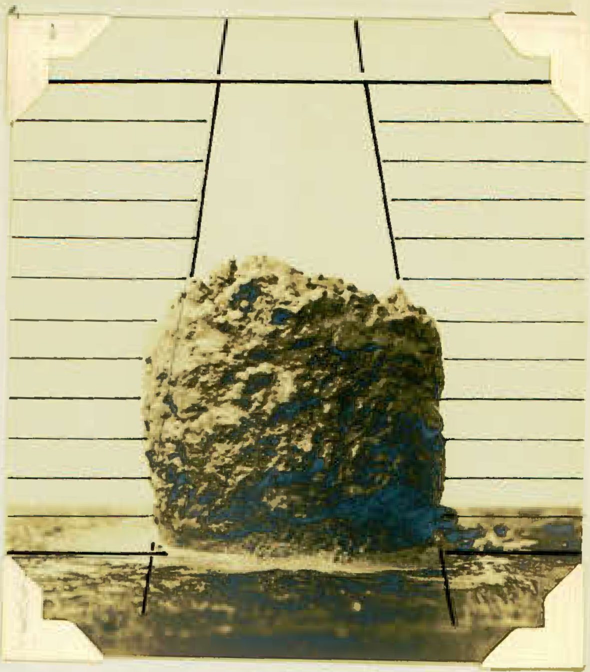


Fig.15. Slump 4¾inches. Batch4.04
1:2:3. W/C,0.55
Compare with fig. 14,
identical concrete.

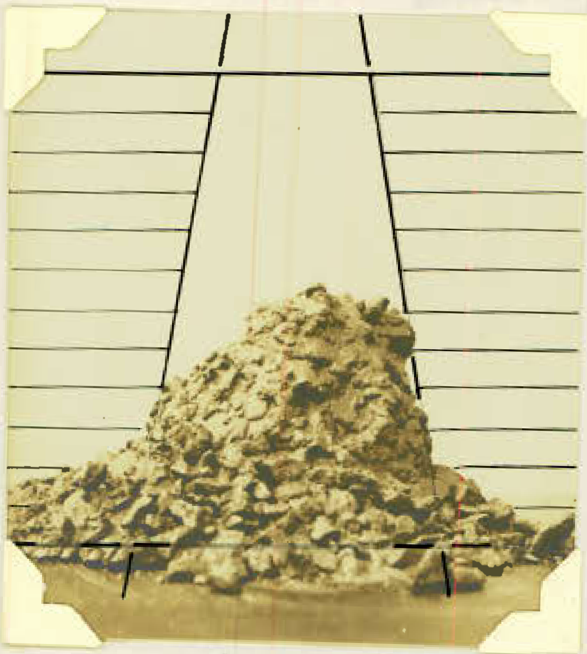


Fig.16. Slump 5¾inches,Batch 3.02
1:2.4:3.6 W/C,0.65
"Wet" consistency."Shear"
slump has taken place.

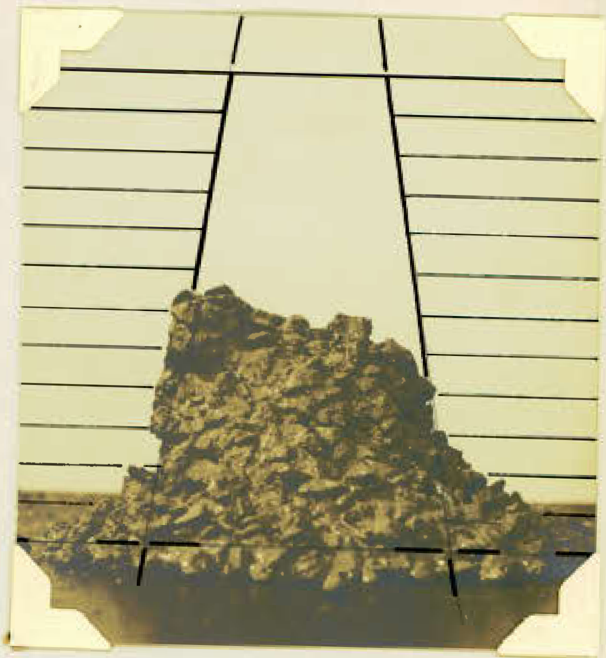


Fig.17. Slump 6inches. Batch3.09
1:2:4:3.6 W/C,0.70
"Wet" concrete. "shear"
slump.

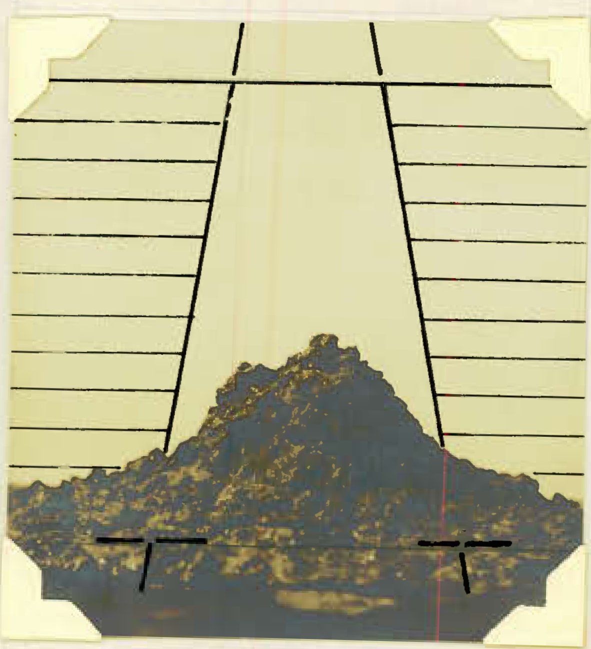


Fig.18. Slump 6¾inches. Batch 3.05
1:2.4:3.6 W/C?0.75
Tendency to segregation.

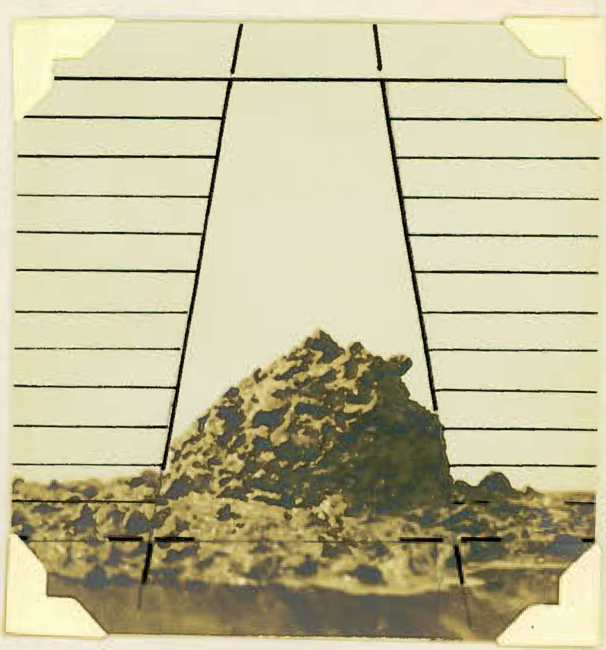


Fig.19. Slump 7inch. Batch 3.04
1:2.4:3.6 W/C?0.80
"Wet" consistency
Segregating mix.

Fig.20. Slump $7\frac{1}{4}$ inches.Batch 5.02
1:1.5:2.25 W/C, 0.50

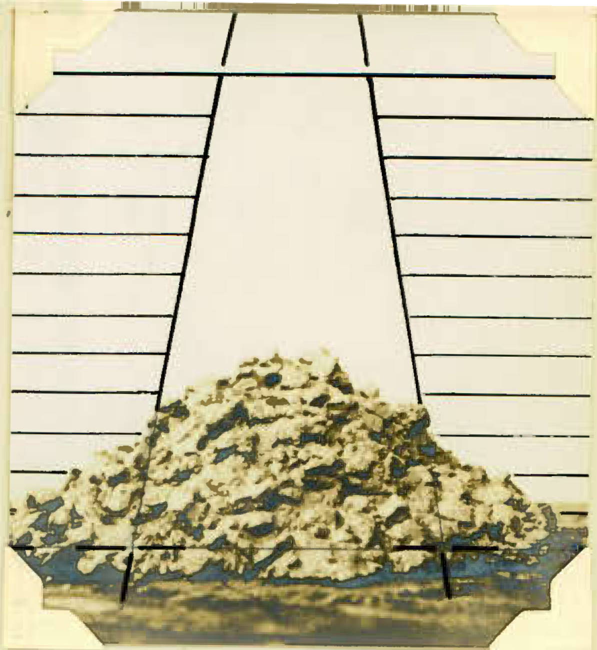


Fig.21. Slump $7\frac{1}{2}$ inches.Batch 4.12
1:2:3. W/C, 0.60
"Wet" consistency. In contrast to fig. holds mortar well.

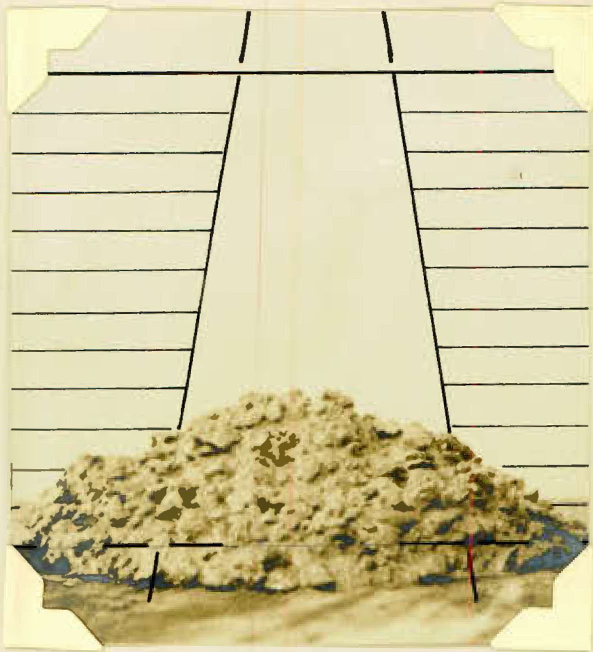


Fig.22. Slump $8\frac{1}{4}$ inches. Batch6.04
1:1.5:2.25 W/C,0.475

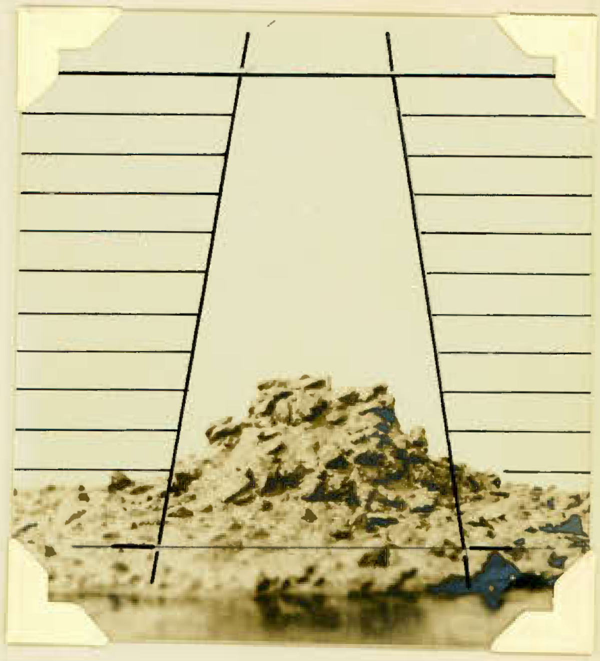


Fig.23. Slump $8\frac{1}{4}$ inches. Batch4.07
1:2:3 W/C, 0.65

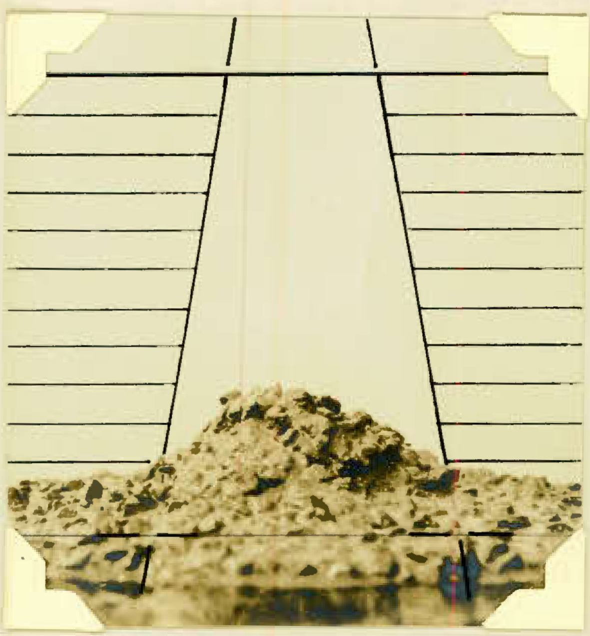


Fig.24. Slump $8\frac{1}{2}$ inches Batch.4.06
1:2:3. W/C, 0.70
"Sloppy" concrete.Note compacted aggregate in central pile. Mortar separating.

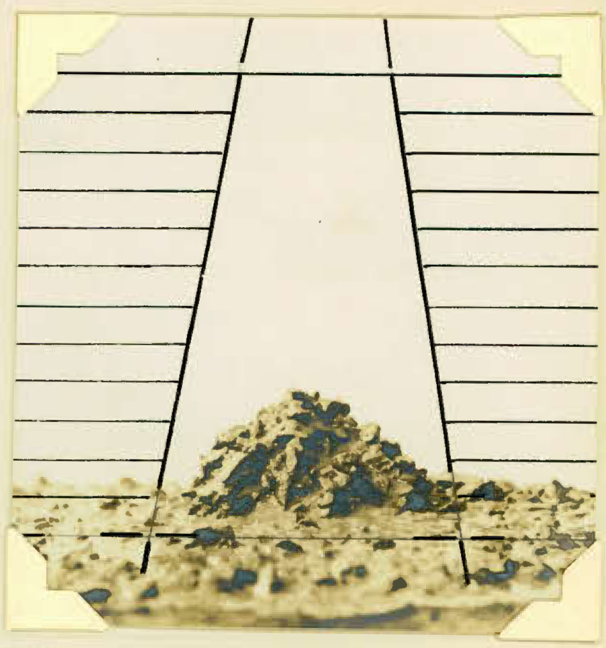


Fig.25. Slump $8\frac{1}{2}$ inches. Batch4.08
1:2:3 W/C,0.75
More water produces more segregation but no further slump.

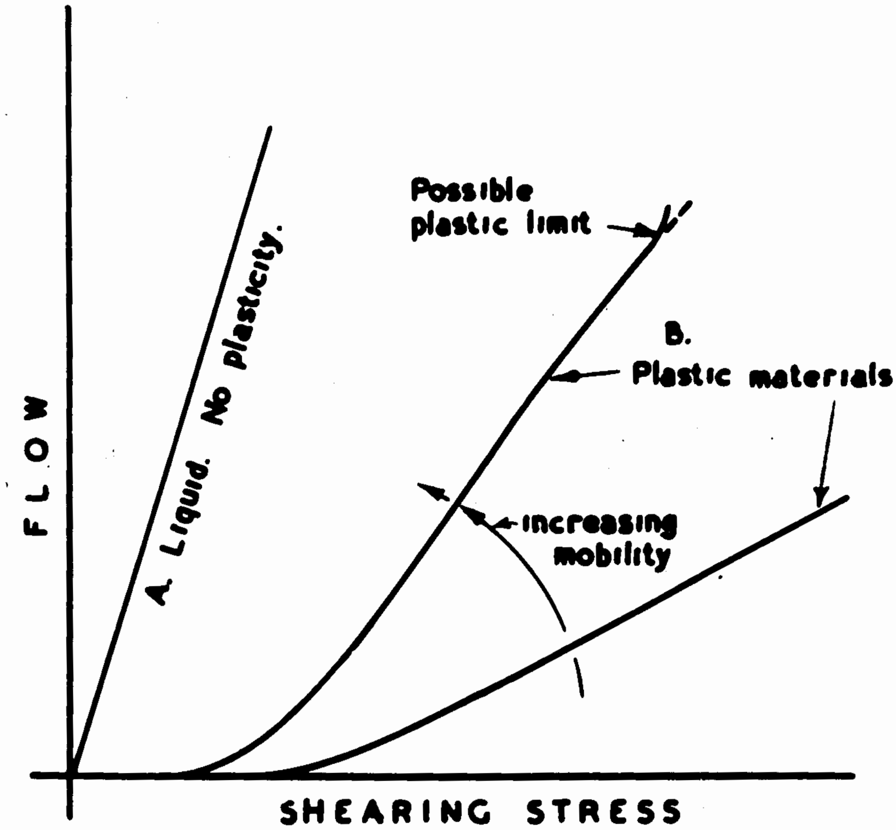


FIGURE 1:

THEORETICAL FORCE FLOW RELATIONSHIP
Representing flow under pressure, after Bingham.

A. Straight line relationship for a viscous liquid.

B. The curves represent plastic materials. Flow does not start until a certain yield value is reached.

The application of the above to non-homogeneous substances should not be accepted without reservation. See Chapter 5.

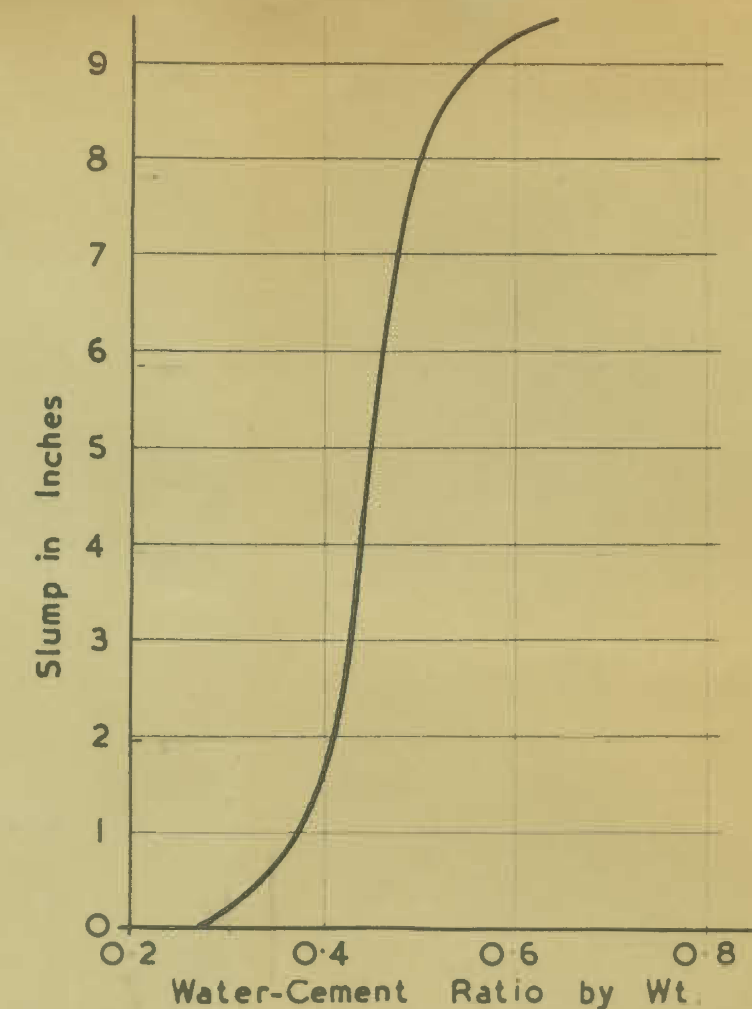


FIG.26. SLUMP CURVE. MIX 1:1·5:2·25

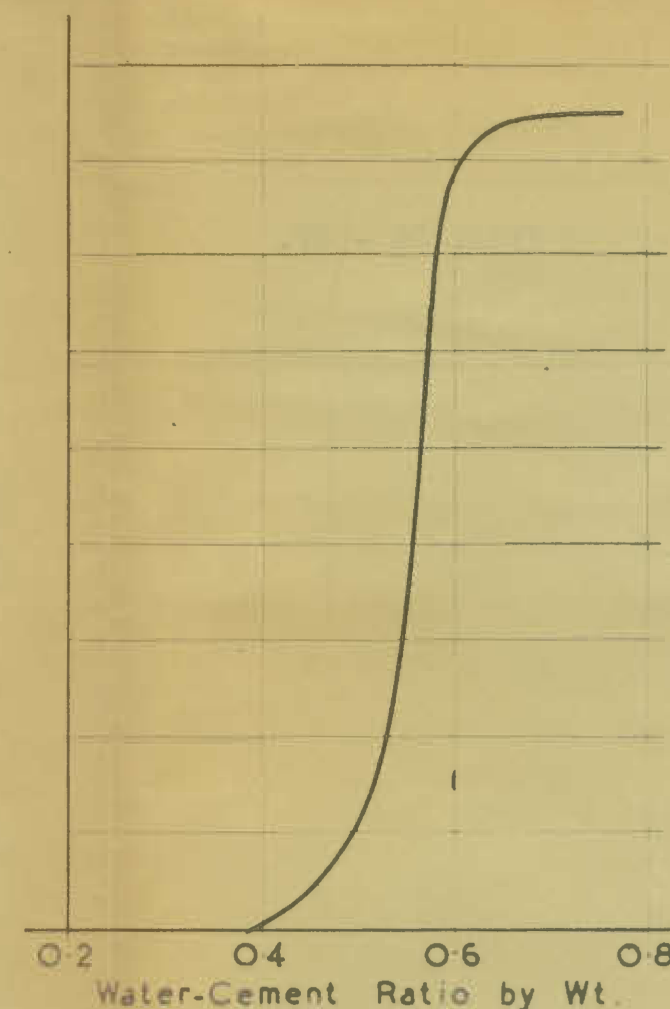


FIG.27. SLUMP CURVE. MIX 1:2:3

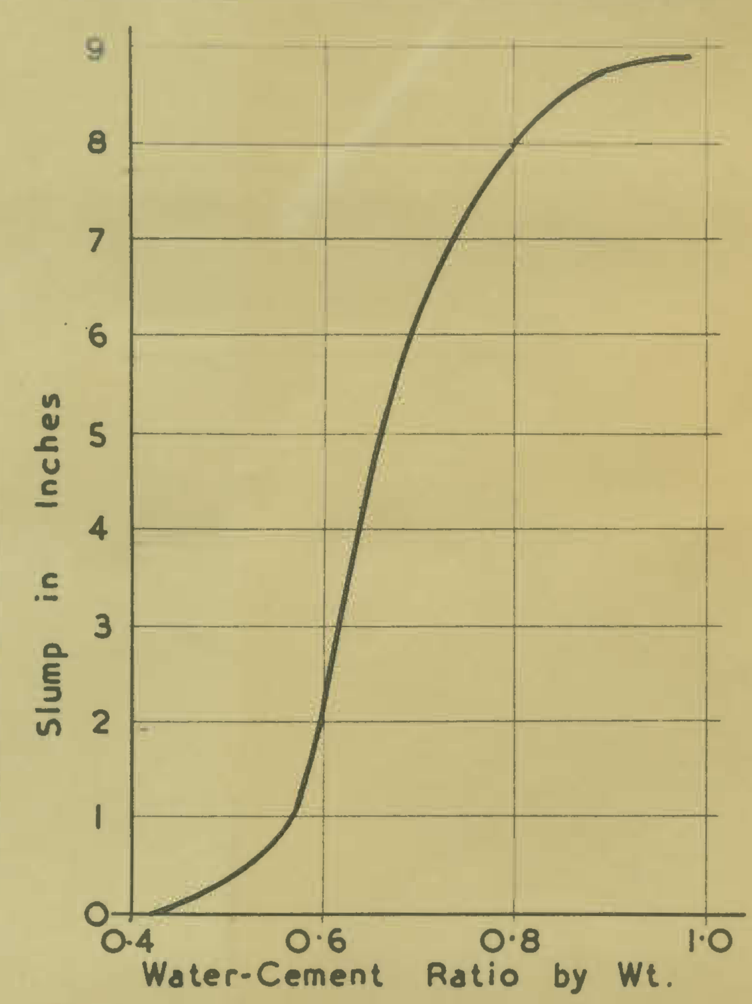


FIG.28. SLUMP CURVE. MIX 1:2·4:3·6

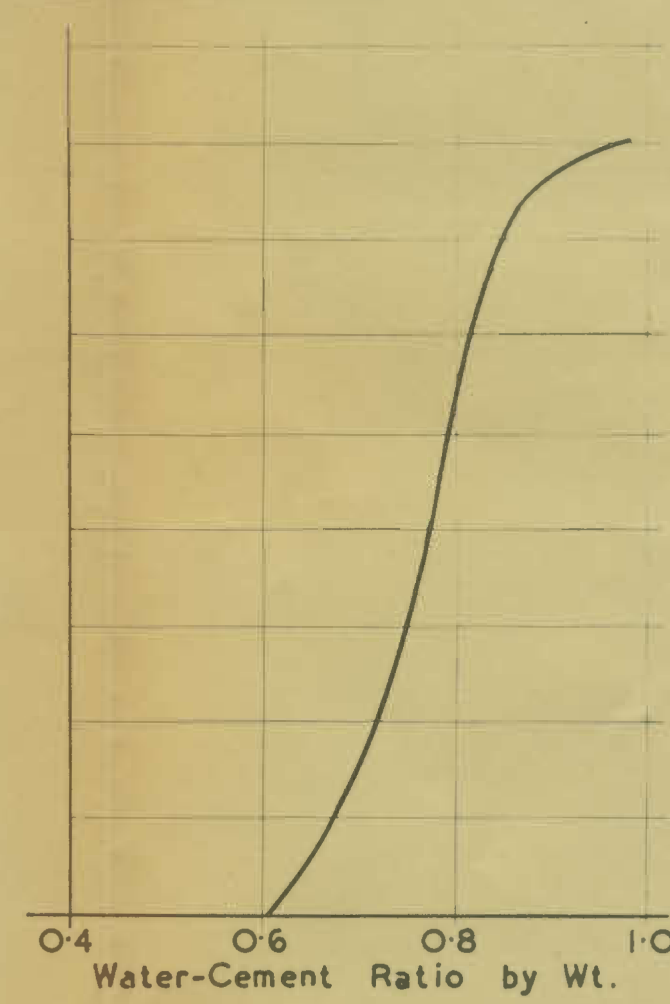


FIG. 29. SLUMP CURVE. 1:2·5:5 MIX

TYPICAL SLUMP CURVES FOR ARBITRARY MIXTURES

For Mix Data See Appendix C

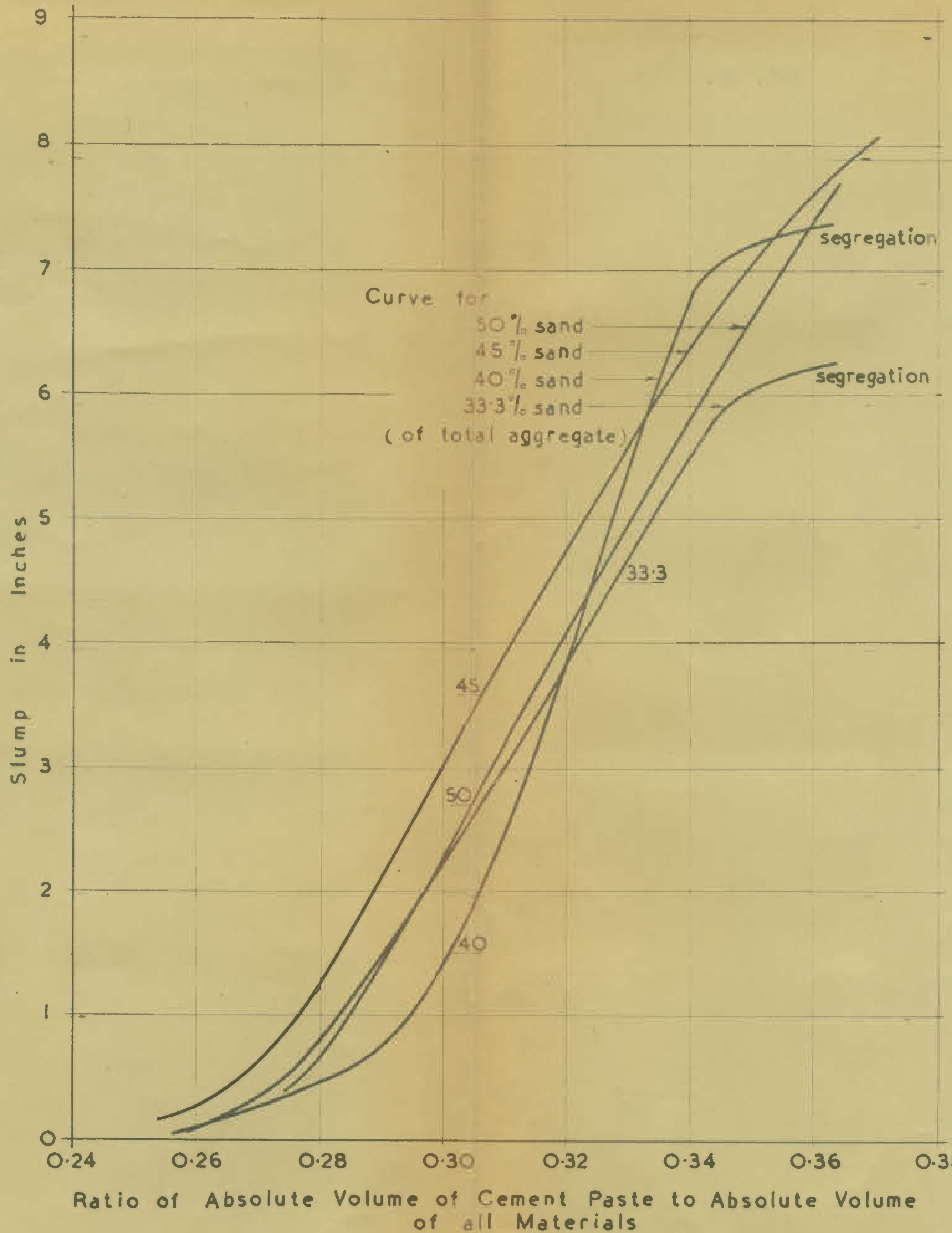


FIG. 30 — SLUMP VS PASTE CONTENT AT A CONSTANT WATER-CEMENT RATIO OF 0·575 BY WT.

Group B Grading. (Appendix C)

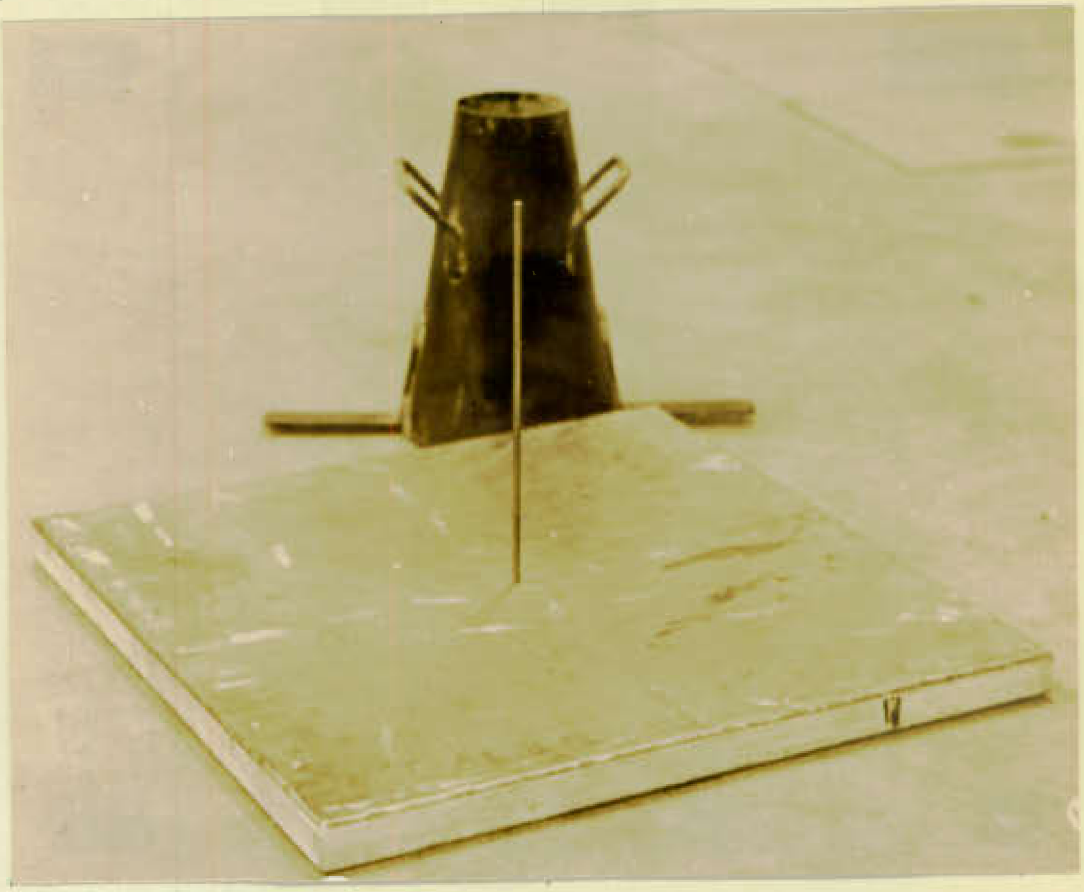


Fig.31. MODIFIED SLUMP APPARATUS.
Note central rod.

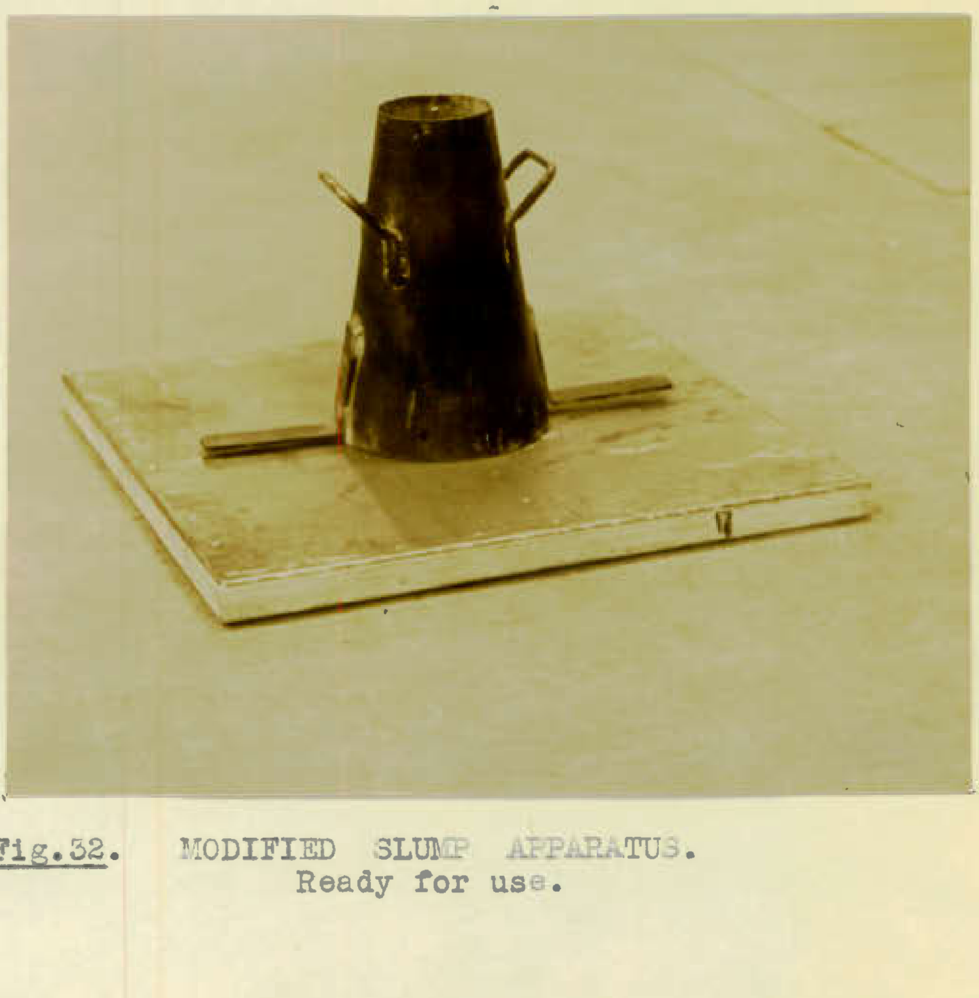


Fig.32. MODIFIED SLUMP APPARATUS.
Ready for use.

FIG. 33 A: Flow Table with Flow Cone in position ready for use.

FIG. 33 B: Moulded specimen before use.

FIG. 33 C: Specimen after fifteen half-inch drops.

FLOW TABLE

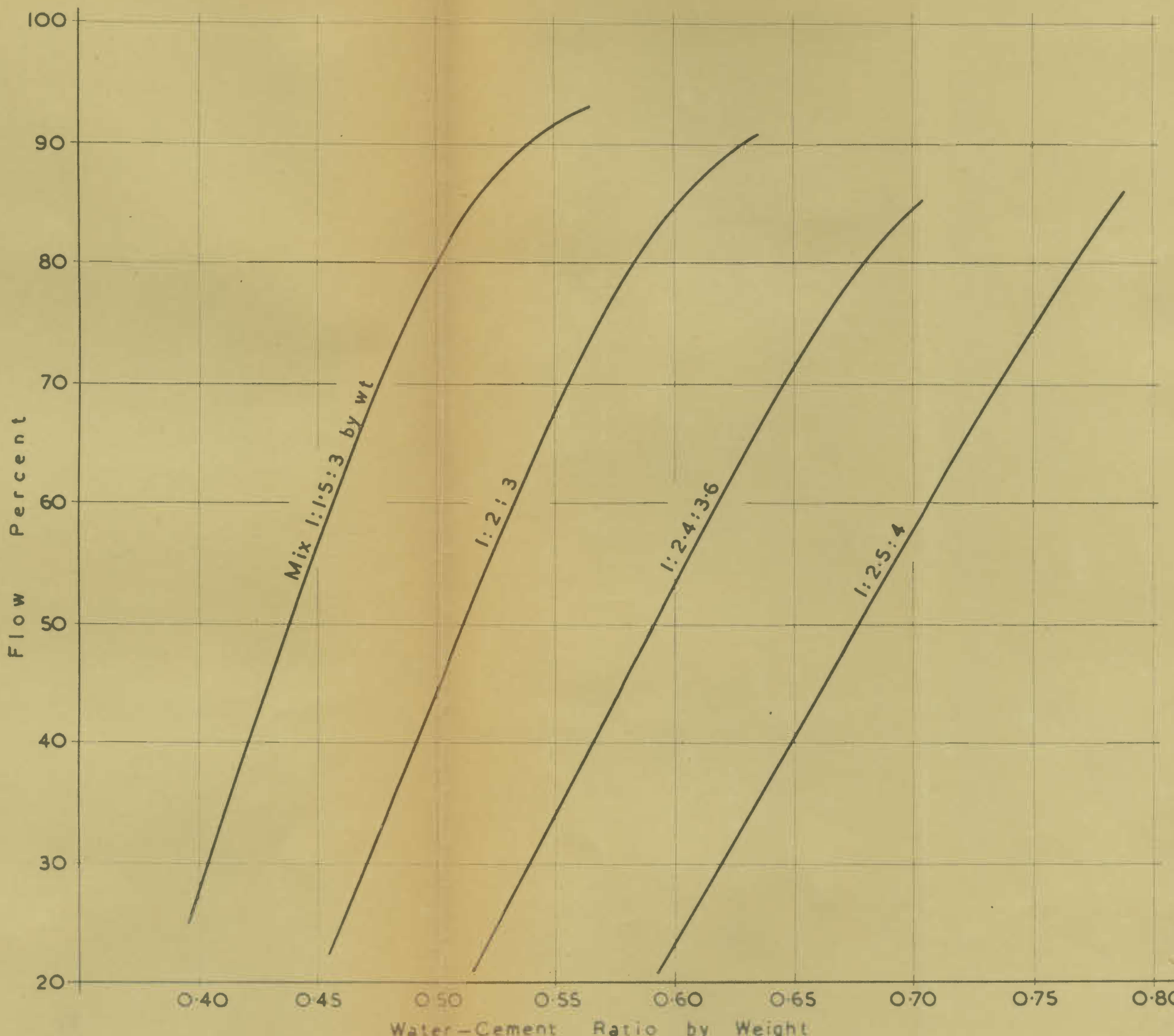


FIG. 34— CHARACTERISTIC FLOW TABLE CURVES ON WATER–CEMENT RATIO BASIS.

For Details of Mixtures Refer to Appx C

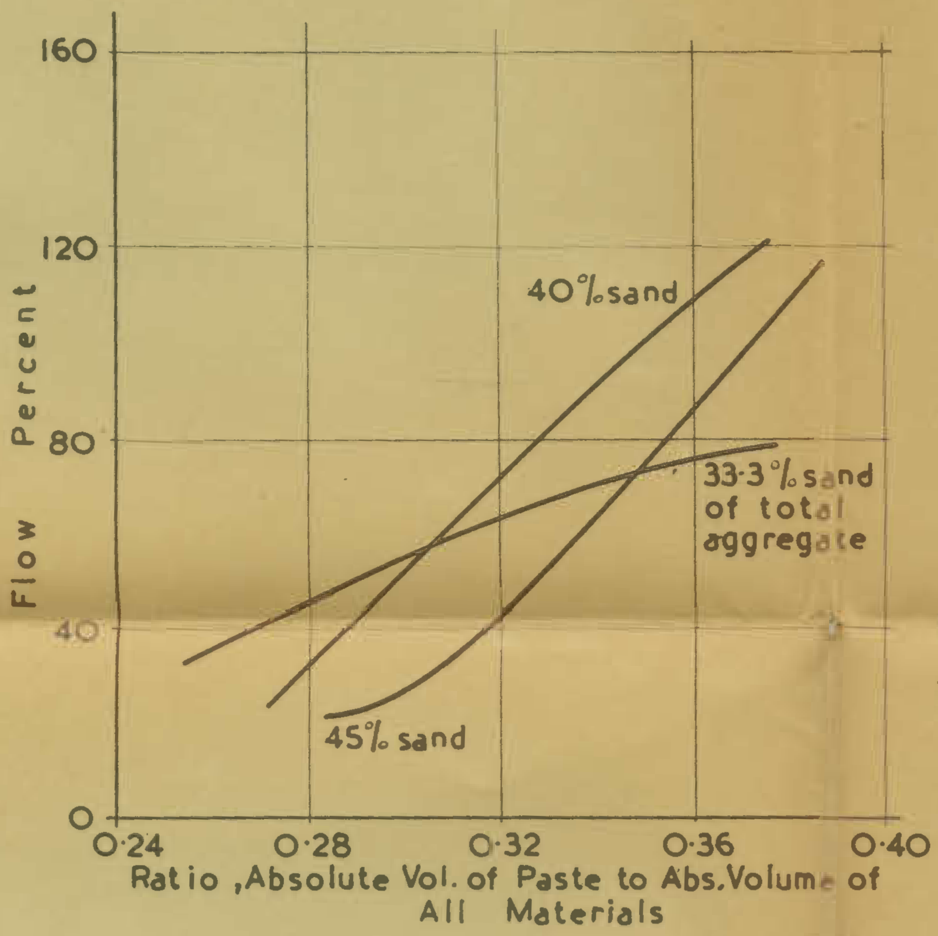


FIG. 35a - TYPICAL FLOW CURVES.. W/C 0·575
Group A Gradations. Other W/C's Omitted.

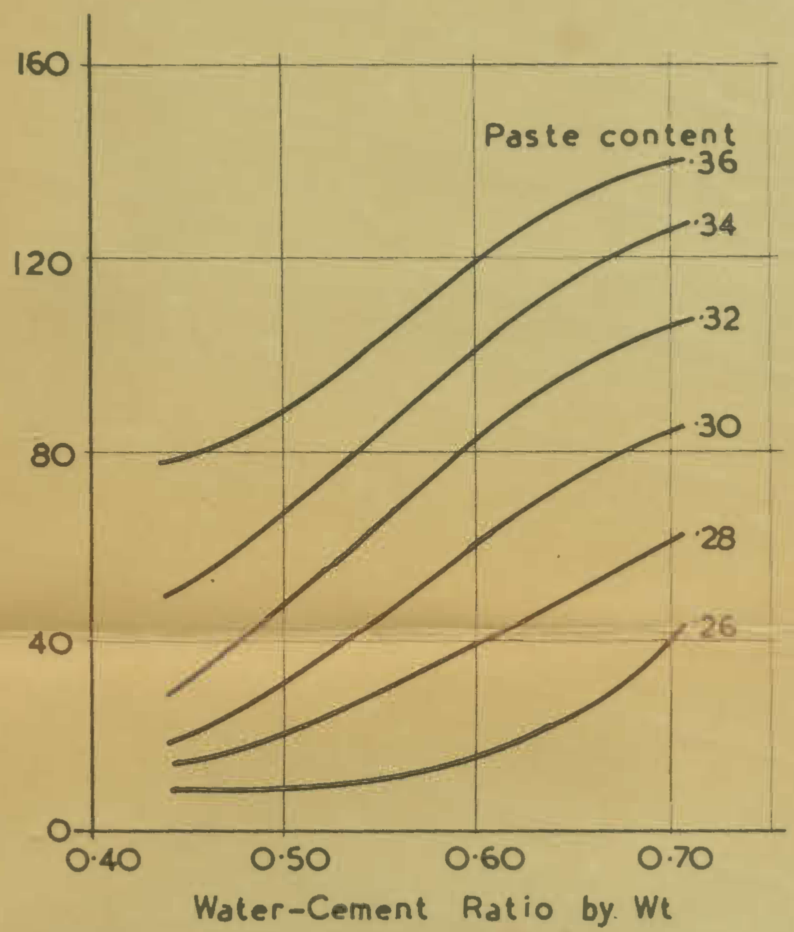


FIG. 35b - FLOW AT VARIOUS PASTE CONTS. FOR DIFFERENT W/C's. Compiled from all Group A Flow Data, 40% Sand

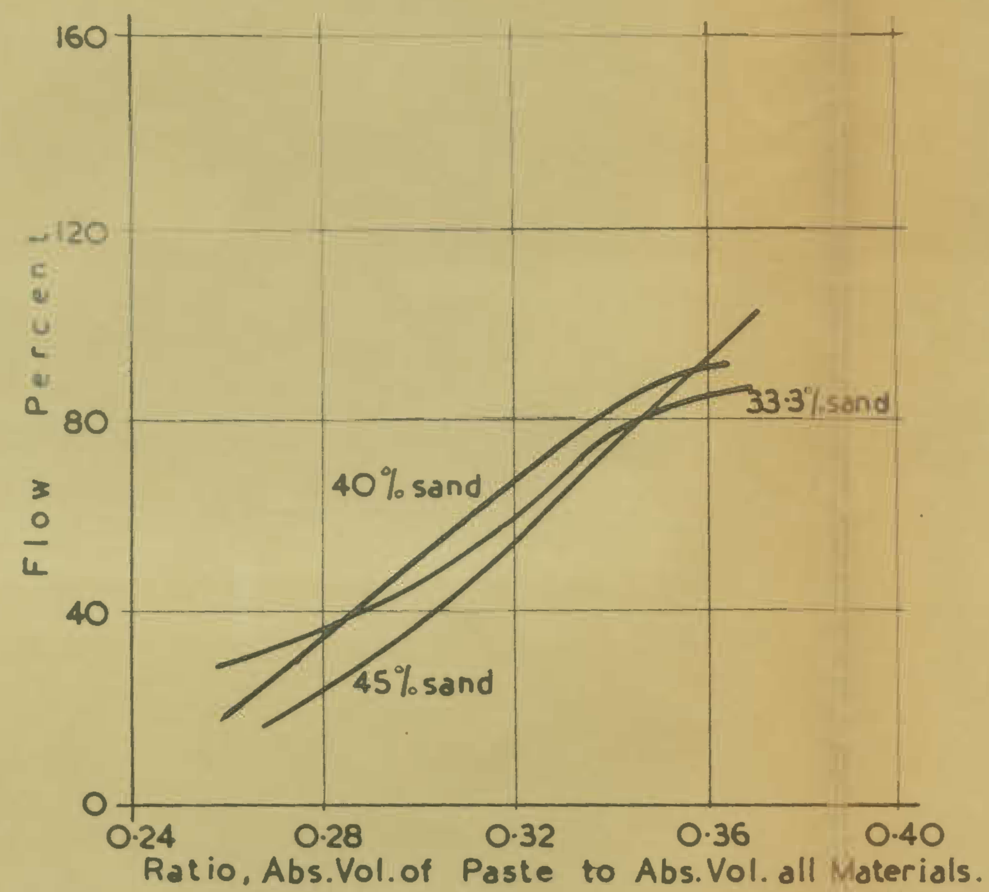


FIG. 36a - TYPICAL FLOW CURVES.. W/C 0·575
Group B Gradations

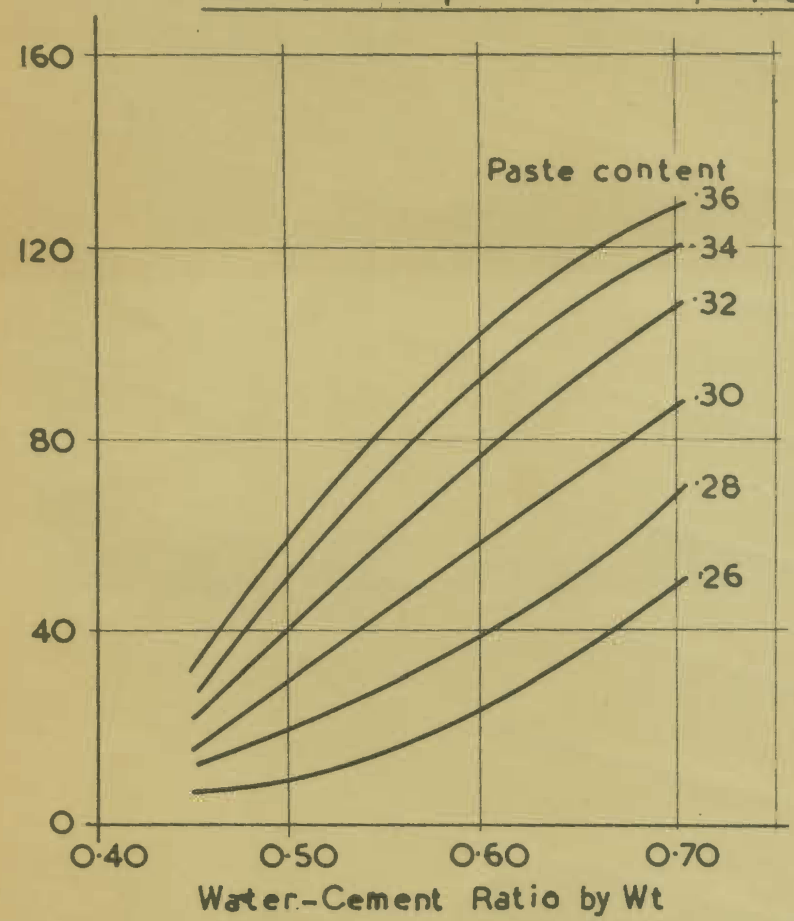


FIG. 36b - FLOW AT VARIOUS PASTE CONTENTS FOR DIFFERENT W/C's
Group B, 40% Sand

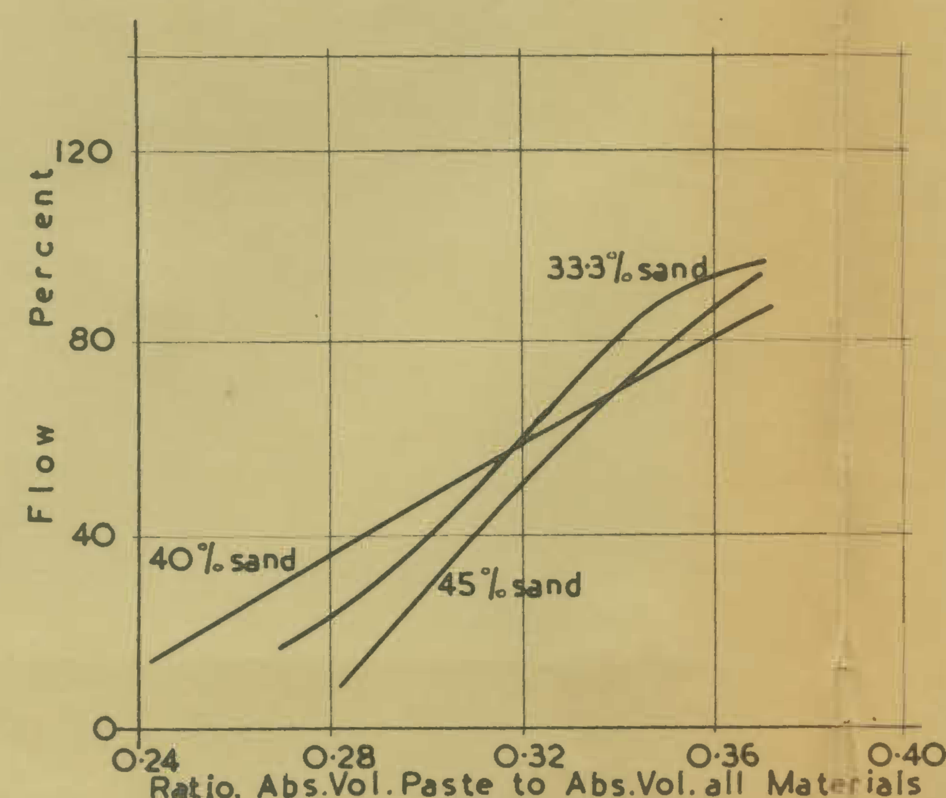


FIG. 37a - TYPICAL FLOW CURVES. W C 0·575
Group C Gradations

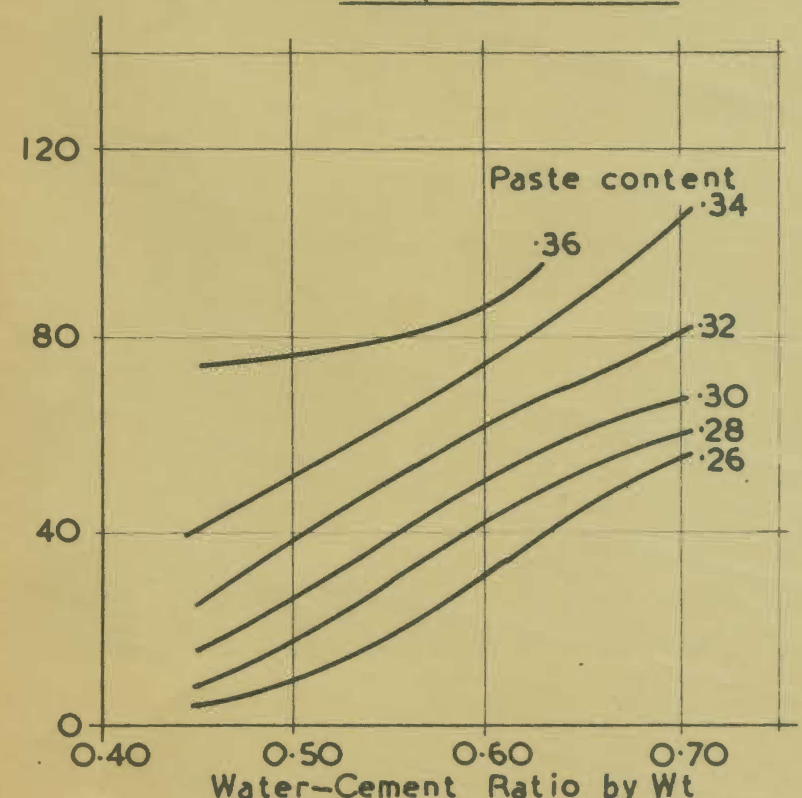


FIG. 37b - FLOW AT VARIOUS PASTE CONTENTS FOR DIFFERENT W/C's
Group C, 40% Sand

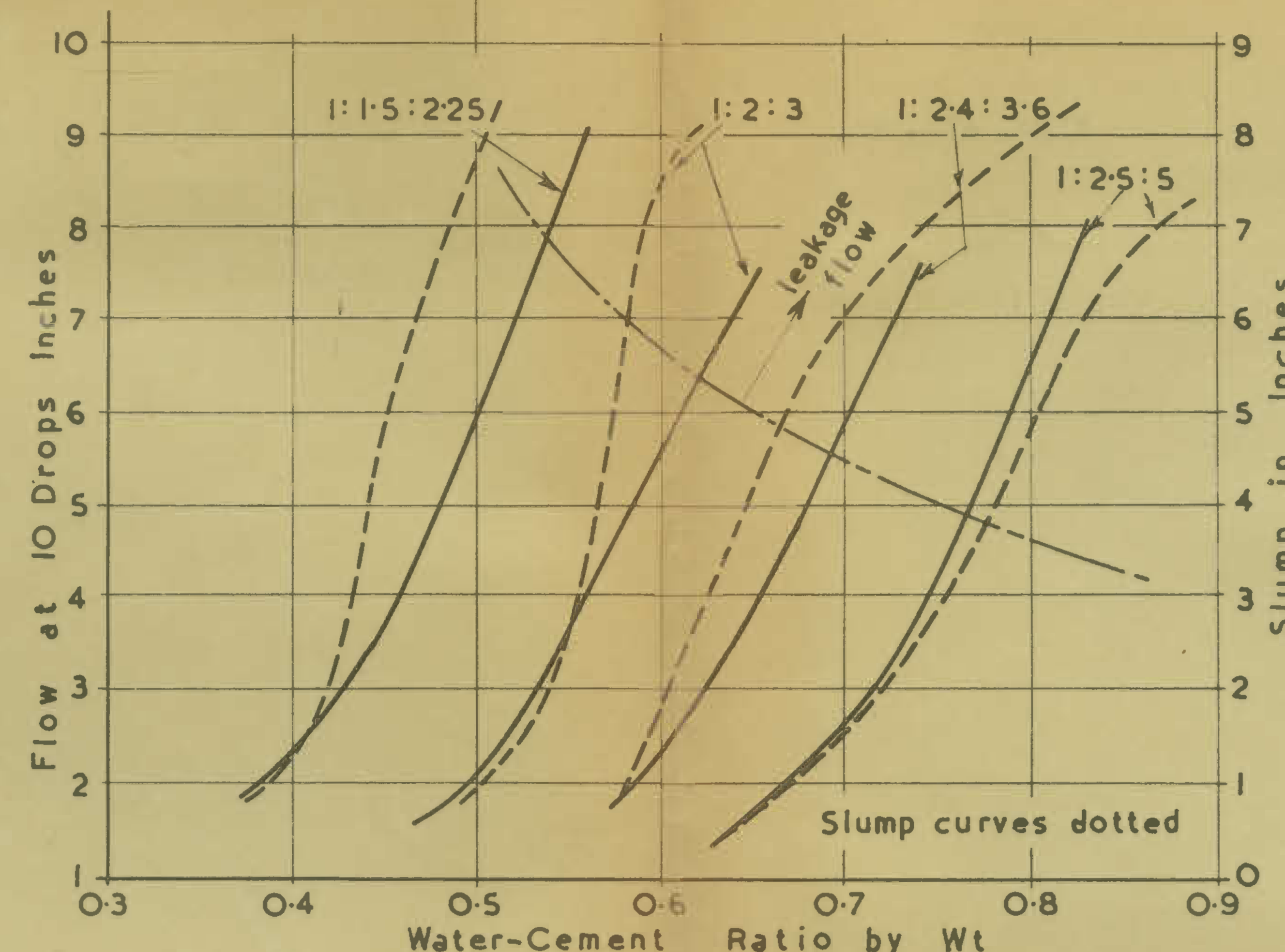


FIG.42 – FLOW TROUGH. RELATIONSHIP BETWEEN FLOW AT 10 DROPS AND SLUMP. (VS W/C.). Data in Appendix C.

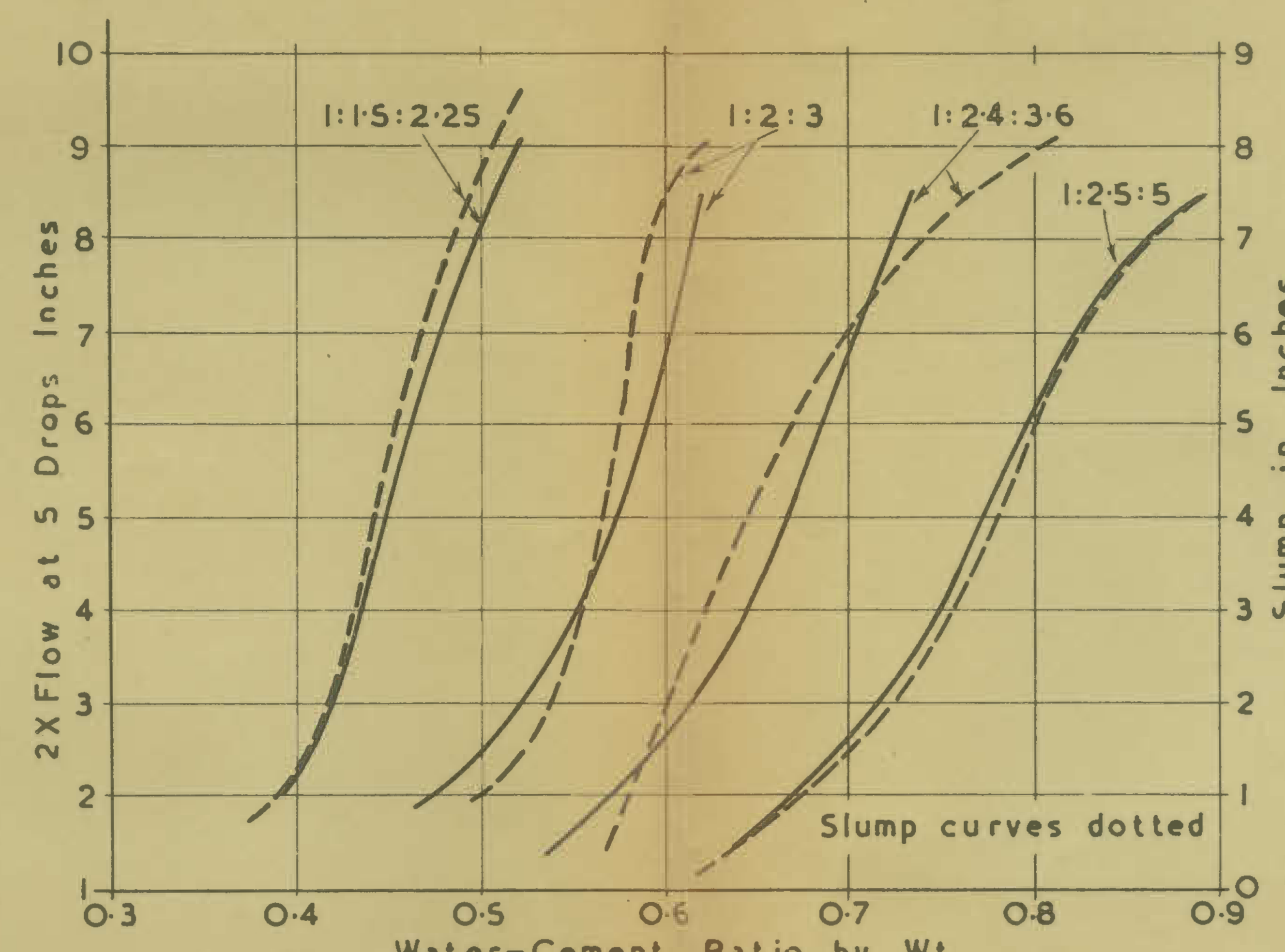


FIG. 43 – FLOW TROUGH. RELATIONSHIP BETWEEN TWICE THE FLOW AT 5 DROPS AND SLUMP. (VS W/C).

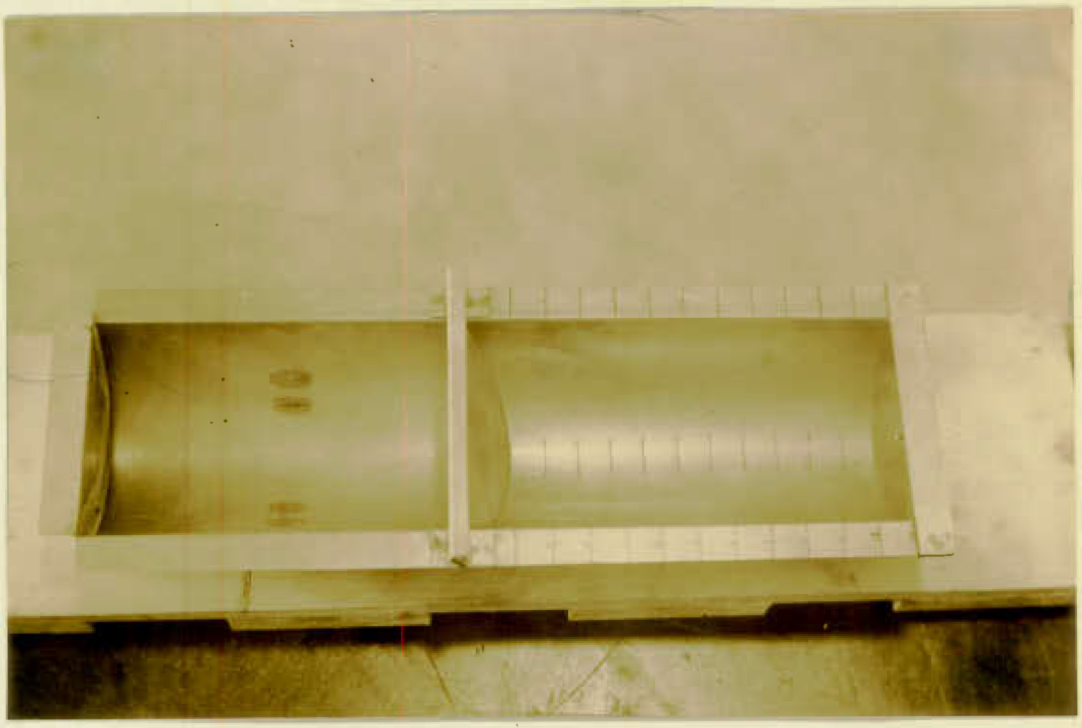


Fig. 38. Burmister's Flow Trough.

Fig. 39. Filling the trough.

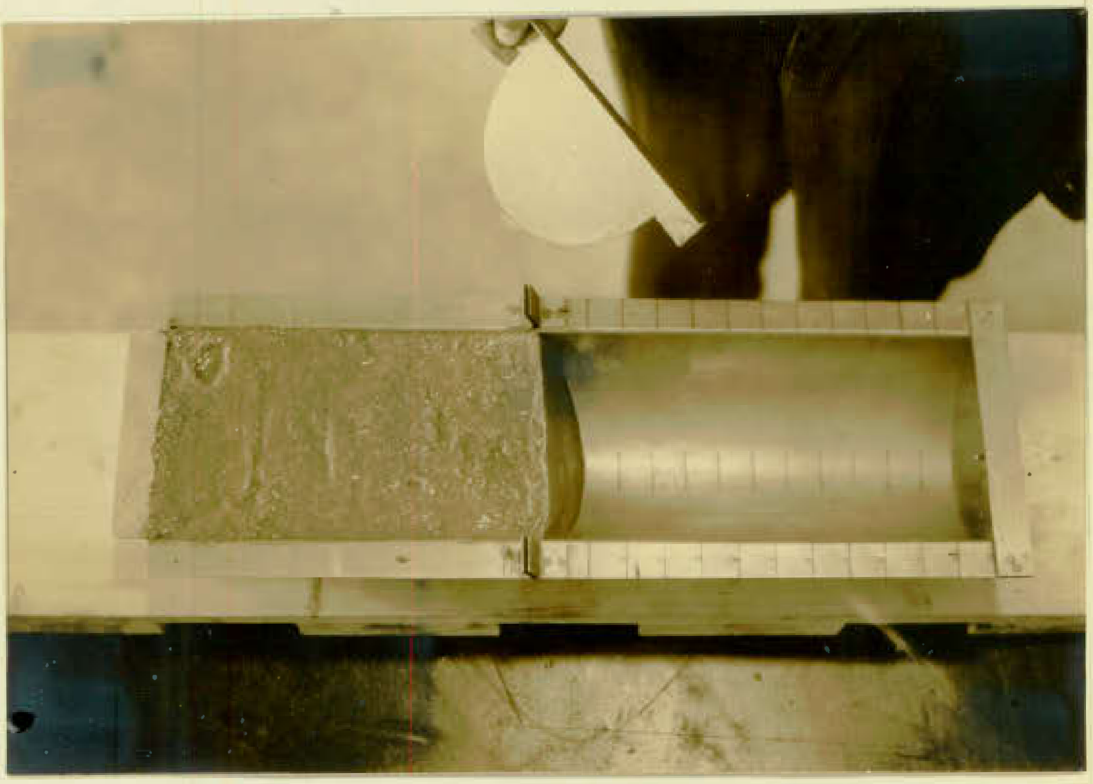


Fig. 41.   Flow Trough: Performing the test.

Fig. 40.   Flow Trough: The gate removed.

Fig.44. Remoulding Apparatus assembled on Flow Table.

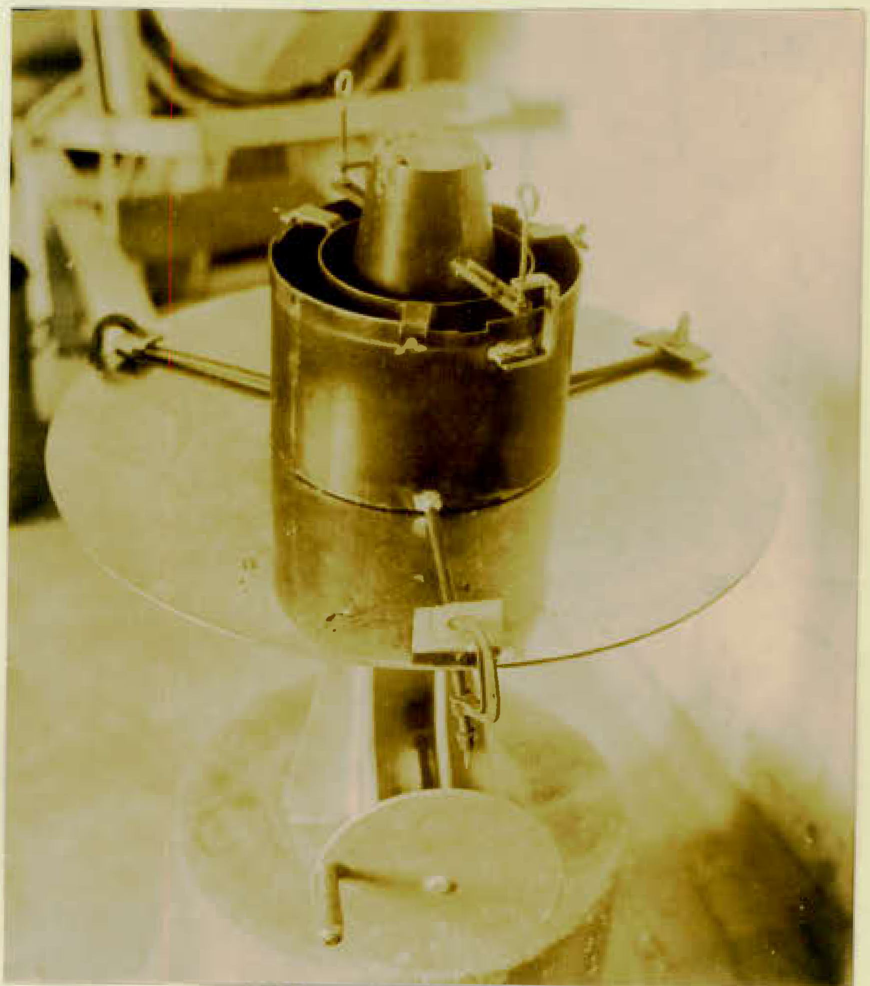


Fig.45. Remoulding Apparatus. Slump cone filled with concrete.

Fig.46. Remoulding Apparatus. Slump cone removed.

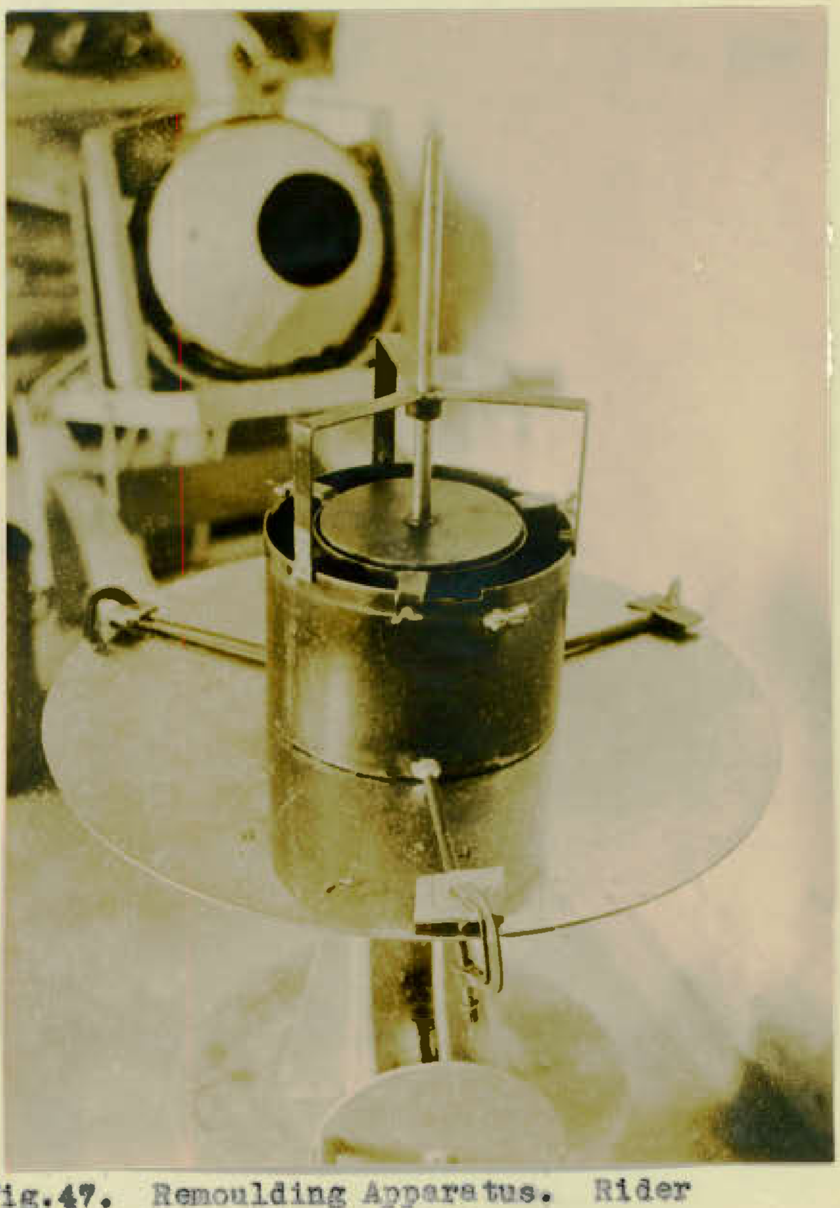


Fig.47. Remoulding Apparatus. Rider assembly in place.

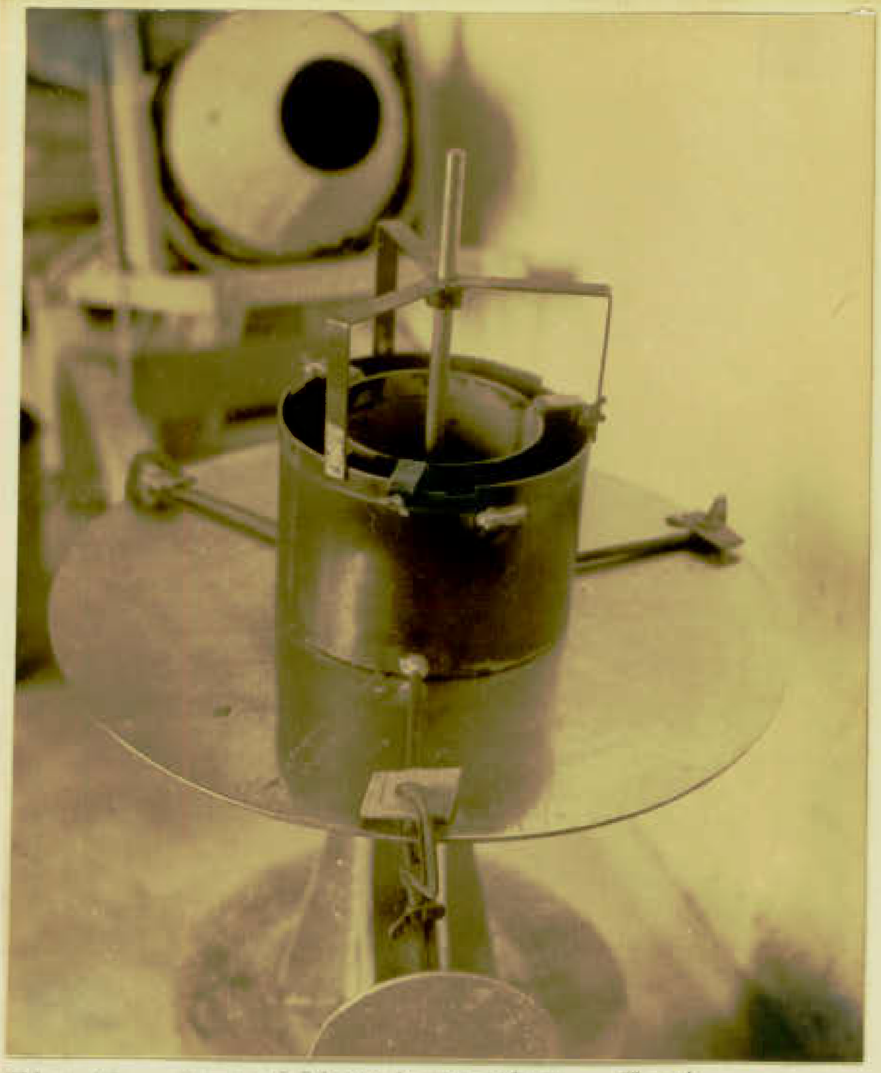


Fig.48. Remoulding Apparatus. Test completed.

Fig.49. Segregation in concrete after testing. Mortar has flowed under the ring leaving coarser particles in the centre.

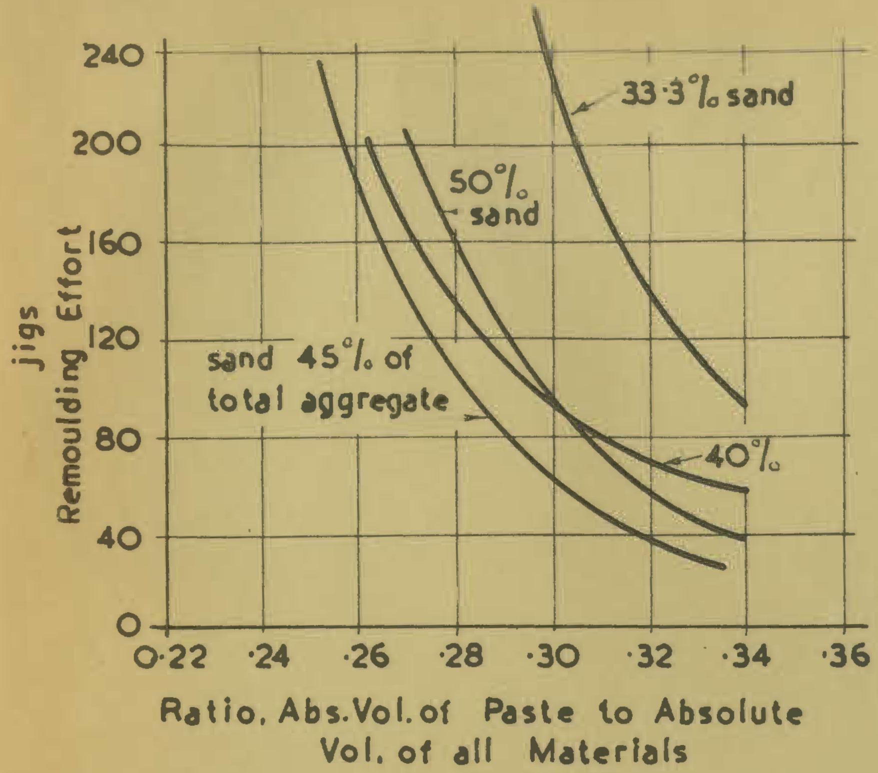


FIG. 50A, WATER-CEMENT RATIO 0·45

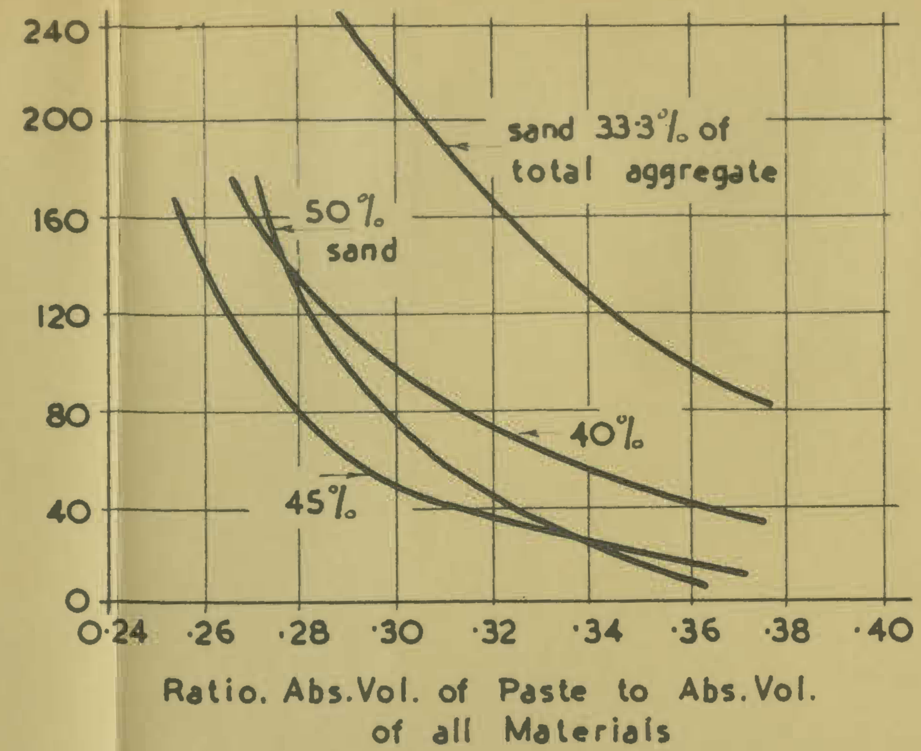


FIG. 51A, WATER-CEMENT RATIO 0·575 BY WT

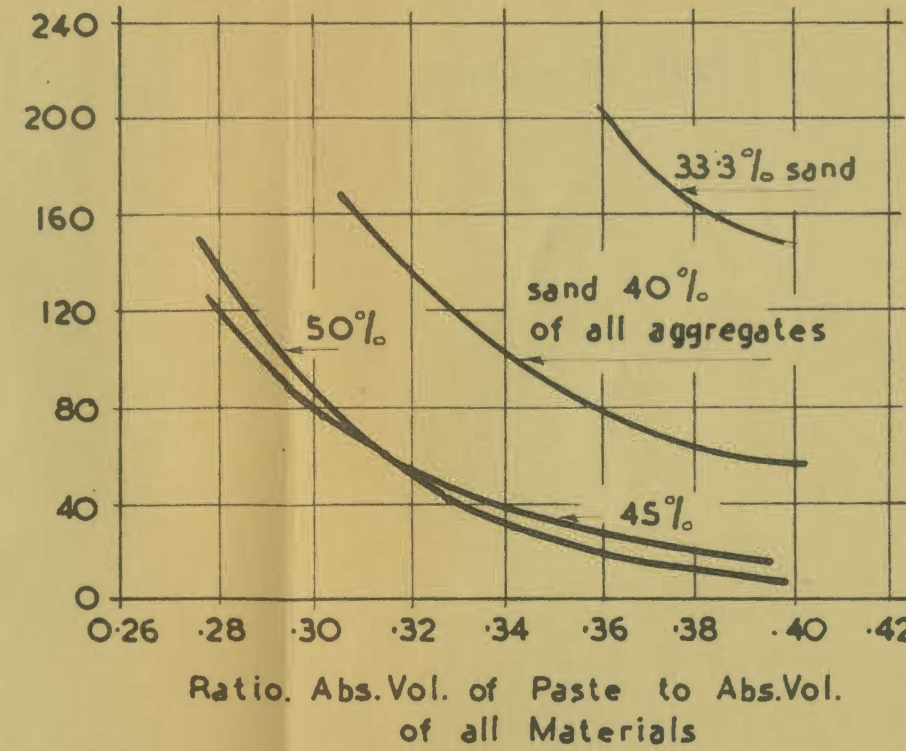


FIG. 52A, WATER-CEMENT RATIO BY WT 0·70

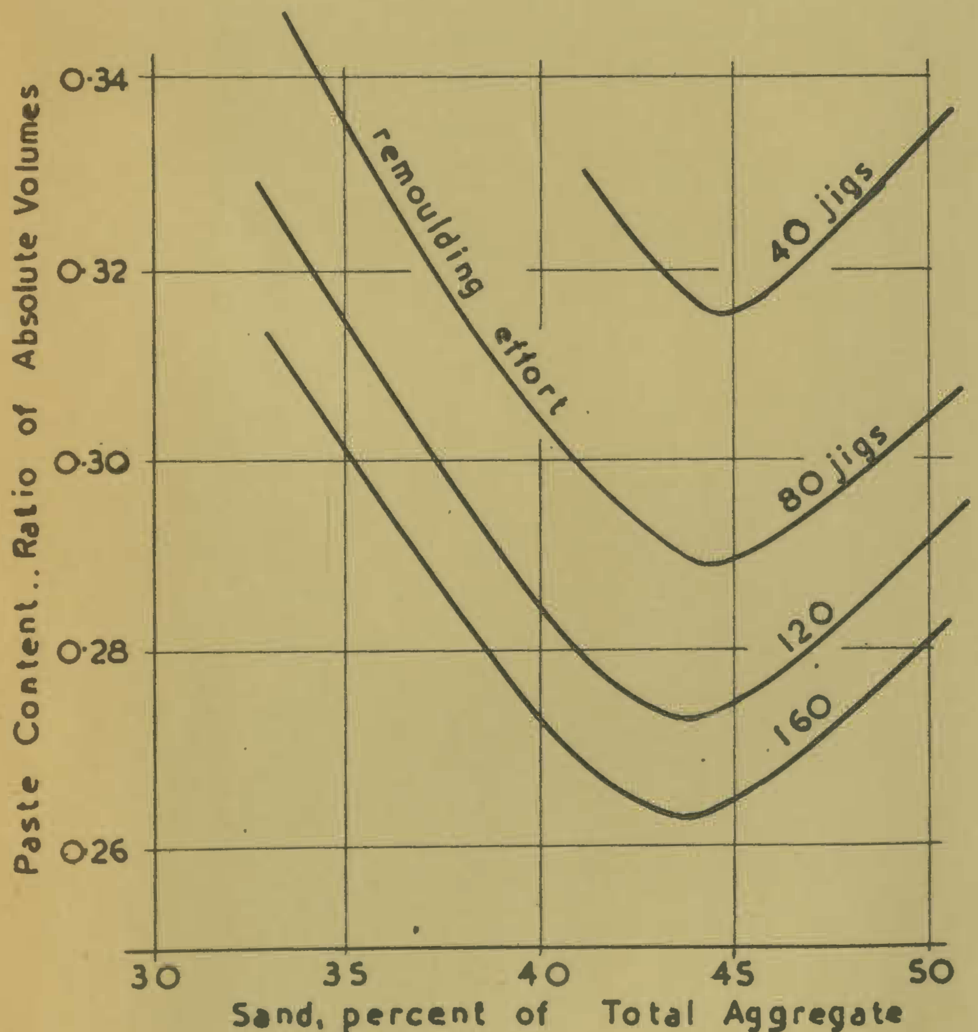


FIG. 50B, W/C 0·45

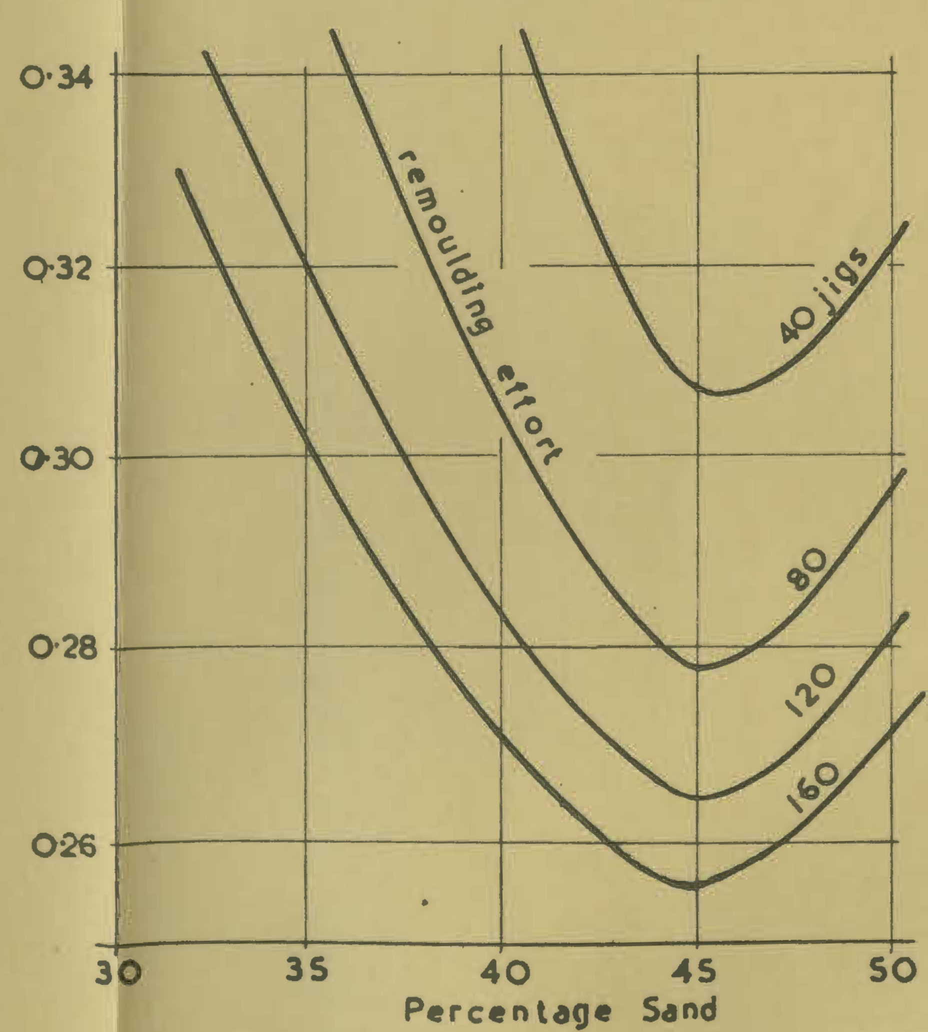


FIG. 51 B, W/C 0·575

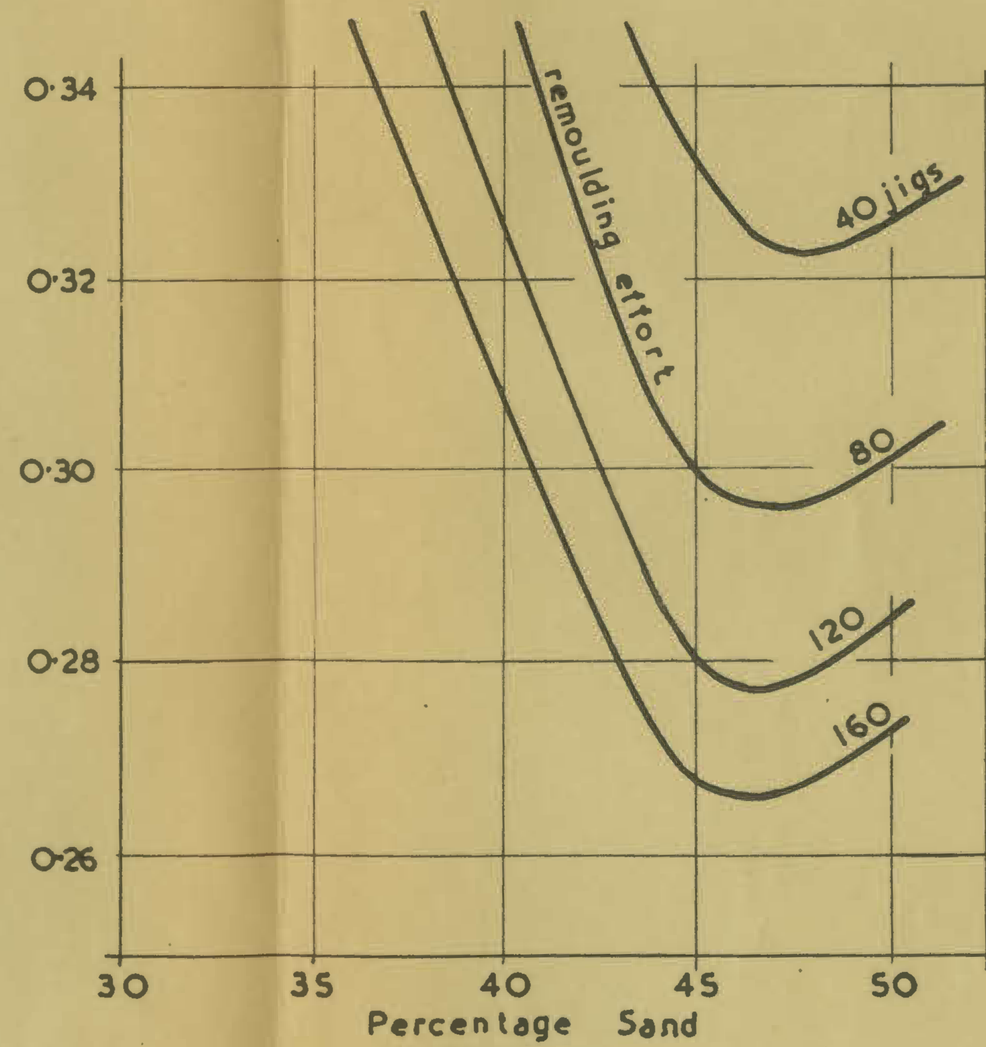
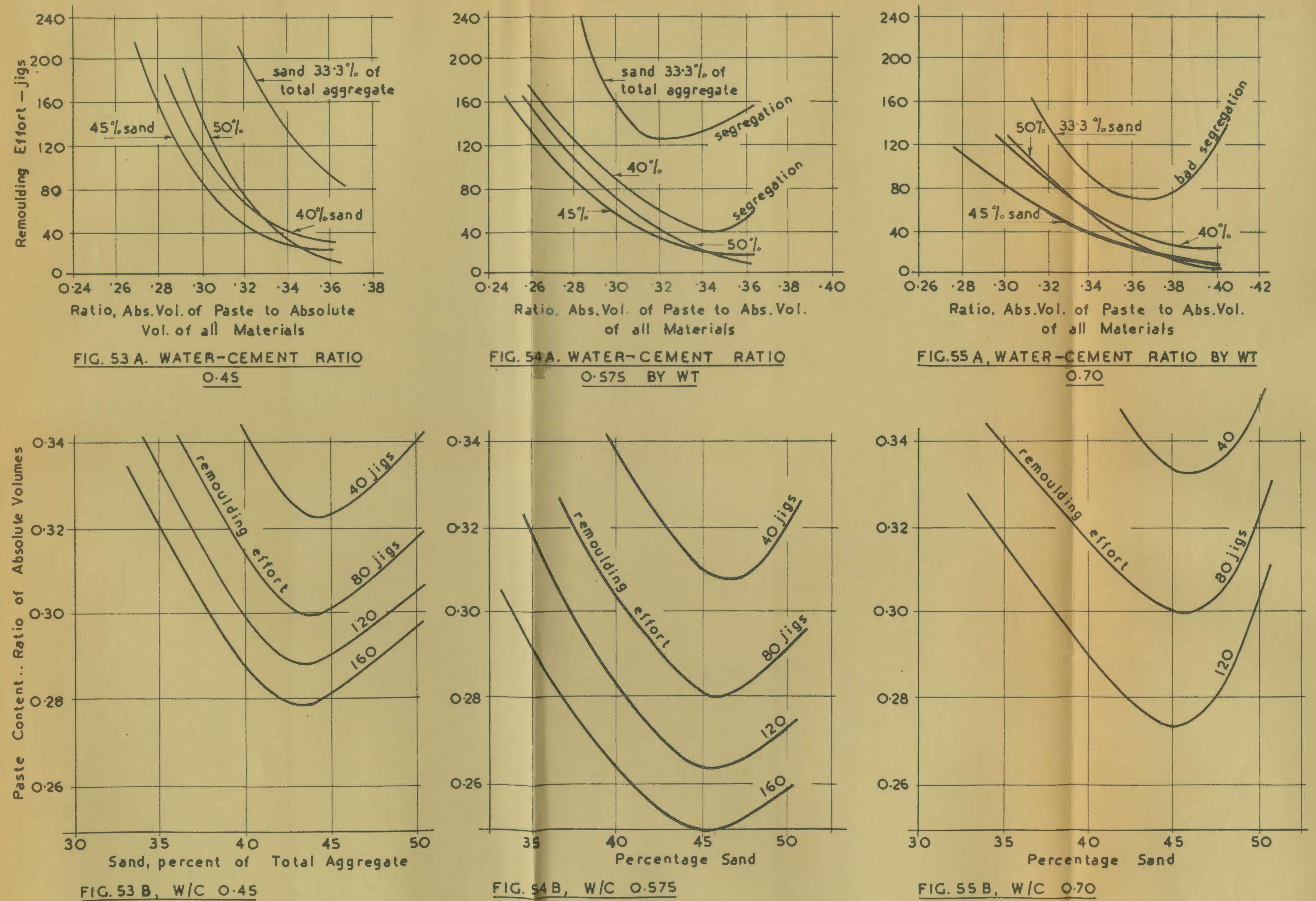


FIG. 52 B, W/C 0·70

RELATION OF REMOULDING EFFORT TO PASTE CONTENT AND PERCENTAGE SAND IN AGGREGATE

GROUP B GRADINGS



RELATION OF REMOULDING EFFORT TO PASTE CONTENT AND PERCENTAGE SAND IN AGGREGATE

GROUP C GRADINGS

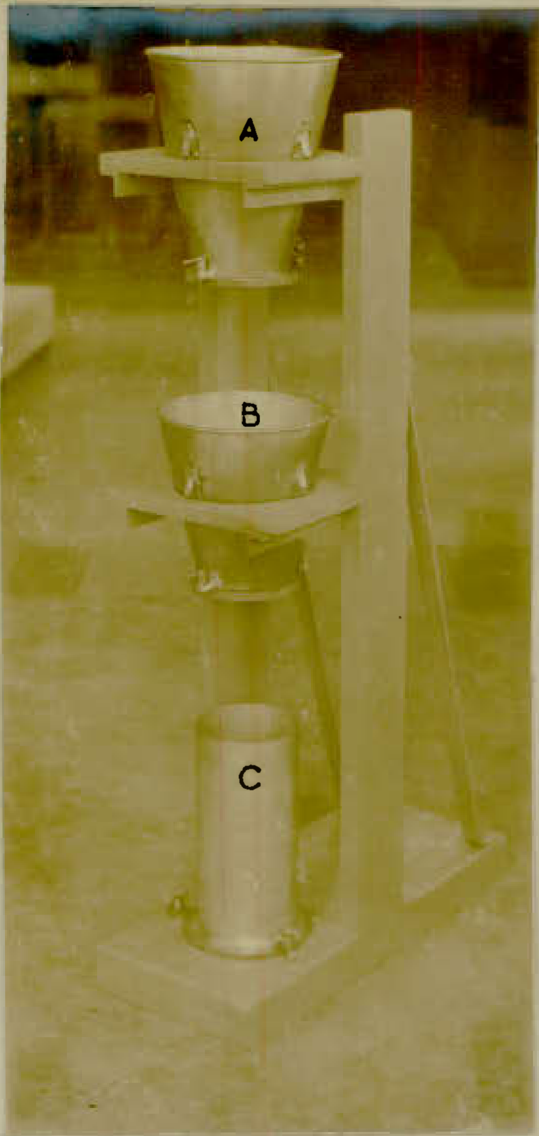


Fig.56. Standard Compacting Factor Apparatus.

Fig.57. Upper Hopper charged.

Fig.58. Concrete in lower Hopper.

Fig.59. Fall completed Concrete in container.

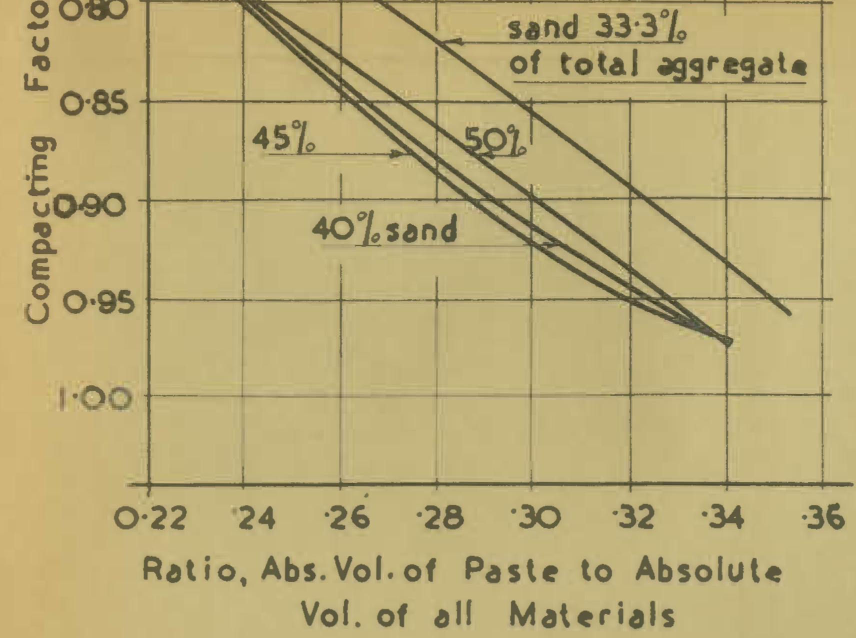


FIG. 60 A. WATER-CEMENT RATIO 0·45

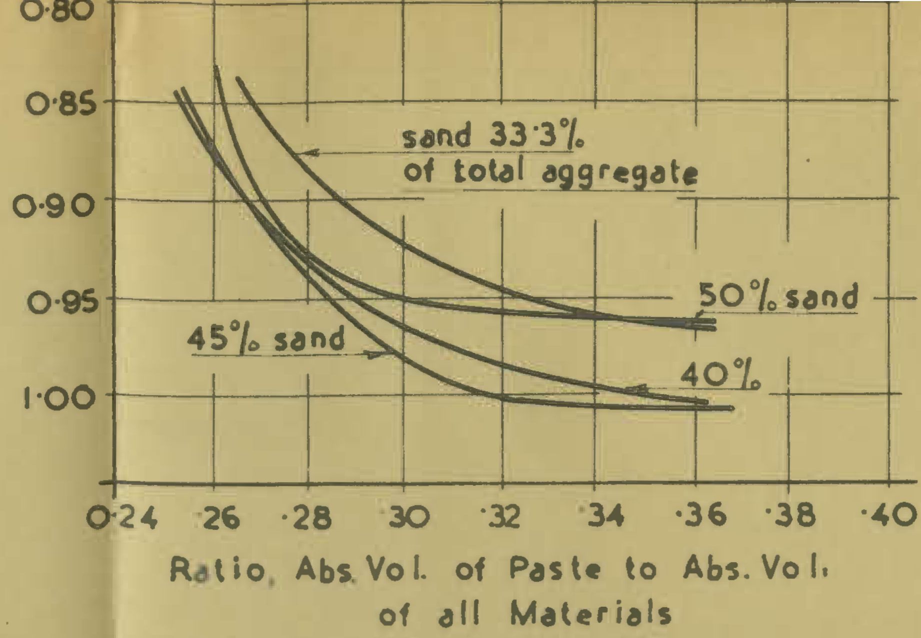


FIG. 61 A. WATER-CEMENT RATIO 0·575 BY WT

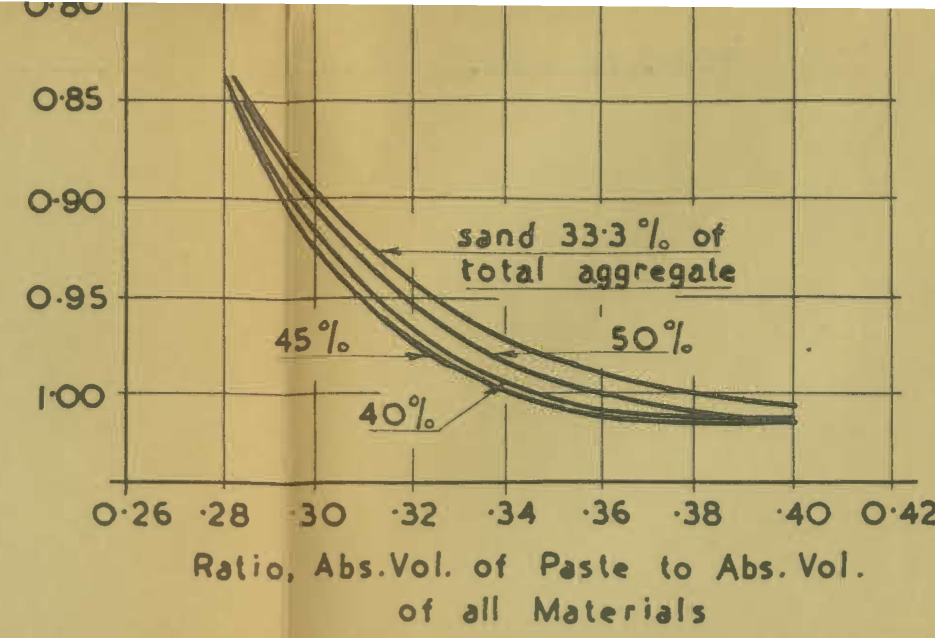


FIG. 62 A, WATER-CEMENT RATIO BY WT 0·70

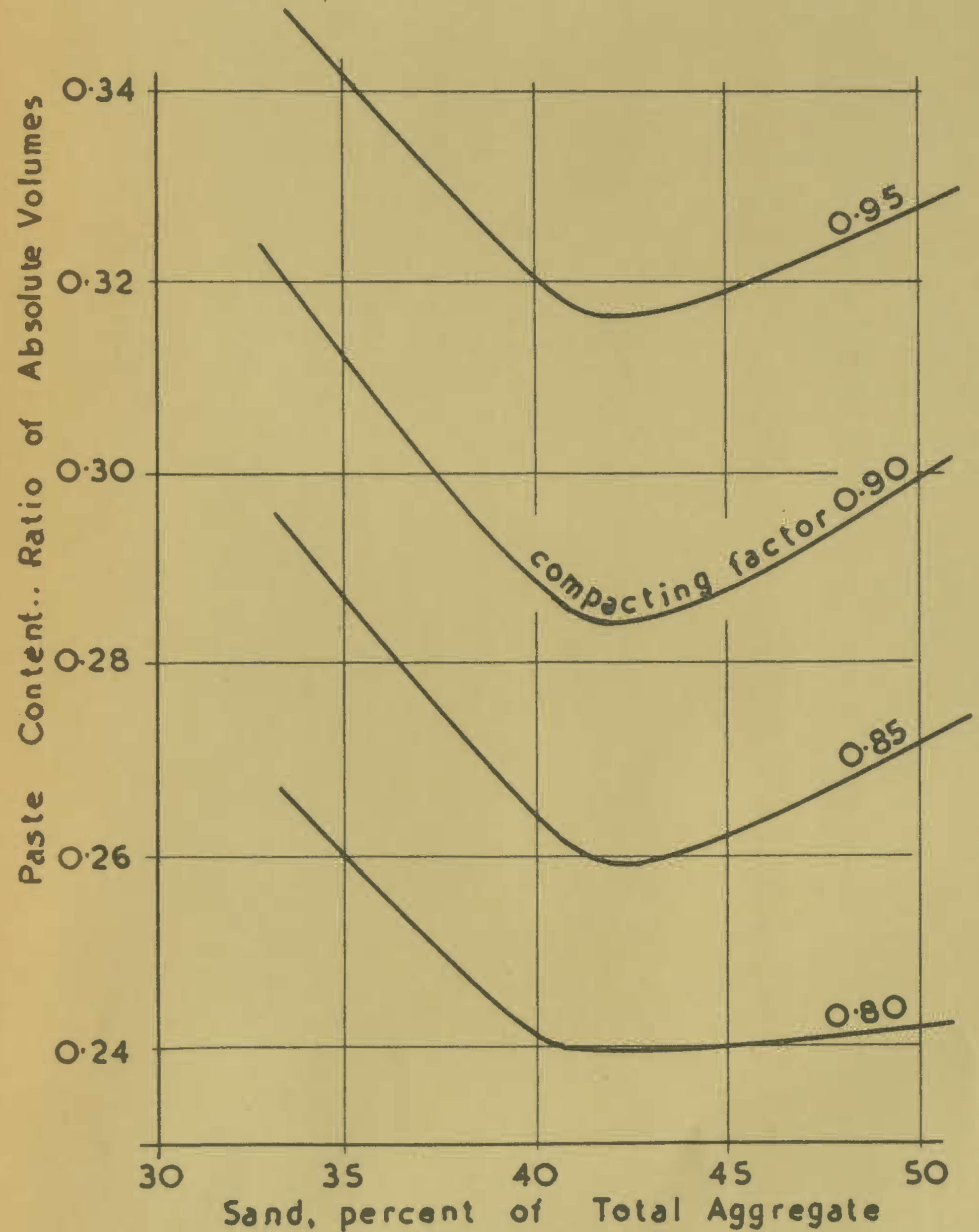


FIG. 60 B, W/C 0·45

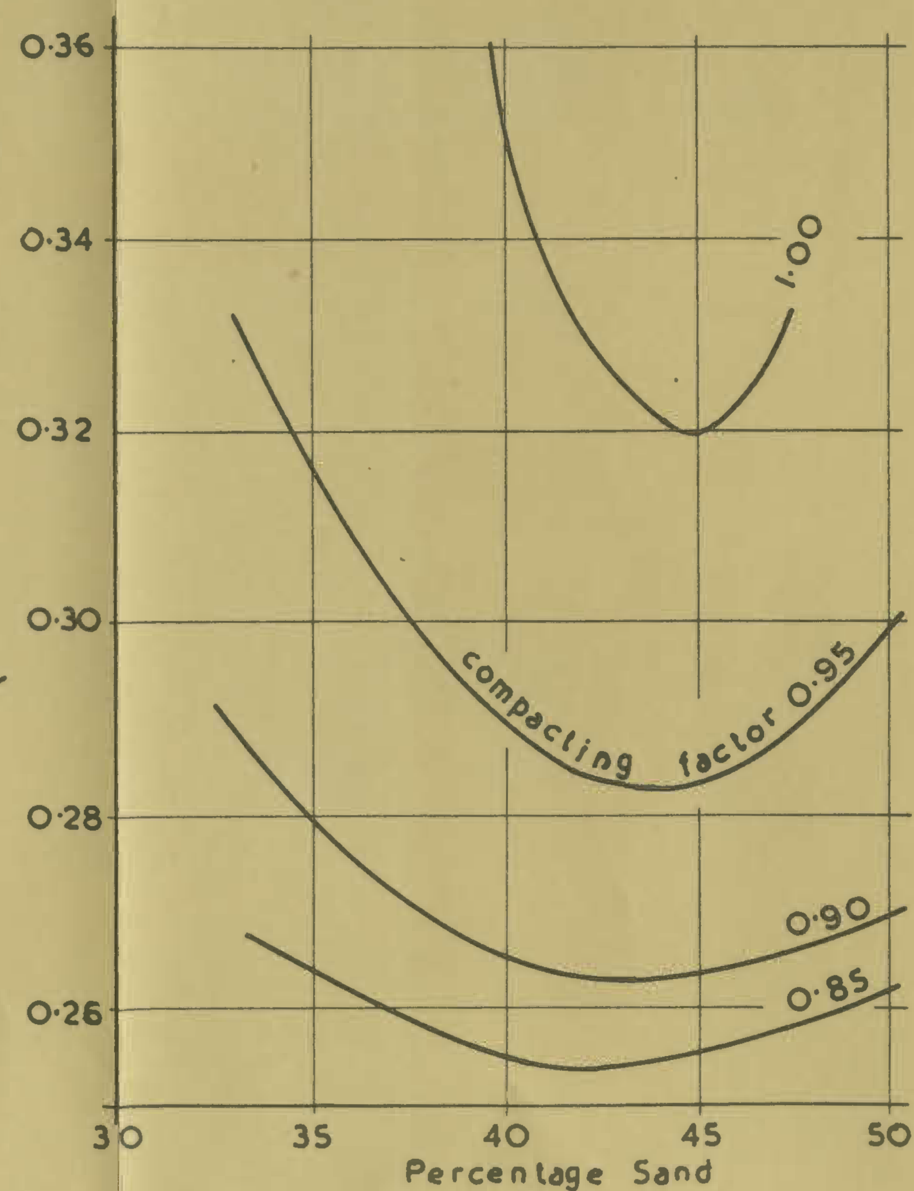


FIG. 61 B, W/C 0·575

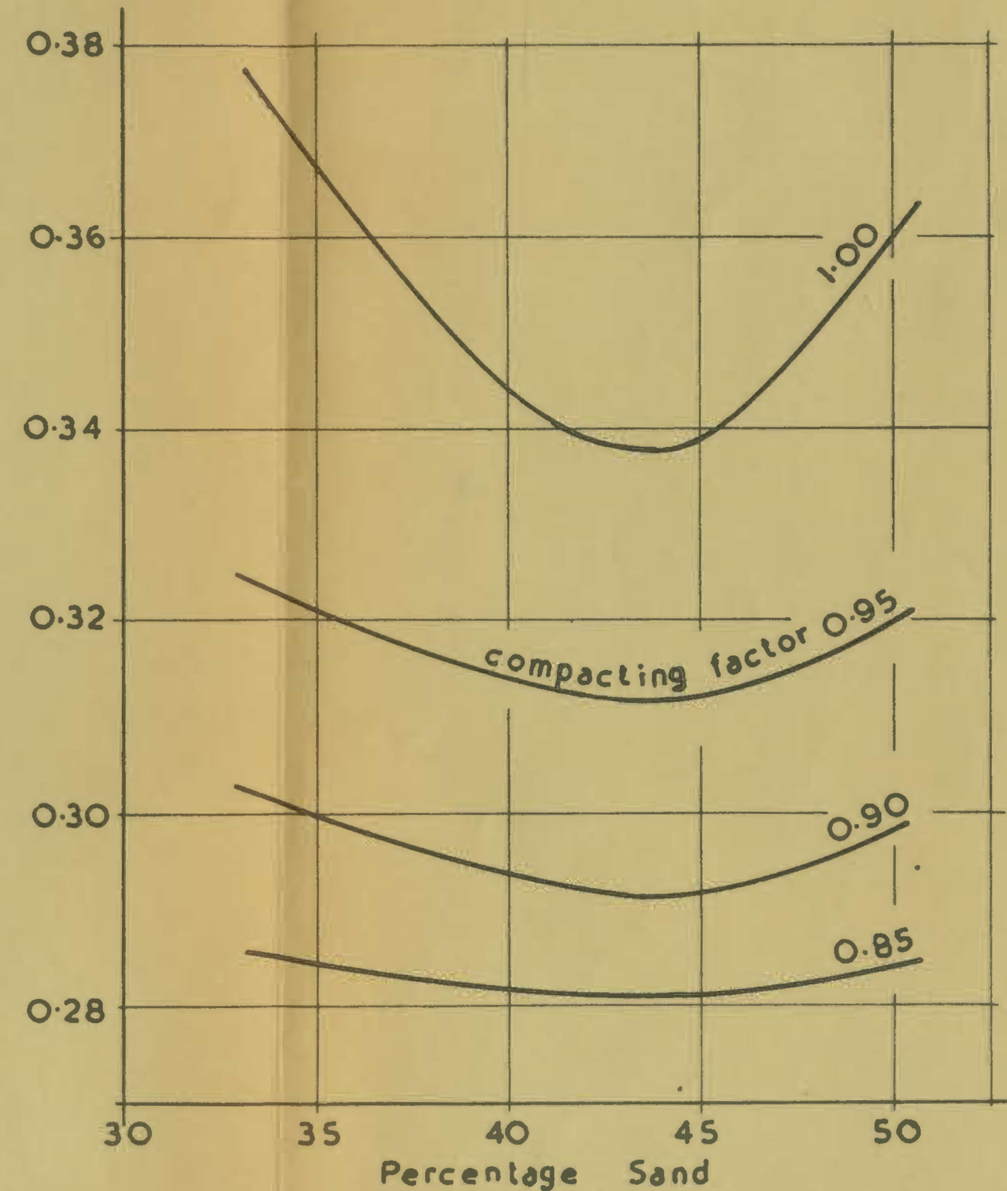


FIG. 62 B, W/C 0·70

RELATION OF COMPACTING FACTOR TO PASTE CONTENT AND PERCENTAGE SAND IN AGGREGATE

GROUP B GRADINGS

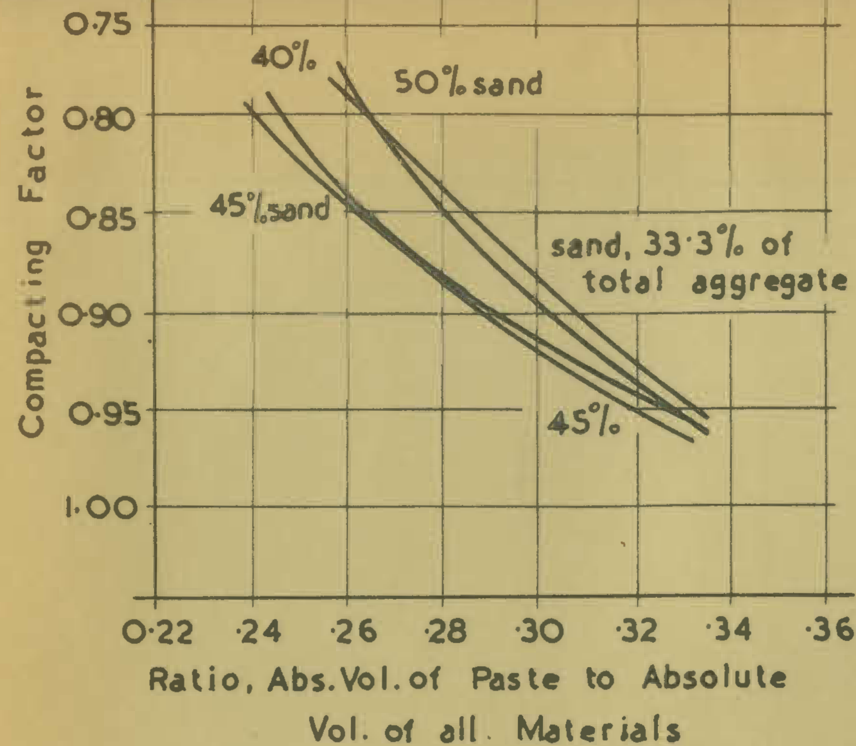


FIG. 63 A. WATER-CEMENT RATIO 0·45

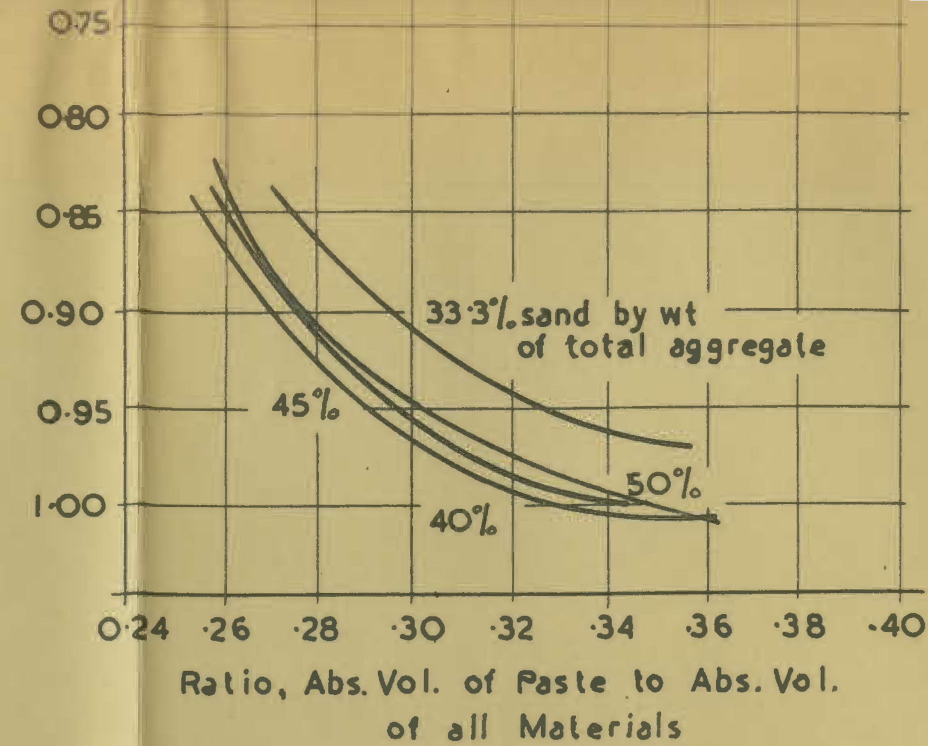


FIG. 64 A. WATER-CEMENT RATIO 0·575 BY WT

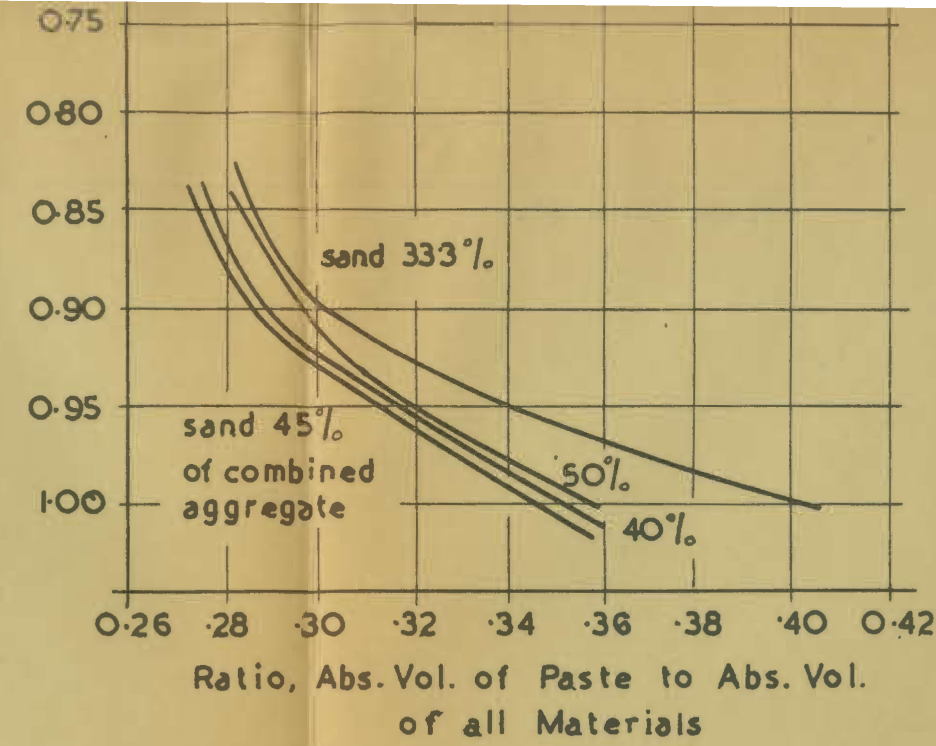


FIG. 65 A. WATER-CEMENT RATIO BY WT 0·70

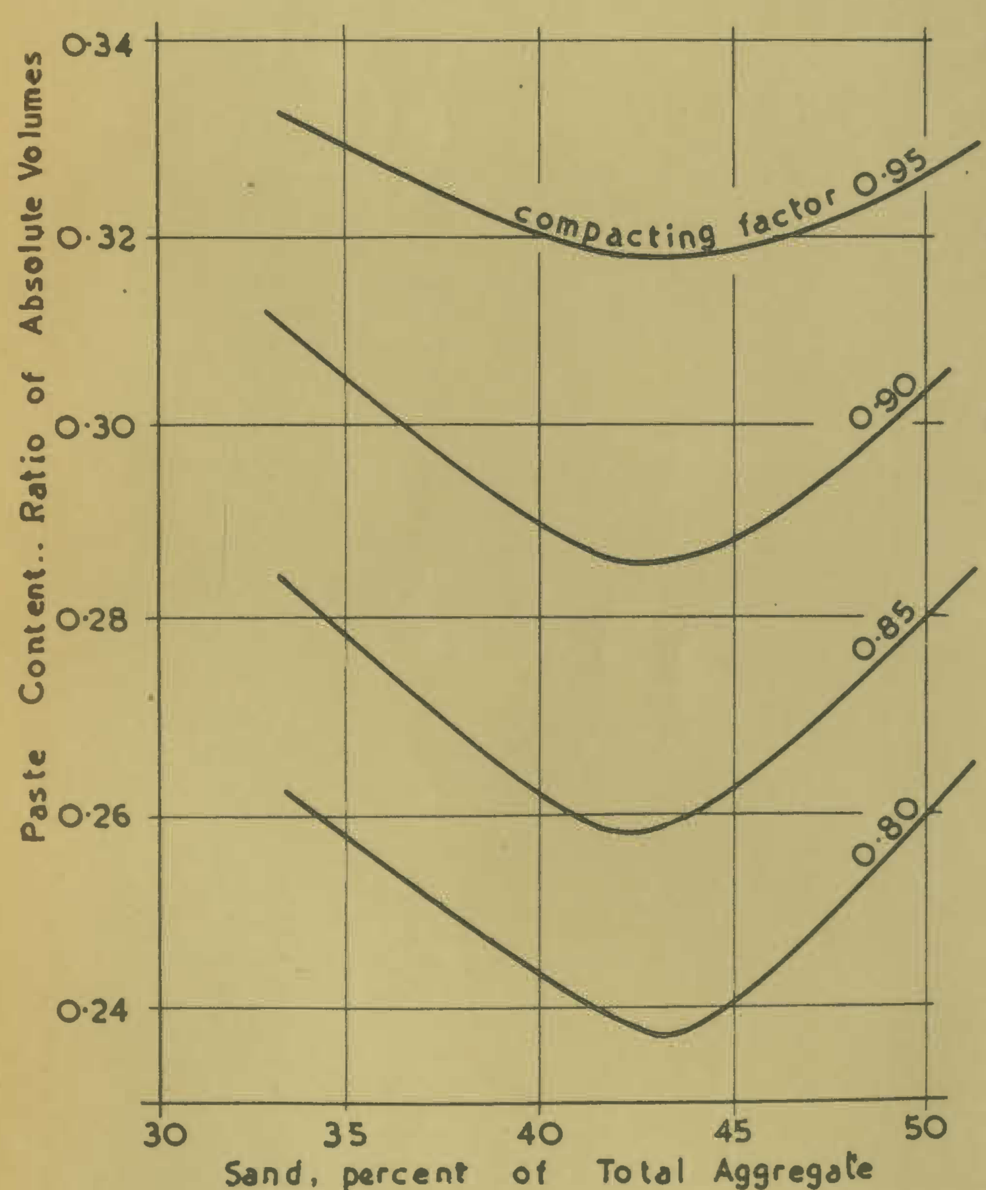


FIG. 63 B. W/C 0·45

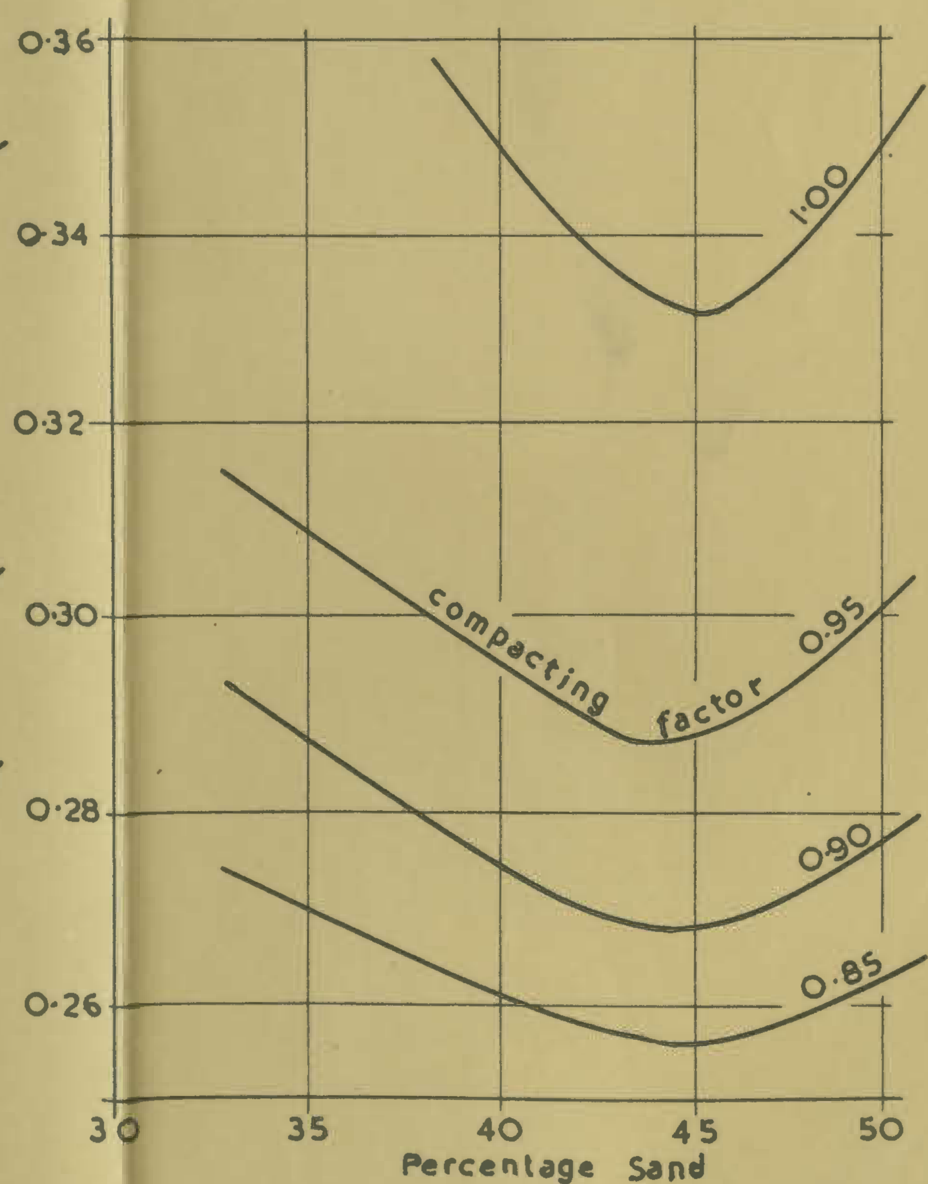


FIG. 64 B. W/C 0·575

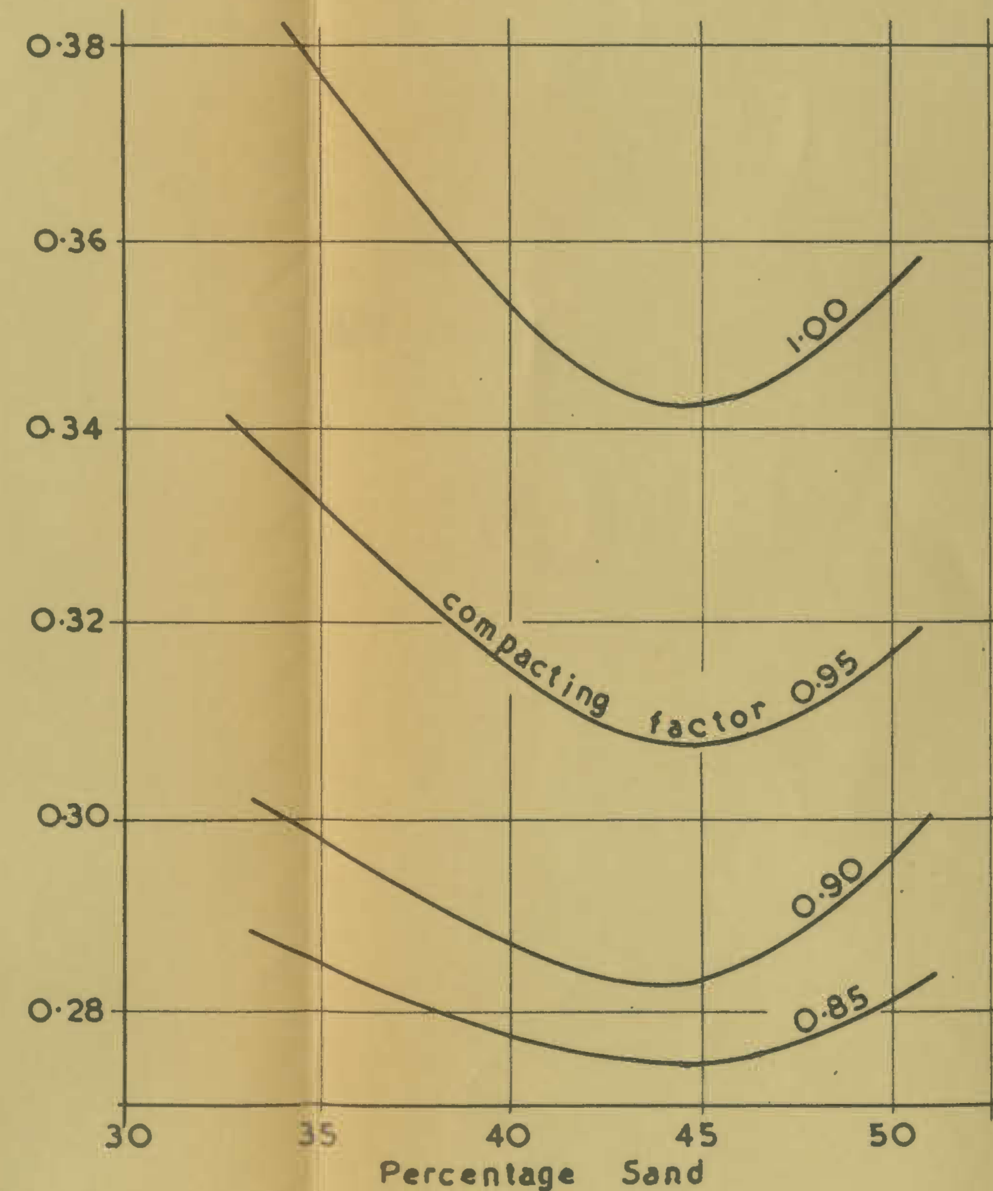
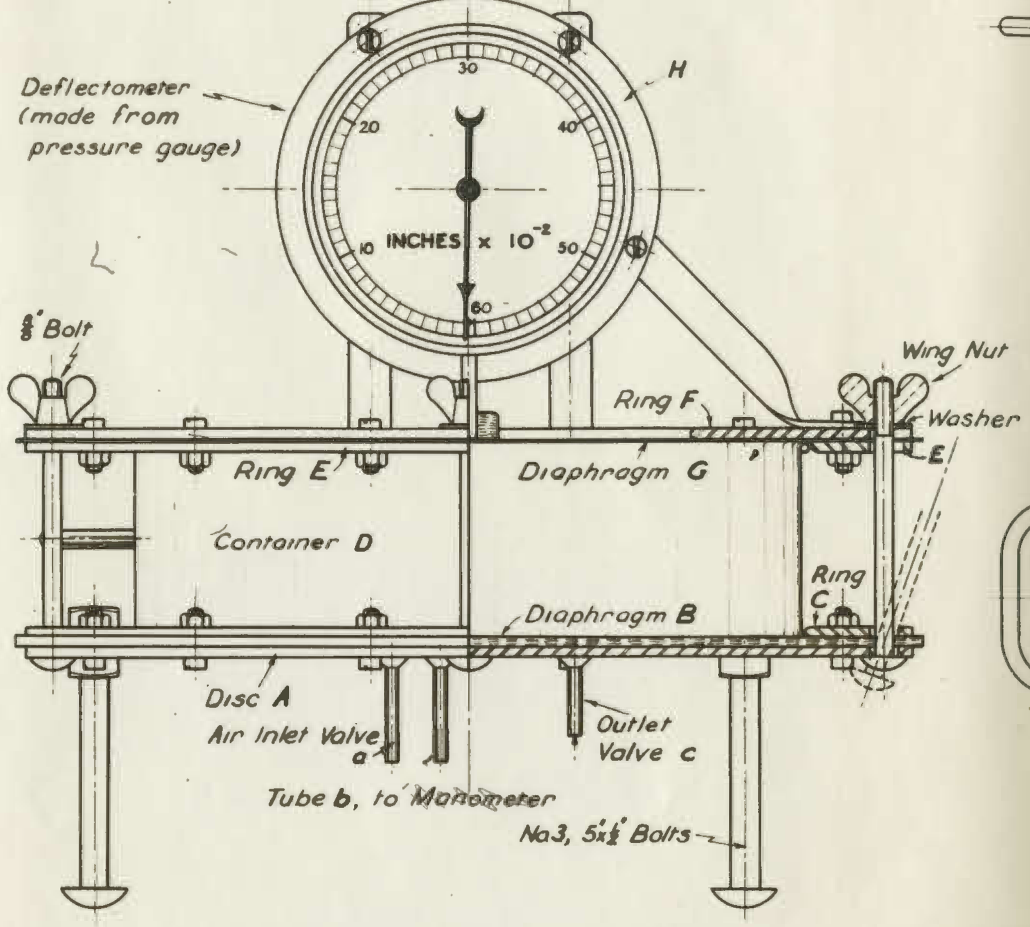


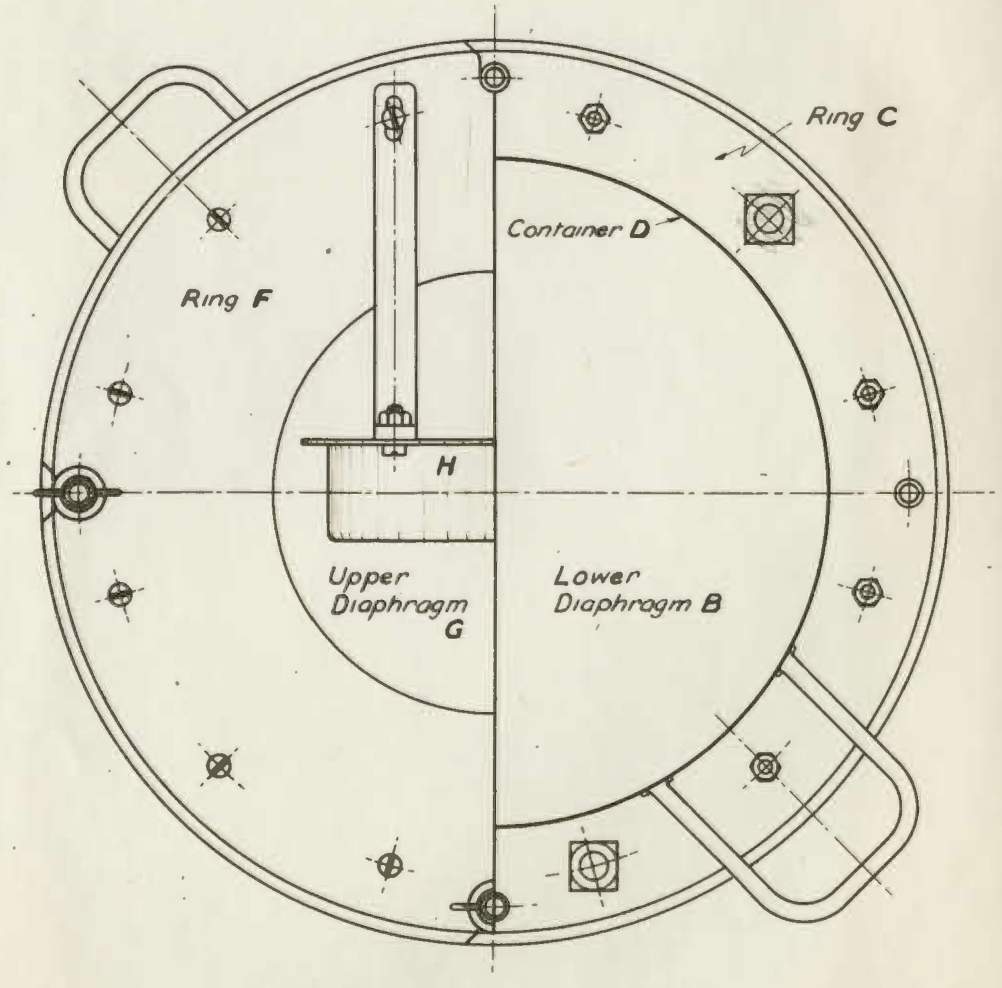
FIG. 65 B. W/C 0·70

RELATION OF COMPACTING FACTOR TO PASTE CONTENT AND PERCENTAGE SAND IN AGGREGATE

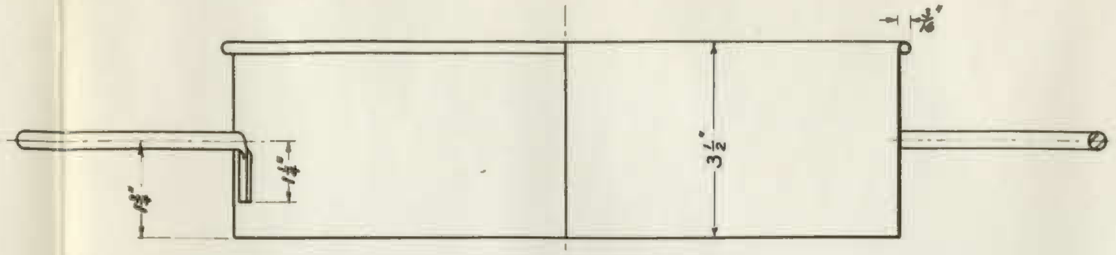
GROUP C GRADINGS



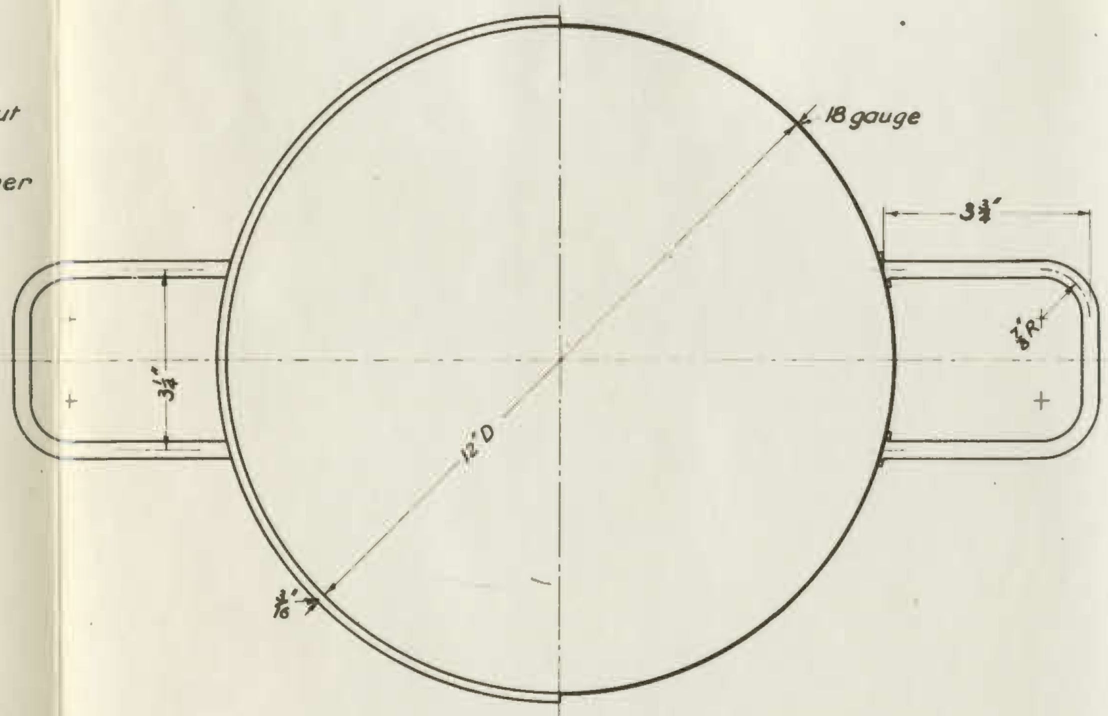
½ SECTIONAL ELEVATION OF APPARATUS



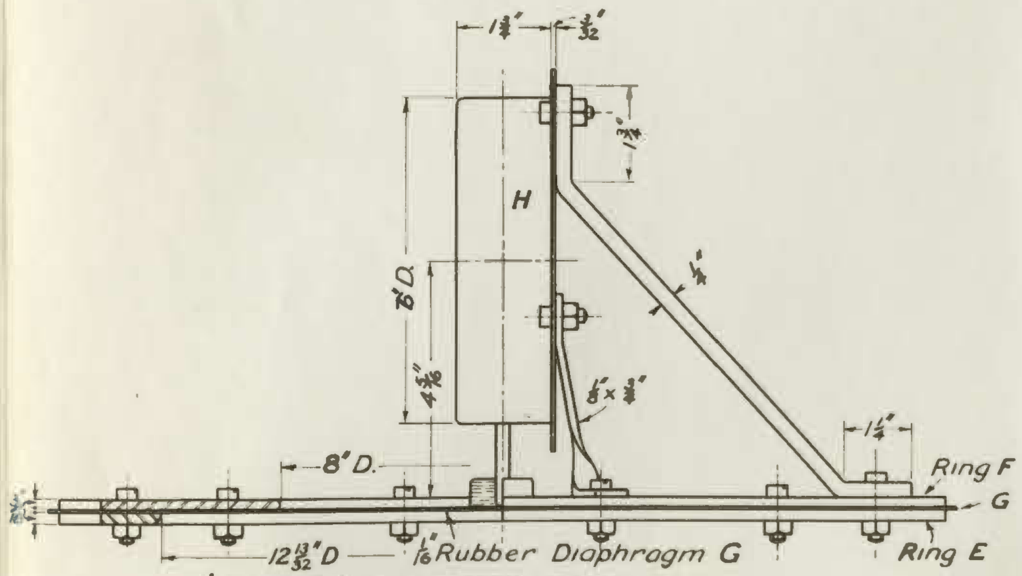
½ SECTIONAL PLAN OF APPARATUS



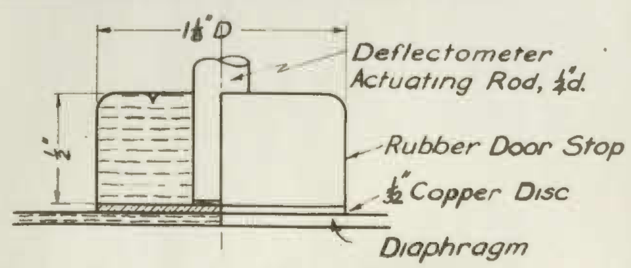
½ SECTIONAL ELEVATION OF CONTAINER



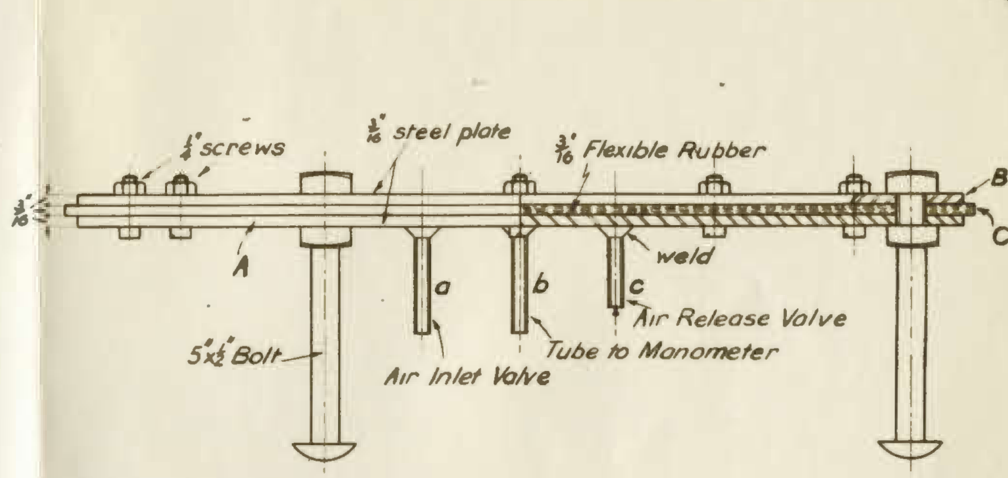
½ SECTIONAL PLAN OF CONTAINER



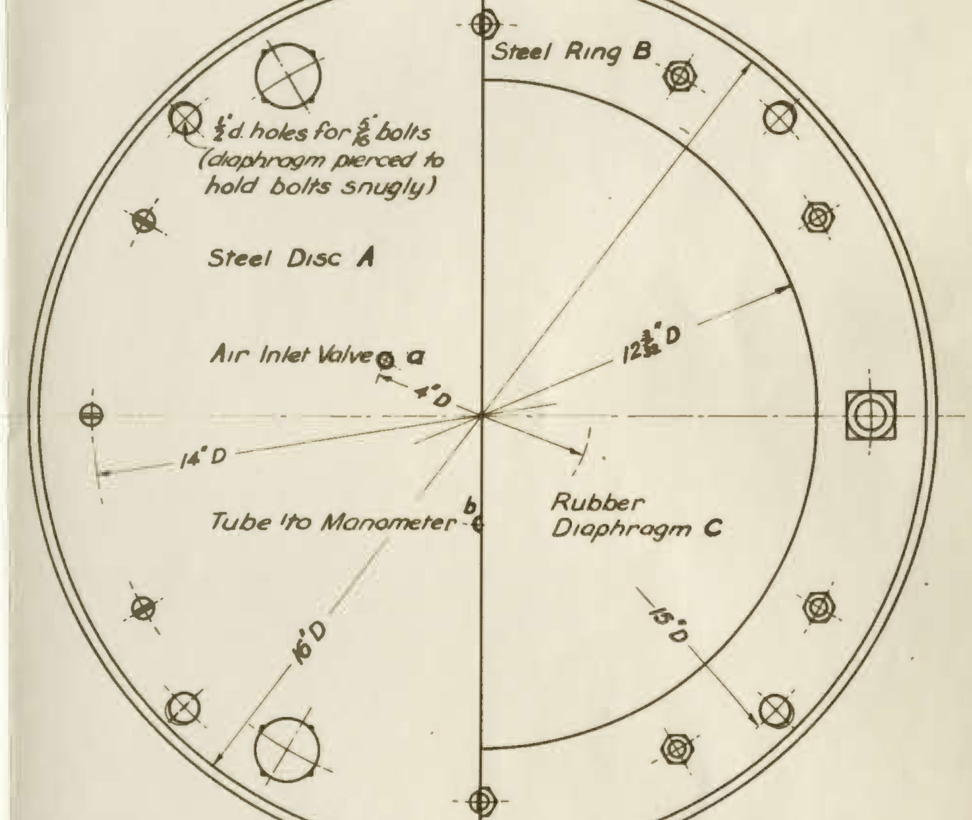
½ SECTIONAL SIDE ELEVATION OF UPPER ASSEMBLY



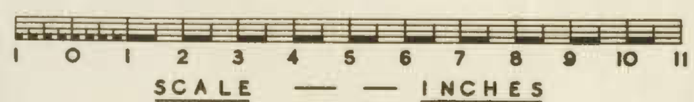
DETAIL OF DEFLECTOMETER ATTACHMENT



½ SECTIONAL ELEVATION OF LOWER ASSEMBLY



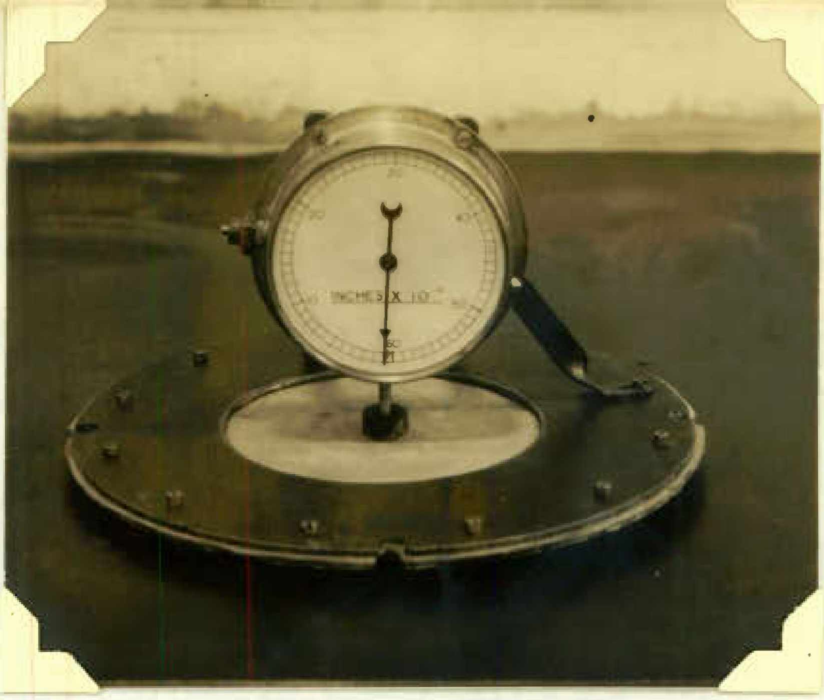
½ PLAN AND ½ UNDERSIDE OF LOWER ASSEMBLY



PRESSURE TEST APPARATUS

FOR DETERMINING THE MOBILITY OF FRESH CONCRETE

UNIVERSITY OF CAPE TOWN — CIVIL ENGINEERING DEPT.		
DESIGNED AND MADE MAY 1948	DRAWN AUGUST 1948	V. L. GRANGER, B.Sc.(Eng.), A.M.I.C.E.



Figs. 67 and 68. PRESSURE TEST APPARATUS.
Upper assembly ring F,
8" internal diameter.

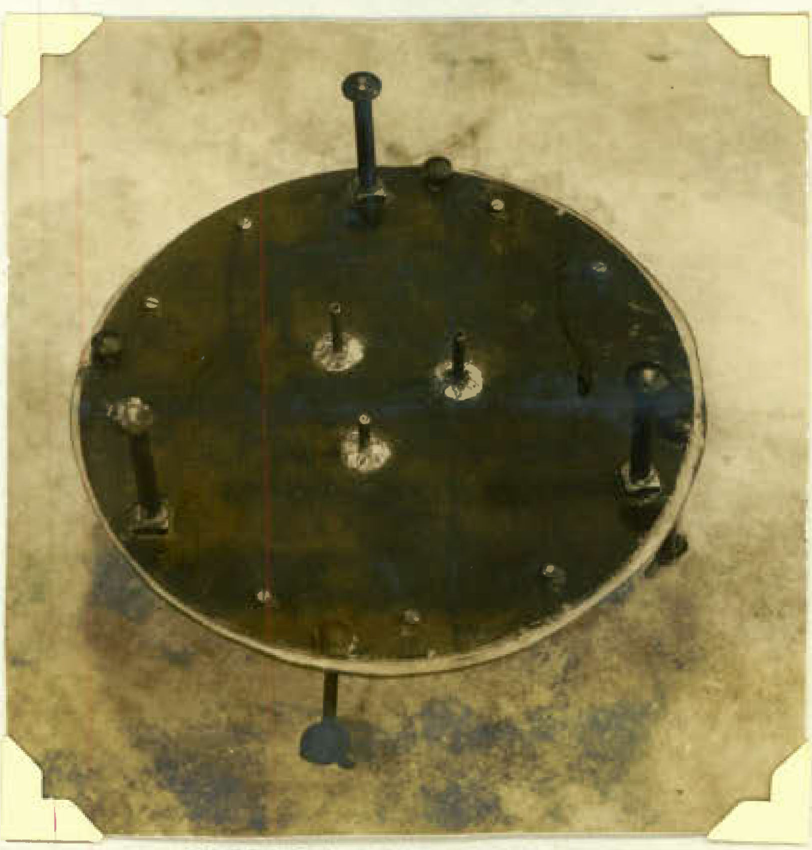


Fig. 69. PRESSURE TEST APPARATUS.
Underside of lower assembly.

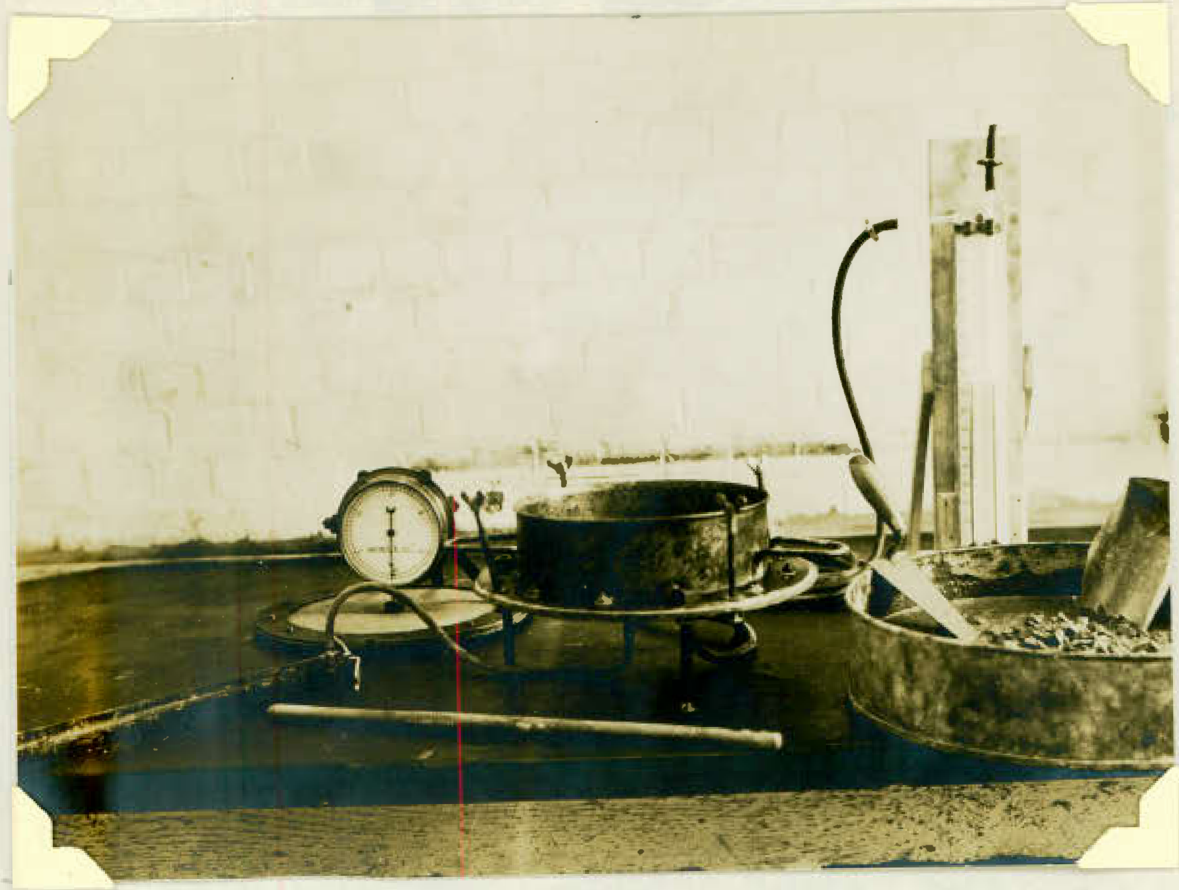


Fig. 70. PRESSURE TEST APPARATUS.
Ready for use.
Ring F, 12" internal diameter.

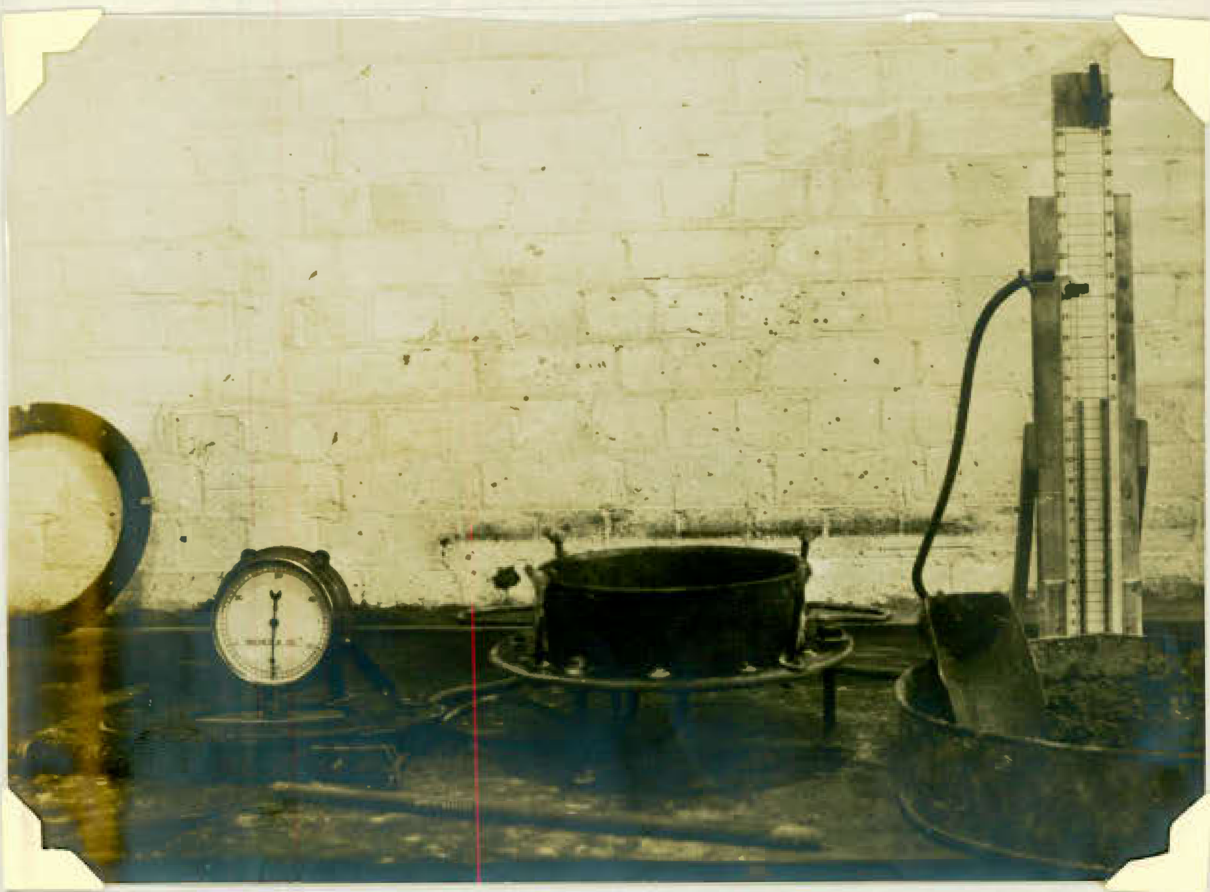


Fig. 71. PRESSURE TEST APPARATUS.
Ready for use.
Ring F. 8" internal diameter. Note larger manometer.

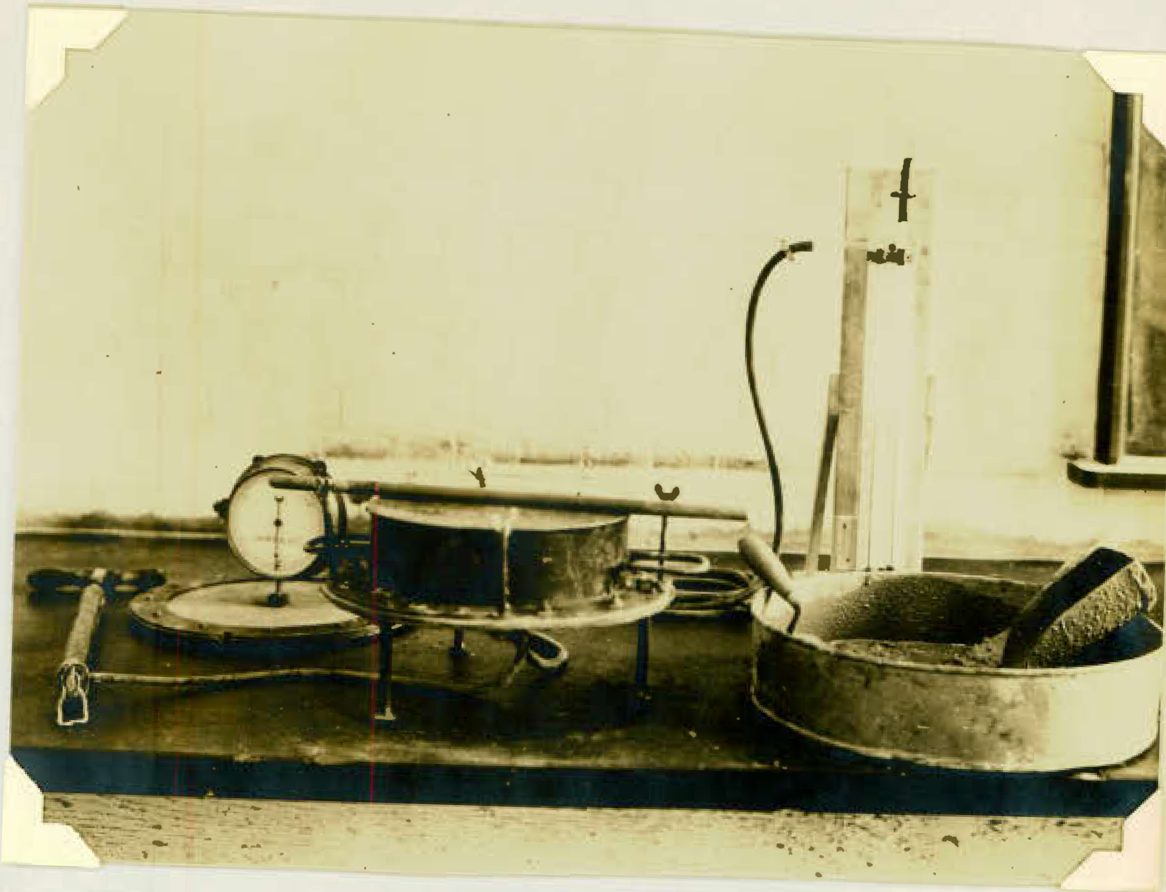


Fig. 72. PRESSURE TEST APPARATUS/
Container filled.

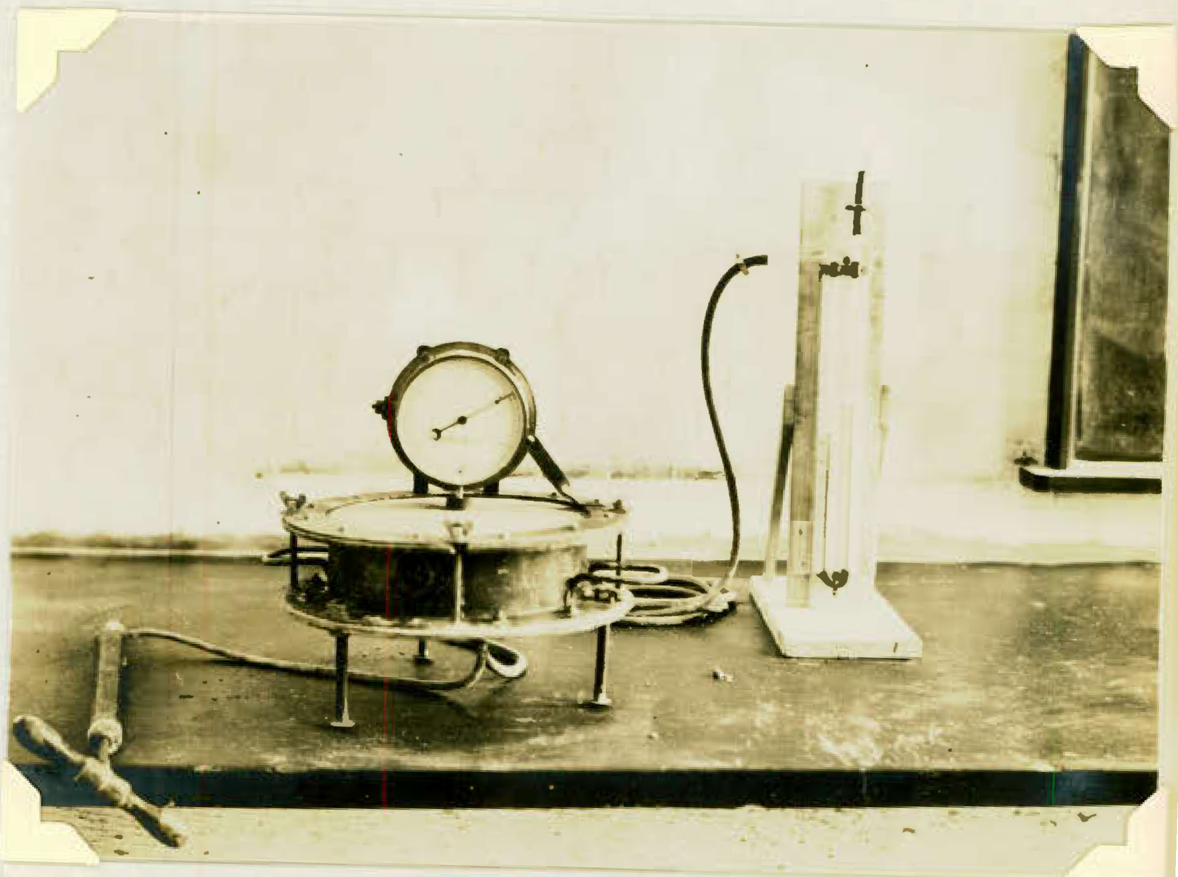


Fig. 73. PRESSURE TEST APPARATUS.
Concrete under test.

Figs. 74 and 75. PRESSURE TEST APPARATUS.

Field use.

UNIVERSITY OF CAPE TOWN. CIVIL ENGINEERING LABORATORY

CHECK LIST FOR RATING OF CHARACTERISTICS OF FRESH CONCRETE

NOTE: On the following form, check or encircle the appropriate word applying to each property. If conditions warrant, word at either end of scale may be qualified further by adding suc words as "very", "moderately" or "slightly" in blank space immediately preceding the word.

Description of Work...
Batch No.......Mix Data.......................... W/C............
....
Date...................Hour..................Time after Mixing......
Temperature........Relative Humidity........Mixing Conditions......
Remarks...
Observer... Rating No.

1 Consistency: dry stiff medium wet sloppy
a. Slump......ins.
b. Flow Table
5 Drops:.....ins.
10 Drops:.....ins.
15 Drops:.....ins.
c. Flow Trough.
5 Drops:.....ins.
10 Drops:.....ins.
Flow.......per cent. Plasticity Coefficient..........

2 Stiffening: Remarks...
a. Rate: ......rapid. normal. ....slow.
b. Apparent cause: evaporation absorption chemical action

3 Plastic Characteristics:
a. Pressure Test:

Deflections (ins)	10	20	30	40	50	60
Pressure (ins.mercury) for 1st Deflection						
2nd Deflection						
3rd Deflection						

b. Cohesiveness: ......tacky. normal. ......short.
c. Resistance to indentation:
......hard. firm. ......soft.
d. Plasticising component:
......smooth. balanced. ......harsh.

4 Apparent Composition of Mix:
a. Cement content: .....lean. O.K. ......rich.
b. Consistency of paste:
.....thin. O.K. ......thick.
c. Char. of cement:.....gritty. O.K. ......sticky.
d. Proportion of sand.....undersanded O.K. ......oversanded.
e. Gradation of sand......grainy O.K. ......earthy.
f. Gradation of coarse aggregate:
......rocky. O.K. ......pebbly.

5 Segregation:
a. In testing: none slight considerable excessive
Details...
b. Bleeding: none slight considerable excessive
.........slow ....rapid

6 Other Workability Factors:
a. Visual rating ....good. fair. ....poor.
b. Finishing quality......good. fair. ....poor.
c. Remoulding test:mobility: no. of jigs...Ring clearance..in.
d. Standard Compacting Factor Test:
Weight of Container empty.......................
Weight of Container concrete..................
Nett weight of concrete.........................
Computed compacting factor......................

7 Suitability Relative to concrete for .... Quality Index
a. Rating: ......good fair ......poor

8 Record of Cubes Made
Serial Nos:...
Dates to be Tested:..................................

Fig. 113

CITY OF CAPE TOWN | CITY ENGINEER'S DEPARTMENT

CHECK LIST FOR RATING OF CHARACTERISTICS OF FRESH CONCRETE

NOTE: On the following form, check or encircle the appropriate word applying to each property. If conditions warrant, word at either end of scale may be qualified further by adding such words as "very", "moderately" or "slightly" in blank space immediately preceding the word.

Locality and Description of Work..................................
Foreman..........................Observer..........................
Mix Data..W/C........
Date.................Hour........... Approx. Time to Place.....
Weather...
Control Methods...

		Rating No.
1	Consistency: dry stiff medium wet sloppy a. Slump........ins. b. Flow Trough. 5 Drops:........ins. 10 Drops:........ins. Plasticity Coefficient...............	
2	Stiffening: Remarks...................................... a. Rate: ......rapid. normal. ......slow. b. Apparent cause: evaporation absorption chemical actn	
3	Plastic Characteristics: a. Pressure Test: (see table below) b. Cohesiveness: ....tacky. normal. ......short. c. Resistance to indentation: ....hard. firm. ......soft. d. Lubricating component: ....smooth. balanced. ......harsh.	
4	Apparent Composition of Mix: a. Cement content:........lean. O.K. ......rich. b. Consistency of paste: ....thin. O.K. ......stiff. c. Char. of cement:.......gritty. O.K. ......sticky. d. Sand content:.......undersanded O.K. ......oversanded. e. Gradation of sand......grainy. O.K. ......earthy. f. Gradation of coarse aggregate: ....rocky. O.K. ......pebbly.	
5	Segregation: a. From pile on flat surface; none slight considerable excessive b. In form: none slight considerable excessive Details... c. Bleeding: none slight considerable excessive d. Laitance: none slight considerable excessive	
6	Other Workability Factors: a. Visual rating: ....good. fair. ......poor. b. Finishing quality:.....good. fair. ......poor.	
7	Suitability for this job.......................... Quality Index..Y.... a. Rating: ......good. fair. .....poor.	
8	Suggestions for improvement.......................................	
9	Record of Cubes Made: Serial Nos:.. Dates to be tested:................................	

Pressure Test (3a):

Deflections (ins)	10	20	30	40	50	60
Pressure (ins.mercury) for 1st Deflection						
2nd Deflection						
3rd Deflection						

Fig. 114

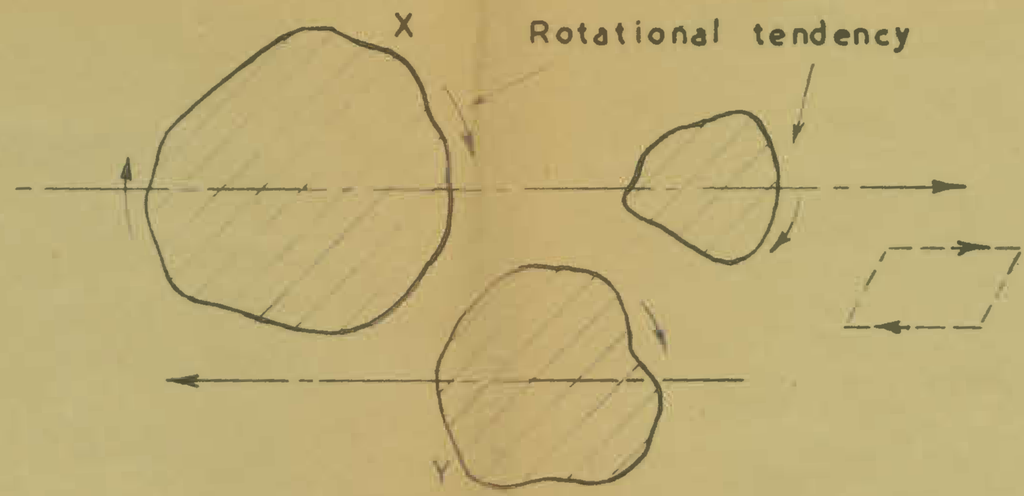


FIG. 115A.. SOLID PARTICLES X & Y APPROACHING EACHOTHER

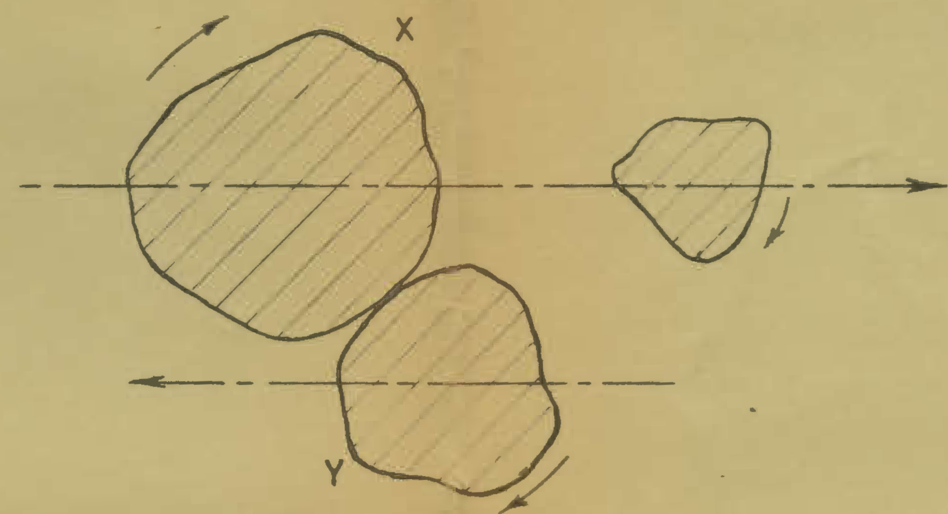


FIG. 115 B.. NEAR CONTACT; X & Y ROTATING AS A GROUP

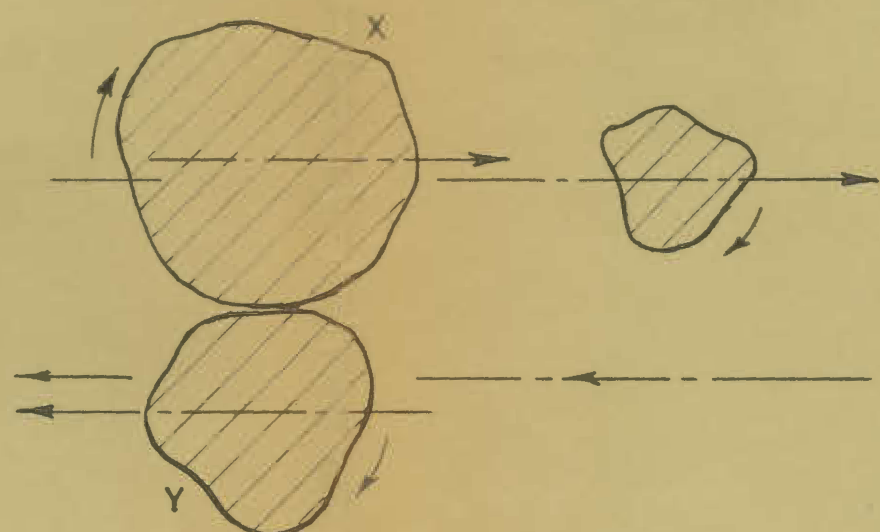
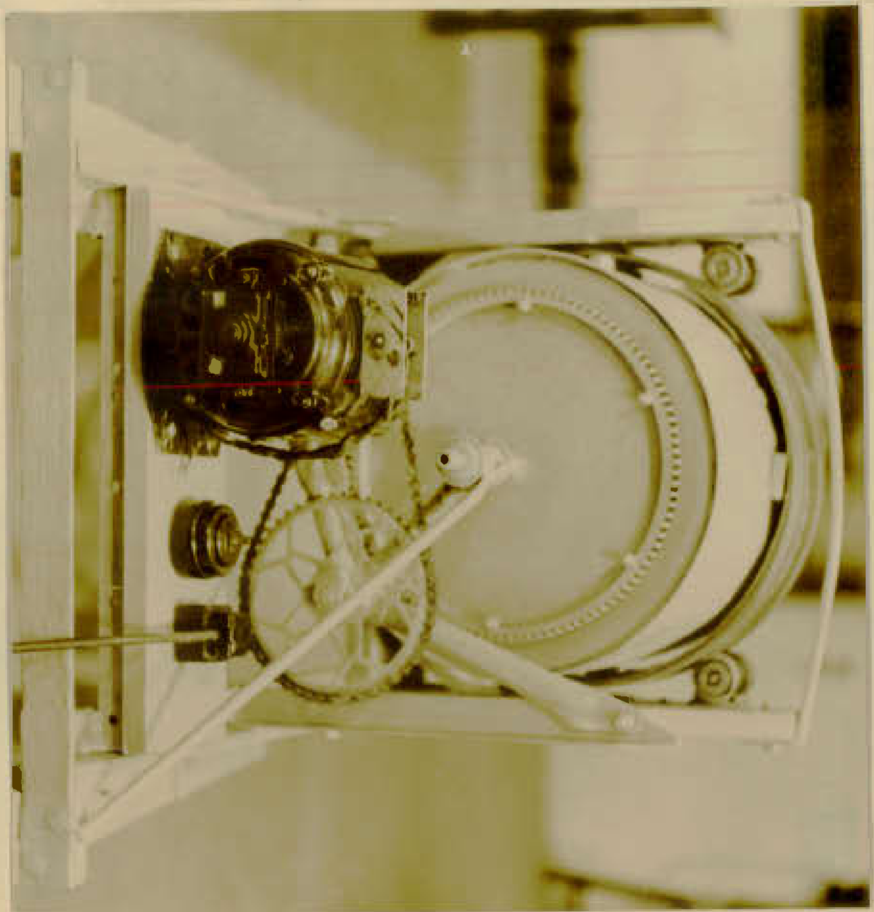
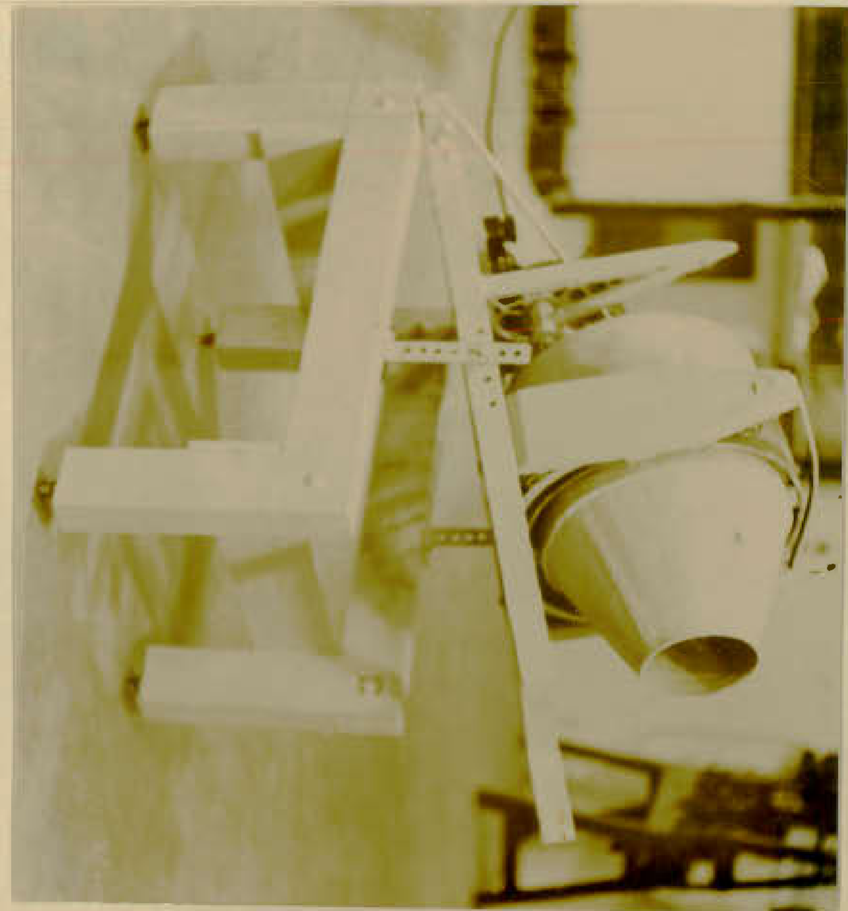


FIG. 115C.. X & Y HAVE BEEN DISPLACED FROM THEIR ORIGINAL STRATA

BEHAVIOUR OF SOLID PARTICLES IN A SUSPENSION DURING FLOW





FIGS. 116 TO 118: LABORATORY CONCRETE MIXER

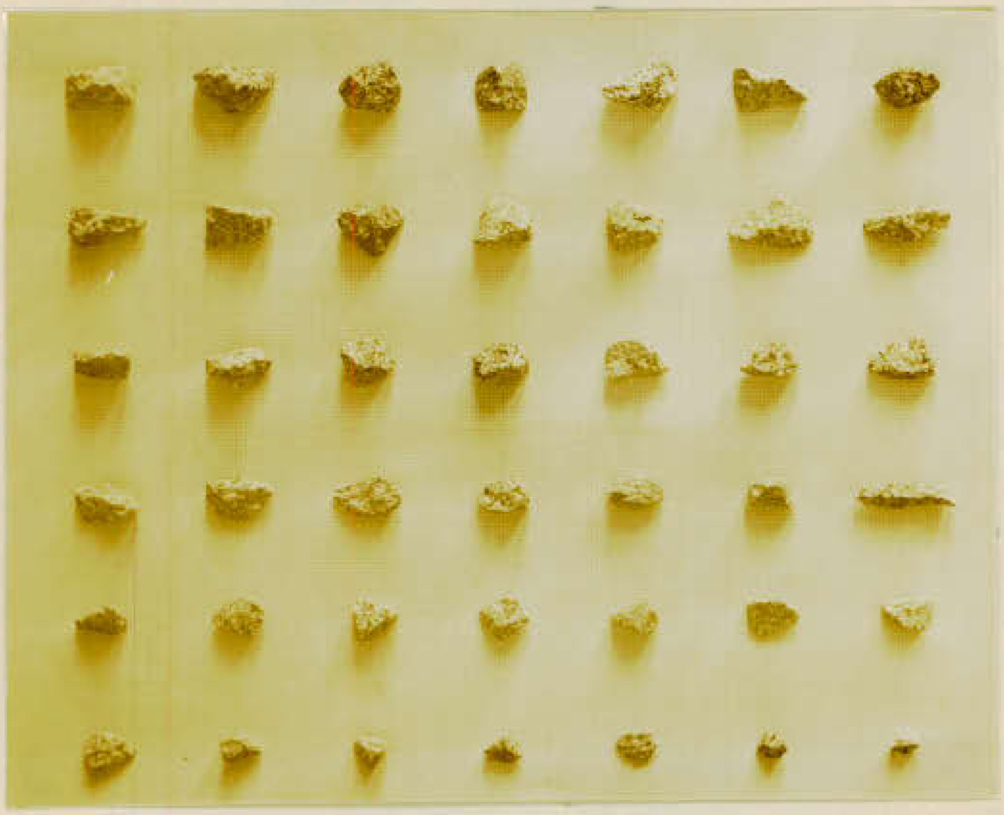


Fig. 122. Sample of Nominal $\frac{3}{4}$" Crusher run Brackenfel Granite (washed.)

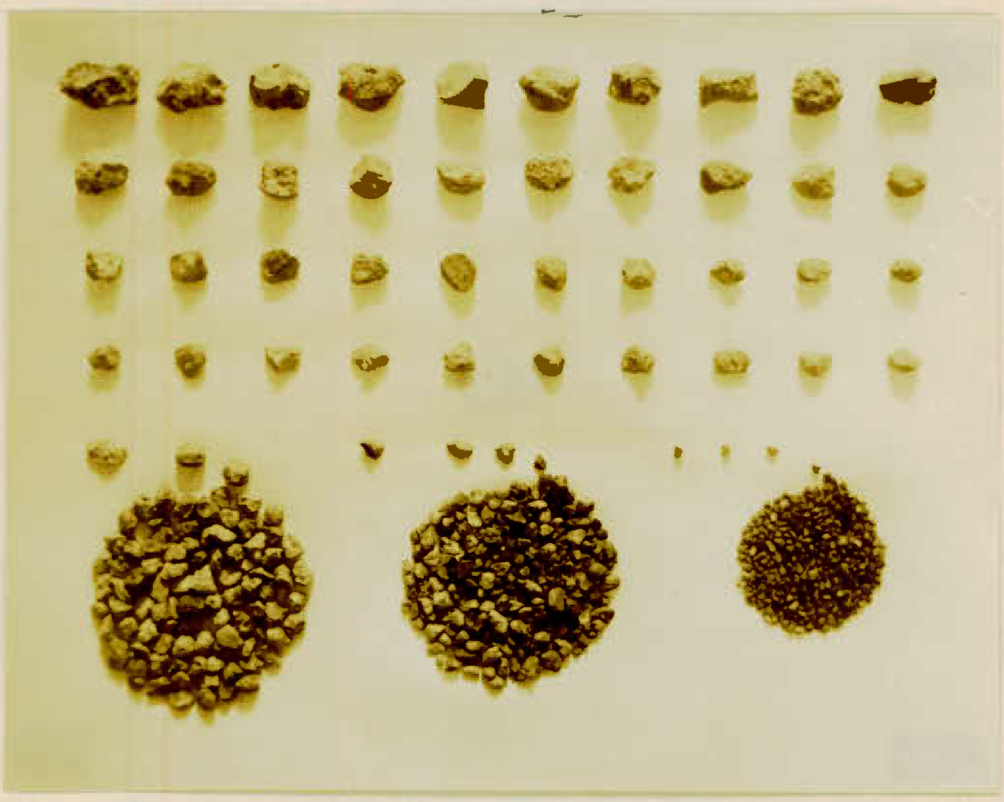


Fig. 123. Sample of $\frac{3}{4}$" maximum Durbanville Laterite Gravel (washed.)

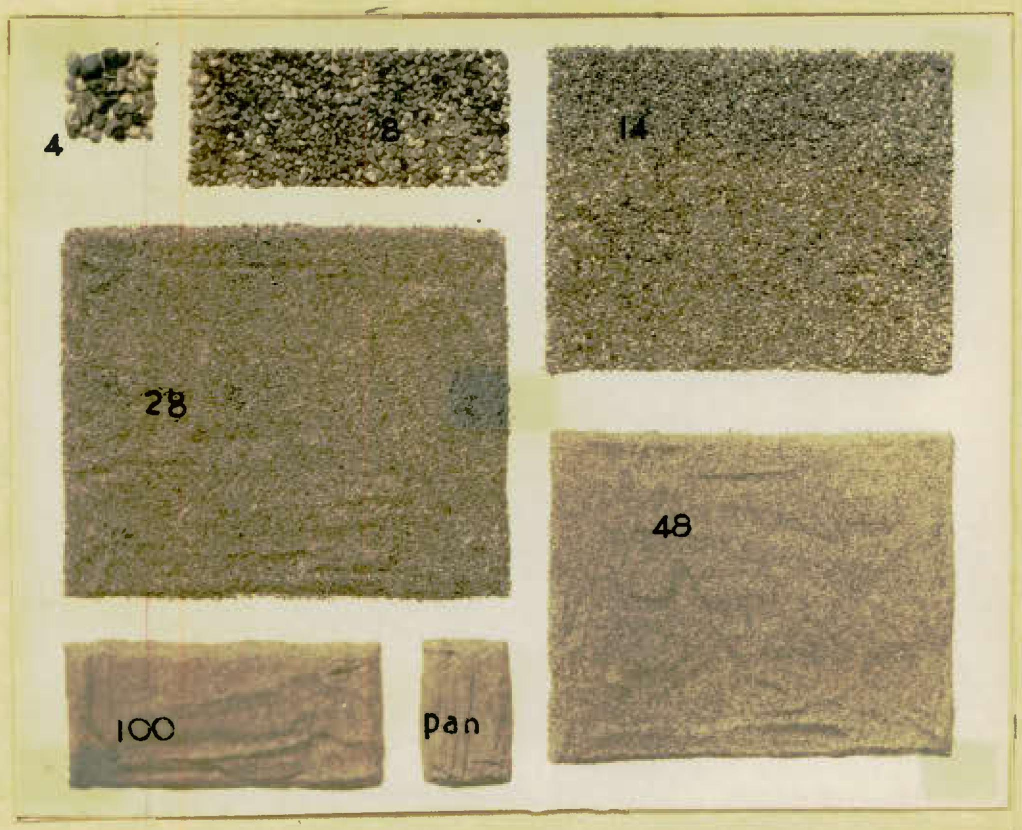


Fig. 124. Malmesbury River Sand separated into Tyler Sieve sizes. (Retained on each sieve indicated.)

Fig. 125. Woolf Cone and sand samples in the following states:
a) Room dry
b) Saturated and surface dry
c) Damp.

NOTE: Percentages on the curves indicate the amount of sand in each series of batches expressed as a percentage of the weight of the combined aggregate

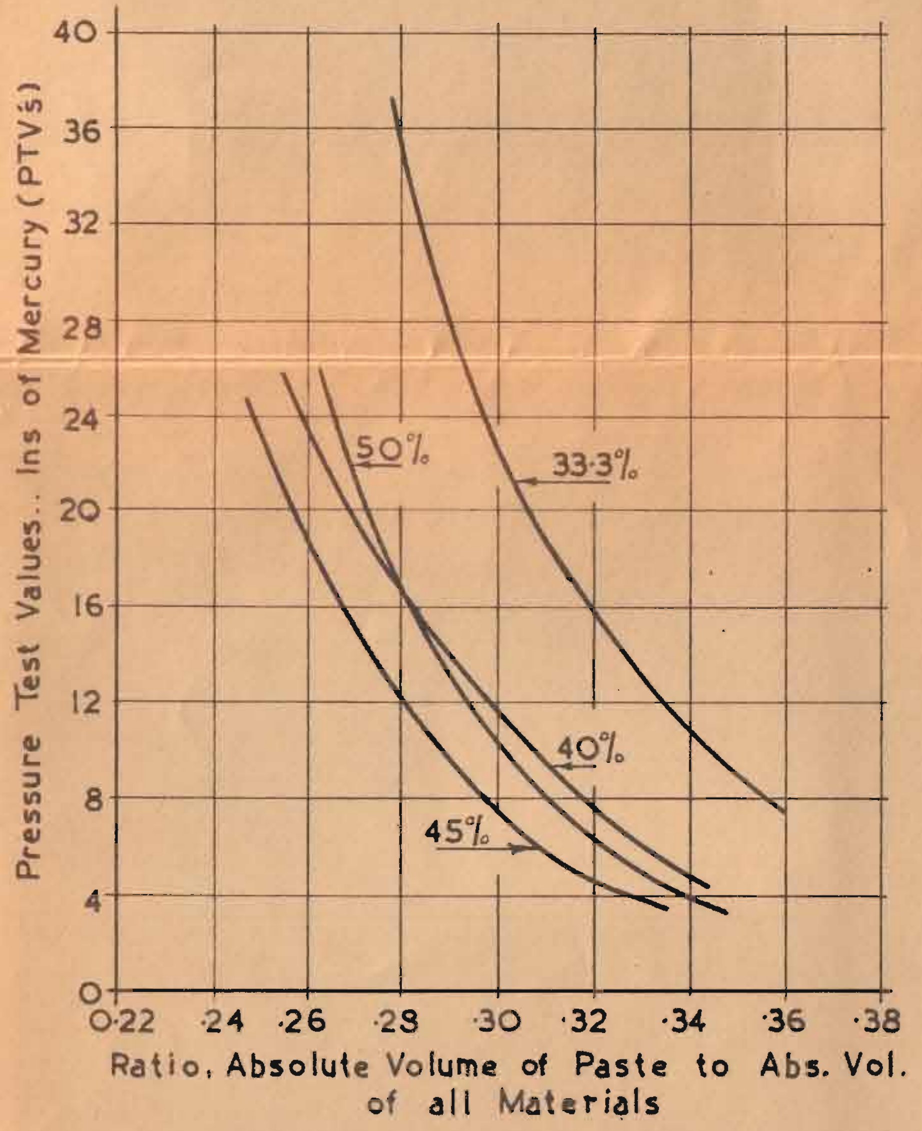


FIG. 79 A. WATER-CEMENT RATIO BY WT 0·45

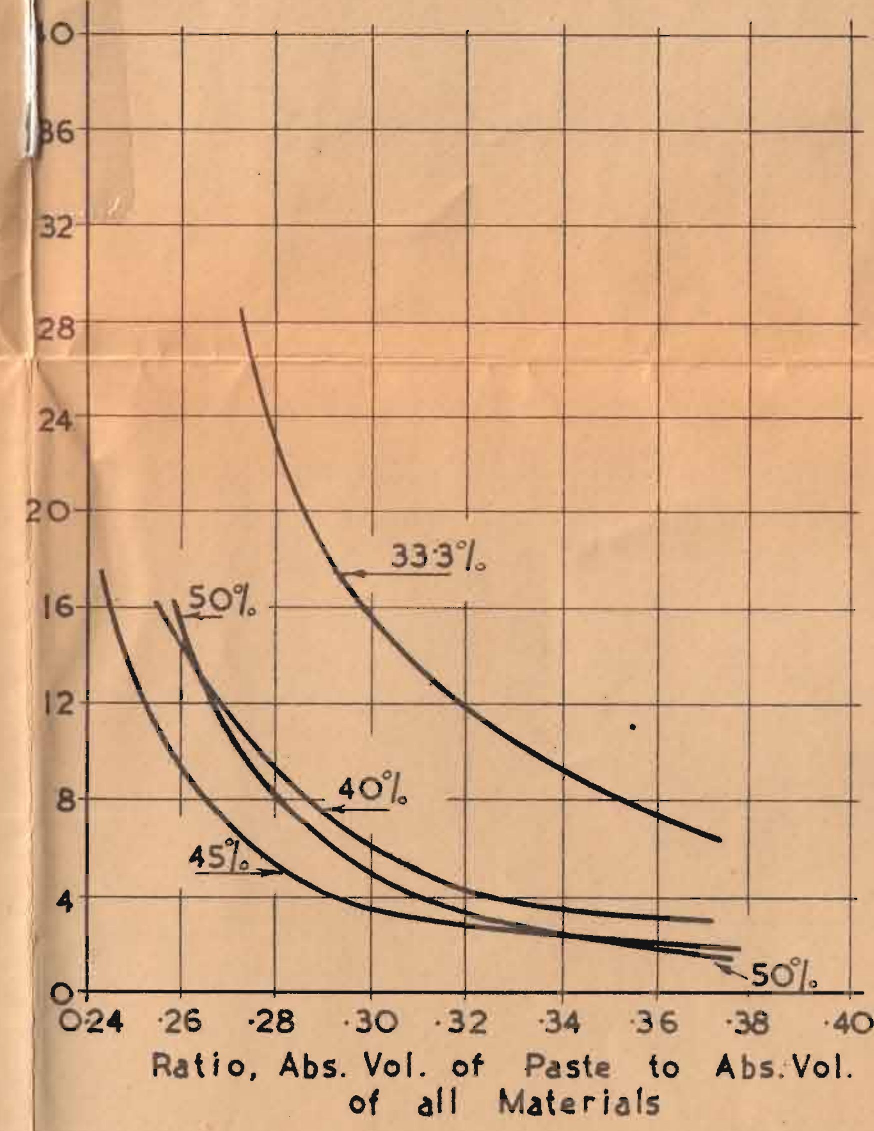


FIG. 80 A. WATER-CEMENT RATIO BY WT 0·575

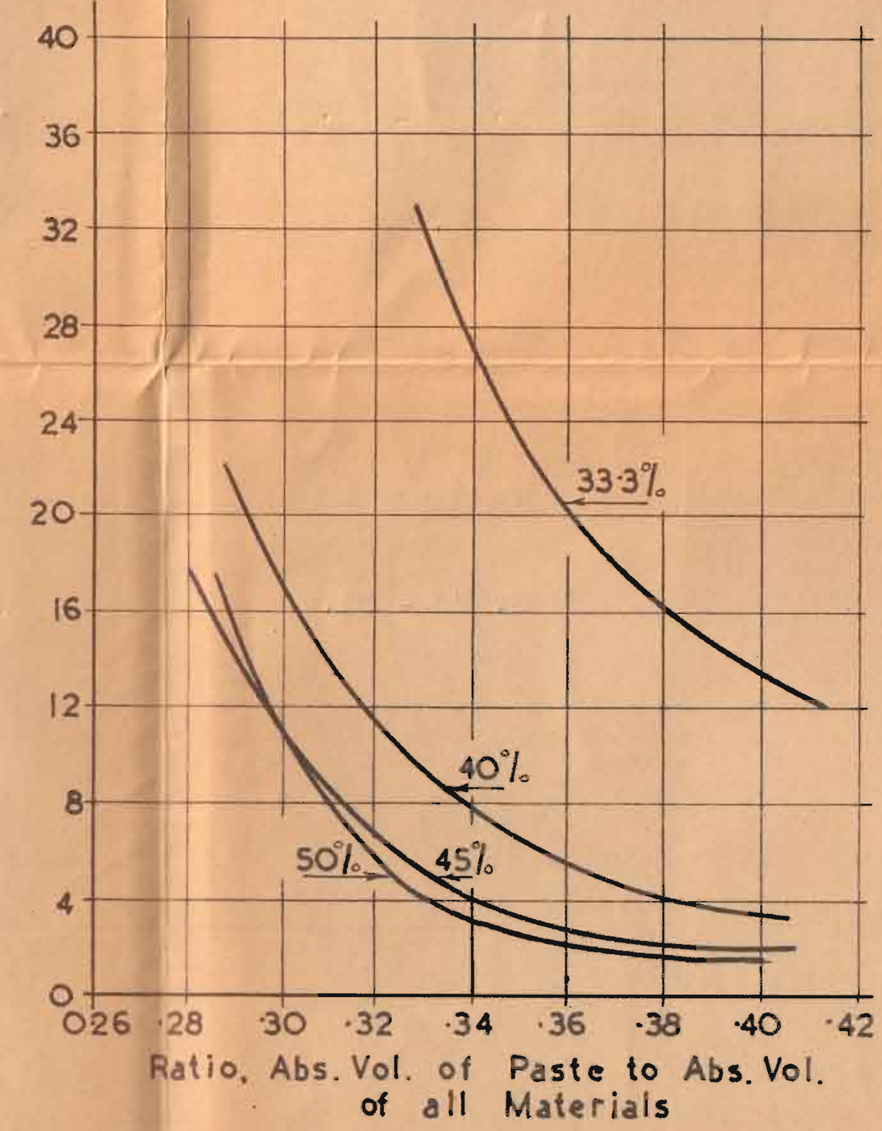


FIG. 81 A. WATER-CEMENT RATIO BY WT. 0·70

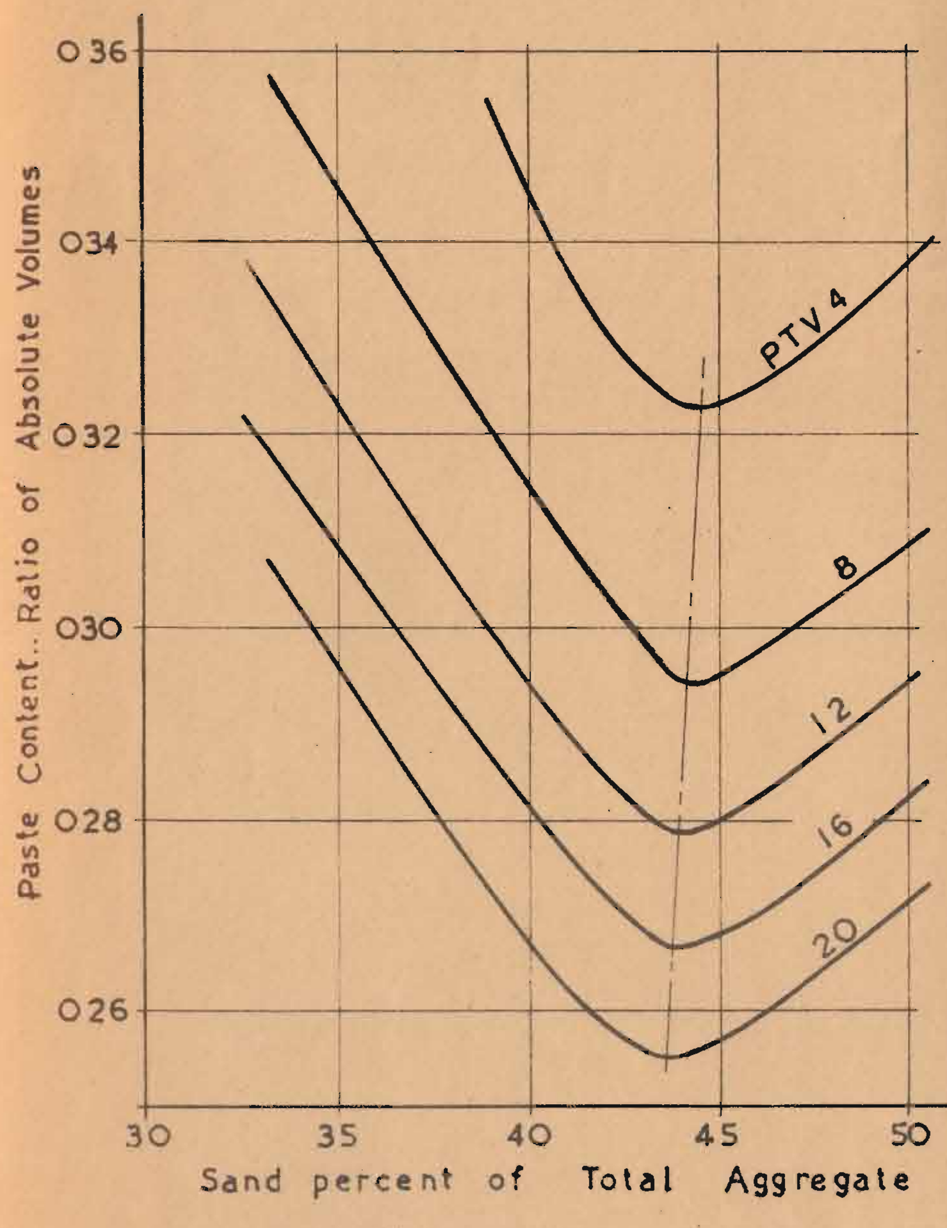


FIG. 79 B, W/C 0·45

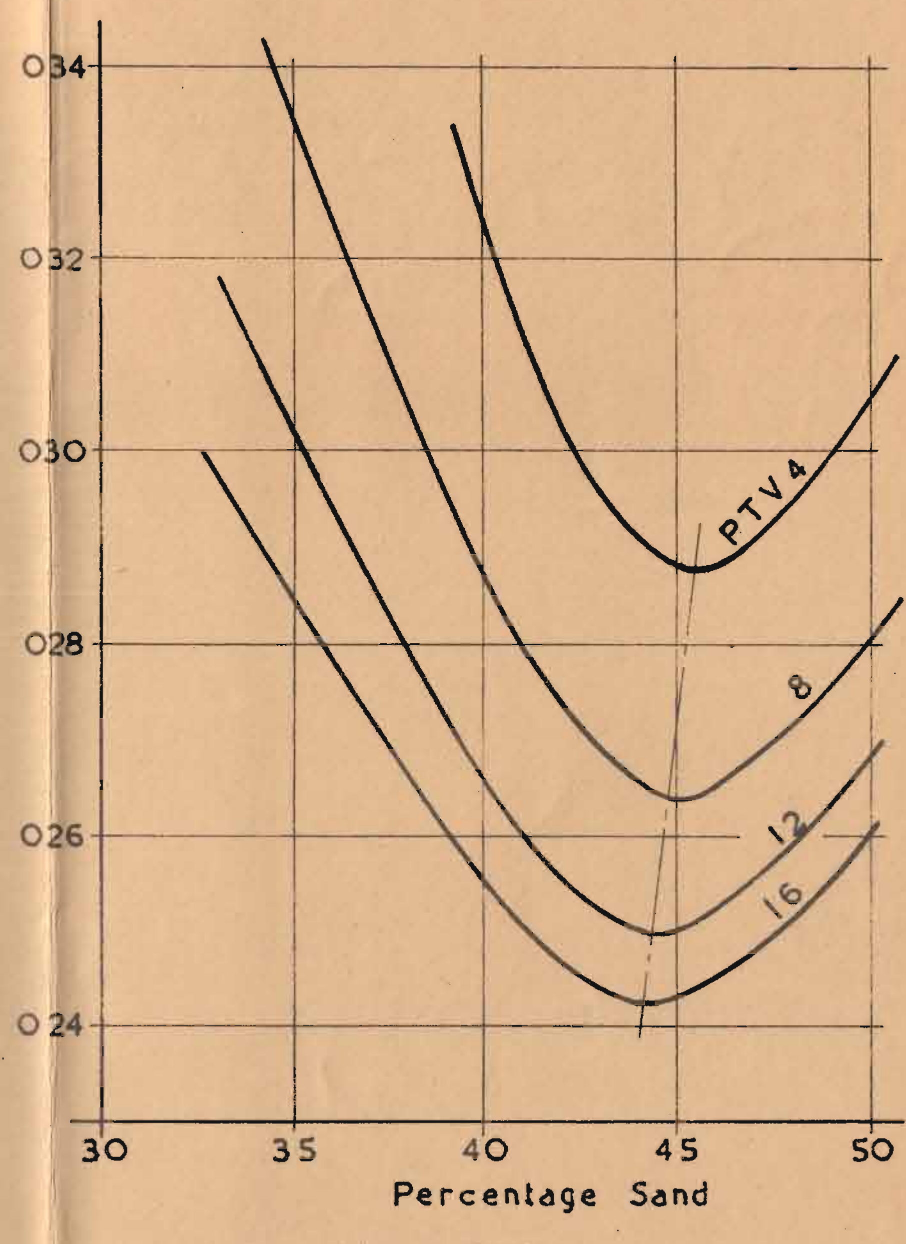


FIG. 80 B, W/C 0·575

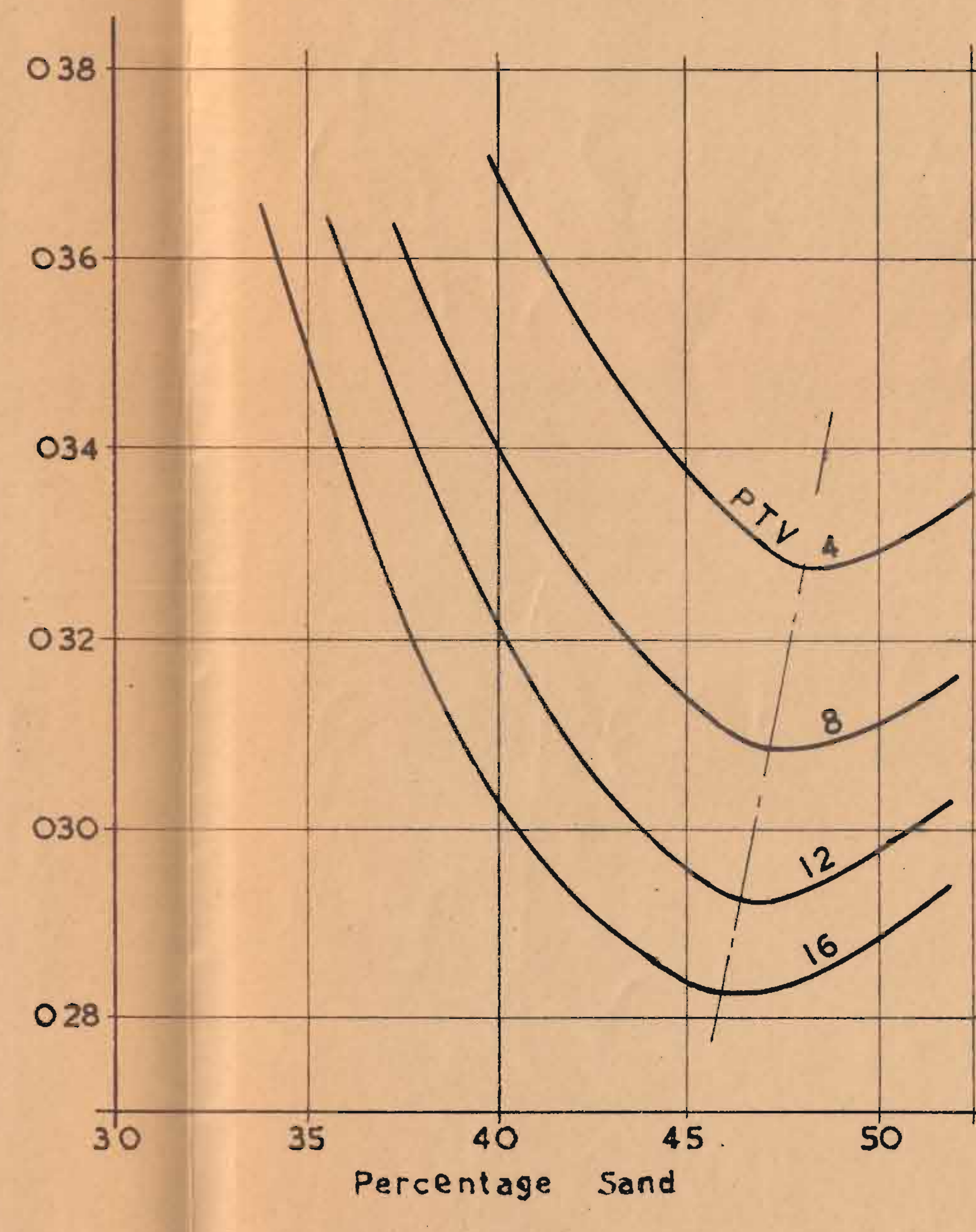


FIG. 81 B, W/C 0·70

RELATION OF PRESSURE TEST VALUES TO PASTE CONTENT AND PERCENTAGE SAND IN AGGREGATE

GROUP B GRADINGS

<u>NOTE</u>: Percentages on the curves indicate the amount of sand in each series of batches expressed as a percentage of the weight of the combined aggregate.

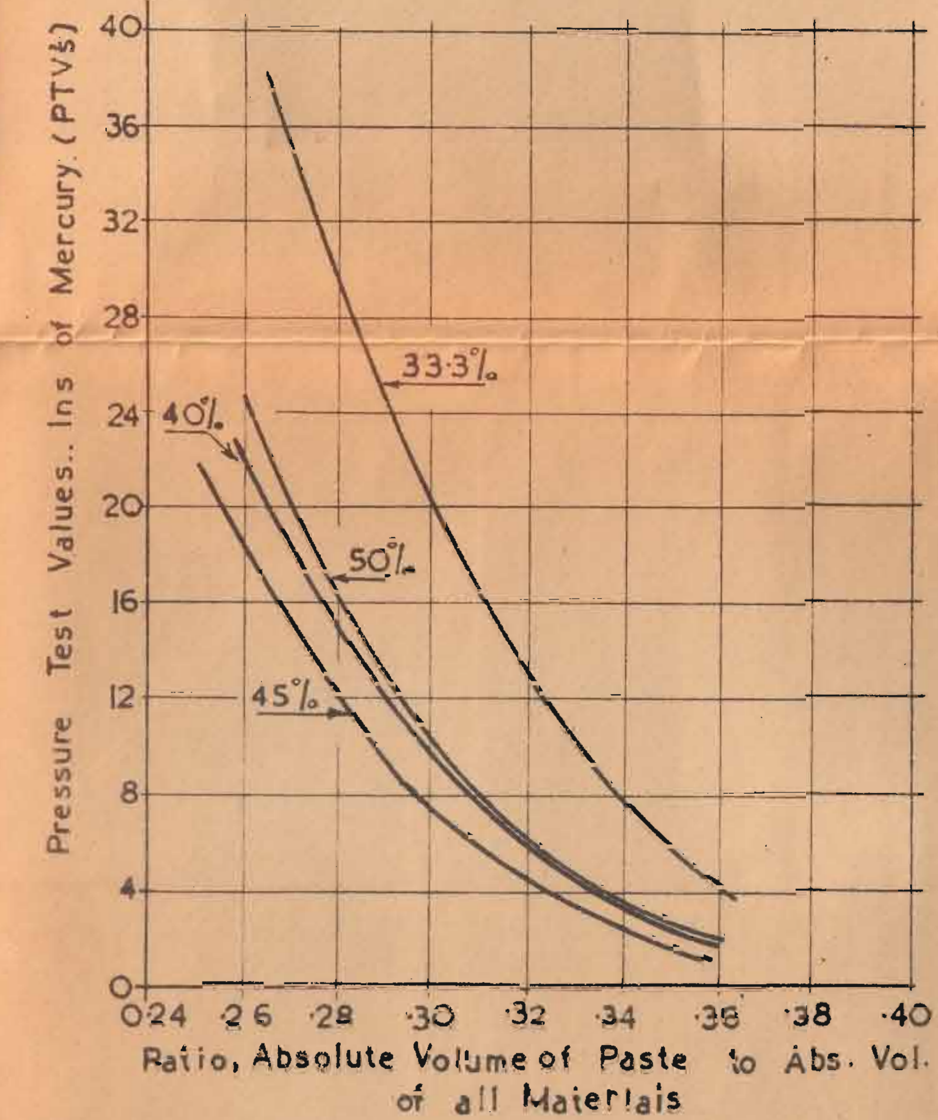


FIG. 82A WATER-CEMENT RATIO BY WT 0·45

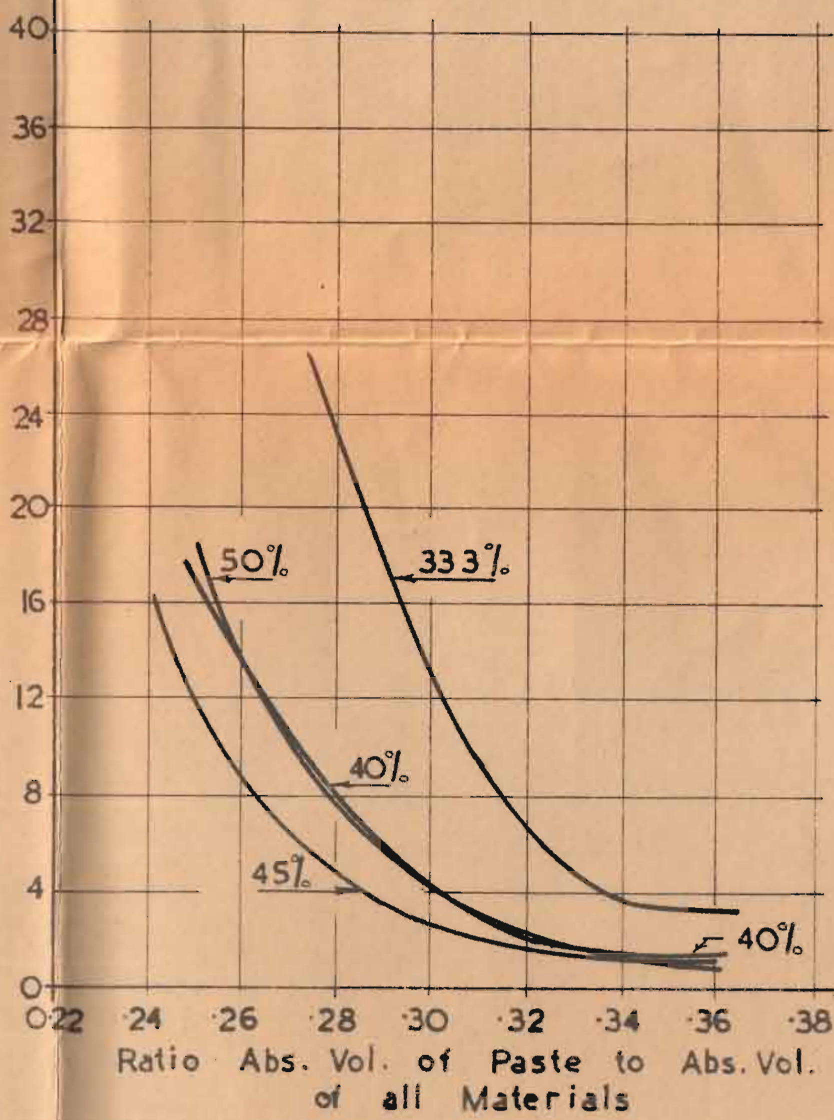


FIG 83A WATER-CEMENT RATIO BY WT 0·575

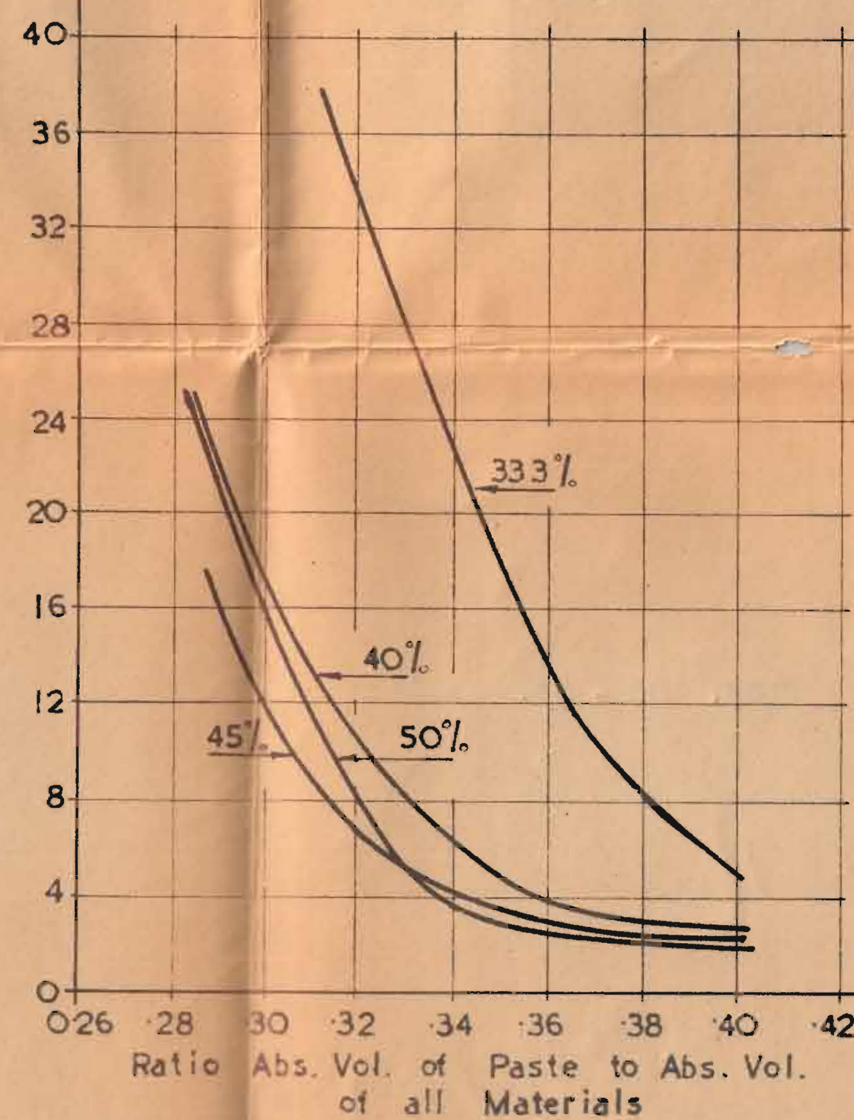


FIG 84A WATER-CEMENT RATIO BY WT 0·70

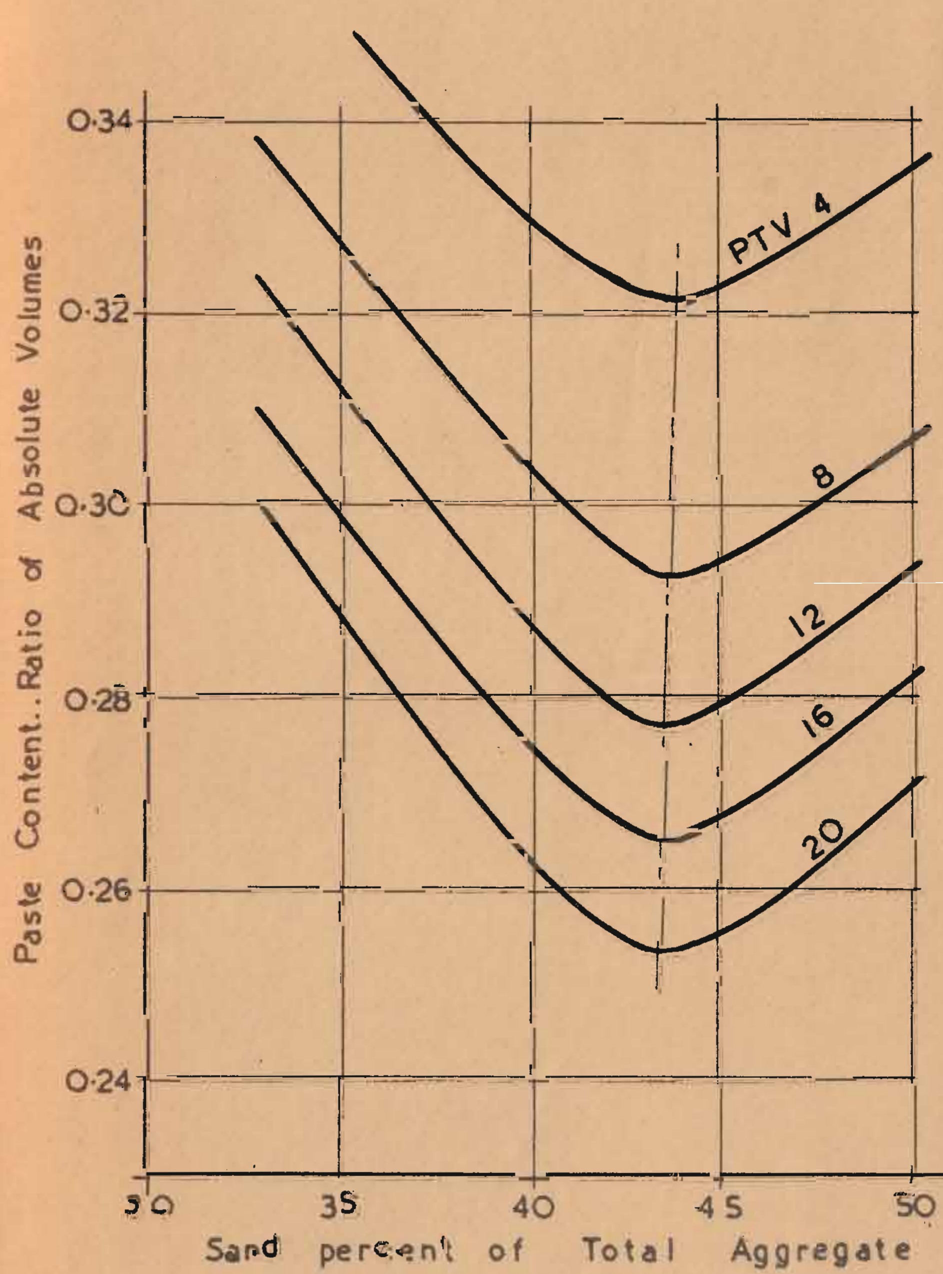


FIG. 82B. W/C 0·45

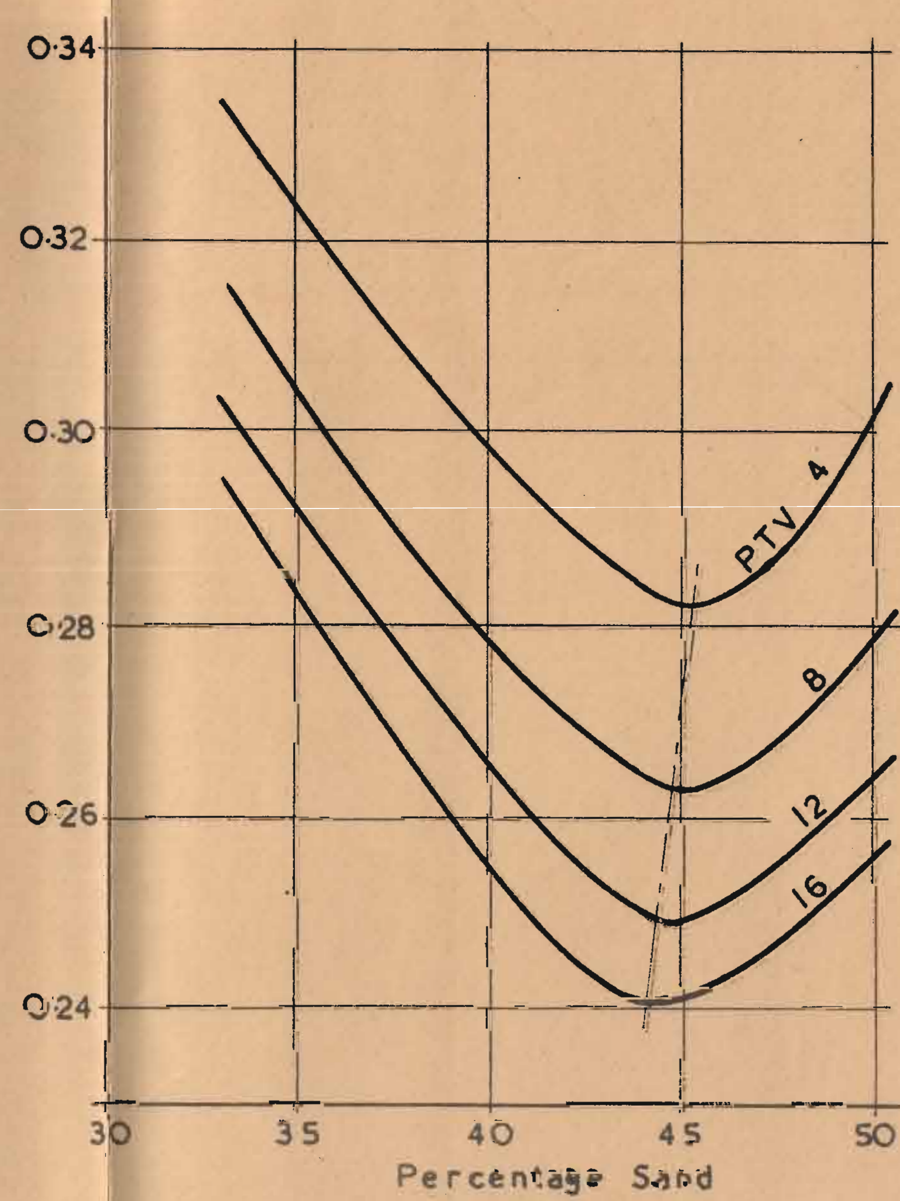


FIG. 83B. W/C 0·575

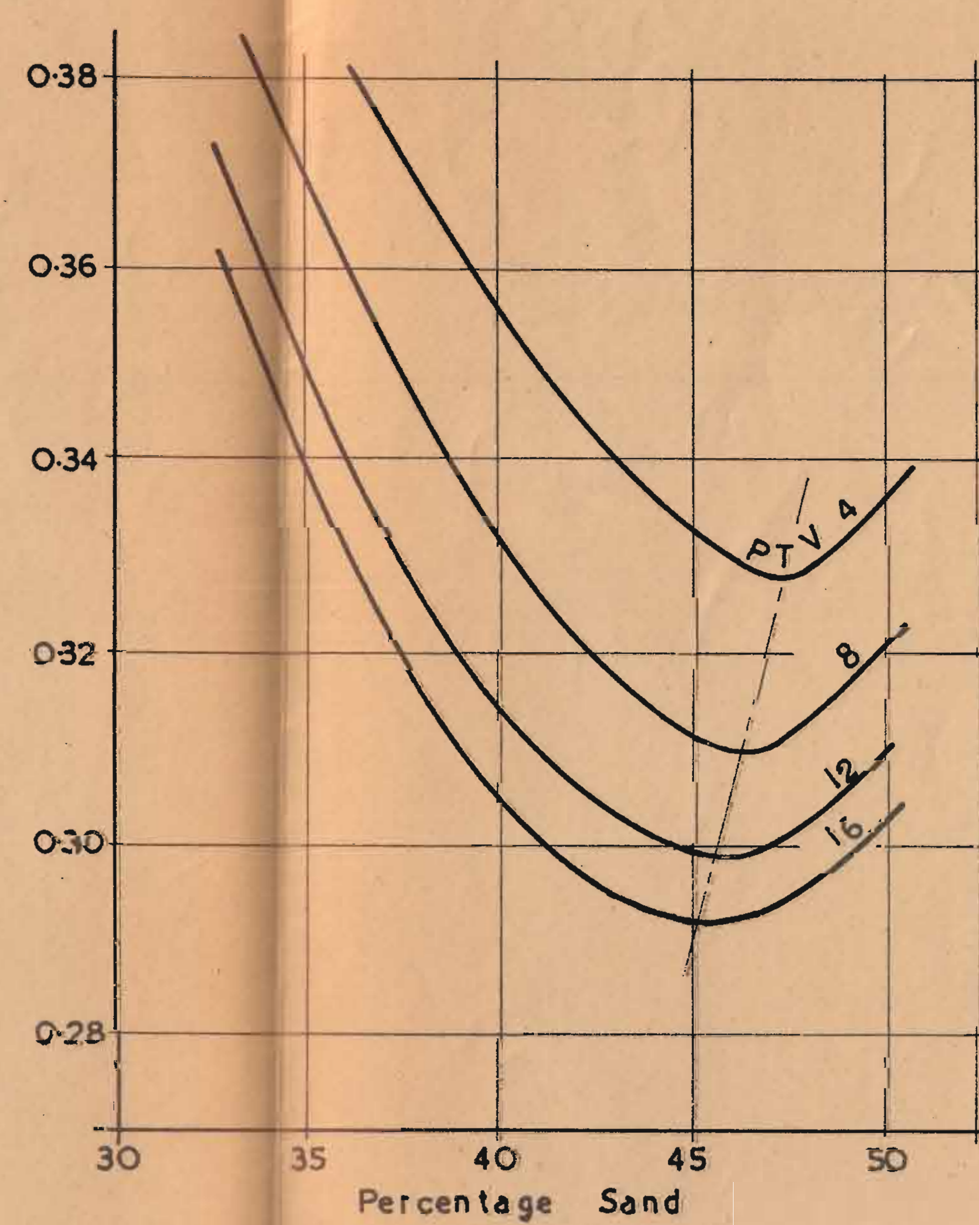


FIG. 84B. W/C 0·70

RELATION OF PRESSURE TEST VALUES TO PASTE CONTENT AND PERCENTAGE SAND IN AGGREGATE

GROUP C GRADINGS

NOTE : Percentages on the curves indicate the amount of sand in each series of batches expressed as a percentage of the weight of the combined aggregate

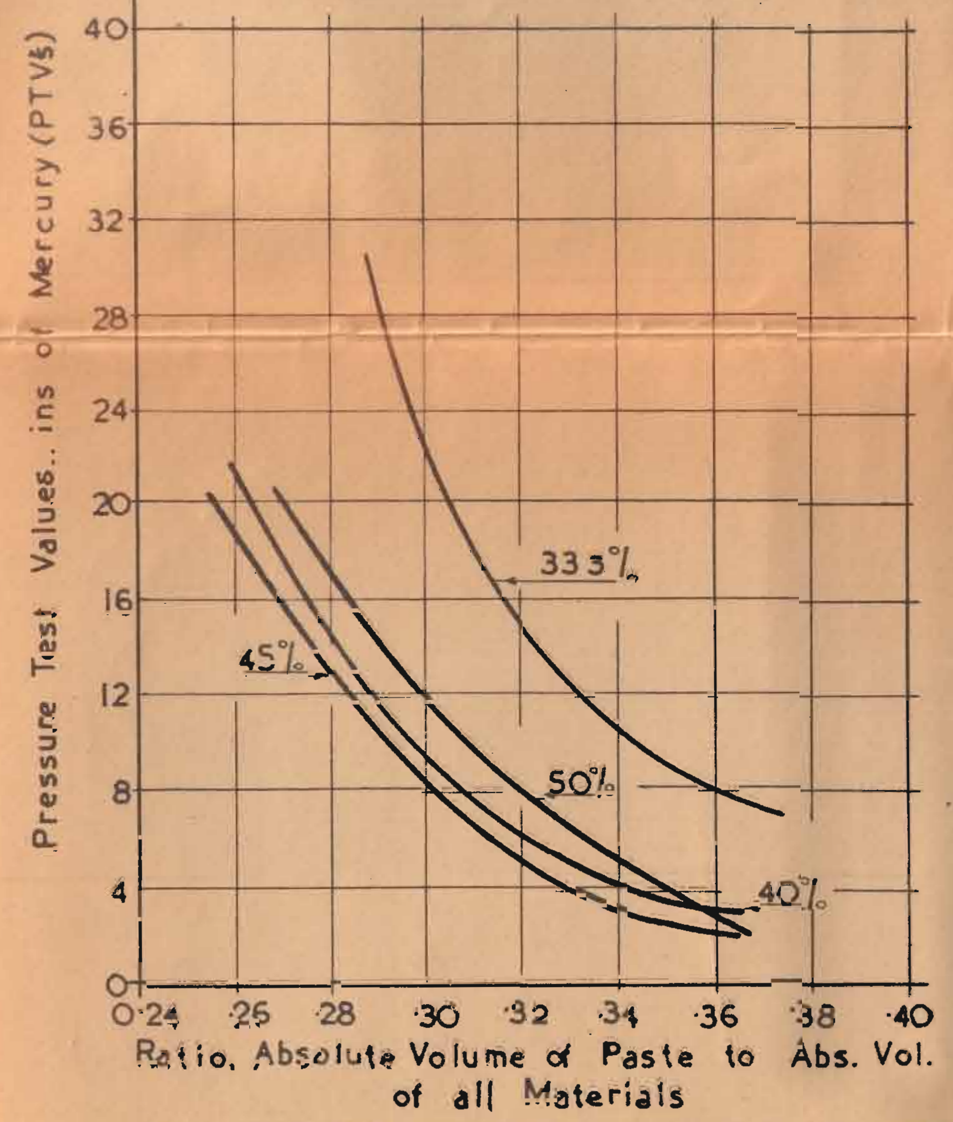


FIG. 85 A. WATER-CEMENT RATIO BY WT 0·45

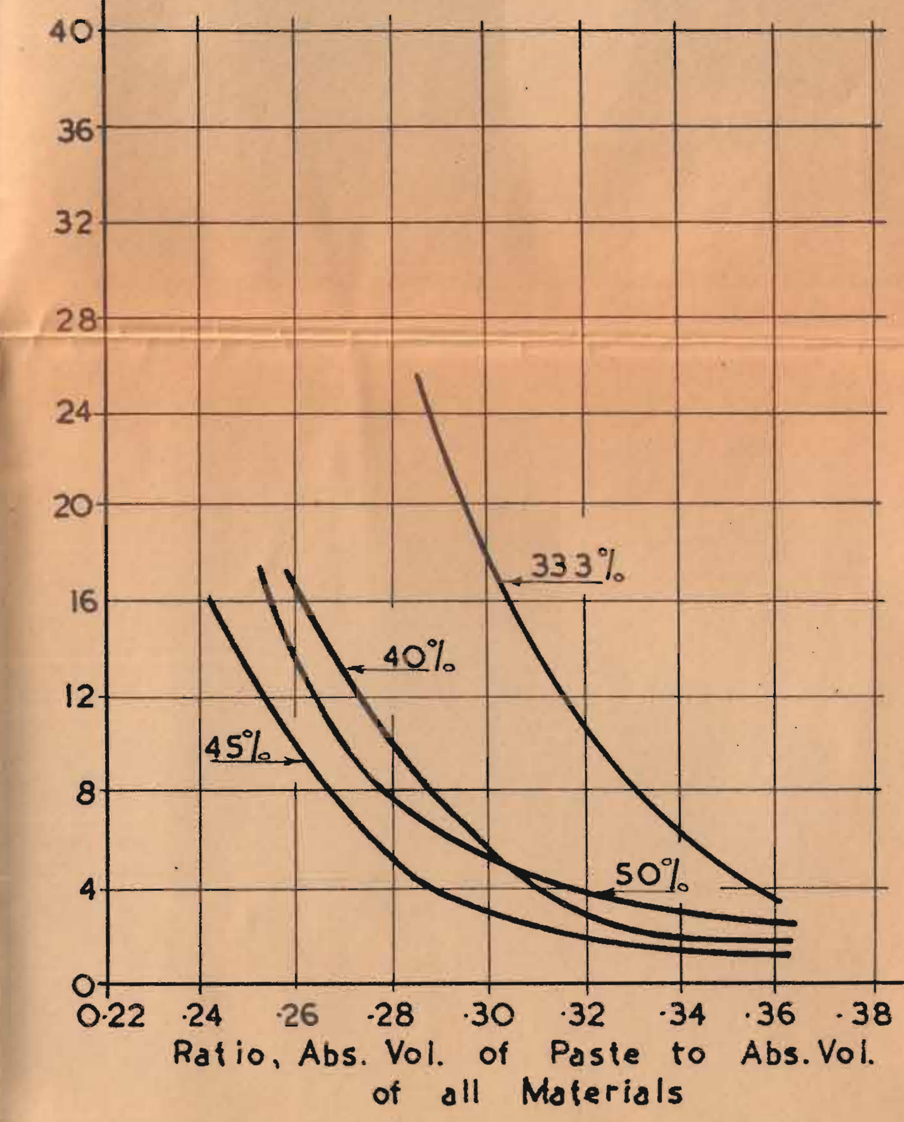


FIG. 86 A. WATER-CEMENT RATIO BY WT 0·575

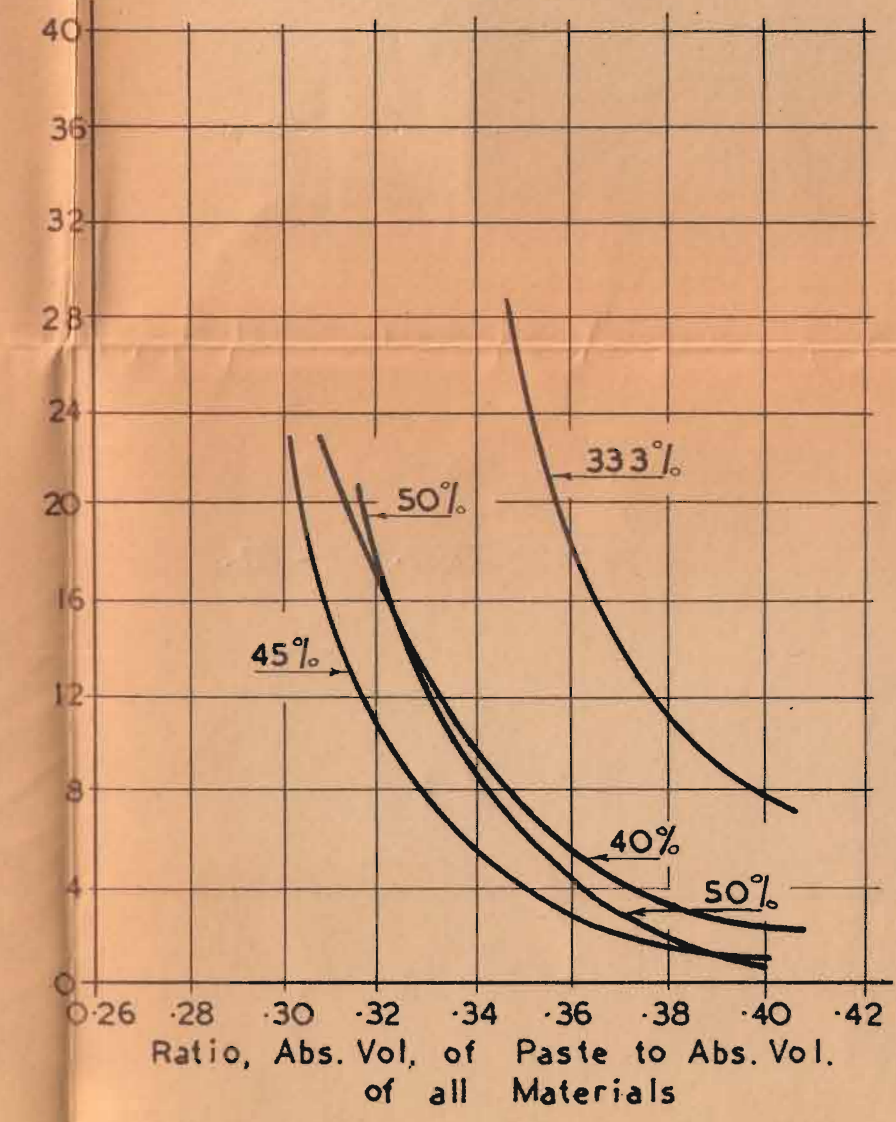


FIG. 87 A. WATER-CEMENT RATIO BY WT 0·70

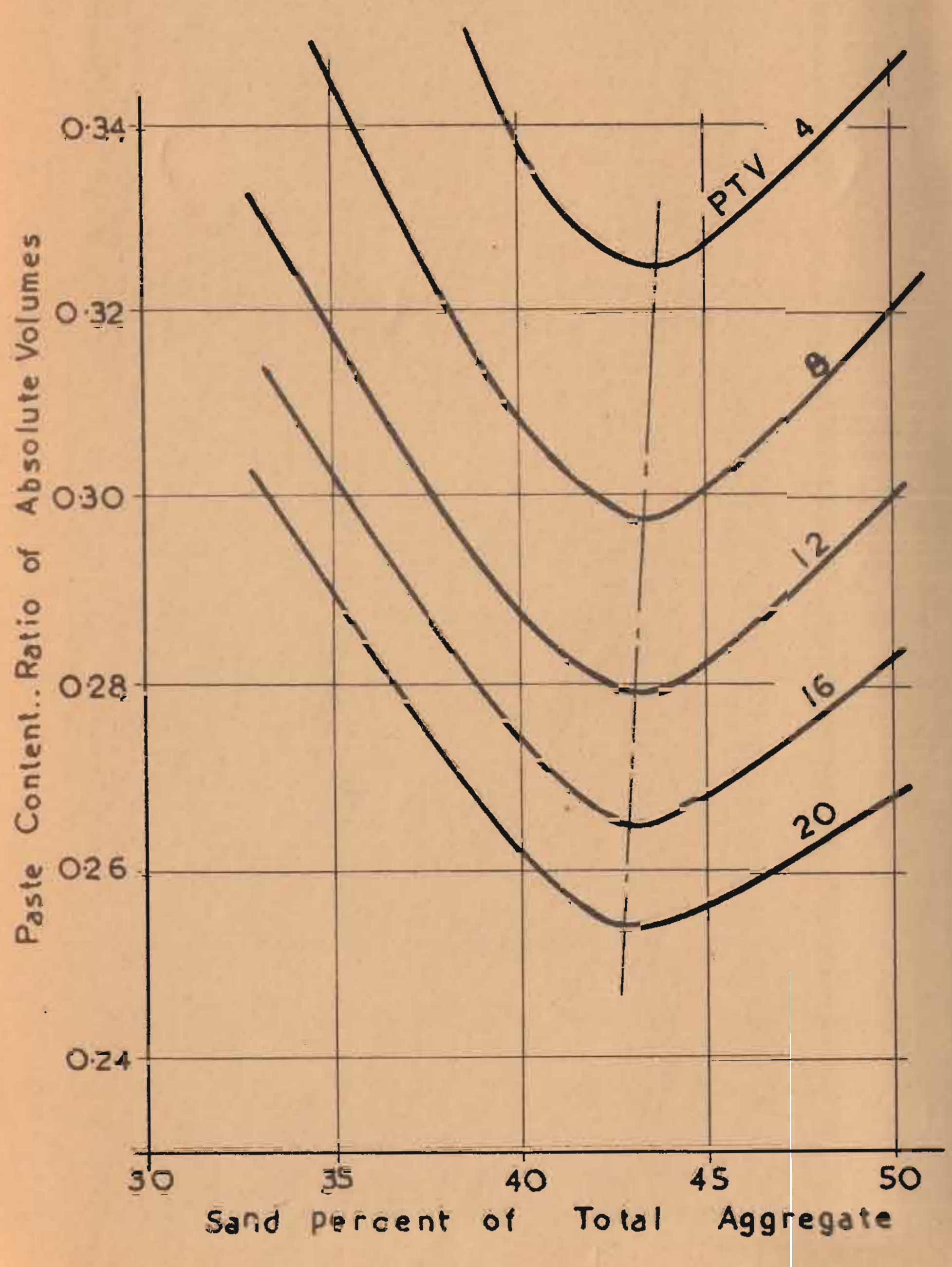


FIG. 85 B, W/C 0·45

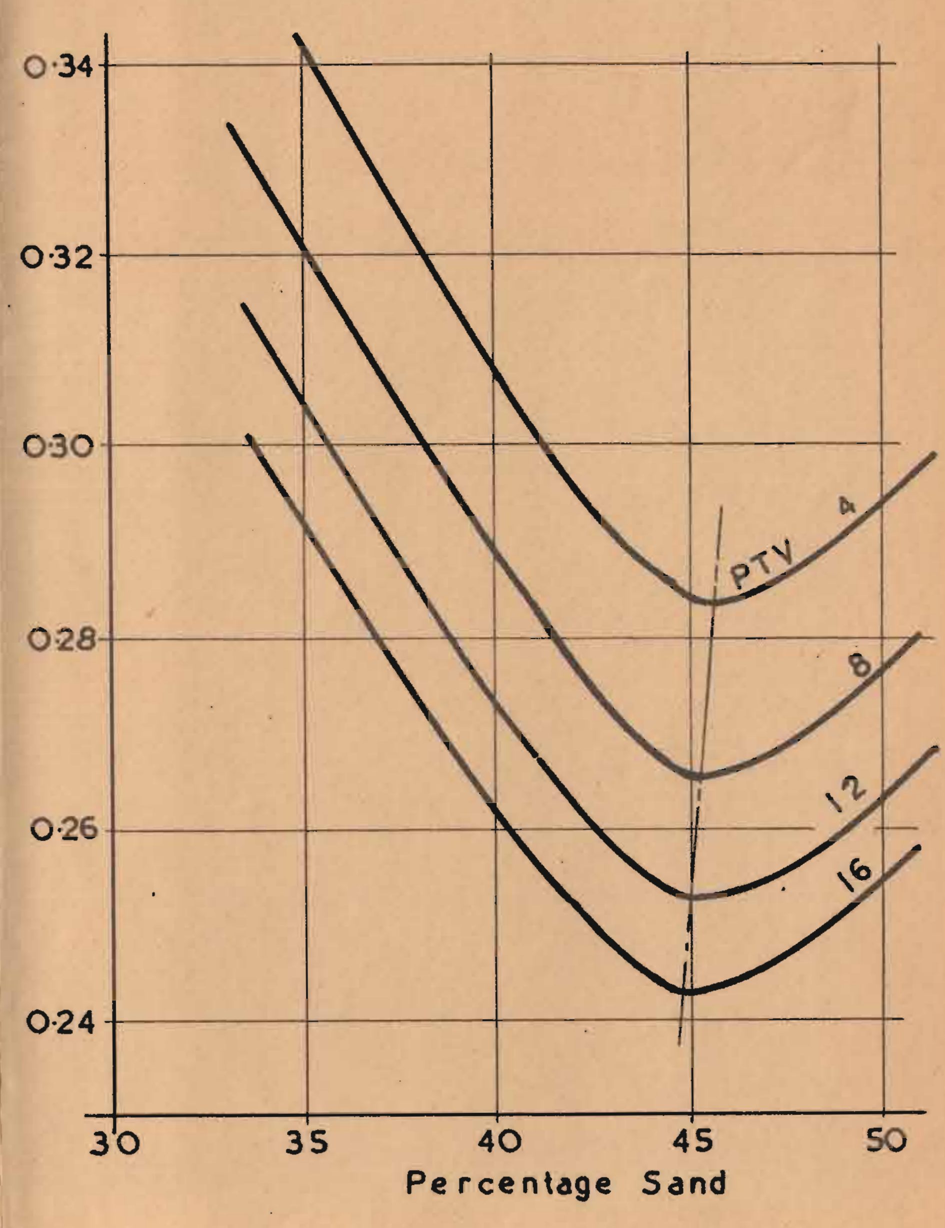


FIG. 86 B, W/C 0·575

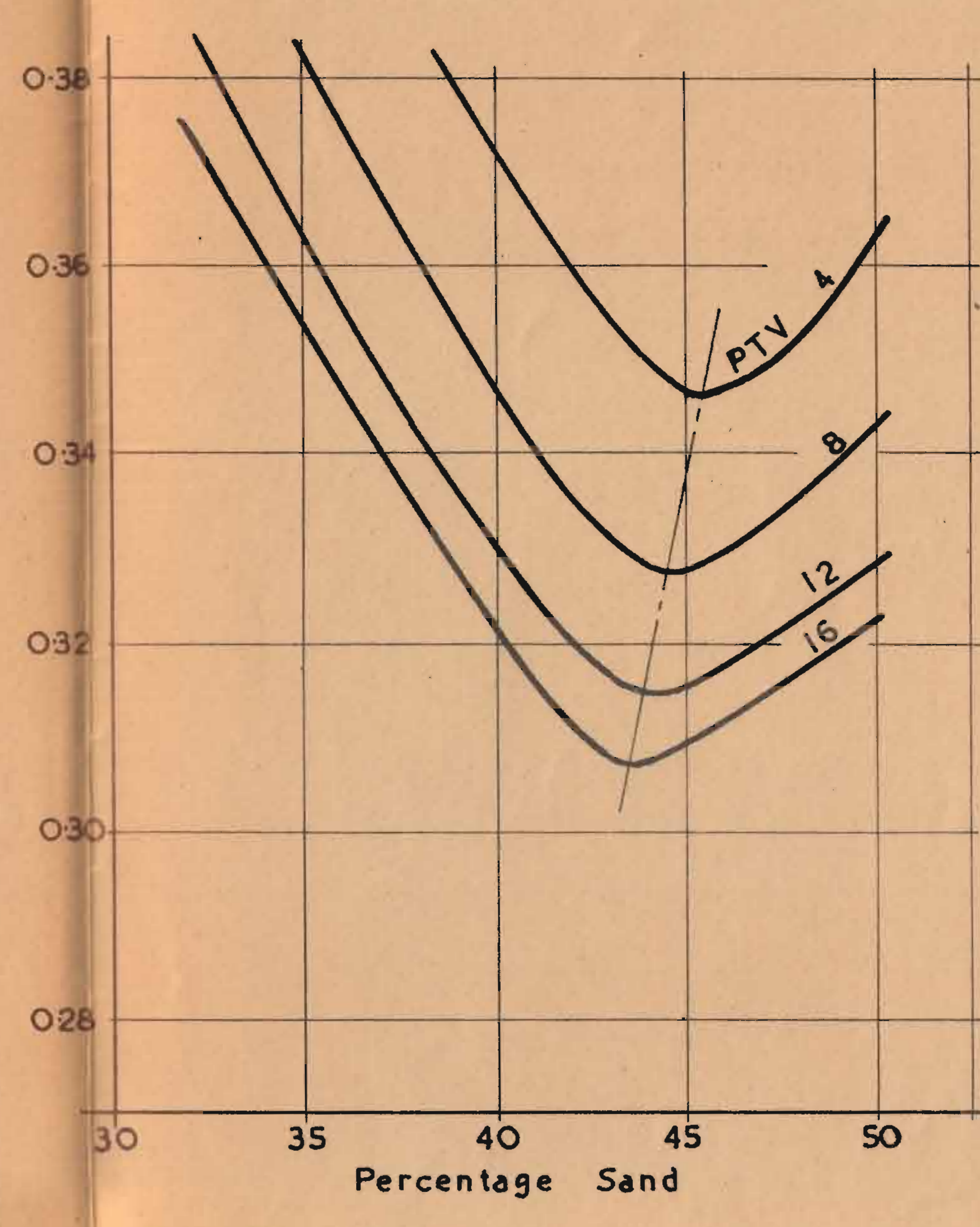


FIG. 87 B, W/C 0·70

RELATION OF PRESSURE TEST VALUES TO PASTE CONTENT AND PERCENTAGE SAND IN AGGREGATE

GROUP D GRADINGS

NOTE: Decimals on the individual curves indicate water-cement paste content expressed as the ratio of absolute volume of paste to sum of absolute volumes of all materials.

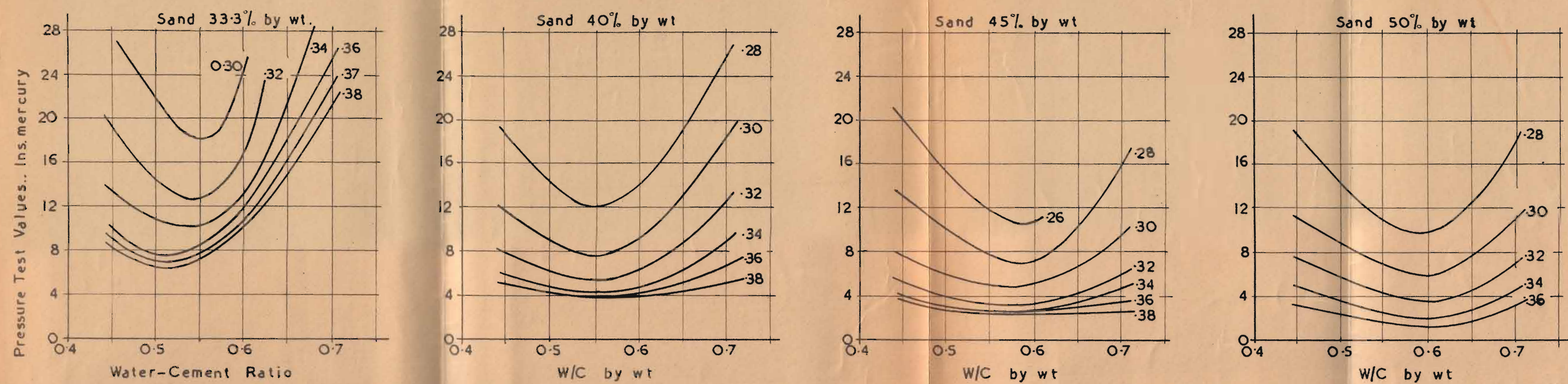


FIG. 88: GROUP A

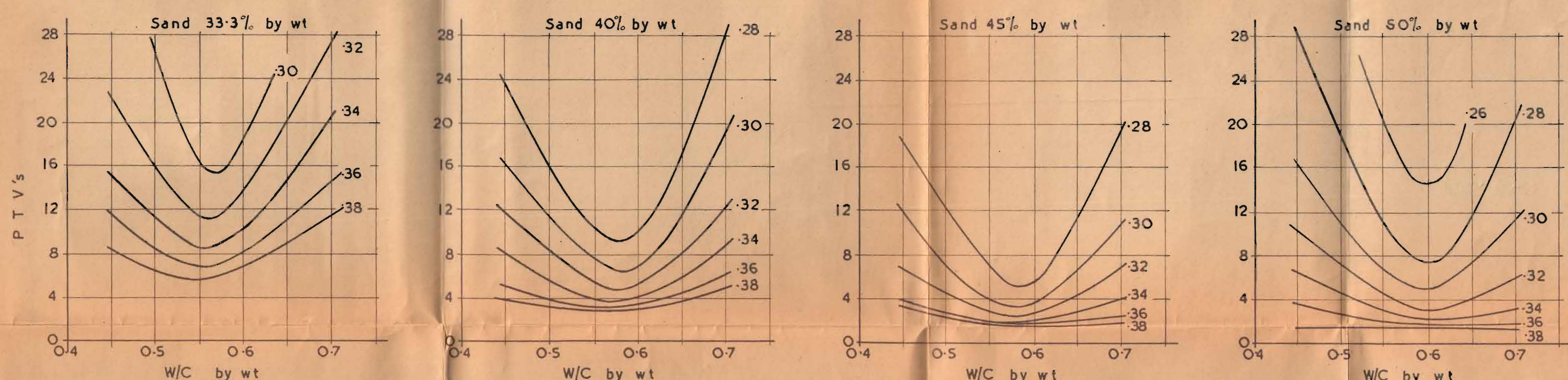


FIG. 89: GROUP B

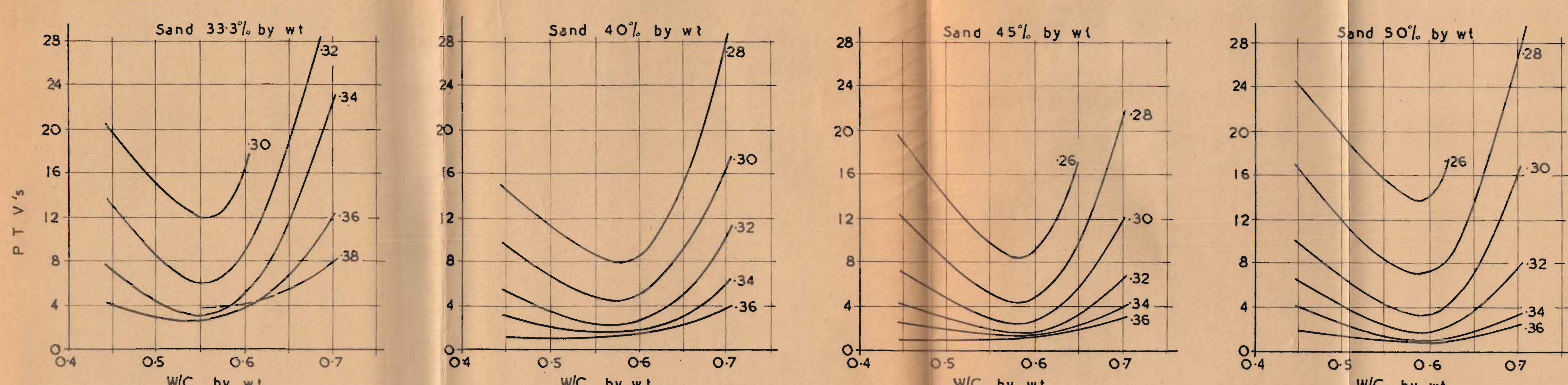


FIG. 90: GROUP C

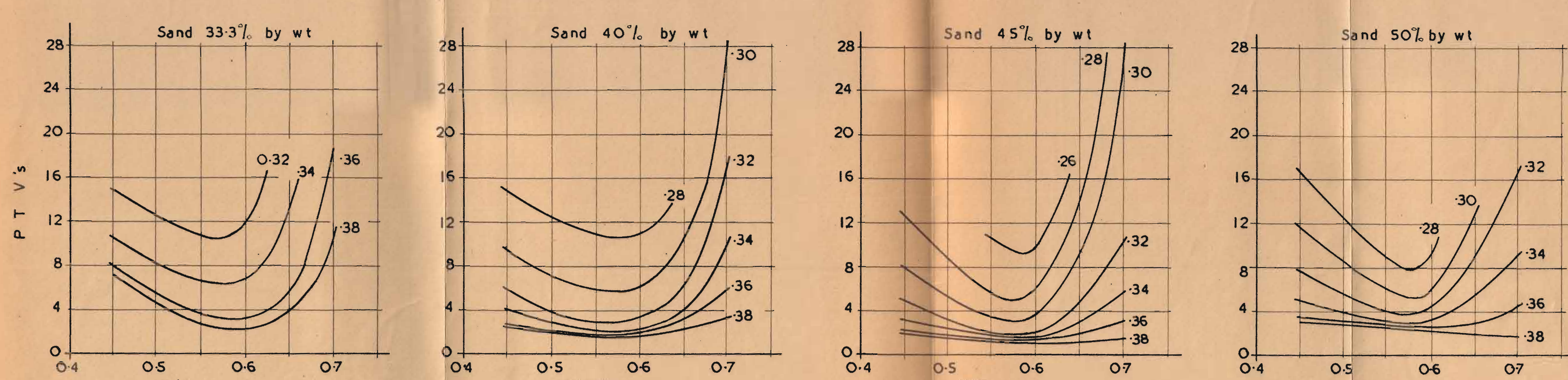


FIG. 91: GROUP D

RELATION OF PRESSURE TEST VALUES TO WATER-CEMENT RATIO AND PASTE CONTENT

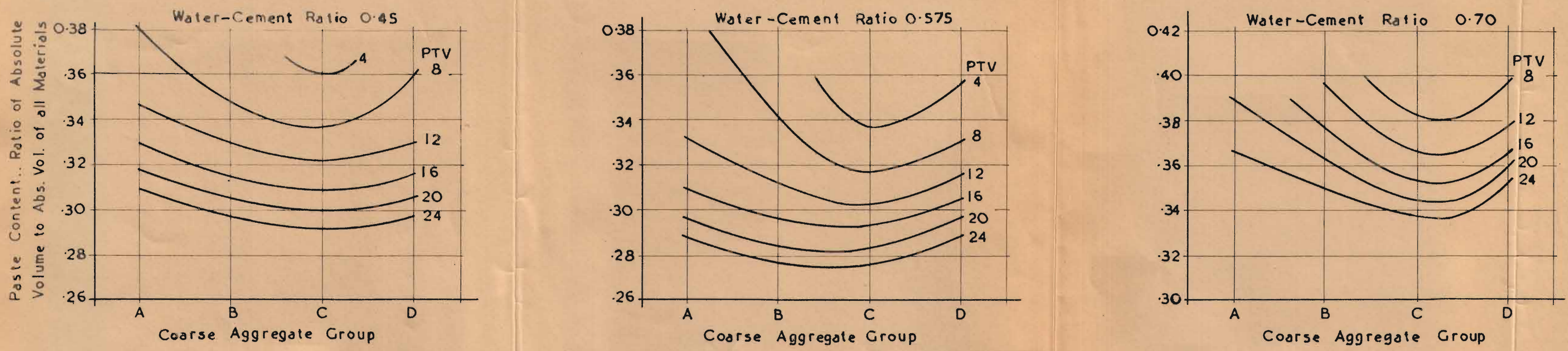


FIG. 92.. DATA FOR CONCRETES HAVING 33·3% SAND BY WT OF TOTAL AGGREGATE

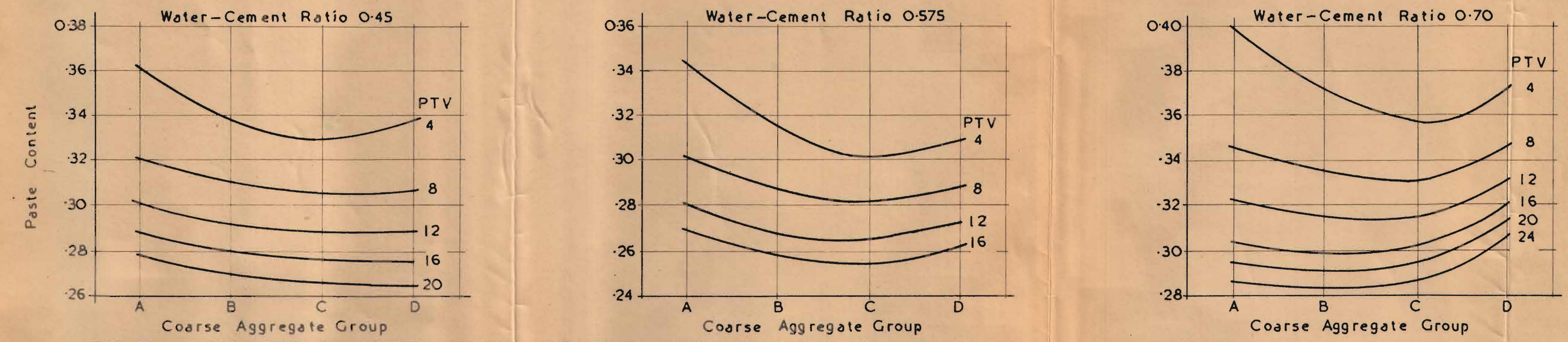


FIG. 93.. DATA FOR CONCRETES HAVING 40% SAND BY WT OF TOTAL AGGREGATE

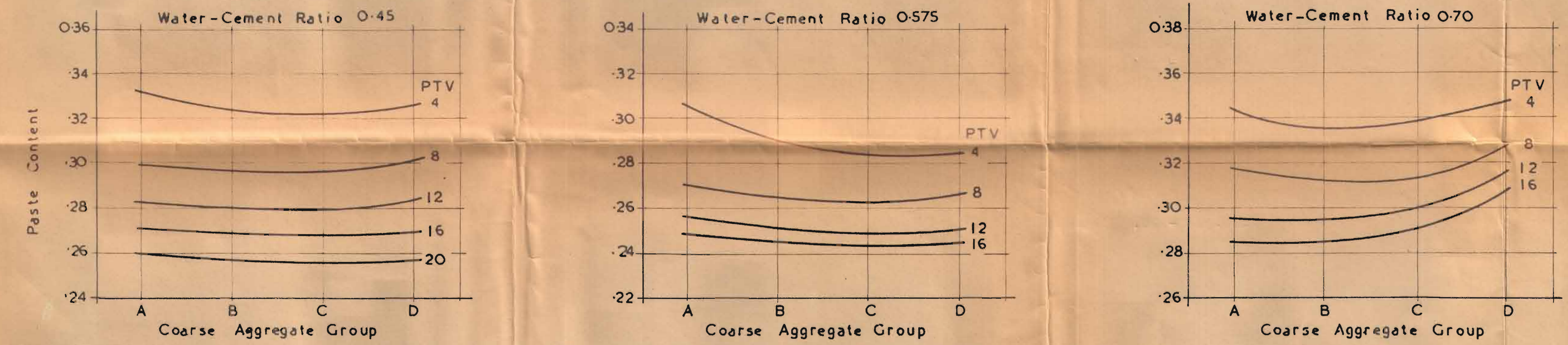


FIG. 94.. DATA FOR CONCRETES HAVING 45% SAND BY WT OF TOTAL AGGREGATE

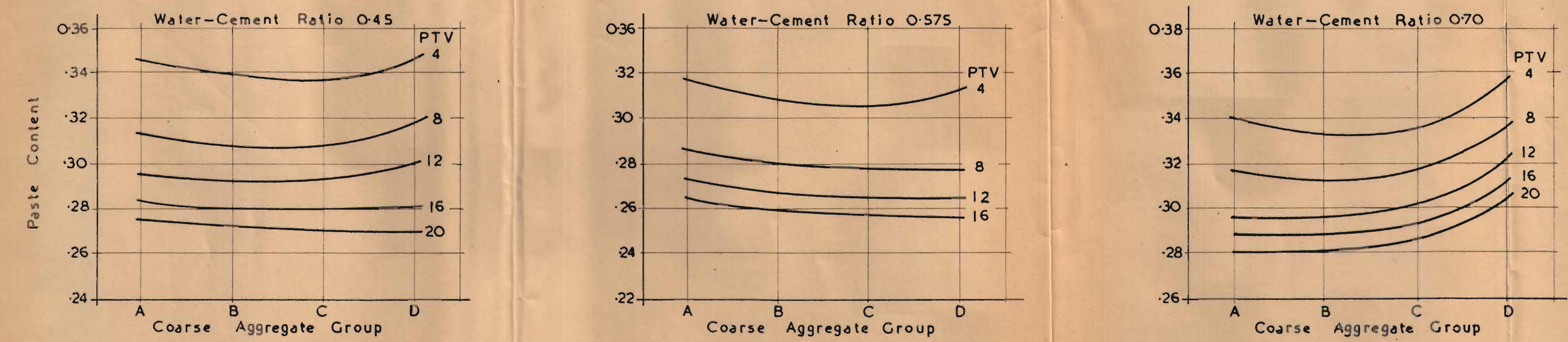


FIG. 95 DATA FOR CONCRETES HAVING 50% SAND BY WT OF TOTAL AGGREGATE

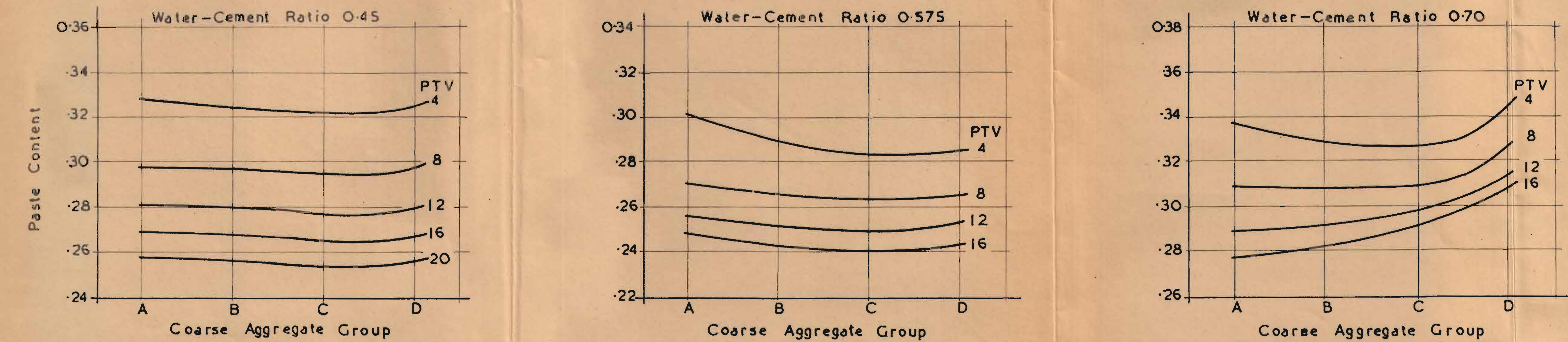


FIG. 96 DATA FOR CONCRETES HAVING THE OPTIMUM GRADING (% SAND) FOR EACH COARSE AGGREGATE GRADING AND W/C.

RELATION BETWEEN WATER-CEMENT PASTE CONTENT AND GRADATION OF COARSE AGGREGATE FOR FIXED WATER-CEMENT RATIO'S AND PROPORTIONS OF FINE AGGREGATE

NOTE: Percentages on the curves indicate the amount of sand in each series of batches expressed as a percentage of the weight of the combined aggregate

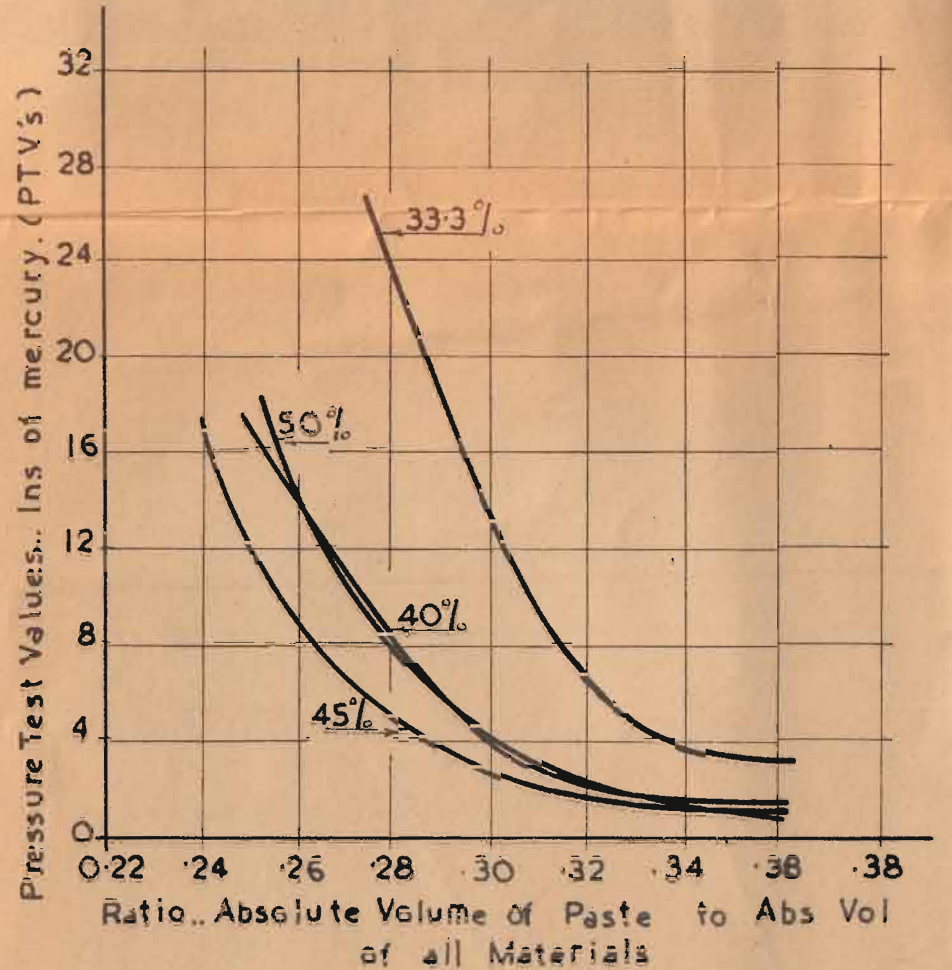


FIG. 97A CRUSHED BRACKENFEL GRANITE and Malmsbury River Sand. Water-Cement Ratio 0·575.

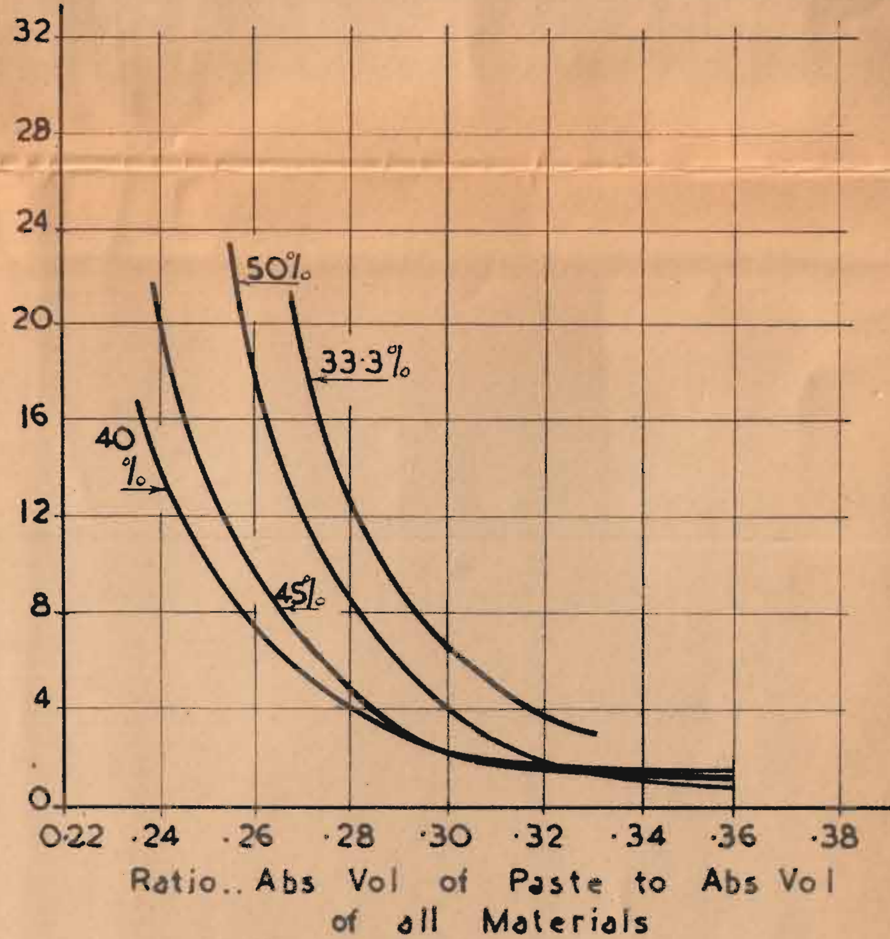


FIG 98A..IRREGULAR DURBANVILLE LATERITE GRAVEL and Malmsbury River Sand. Water-Cement Ratio 0·575

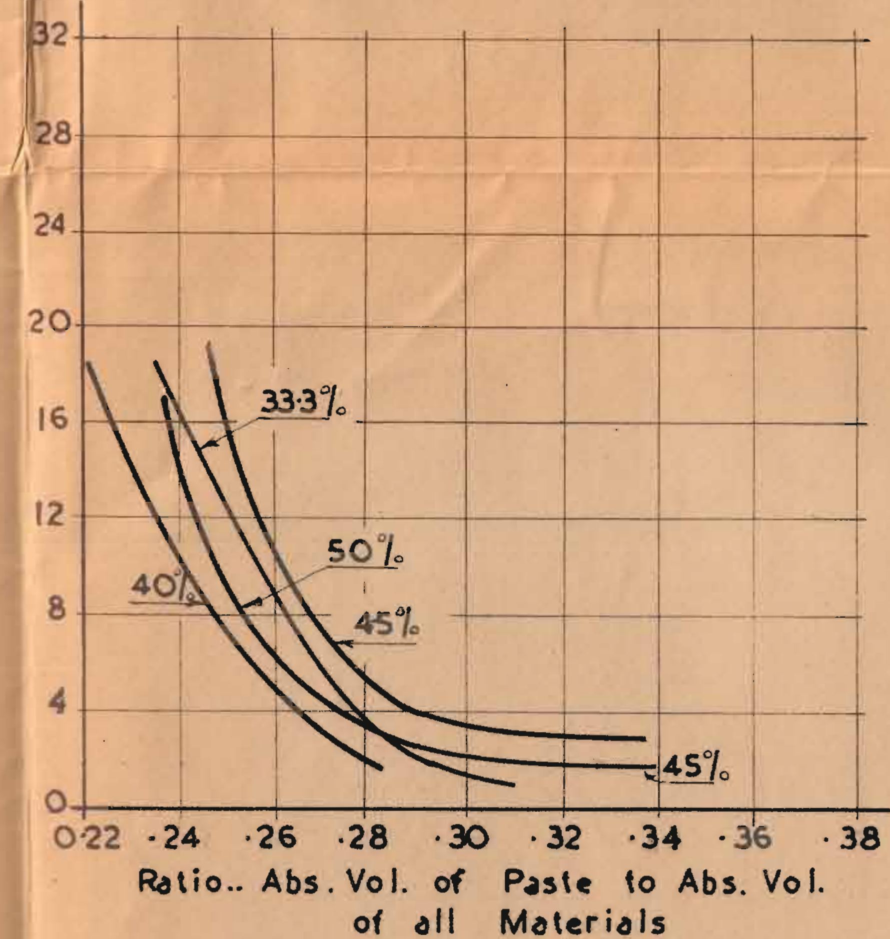


FIG 99A..ROUNDED LIESBEEK RIVER GRAVEL and Malmsbury River Sand. Water-Cement Ratio 0·575

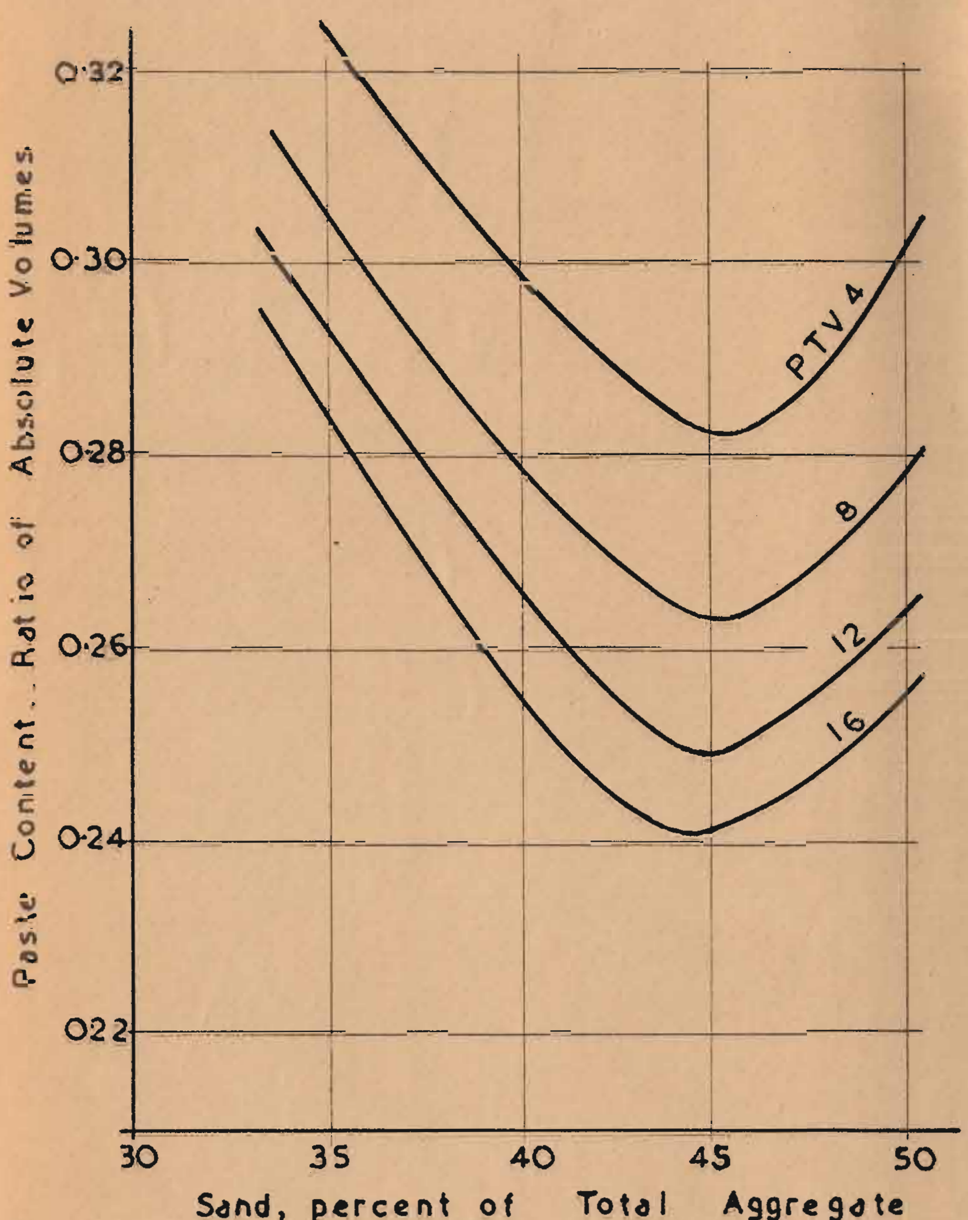


FIG. 97 B.. DERIVED FROM FIG. 97A

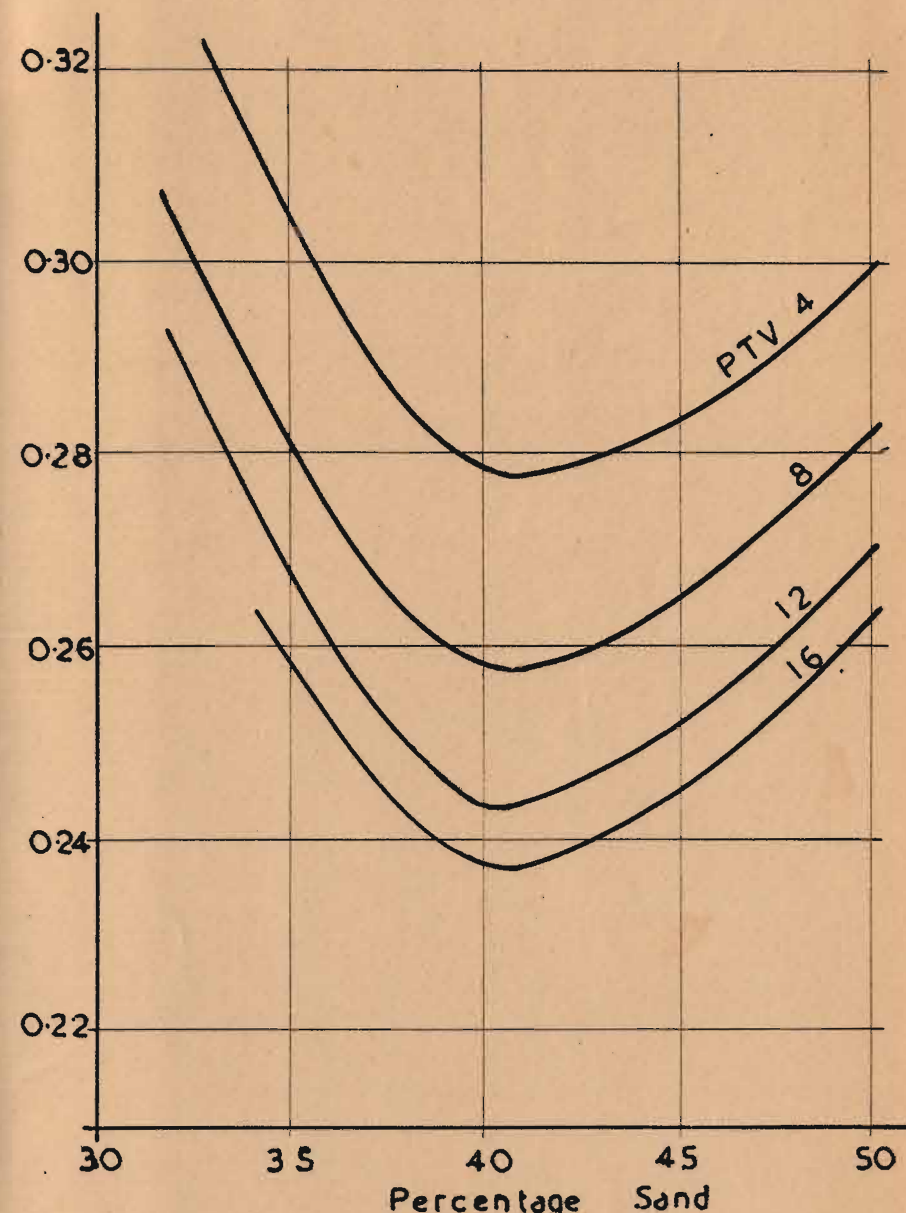


FIG. 98B.. DERIVED FROM FIG. 98A.

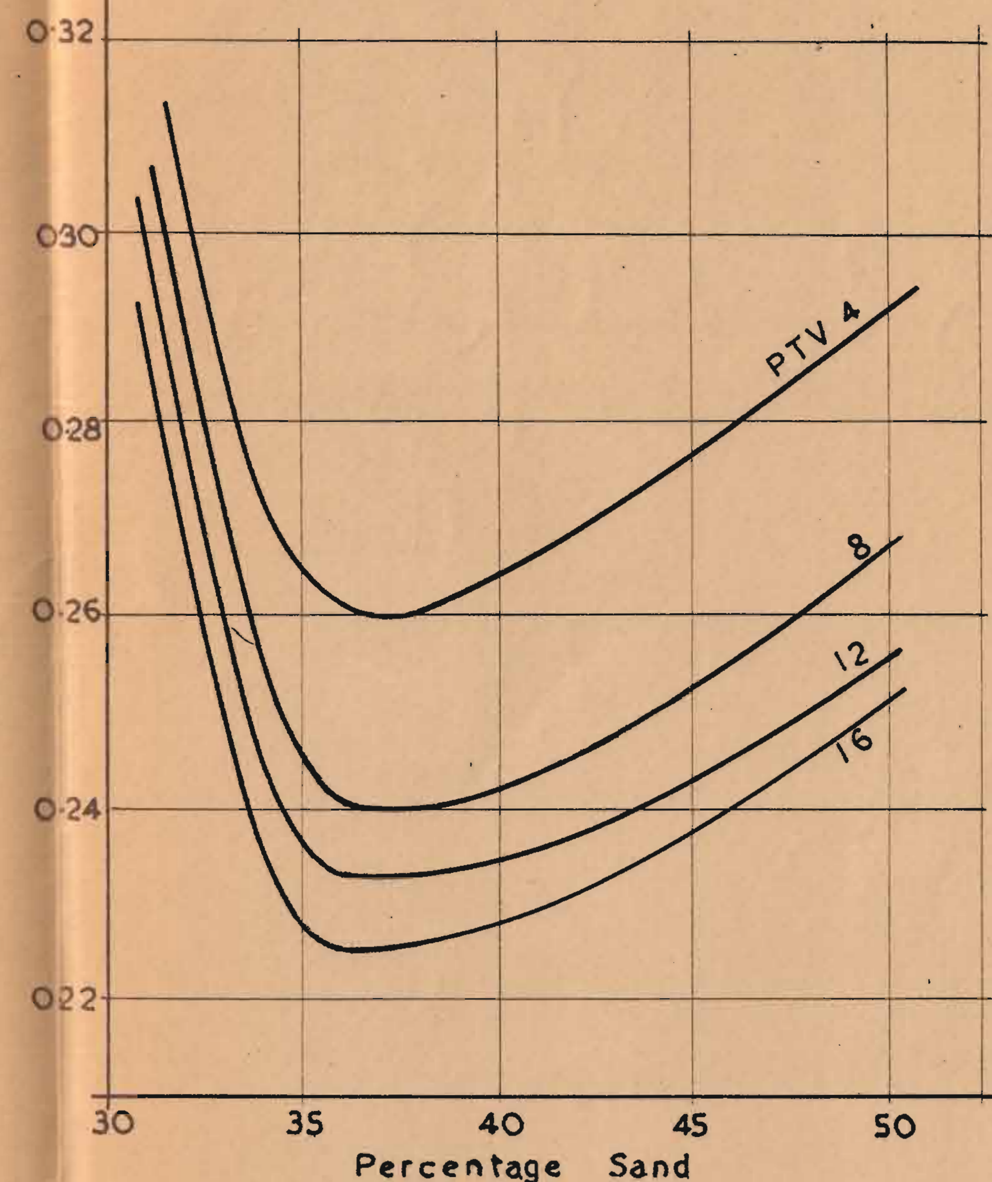


FIG. 99B.. DERIVED FROM FIG. 99A

RELATION OF PRESSURE TEST VALUES TO PASTE CONTENT AND PERCENTAGE SAND IN AGGREGATE

COMPARISON OF MIXTURES SIMILAR IN ALL RESPECTS EXCEPT SHAPE AND TEXTURE OF COARSE AGGREGATE

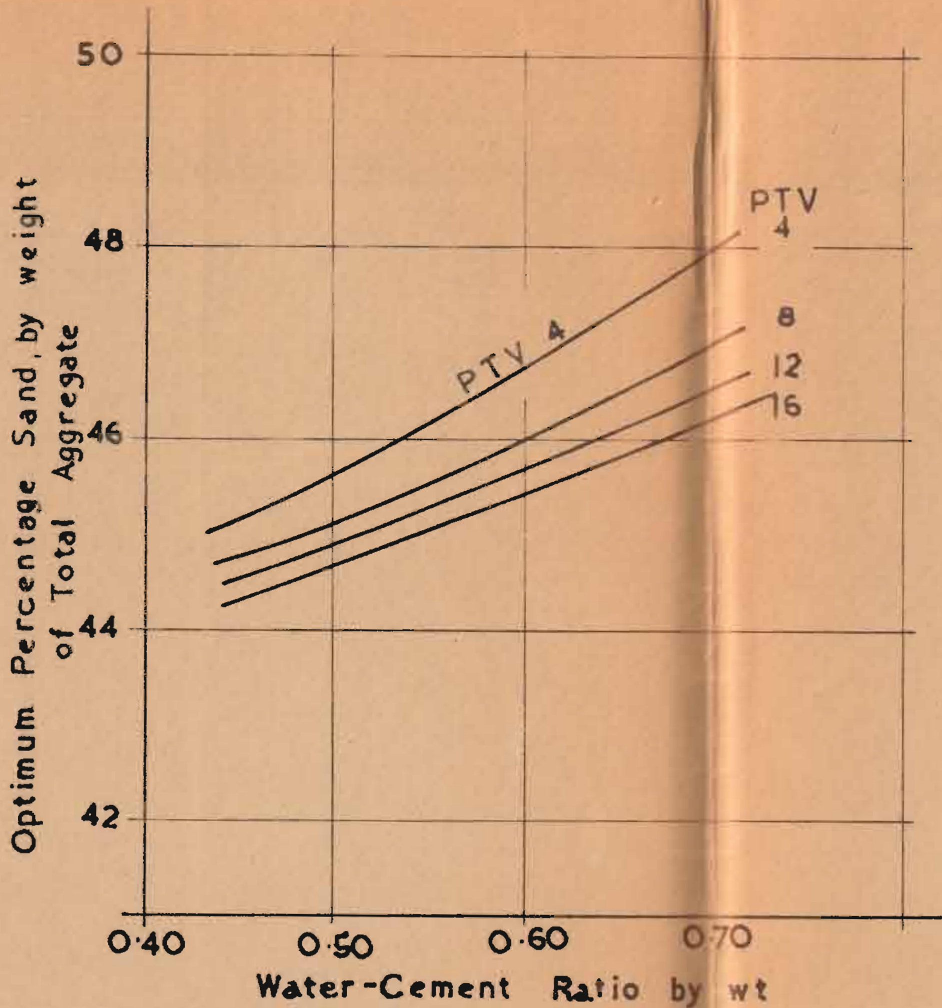


FIG. 100.. GROUP A

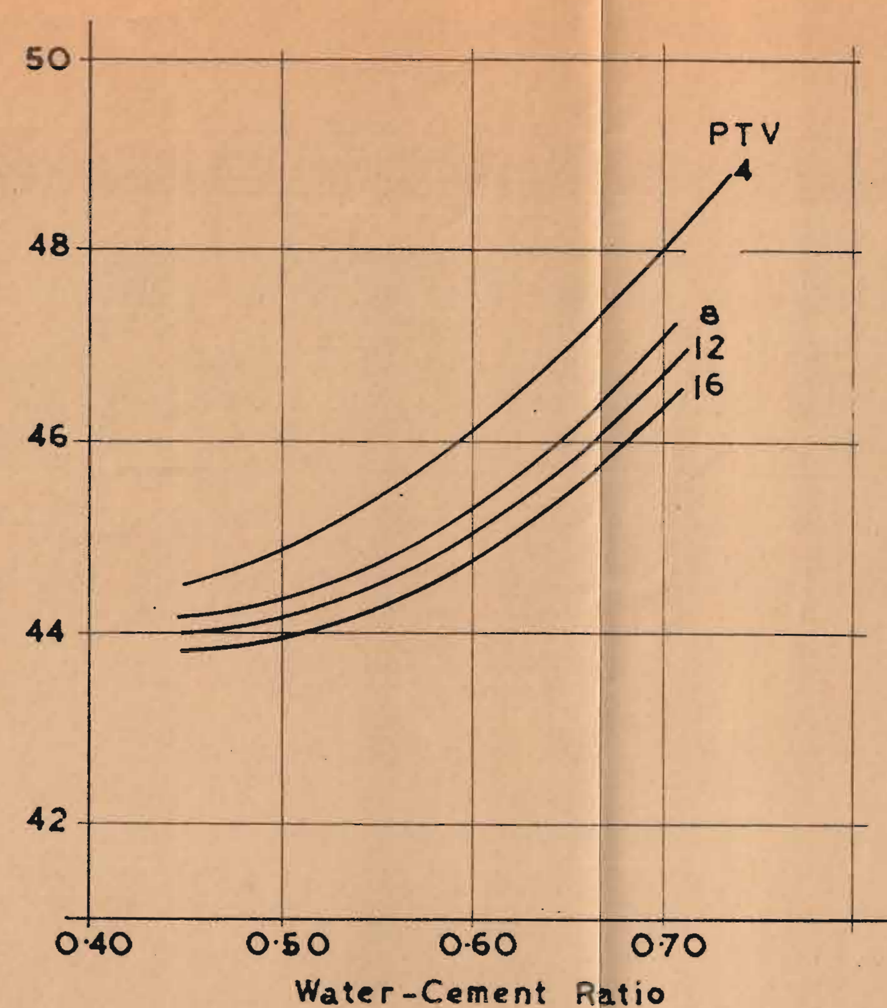


FIG. 101.. GROUP B

Appendix C gives gradings, mixtures, test results, etc.

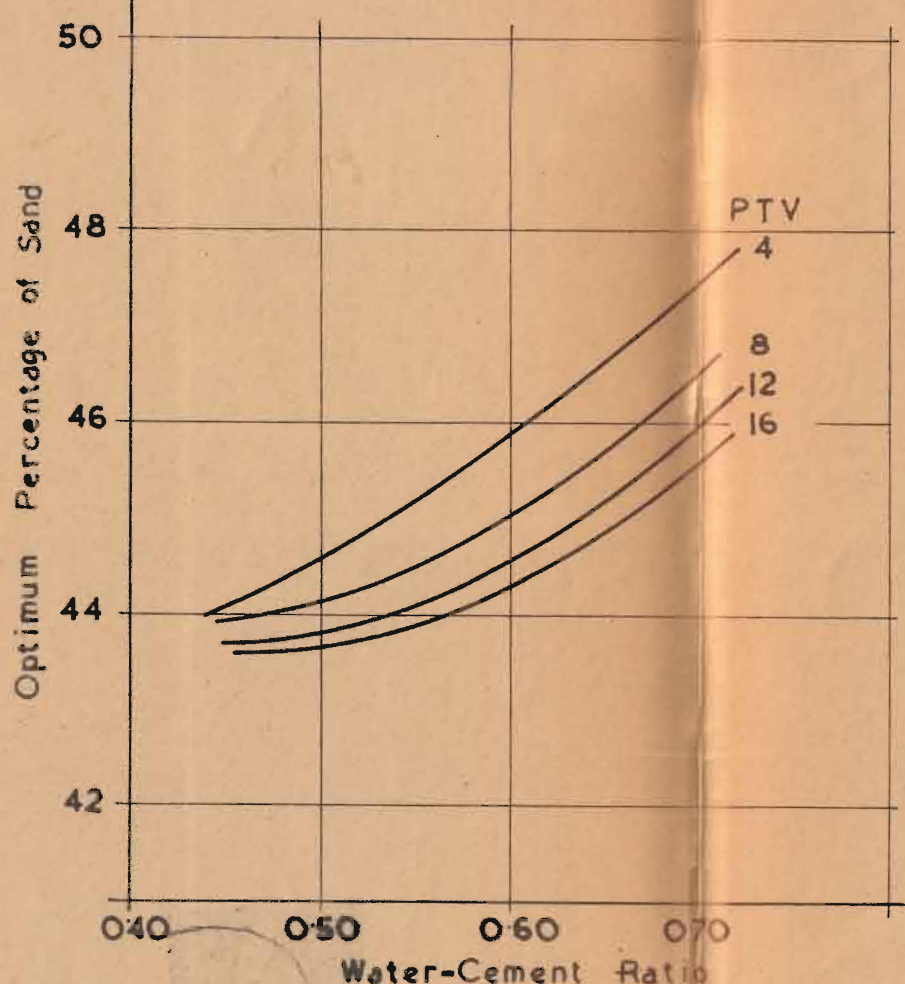


FIG. 102.. GROUP C

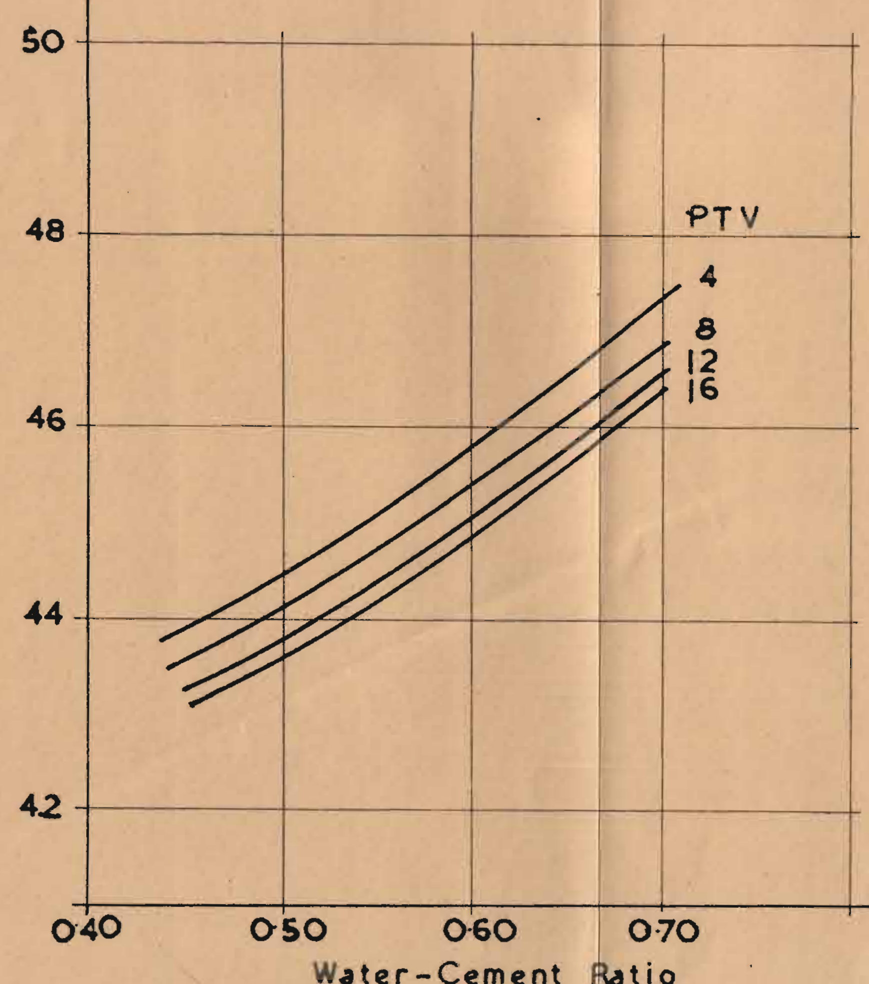


FIG. 103.. GROUP D

RELATION OF WATER CONTENT OF CEMENT PASTE TO OPTIMUM PERCENTAGE OF SAND

NOTE: All these results represent GROUP B series (Ref. Appendix C)

+ W/C .. 0.45
o W/C .. 0.575
△ W/C .. 0.70

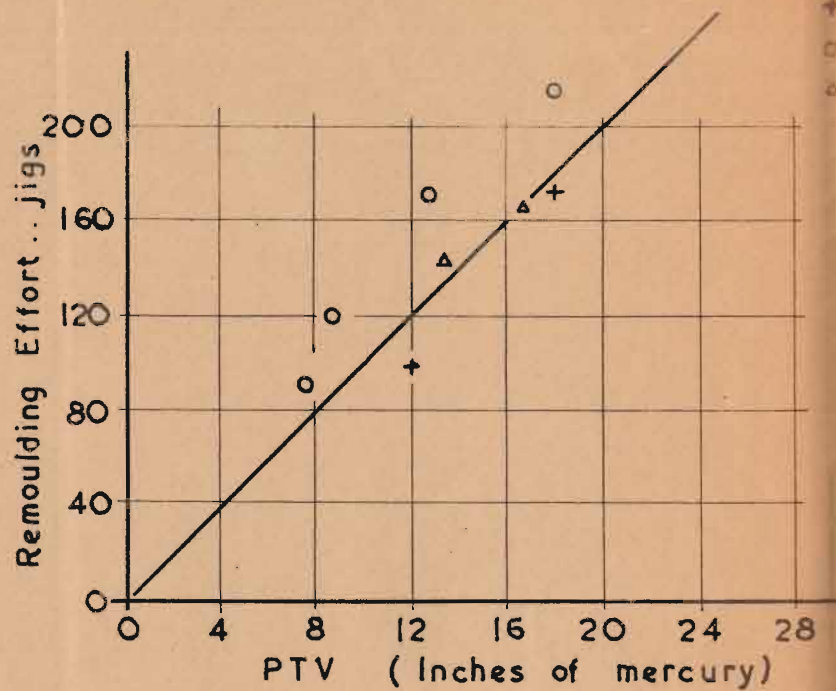


FIG. 104 .. SAND 33·3% (of total aggregate)

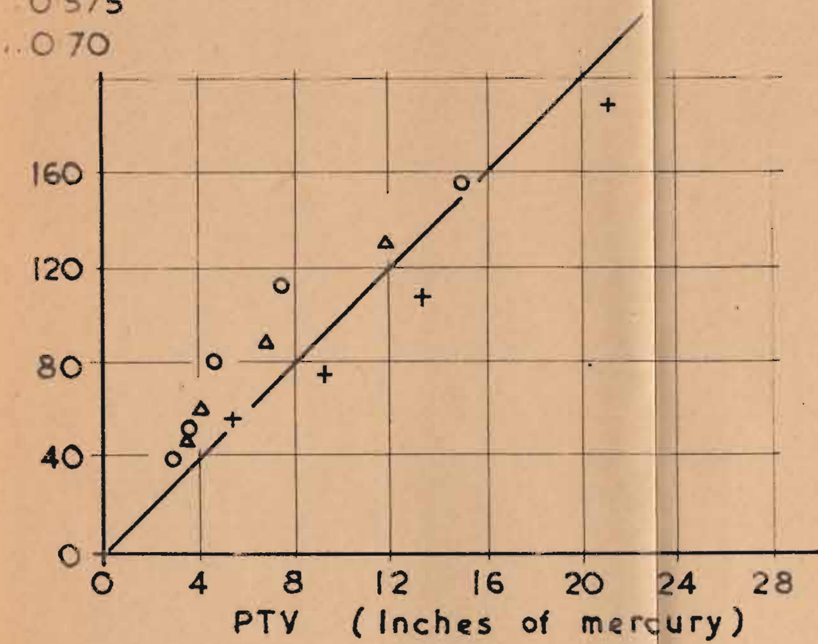


FIG. 105 .. SAND 40%

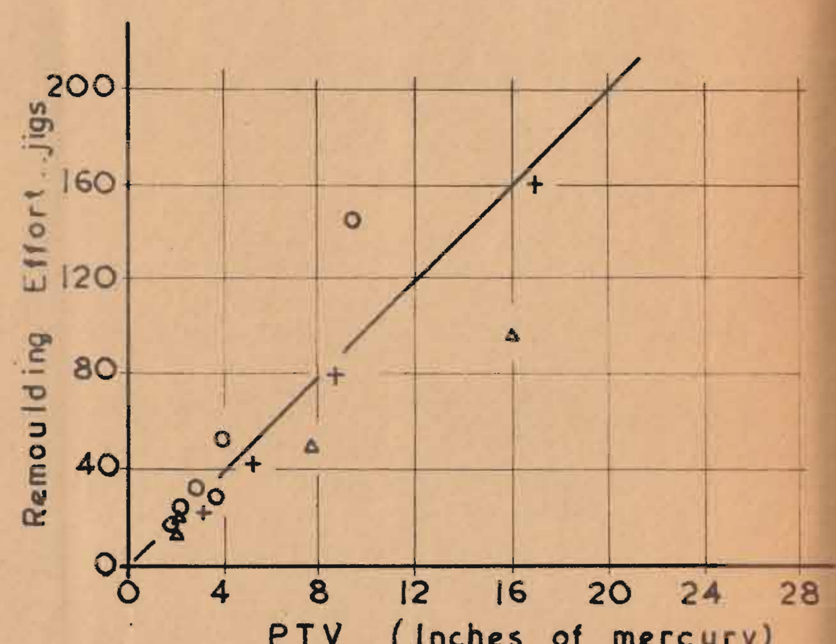


FIG. 106 .. SAND 45%

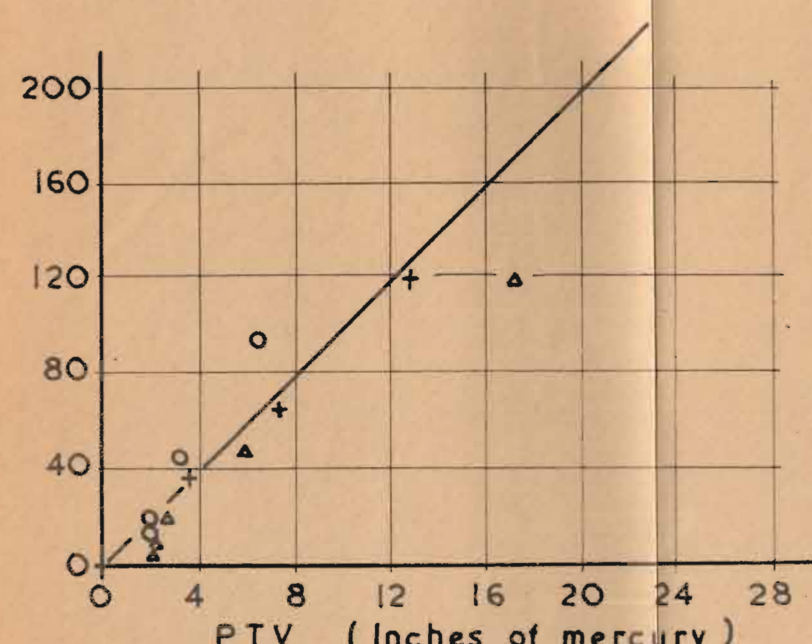


FIG. 107 .. SAND 50%

RELATION OF REMOULDING EFFORT TO PRESSURE TEST VALUES

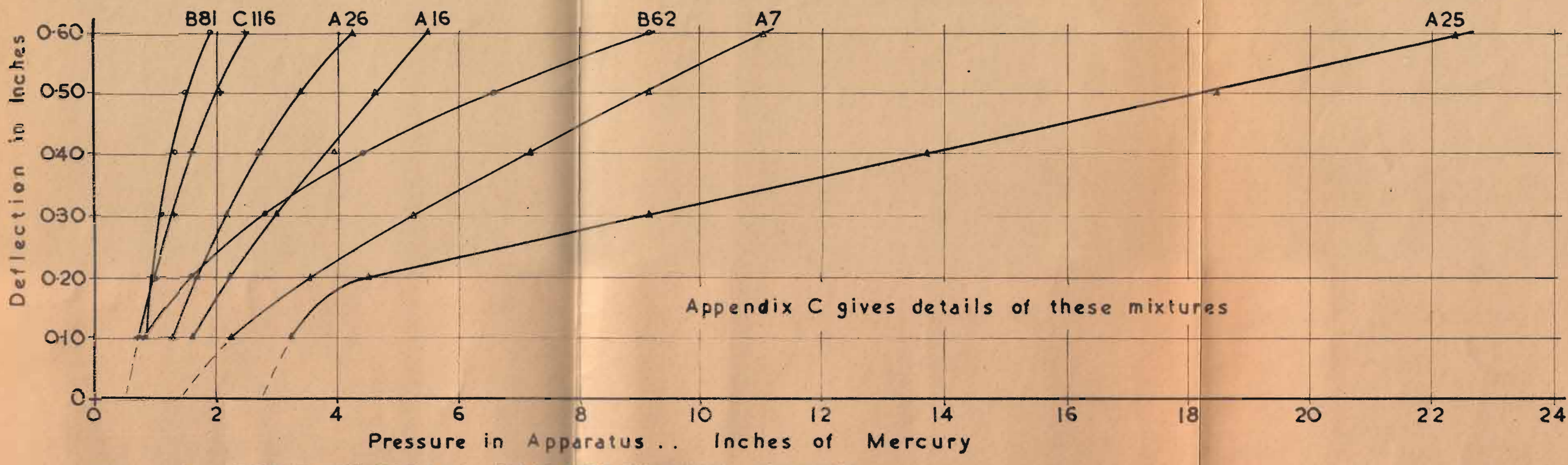


FIG. 108 . . SOME TYPICAL CHARACTERISTIC CURVES

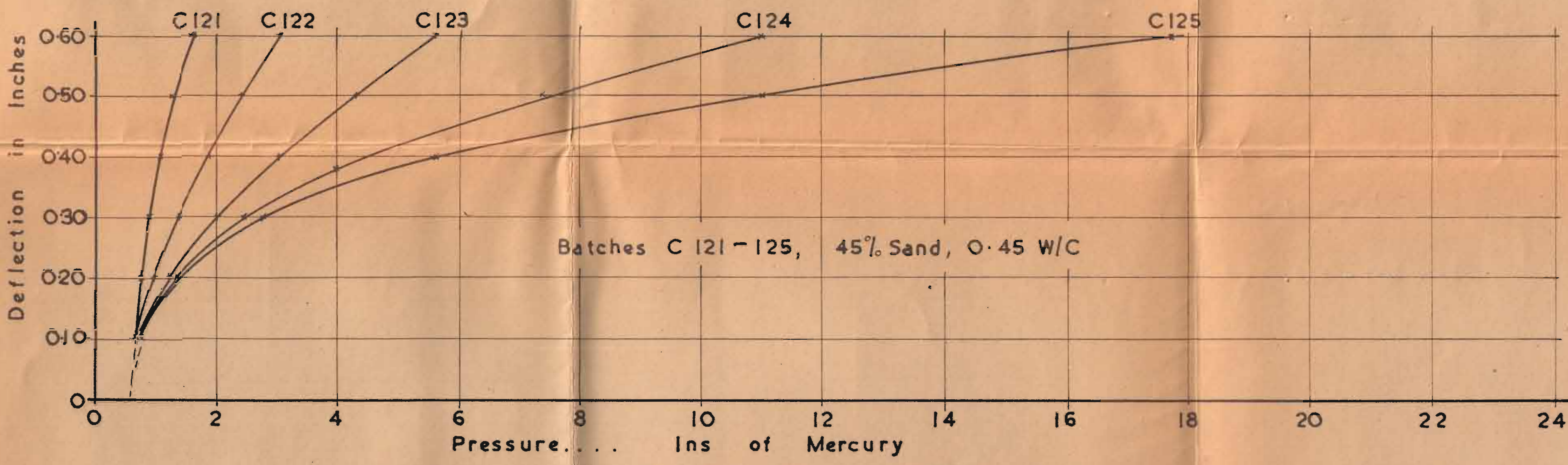


FIG. 109 . . TYPICAL FAMILY OF CURVES FOR CHANGING PASTE CONTENT

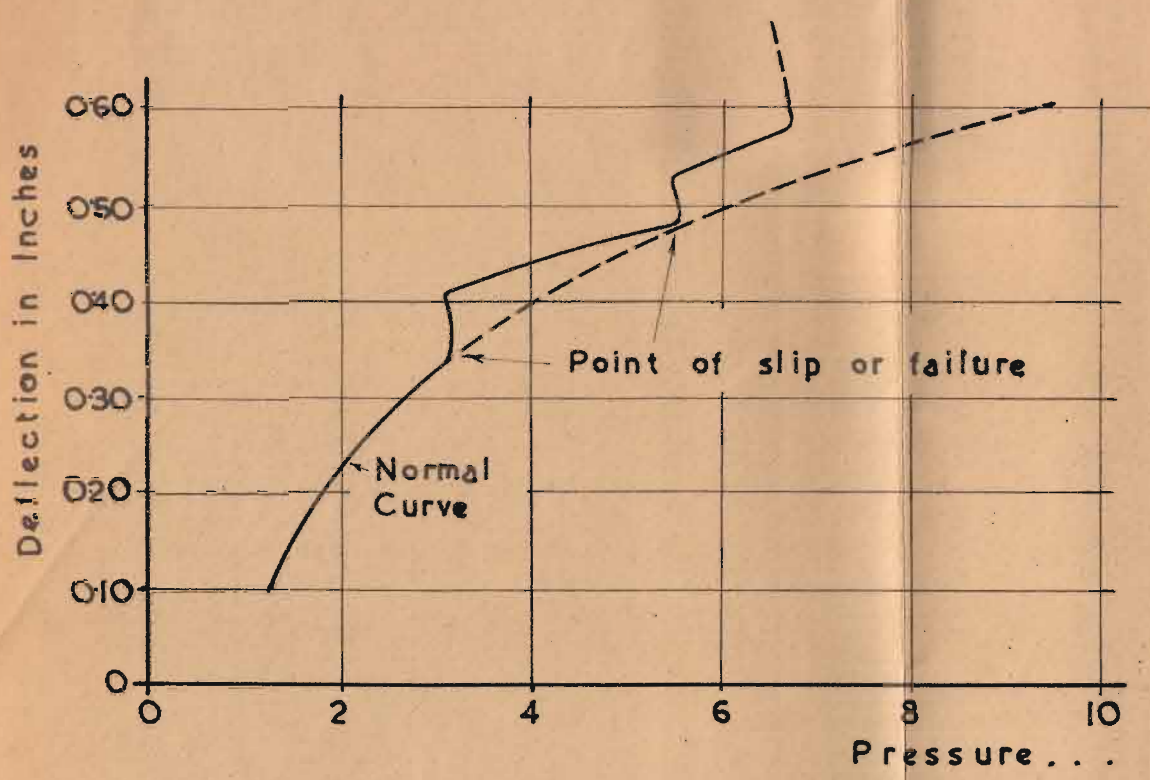


FIG. 110 . . FLOW OCCURRING IN SLIPS, EACH FOLLOWING AN INCREASE IN PRESSURE

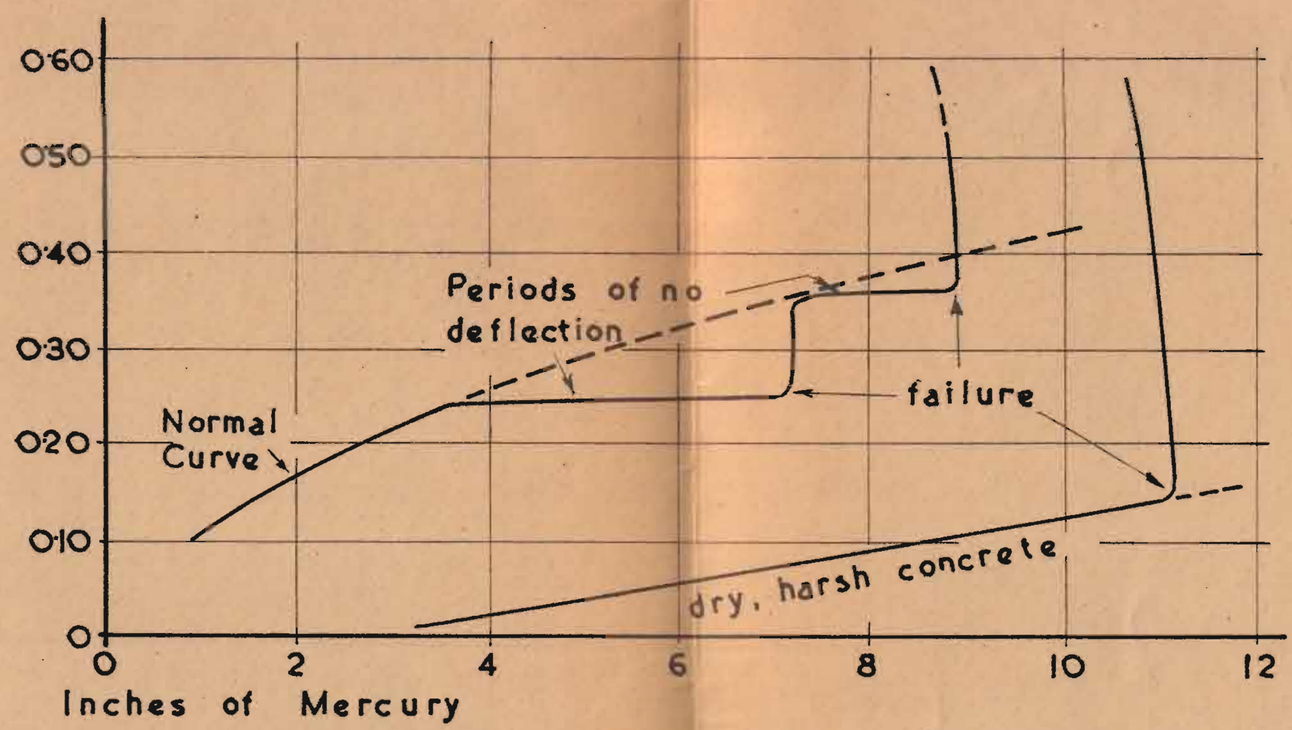


FIG. III . . DISCONTINUOUS FLOW AND MECHANICAL FAILURE OF SPECIMEN

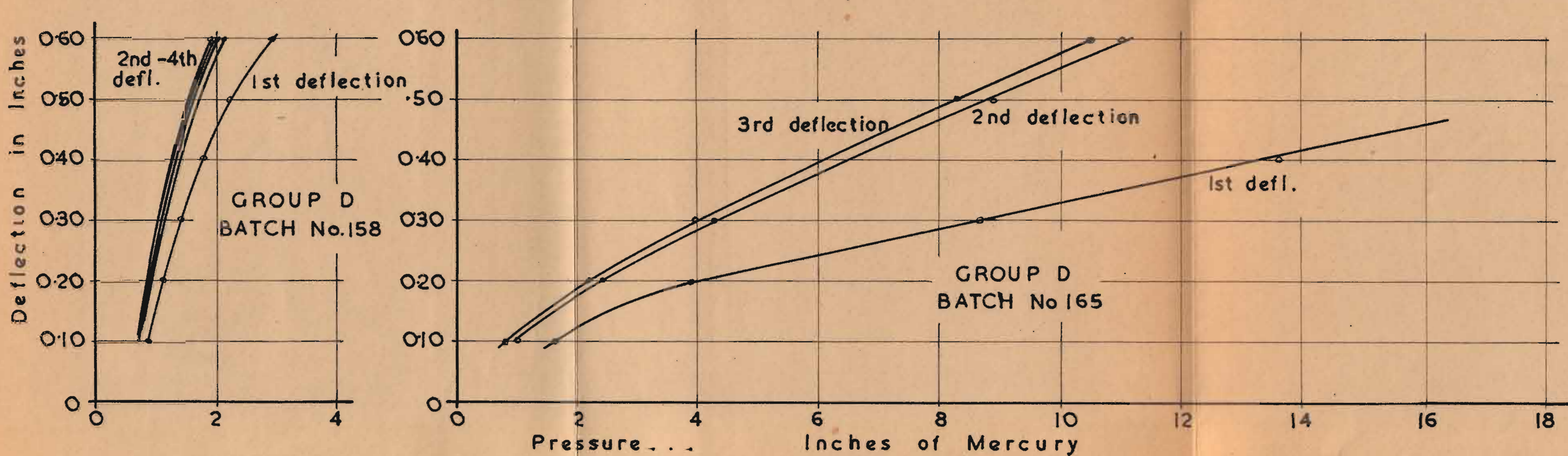


FIG. 112 . . EFFECT OF REPEATED DEFLECTIONS

PRESSURE TEST CHARACTERISTIC CURVES

NOTE: Percentages on the curves indicate the amount of sand in each series of batches expressed as a percentage of the weight of the combined aggregate.

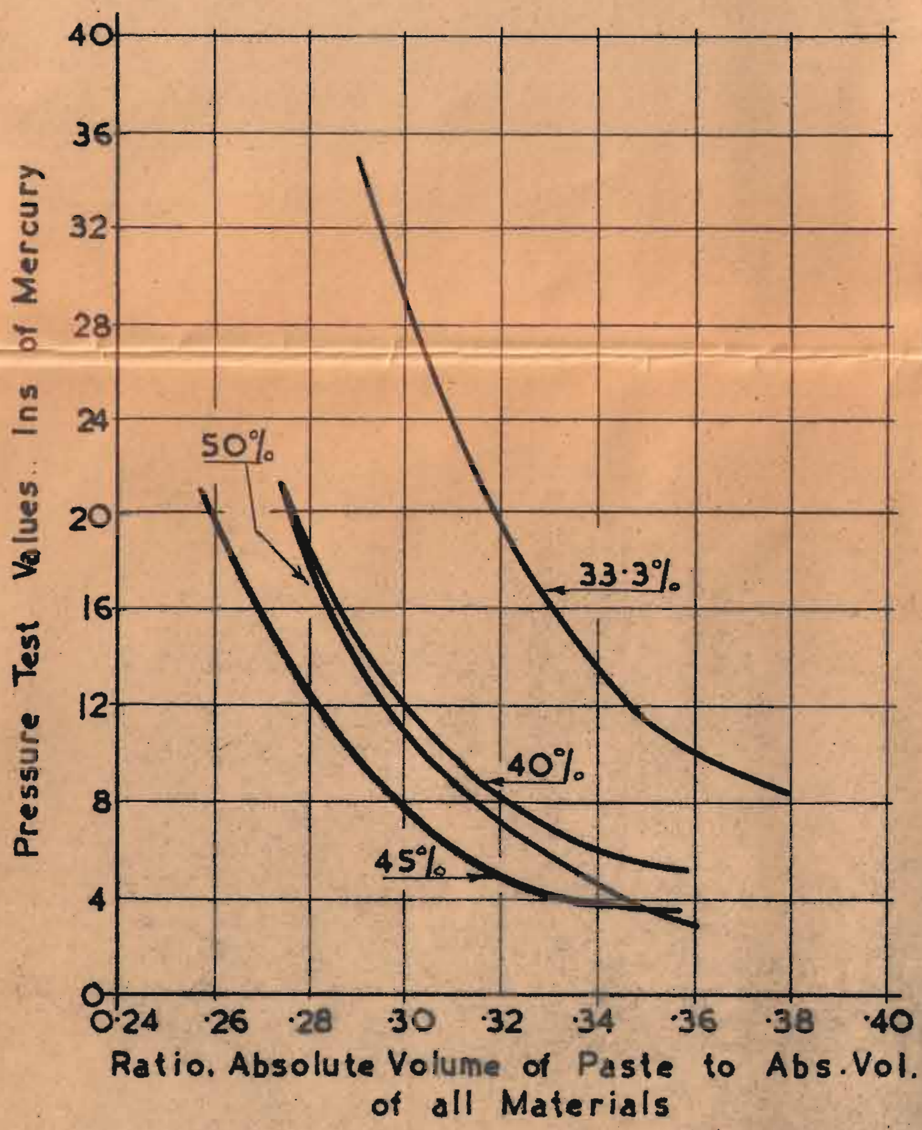


FIG. 76 A. WATER-CEMENT RATIO BY WT 0·45

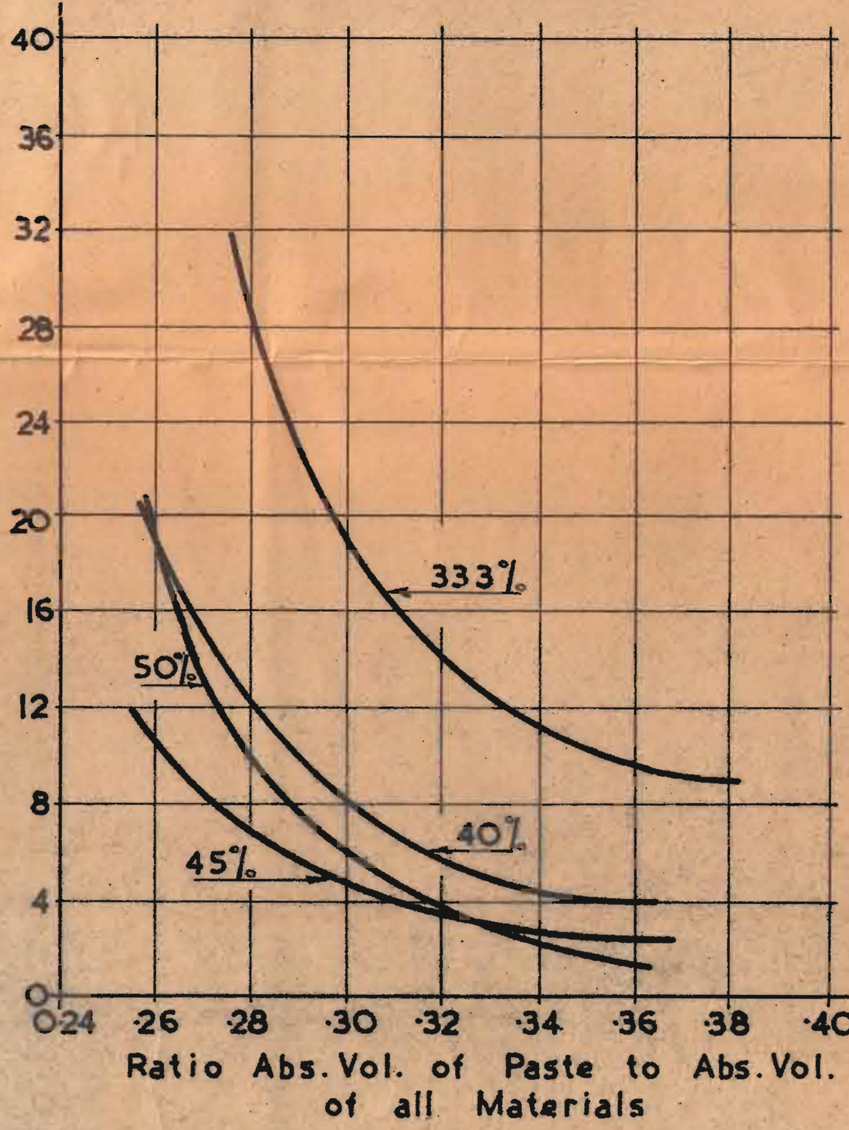


FIG. 77 A. WATER-CEMENT RATIO BY WT 0·575

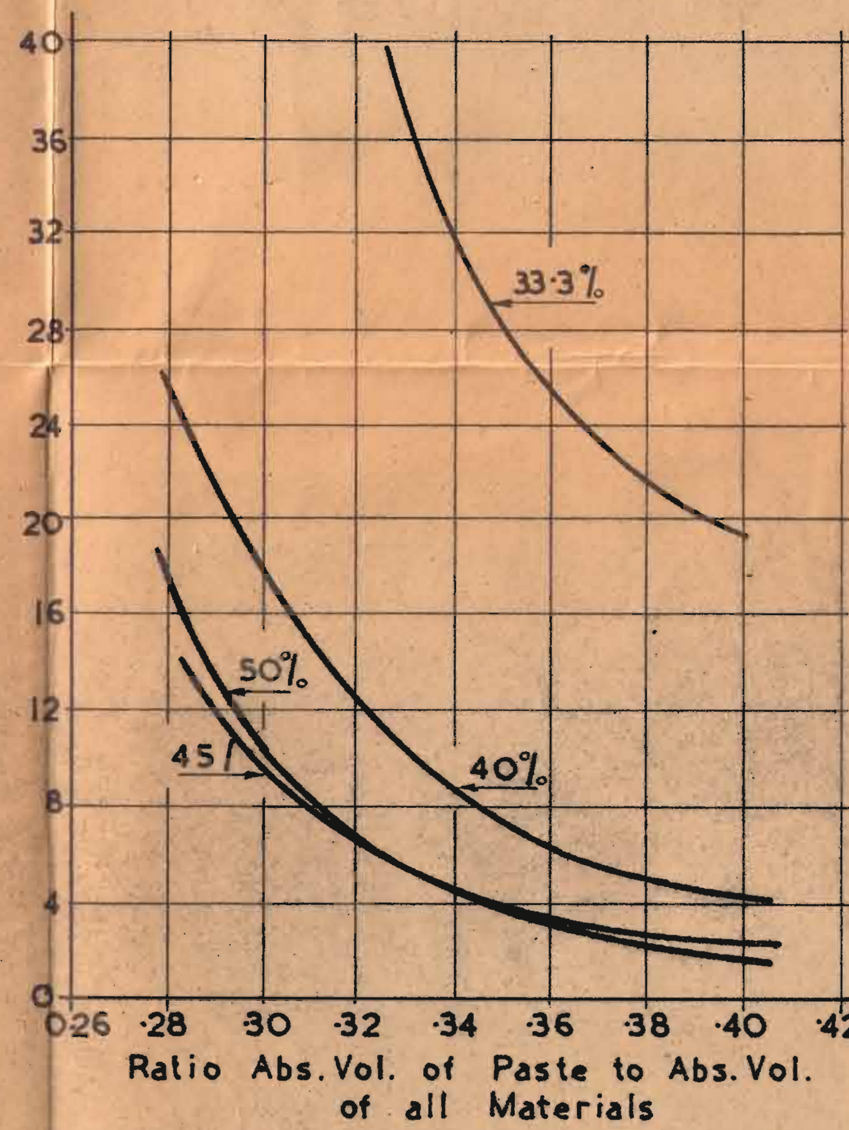


FIG. 78 A. WATER-CEMENT RATIO BY WT 0·70

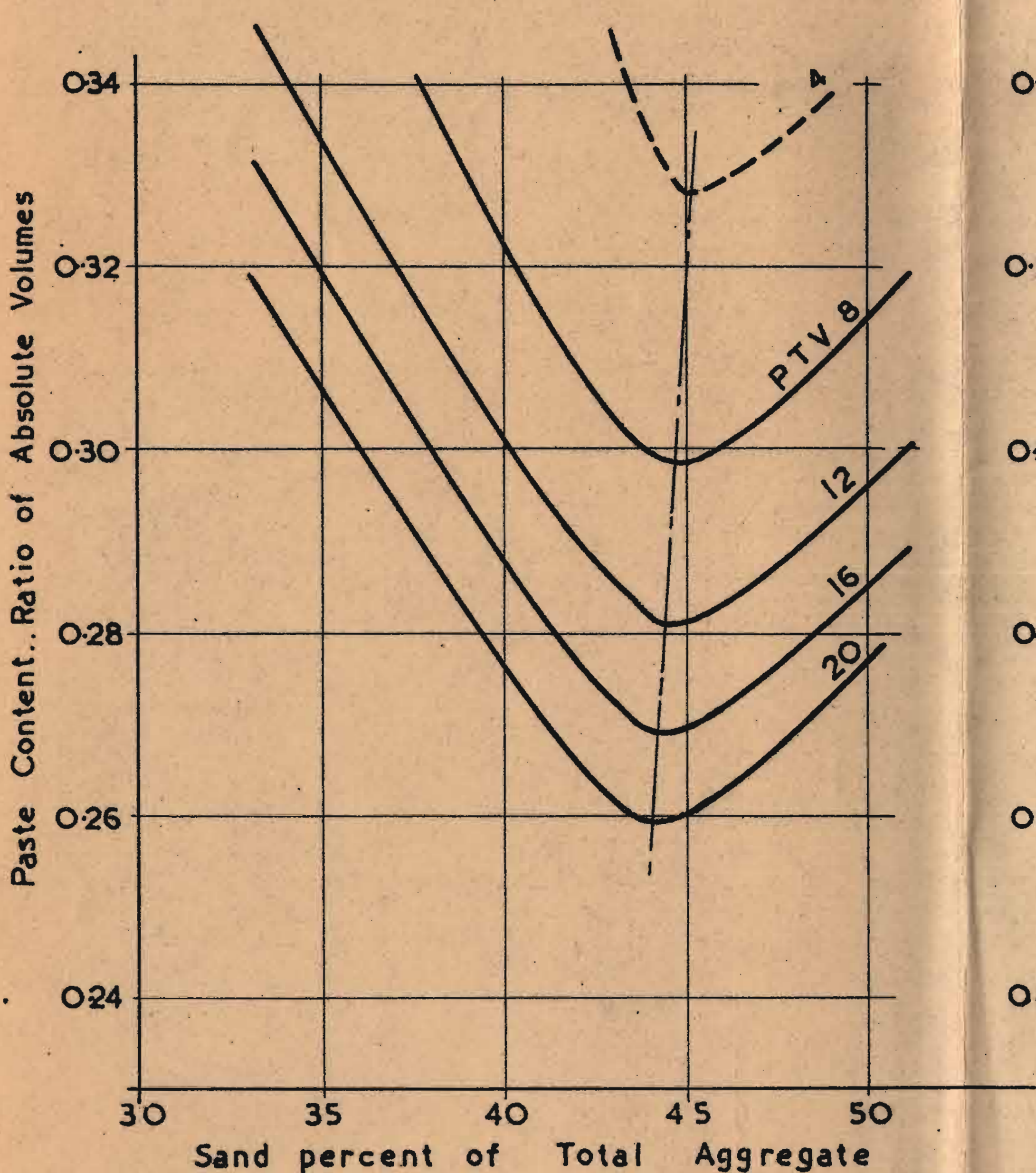


FIG. 76 B. W/C 0·45

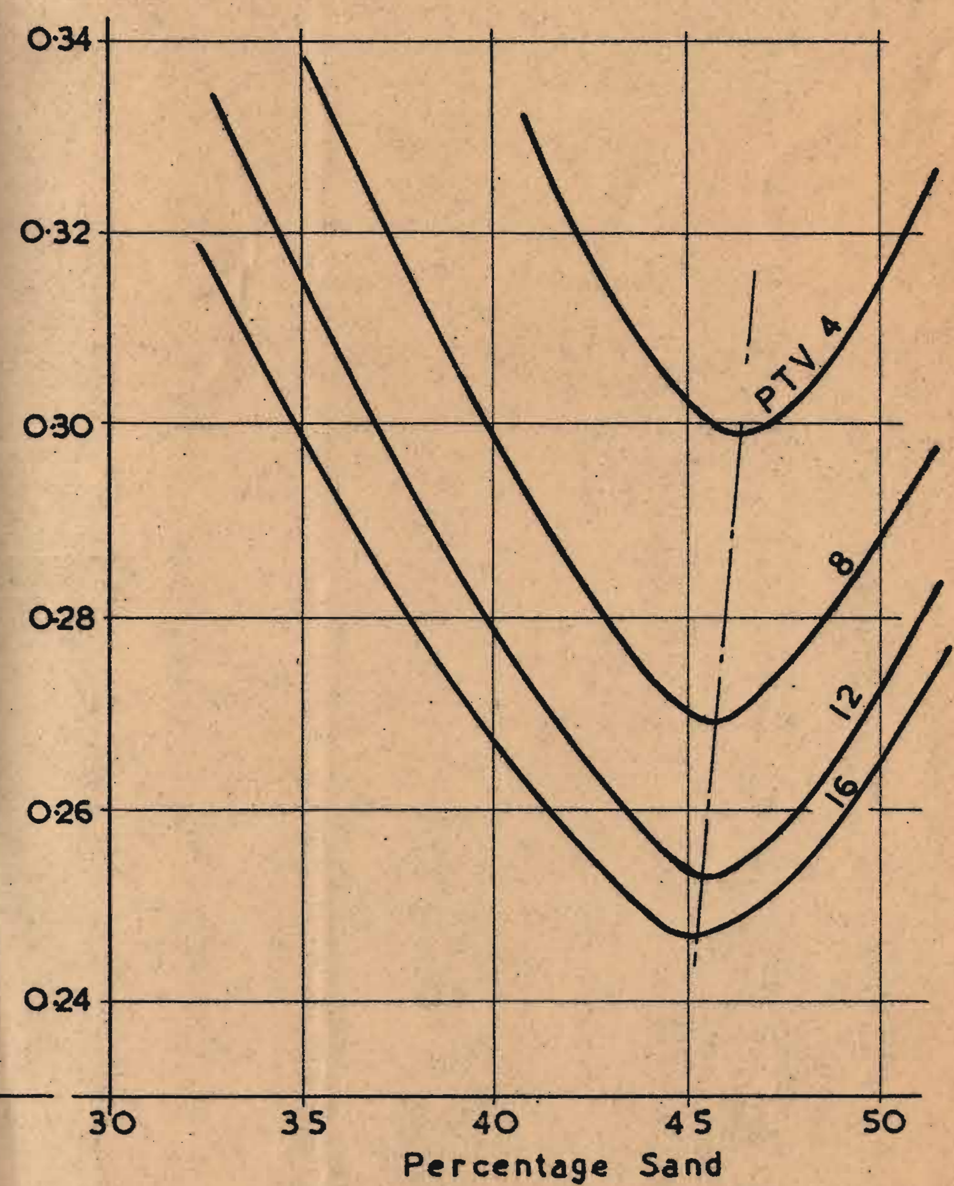


FIG. 77 B. W/C 0·575

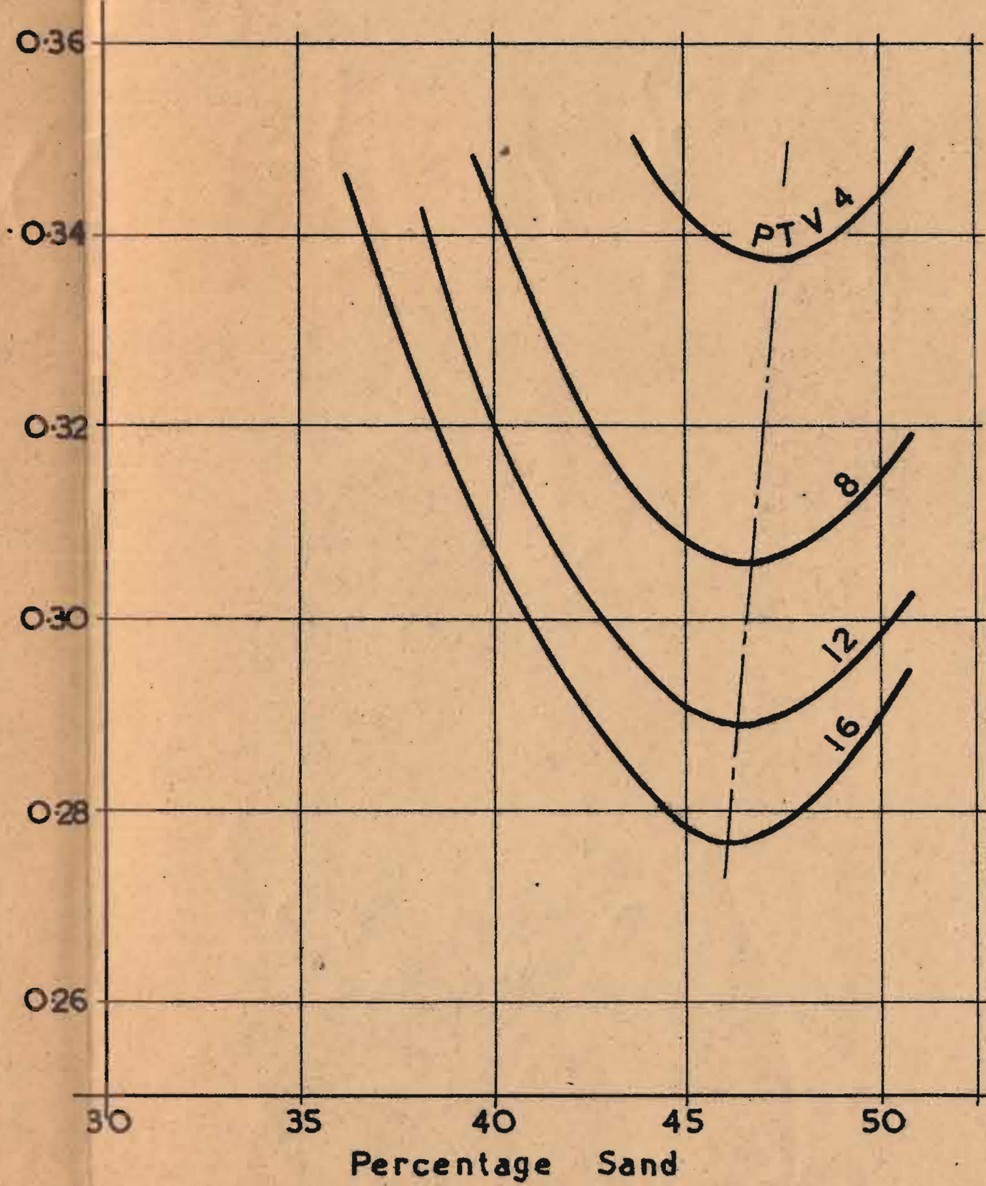


FIG. 78 B. W/C 0·70

RELATION OF PRESSURE TEST VALUES TO PASTE CONTENT AND PERCENTAGE SAND IN AGGREGATE

GROUP A GRADINGS

GRADING CURVES FOR MIXTURES USING CRUSHED BRACKENFEL GRANITE AND MALMSBURY RIVER SAND

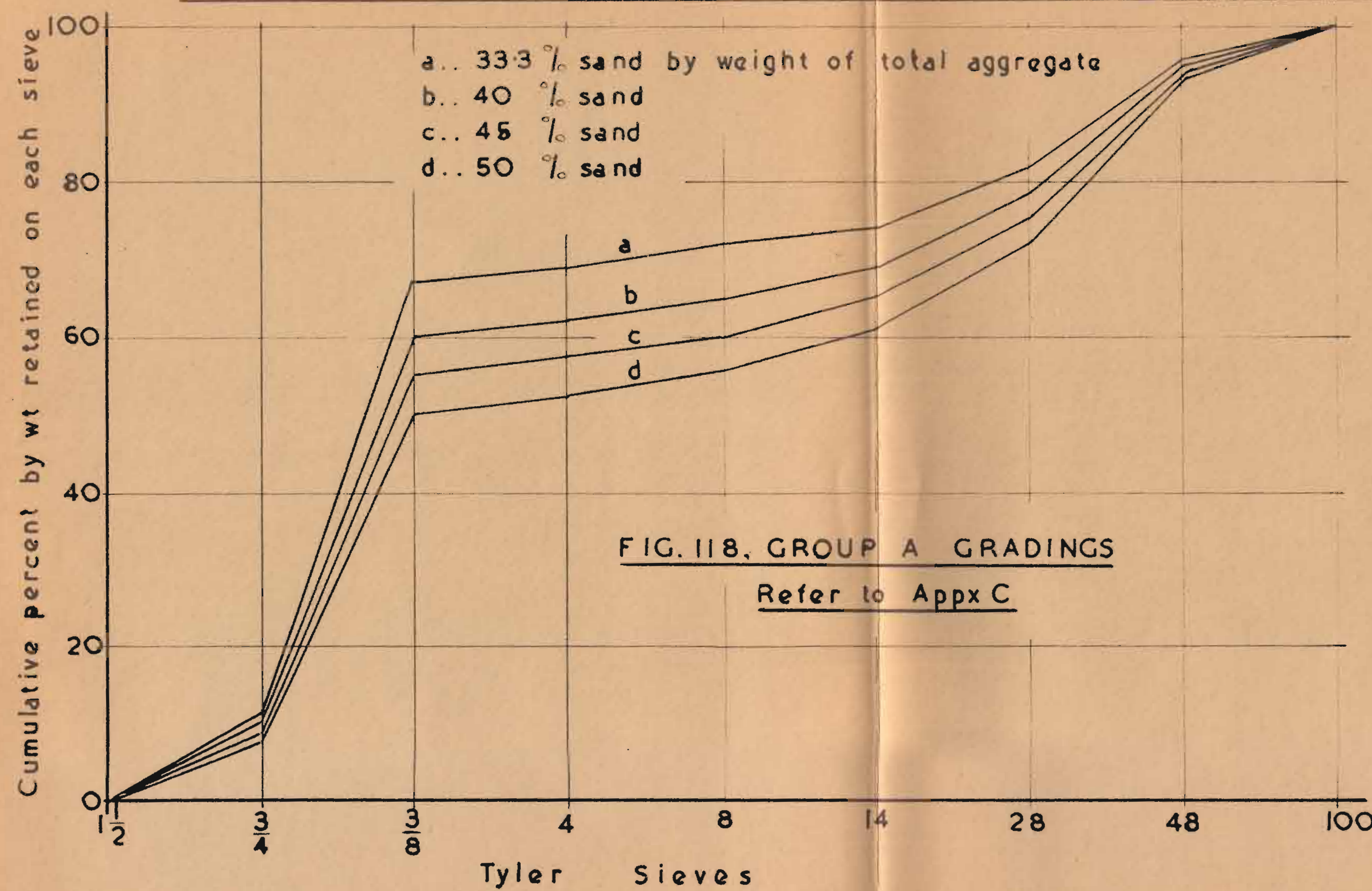


FIG. 118. GROUP A GRADINGS
Refer to Appx C

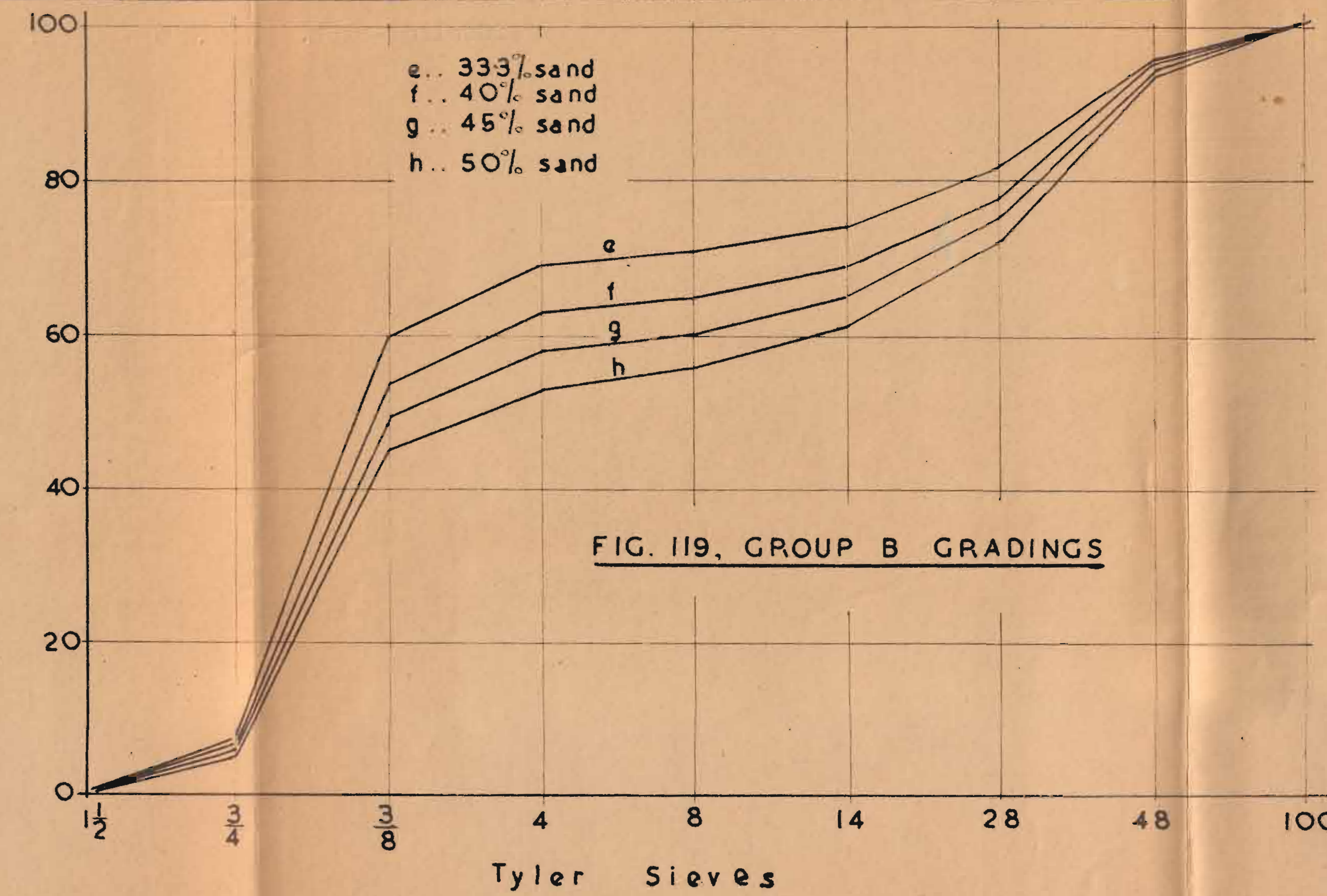


FIG. 119. GROUP B GRADINGS

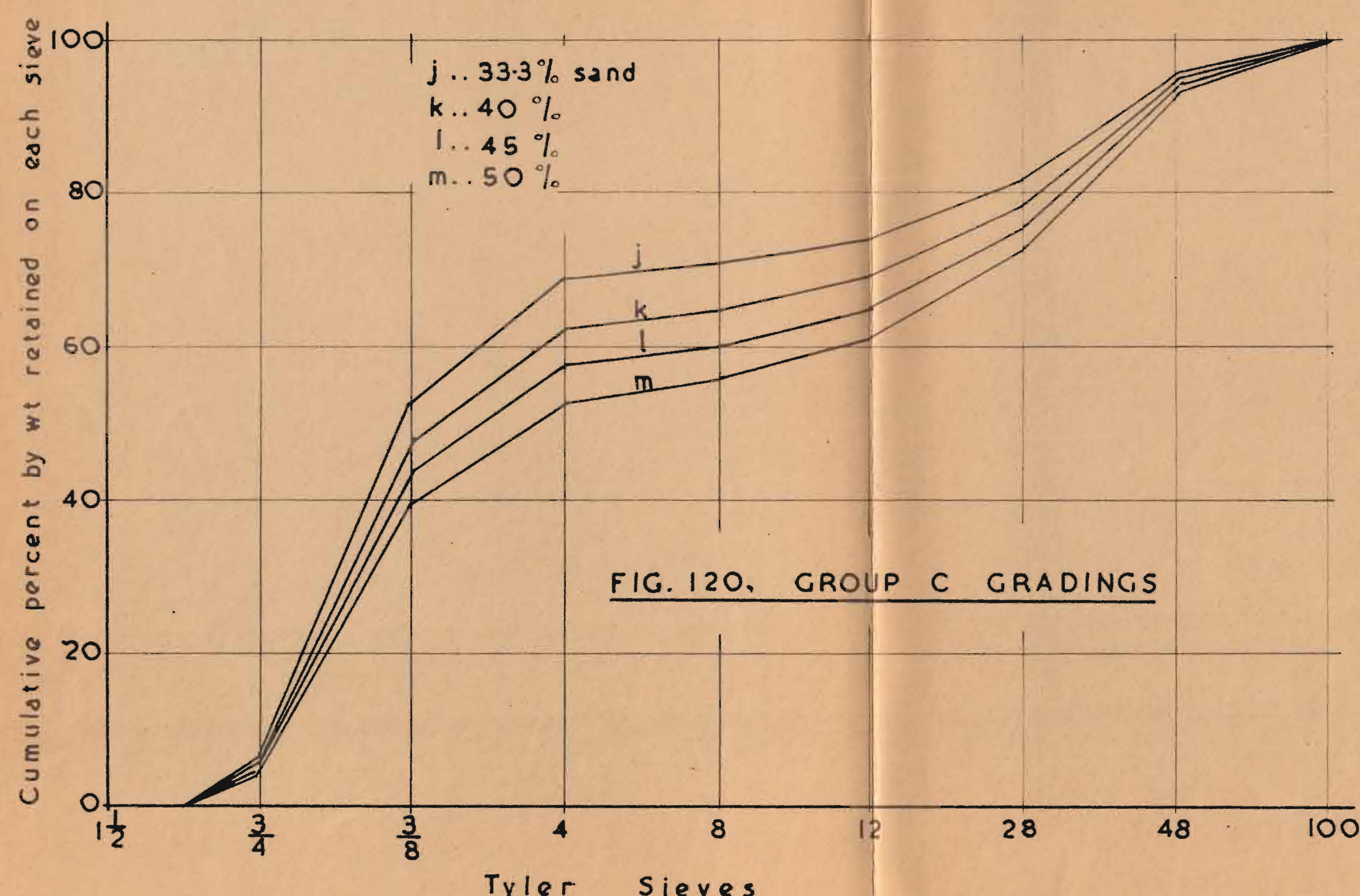


FIG. 120. GROUP C GRADINGS

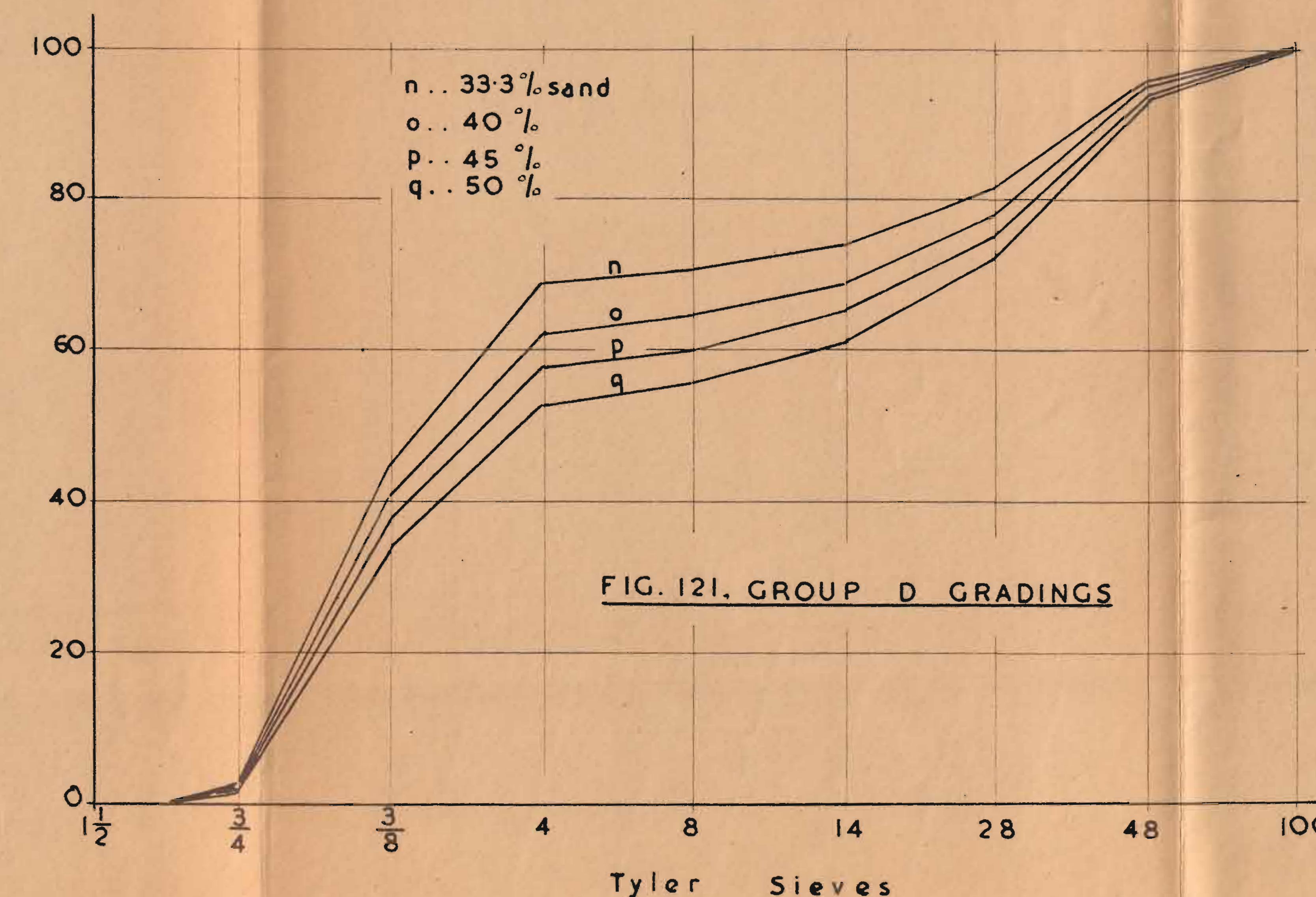


FIG. 121. GROUP D GRADINGS